BAYLOR GEOLOGICAL STUDIES

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Bulletin No. 42

Cenozoic Evolution of the Canadian River Basin

PAUL N. DOLLIVER

"Creative thinking is more important than elaborate equipment--"

FRANK CARNEY, PH.D.
PROFESSOR OF GEOLOGY
BAYLOR UNIVERSITY
1929-1934

Objectives of Geological Training at Baylor

The training of a geologist in a university covers but a few years; his education continues throughout his active life. The purposes of training geologists at Baylor University are to provide a sound basis of understanding and to foster a truly geological point of view, both of which are essential for continued professional growth. The staff considers geology to be unique among sciences since it is primarily a field science. All geologic research including that done in laboratories must be firmly supported by field observations. The student is encouraged to develop an inquiring objective attitude and to examine critically all geological concepts and principles. The development of a mature and professional attitude toward geology and geological research is a principal concern of the department.

Frontis. Sunset over the Canadian River from near the abandoned settlement of Old Tascosa, Texas. The rampart-like cliffs on the horizon first inspired the name "Llano Estacado" (Palisaded Plain) among Coronado's men.

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Cenozoic Evolution of the Canadian River Basin

Paul N. Dolliver

ABSTRACT

Given the landscape scale and time span being considered, the Cenozoic history of the Canadian River basin is best depicted in terms of changing surface geology, landscape and drainage network morphology, climate/ vegetation, and hydrology.

Drainage history of what is now the Canadian basin began with regression of a Late Cretaceous epicontinental sea during early stages of Laramide tectonism. Rising cratonic uplifts governed the pattern of continental emergence and early subaerial drainage. Major southeast-flowing rivers developed by early Eocene time, following paths of tectonic "least resistance" to the Gulf of Mexico. These avenues of regional fluvial sediment transport persisted throughout late Eocene erosion surface formation and subsequent widespread Oligocene-Miocene aggradation.

Ogallala sediments and the topography that they obscure permit the earliest detailed reconstruction of the proto-Canadian basin. Most basal gravel of the Ogallala Formation within the Canadian basin area originated in the southern Sangre de Cristo Range. Basal Ogallala sedimentation was triggered by late Miocene-early Pliocene uplift of a climatically modified Eocene erosion surface. A sparse network of entrenched montane border streams carried Ogallala sediment eastward and southeastward across northeastern New Mexico. Ogallala drainage of the Texas-Oklahoma Panhandle region was largely directed into an irregular array of solution-collapse depressions. Farther east, early Ogallala streams probably again flowed through discrete fluvial valleys.

Basal Ogallala deposition was followed by progressive valley and basin alluviation. Finer grained sediment eventually produced a coalescent plain of alluviation. The terminal alluvial plain was drained by a few laterally migrating consequent streams.

Detailed knowledge of the pre-Pleistocene Canadian montane border is restricted to the region south of the Ocate volcanic field. During Pliocene time, most of the Ocate region was a southeast-inclined erosion surface, which was drained by consequent trunk streams occupying essentially their modern positions. Pliocene montane border drainage headed in fault-bounded alluvial valleys and emerged from the mountains through narrow breaches in the Creston hogback. Sediment was dispersed east of the Creston onto a low relief piedmont alluvial plain. Late Pliocene-Pleistocene modification of this system of fluvial transport consisted of progressive and episodic entrenchment in response to epeirogenic uplift and cyclic climatic change.

Eastward-flowing Raton-High Plains Canadian tributaries established their modern courses during a short interval spanning the Pliocene-Pleistocene boundary. Lateral diversion of streams draining the terminal Ogallala alluvial plain intensified under the influence of late Pliocene epeirogenic movement. The drainage network changed radically as formerly consequent streams were reoriented subsequent to structures such as the Sierra Grande arch. The new drainage pattern rapidly stabilized as continued tectonism and initial Pleistocene glaciation caused widespread entrenchment. Entrenchment was most pronounced just north of the Canadian-Arkansas divide, where the early Pleistocene Cimarron River became incised to near its present level. Most changes in the fluvial landscape after network stabilization were confined to stream valley deepening and widening brought on by middle to late Pleistocene climatic reversals.

The south-flowing Ute Creek and the upper Canadian River also established their anomalous courses in accordance with the pattern of late Pliocene epeirogenic uplift. Ute Creek followed essentially its modern course before the end of the Pliocene. Lower Ute Creek valley originated with late Pliocene tectonism and achieved its present dimensions largely as a result of Pleistocene climatic change. Climate-related hydrologic shifts also induced downstream Canadian base-level fluctuations, which further promoted Ute Creek entrenchment, alluviation, and possible piracy near its confluence with the Canadian River.

The north-south reach of the upper Canadian River probably evolved by early Pleistocene time through headward migration and beheading of east-flowing montane drainage. Like Ute Creek, initial entrenchment of the south-flowing Canadian (to at least 65% of its present depth) occurred during late Pliocene-early Pleistocene tectonism. Climatically induced basin hydrologic changes and related downstream base-level lowering were responsible for most Pleistocene incision.

The montane headwaters of the Pecos River formerly flowed eastward into the Canadian River. The two fluvial systems remained linked throughout at least most of early to middle Pleistocene time. Sometime during or shortly after the middle of Pleistocene time, the Pecos River incorporated its upper drainage through headward

migration and capture of east-flowing montane drainage. Pecos-Canadian piracy produced the prominent right-angle bend of the Canadian River.

Development of the broad east-west-trending Canadian River valley began with termination of the Ogallala erosion cycle, was promoted by Pliocene-Pleistocene tectonism, and accelerated during Pleistocene climate- and drainage-related hydrologic changes. However, the most important factor in the valley's evolution was subsurface dissolution of Permian evaporites. Solution accelerated with heightened early Pleistocene groundwater recharge, triggering widespread vertical collapse without involving appreciable lateral migration of shallow dissolution fronts. This imparted a steeper, more easterly slope to the Panhandle High Plains surface and markedly influenced the location and dimensions of the Canadian valley. By middle Pleistocene time, the valley was almost as wide and about half as deep as the modern breaks. The middle-late Pleistocene history of the Canadian breaks is one of cyclic incision and alluviation.

Most Pleistocene changes in the Osage Plains Canadian drainage resulted from superposition of Ogallala alluvial/erosional plain streams onto Paleozoic bedrock and from cyclic climatic change. Progressive development of subsequent drainage involved stream incision, lateral channel shift, and headward tributary migration and piracy. The process advanced most rapidly during waxing middle Pleistocene (Kansan) glaciation.

INTRODUCTION*

PURPOSE

Some problems require that geologists work as historians; the task of recounting the development of a drainage basin is one such problem. Leopold, Wolman, and Miller (1964, p. 421) expressed the need for an historical perspective in this way:

> A river or drainage basin might best be considered to have a heritage rather than an origin. It is like an organic form, the product of a continuous evolutionary line through time.

The intent of this study is to trace the "evolutionary line" of the Canadian River basin.

Canadian basin evolution will be presented as the action of a fluvial system on a discrete but changing portion of the landscape. Factors influencing both the fluvial system and landscape will be described and related to one another within limitations imposed by the geographic scope, time span, and data to be considered.

LOCATION

The Canadian River flows 906 mi from headwaters in southern Colorado to its confluence with the Arkansas River in eastern Oklahoma. It drains a basin of roughly 47,600 sq mi encompassing parts of four states (Fig. 1).

The source of the Canadian River is high on 13,400-ft Purgatoire Peak in the Culebra Range of south-central Colorado. After a short reach in Colorado, the river continues southeastward into northern New Mexico, tracing a course out of the Sangre de Cristo Mountains. The Canadian turns southward near the town of Raton and parallels the mountain front for over 100 mi. All sizeable tributaries entering this stretch of the river drain the eastern flank of the Sangre de Cristo Mountains. Points of major tributary exit from the mountains coincide with the settlements of Cimarron, Mora, and Las Vegas.

At Conchas Reservoir, the south-flowing Canadian inscribes a broad right angle bend to the east. This easterly course is maintained for over 260 mi across the High Plains of northeastern New Mexico and the Texas Panhandle. The river flows by the plains cities of Tucumcari, New Mexico, and Amarillo, Texas, receiving additional discharge from mostly south-flowing tributaries. The Canadian basin begins to narrow in the vicinity of Amarillo, and most perennial flow farther east is confined to the Canadian and North Canadian Rivers. These plains streams gradually approach one another along subparallel courses, past the Panhandle towns of Borger and Canadian in Texas and Beaver in Oklahoma.

The Canadian traces three huge meander-like bends in northwestern Oklahoma before approaching to within 8 mi of the North Canadian near Canton Reservoir. The narrow basin, now defined by two adjacent parallel-flowing rivers, continues southeastward for 75 mi to the vicinity of Oklahoma City and Norman. The Canadian watershed broadens farther to the east before emptying into Eufaula Reservoir. Canadian drainage below Eufaula Dam is confined to a single meandering channel, which joins the Arkansas River not far downstream.

METHODS

A major part of constructing a drainage basin history such as this involves synthesizing a large and diverse body of published work. Aside from providing a general background, the literature was essential in developing several lines of inquiry. The limits of personal field observation were greatly extended by published accounts of tectonic and physiographic setting and of past changes in that setting. Most determinations of gravel provenance were made possible by detailed lithologic descriptions of source areas. Summations of climatic change, paleohydrologic reconstructions, and assessments of the role of evaporite dissolution on basin development are based almost entirely on data collected and interpreted by others. Finally, published absolute age determinations and erosion-surface correlations permitted the placement of drainage events within an absolute time frame.

Gravel and bedrock lithologic determinations comprise much of the original data base used in this study.

*A thesis submitted in partial fulfillment of the requirements for the M.S. degree in Geology, Baylor University, 1982.

Samples were collected from gravels which cap a variety of terrace, pediment, and alluvial surfaces and from miscellaneous bedrock exposures (Fig. 1, and Appendix A). Two gravel sampling procedures were employed. Representative samples consist of all clasts exceeding ¾ in (2 cm) in diameter collected from a 1 sq m area of surficial gravel. Diverse sample collecting involved the selection of individual cobbles that reflected the greatest lithologic diversity present at a locality.

A freshly broken surface of each clast and bedrock sample was examined to determine gross lithology. Several specimens were also studied in thin section to more precisely define distinctive elements of their petrography. In the case of representative gravel samples, lithologic analyses were used to subdivide the sample into six categories: metamorphics with non-directional structure, metamorphics with directional structure, clastics, nonclastics, plutonics, and volcanics (Appendix C). This gross summation of gravel composition was a useful means of denoting gravel provenance and detecting drainage-related changes in provenance.

Much of Canadian River basin history is chronicled in remnants of alluvium- and basalt-covered erosion surfaces. The morphology and physiographic setting of many of these surfaces were deduced from published topographic and geologic maps. All specific determinations of gradient, elevation, and relief were made from 1:24,000 scale topographic maps.

Several projected profiles were drawn along selected transects of the upper Canadian basin and Canadian breaks. The method of profile construction was adapted from a procedure described in King (1966, p. 236-238). Profiles generally supplement other depictions of modern Canadian basin physiography and specifically highlight topographic evidence of basin history.

PREVIOUS WORKS

This study presents the Canadian River basin from the perspective of late 20th century science. Previously established facts and reasonings that support this portrayal will be introduced at appropriate intervals in the text. Such an approach has two advantages. It minimizes the need for a preliminary recitation of previous works, and it allows for a brief recounting of precursors to the modern scientific view of the Canadian River and its basin.

Many non-scientific perceptions of the Canadian River come to light in deciphering the origin of its name. The notion that "Canadian" refers to the trappers who frequented the basin in the 18th and early 19th centuries is a popular one (Shirk, 1974, p. 42). Indeed, in 1739 two French Canadian trappers (the Mallet brothers) were possibly the first white men to lead a party down the length of the river (Folmer, 1939, p. 170.). Their enterprise revealed a route between Spanish Santa Fe and French outposts on the lower Arkansas River. While never achieving the prominence of the Santa Fe Trail, the valley of the Canadian River did become an important commercial thoroughfare and emigrant trail. The route was variously known as the "Great Spanish Trail," the "Marcy Road," or one of several "California Roads" (Pool, 1975, p. 108). However, the name "Canadian" predates the river's use as a route between Santa Fe and the eastern settlements.

Lieutenant J. W. Abert, in recording his 1845 expedition to the upper Arkansas region, noted what he felt to be the origin of the word "Canadian." He referred to "an excursion to the river and great cañon through which it flows, and from which is derived the Canada, or Canadian River" (cited in Hodge, 1949, p. 91). The Spanish word "cañada," meaning "ravine" or "gulch" (Pearce, 1965, p. 24), vastly understates the dimensions of the canyon encountered by Abert's party. The area in question is precisely that shown in Figure 8 (Galvin, 1970, p. 24). In fact, since before Coronado's time, eastbound travelers had skirted the rugged country of the south-flowing Canadian in favor of the river's broad east-west valley. Coronado's men were following this valley when they first viewed the rampart-like cliffs of the Llano Estacado (meaning "stockaded" or "palisaded plain"—see cover) (Bolton, 1964, p. 243). The red rock of these cliffs probably had more to do with the naming of the Canadian than did a spectacular but impassable canyon.

Indian knowledge of the Canadian River predates that of Coronado's company by several millenia. Generations of life along the river are recorded in big game kill sites, flint quarries, campsites, and even the ruins of stone slab houses high on the bluffs of the Llano Estacado (Pool, 1975, p. 13-14). Indian names for the Canadian have also endured and suggest a fascination with the river's color. The Kiowa word "gu' adlpah" ("alongside a red hill or bluff") and the Caddo word "kanohatino" ("red river") are examples of this (Pearce, 1965, p. 24-25). The latter term might easily have been adapted to the Spanish "Canadiano." Interestingly, Spanish maps of the Canadian also carry the names "Rio Rojo" ("red river") and "Colorado" ("red") (*ibid.*).

Names and their contained meaning make up most of pre-19th century "previous works" concerning the Canadian River. Beginning in 1819 with Stephen Long's misguided descent of the "Red" (Canadian) River (James, 1823, p. 166-167), the Canadian basin became the object of scientific scrutiny. Scientists on 19th century exploratory expeditions through the basin described and categorized its natural resources (Fig. 2). The descriptive process continued into the late 19th and 20th centuries with more detailed and comprehensive observations. The context of these observations inevitably expanded to include genetic interpretations of the data being gathered. Discussions presented in succeeding pages are an exercise in such genetic or historical interpretation.

ACKNOWLEDGMENTS

I am indebted to numerous parties and individuals whose material and moral support have made this study possible. Field expenses during early stages of the project were partially defrayed by a Baylor Faculty Research Grant. Field assistance was rendered by many individuals; particular thanks go to Chris Hayward, Philip and Kathy Robinson, and Doug Storey. Sample collection at a number of localities would not have been possible without access permission granted by several New Mexico landowners. Thanks are especially due personnel of Vermejo Ranch and the Philmont Scout Ranch, who granted admission to areas normally closed to the public.

Many hours were occupied in library research, time that was more profitably spent because of assistance

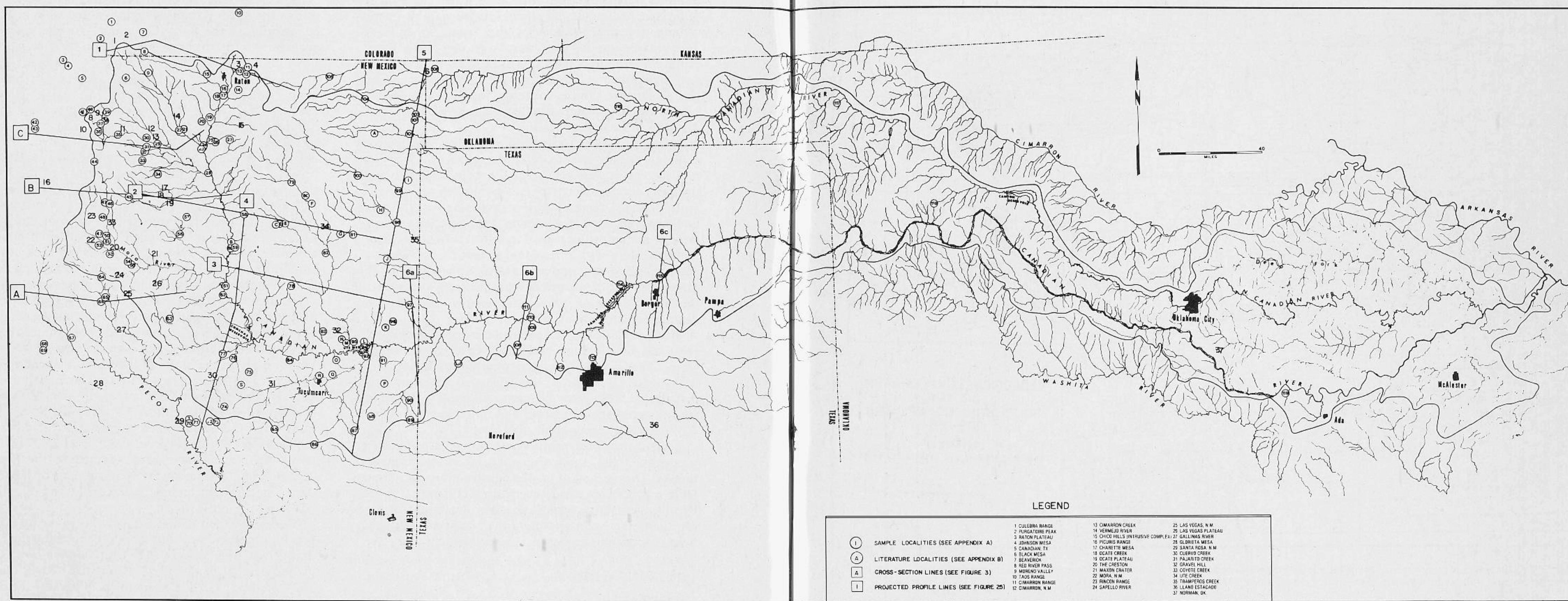

Fig. 1. Map of the Canadian River basin showing sample/literature localities, cross-section lines, and lines of projected profiles. Base adapted from Roberson, 1973, Plate 1.

provided by library personnel. I am especially grateful to library staff members at the following institutions: Baylor University, Colorado Historical Society, Colorado School of Mines, Denver Public Library, New Mexico Institute of Mining and Technology, University of New Mexico, University of Oklahoma, University of Texas at Austin, University of Wisconsin-Madison, and the U.S. Geological Survey Library in Denver. Research assistance was also supplied by employees of the State Agricultural Research Station at Bushland, Texas, and by Mr. John C. Williams of the Canadian Municipal Water Authority.

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Dr. O. T. Hayward, my thesis advisor, deserves more credit than he would willingly acknowledge. His suggestion of the topic, field acumen, attention to method and interpretation, and his sustaining faith in the completion of the project have been an immense help. Geomap/Peppard and Associates has been exceptionally helpful both in lending generous material support and by frequently indulging one of its employee's deviations from duty. Finally, I thank my wife, LaVonne, my family and friends, whose forbearance and support have far exceeded expectations.

Acknowledgment of assistance is not an assignment of responsibility. The reasonings and conclusions on the following pages are my own. To the extent that they have been enhanced by others, I am grateful; to the extent that they are in error, they are my own.

THE PRESENT-DAY CANADIAN RIVER BASIN

To best view the Canadian River as a fluvial system evolving through successive erosion cycles, one must appraise the variables affecting drainage basin morphology that are most appropriate to such a broad perspective. Basin geology, morphology (of both landscape and drainage network), climate/vegetation, and hydrology (chiefly runoff and sediment yield) are regarded as the best characterizations of the fluvial system in light of the landscape scale and time span being considered. The portrayal of the Canadian River basin in the following pages is thus an outline, to which subsequent discussions of basin history will add further dimension.

Discussion of basin geology and morphology follows a physiographic outline—the Canadian River basin being divisible into five physiographic units: Sangre de Cristo Uplift, Raton Section, Pecos-Canadian Valley, High Plains and Osage Plains.

GEOLOGY AND MORPHOLOGY

Sangre de Cristo Uplift

The headwaters of the the Canadian River and several of its major tributaries drain the eastern flank of the Sangre de Cristo Mountains of southern Colorado and north-central New Mexico. Bounded on the west by the downfaulted Rio Grande Depression and terminating eastward in the upturned western limb of the Raton basin (Figs. 3, 4), the Sangre de Cristo Range is a south-trending complex of intrusive and faulted structural elements. Near the source of the Canadian River, a core of Precambrian igneous and metamorphic rocks is mantled by eastward-dipping Cretaceous and early Tertiary age sedimentary rocks, crested with mid-Tertiary volcanics, and broken by Tertiary intrusive bodies. Southward, these intrusives occur as thick sills within sedimentary rocks that dip off uplifted Precambrian metamorphics of

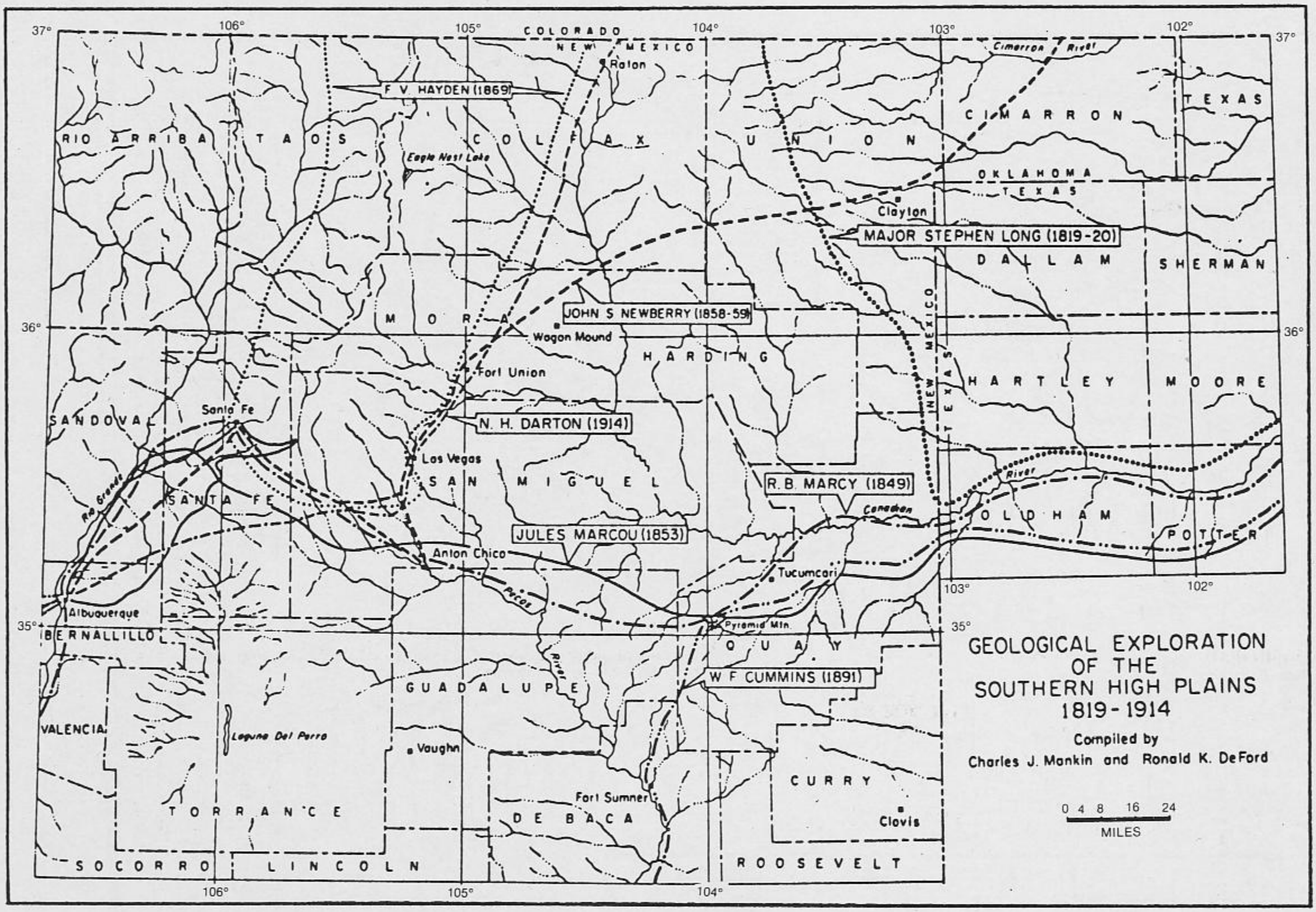


Fig. 2. Map showing the routes of early scientific parties across the western Canadian River basin. Most of these parties, like the nomads, explorers, and travellers before them, followed the avenue of the river. From DeFord, 1972, p. 66, used with permission.

the anticlinal Cimarron Range (Goodnight, 1976, p. 137). Normal faults west of the anticline roughly delineate the structurally complex region of Moreno Valley, a broadly synclinal feature (Fig. 3). South and east of this region the Sangre de Cristo Uplift adjoins the Raton basin along a zone of high angle reverse faults that extends southward to near Las Vegas. This zone commonly forms a distinctive hogback ridge of Paleozoic and Mesozoic sedimentary rocks called the "Creston" (Fig. 5). West of the Creston, upthrust Precambrian and Paleozoic age rocks (comprising the Rincon Range) are less deformed than those of comparable age farther north. Tectonic disruption continues to diminish southward until the Rocky Mountains just beyond the Canadian basin dissipate into the broad syncline of Glorieta Mesa.

The crest of the Sangre de Cristo Mountains, culminating in Wheeler Peak (13,160 ft in elevation), traces the Canadian-Rio Grande drainage divide and, to the south, the Canadian-Pecos River divide. From the Colorado-New Mexico state line south to the Cimarron Range, the Sangre de Cristo Range descends east and southeastward to a broad piedmont. The mountain flank is drained by a network of parallel streams (the largest of which are the Canadian and Vermejo Rivers), which become progressively more entrenched downstream. Streamflow emerges from the mountain front in canyons that are as much as 1000 ft lower than adjacent divides. Entrenchment is even more pronounced to the south, where Cimarron Creek transects the Cimarron Range in a precipitous canyon more than 2500 ft below nearby promontories (Fig. 6). The western flank of the Cimarron Range faces the eastern front of the Taos Range across the broad U-shaped alluvial Moreno Valley. Drainage that is tributary to Cimarron Creek extends the length of the north-south-trending valley, having a northern source near Red River Pass and a southern source in the western fringes of the Ocate Plateau (a re-entrant of the Raton section). The Rincon Range south of Ocate Plateau rises to a low-relief summit region some 1500 to 2000 ft above flat-floored alluvial valleys occupied, or once occupied (Fig. 7), by southward- and eastward-flowing tributaries of the Mora River system. The system's subdendritic (Howard, 1967, p. 2247) network reflects the imprint of regional structural and topographic control imposed by south-trending reverse faults and associated features such as the Creston.

Raton Section

The Raton section is a piedmont plain and plateau unit

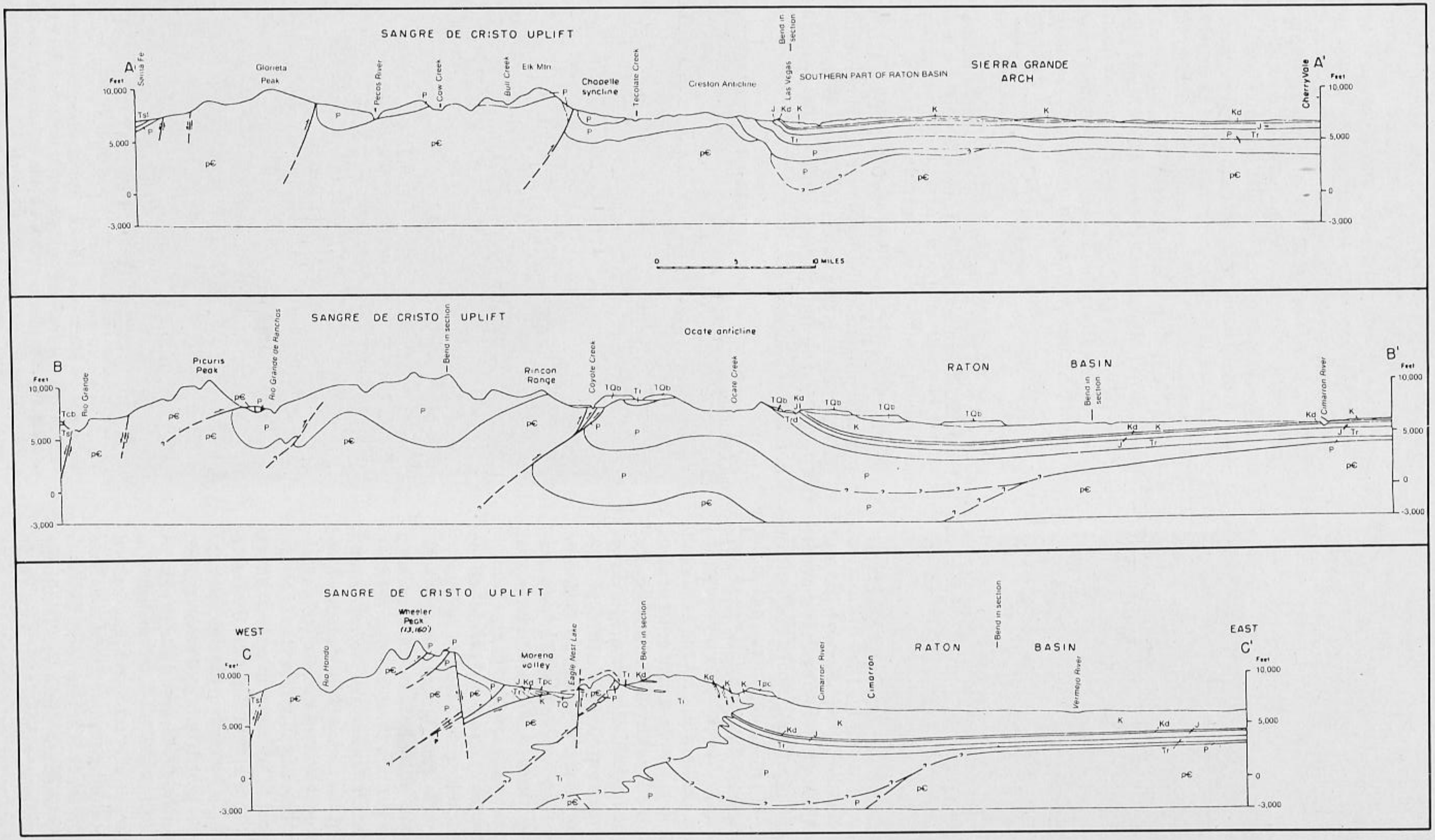


Fig. 3. Diagrammatic cross-sections showing the general structure of the Sangre de Cristo Mountains and western Raton basin, New Mexico. See Fig. 1 for cross-section locations. Symbols: Q—Quaternary, TQv—Tertiary-Quaternary volcanics, Ti—Tertiary, T—Miocene-Pliocene, Kt—Late Cretaceous-Early Tertiary, K—Cretaceous, M—Triassic-Jurassic, P—Permian, Pa—Paleozoic, Pc—Precambrian. The present structural setting was established during Miocene-Pliocene tectonism. Contrasting styles of deformation within the Sangre de Cristo Range help explain differences between Santa Fe and Ogallala deposition. The range's western margin was downfaulted by as much as 7.5 mi (12,000 m), inducing deposition of voluminous syntectonic fans of Santa Fe sediment. East of the structural divide, deformation was directed along west-dipping high-angle reverse faults. Pre-middle Pliocene truncation of the resulting upthrusts evidently produced much of the coarse-grained lower Ogallala Formation. The basal Ogallala was dispersed eastward across the tilted erosional plain and into fluvial valleys and alluvial basins. Adapted from Baltz et al., 1959, pocket.

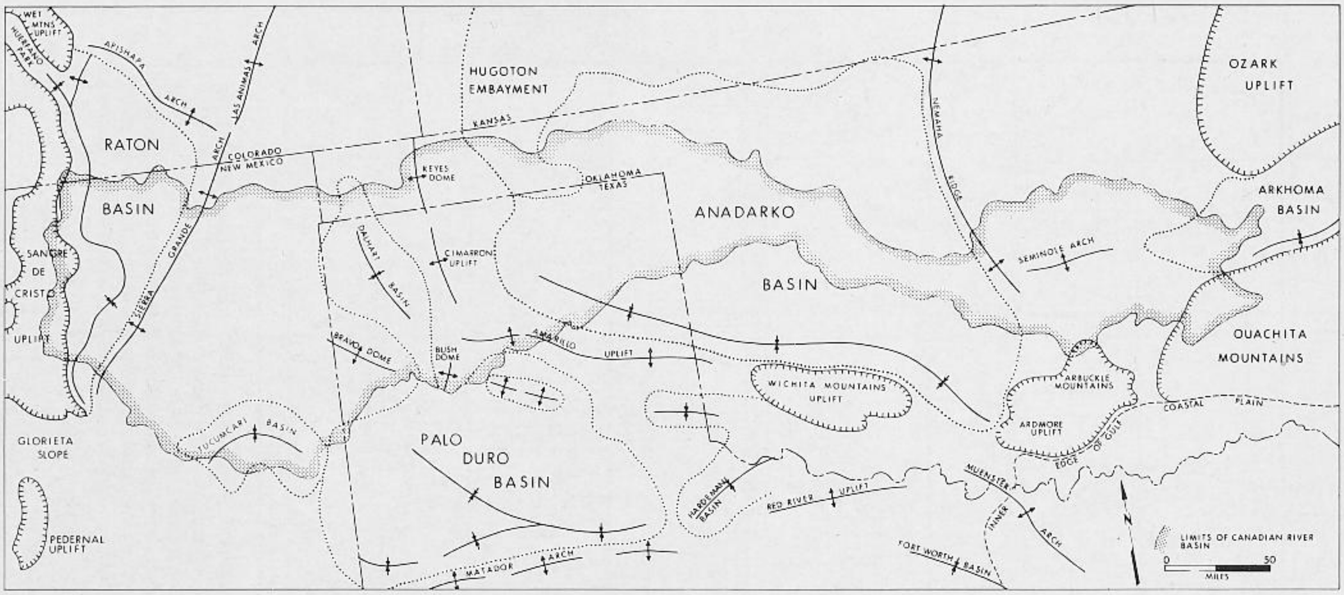


Fig. 4. Map of major tectonic elements within and surrounding the Canadian River basin. Most of these features have affected drainage basin development since regression of the Late Cretaceous epicontinental sea (Fig. 18). Structural features are compiled from AAPG, 1944; Arbenz, 1956; Baltz, 1965, p. 2043; Cronin, 1961, p. 11; Totten, 1956, p. 1963.

that slopes eastward from the southern Rocky Mountains (Fig. 8). The region is structurally (and to an extent areally) defined by two broad features: Raton basin and the Sierra Grande arch (Fig. 4). Raton basin is a north-trending and north-plunging asymmetrical trough with a more gently dipping eastern limb that culminates in the northeast-trending crest of the Sierra Grande arch. East of the axis of the arch, Paleozoic and Mesozoic age strata gradually plunge into the Dalhart basin in the Texas and Oklahoma Panhandles. Regional basement relief of up to 7000 ft within the Raton section (Woodward and Snyder, 1976, pocket) is subtly reflected in the subsurface distribution and structural attitude of Devonian through Cretaceous age sedimentary rocks. Miocene to Holocene volcanics, mid-Tertiary intrusives, and late Tertiary clastics (Ogallala Formation) occur widely on the truncated surface of the older sedimentary units (Fig. 8).

The east-trending northern drainage divide of the Canadian River system transects a region of basalt-capped plateaus and basalt- and Ogallala-veneered upland plains that rise to over 1000 ft above intervening drainage courses. These courses form a radial network projecting outward from the basalt plateau region and the undulating terrain of the Chico Hills intrusive complex. An extensive, relatively undissected outlier of Ogallala clastics and intermittent basalt cover extends southward from the complex. The eastern and southern margins of the outlier face Ute Creek and the Canadian River, respectively, along a bold sandstone escarpment averaging 500 ft in relief. A greatly subdued western scarp overlooks the broad north-south-trending outer valley of the Canadian River (Fig. 9). The inner valley is a southward-deepening canyon that emerges at the scarped boundary between the Raton section and the Canadian-Pecos Valley section. The valley is at this point a 1400-ft gorge incised into a surrounding Mesozoic sandstone upland (Fig. 10). The upland, termed the "Las Vegas Plateau," rises gently westward to the Creston. It merges northward with a Cretaceous shale plain that ascends to basalt-covered Ocate Plateau. Drainage across the southern portion of the Raton section flows into either the east-west elongate watersheds of the Mora River and Ocate Creek or into bedrock depressions dotting broad interfluvial plains.

Fig. 5. View upstream (west) of the Mora River where it crosses the Creston, near Mora, New Mexico. The Creston is a hogback ridge formed by steeply dipping late Paleozoic and Mesozoic sedimentary rocks that flank the Sangre de Cristo Uplift. Several montane Canadian tributaries have been superposed across the Creston. Its prominence and continuity along the Canadian montane border provide a structural datum useful in correlating nearby pediment levels.

Pecos-Canadian Valley

The Canadian River, from its low drainage divide with the Pecos River in the vicinity of Santa Rosa eastward to near Amarillo, occupies an extensive lowland cut into Triassic redbeds. Strata underlying this lowland rise eastward out of the Tucumcari structural basin into an undulatory series of structural highs before plunging into the Anadarko basin (Fig. 4). The Pecos-Canadian Valley itself consists of a broad outer valley that occasionally contains remnant Ogallala and high terrace deposits and a more rugged inner valley through which flow the Canadian River and lower Ute Creek (Fig. 11). At least two alluvial terrace levels flank the inner valley. Sandstone uplands of the Las Vegas Plateau and the Ogallala-veneered High Plains overlook the length of the Pecos-Canadian Valley along east-west-trending escarpments. Drainage tributary to the Canadian River, with the exception of Ute Creek, is by low order ephemeral streams.

High Plains

The portion of the Canadian River basin within the Texas and Oklahoma Panhandles is an essentially featureless piedmont plateau, which is bisected by the "breaks" of the Canadian into the Panhandle High Plains to the north and Llano Estacado to the south. The plateau or High Plains surface is underlain by up to 800 ft of piedmont alluvial and eolian deposits of the Ogallala Formation. An irregular erosion surface incised into Mesozoic age rocks lies beneath the Ogallala (Hawley *et al.*, 1976, p. 238). Structurally, the pre-Ogallala units generally conform to the gentle undulations that define the Dalhart basin, Anadarko basin, and intervening structural highs. The top of the Ogallala Formation, capped by an indurated caliche zone up to 30 ft thick, forms the gently southeast-sloping (less than 10 ft per mile) High Plains surface.

Pleistocene eolian sediments (especially prevalent northeast of major drainage courses) and numerous shallow depressions largely resulting from alternate leaching and deflation of the Ogallala caprock (Judson, 1950, p. 253) impart up to several tens of feet of relief to the otherwise featureless High Plains surface. Drainage from this surface is intermittent and either accumulates in local depressions or is channeled into tributaries of the Canadian and North Canadian Rivers. Longer tributaries form a sparse, generally east-trending subparallel network that rarely breaches the base of the Ogallala cover. A much denser network of short ephemeral streams occupies narrow terraced valleys incised up to 600 ft below adjacent Ogallala uplands, frequently into underlying redbeds of Triassic and Permian age (Fig. 8).

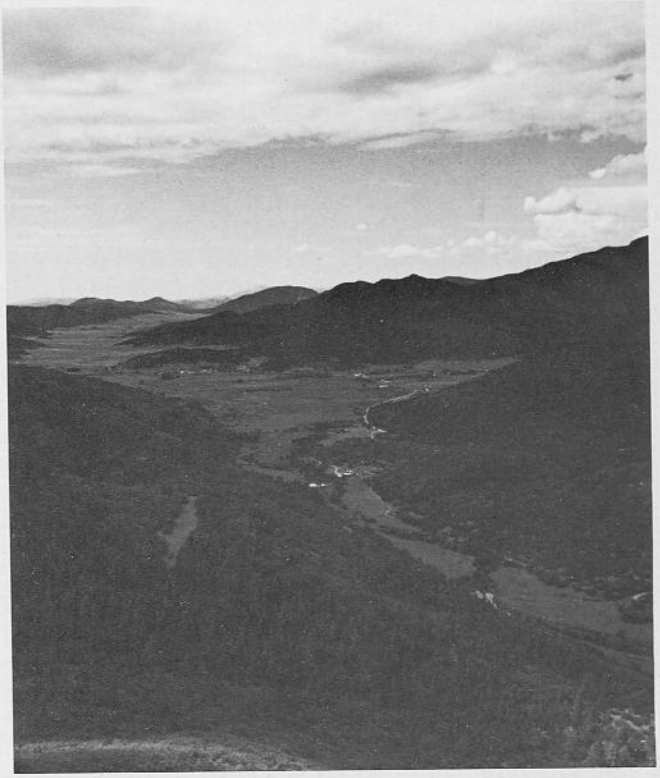


Fig. 7. View south down the "abandoned valley" of Coyote Creek near Guadalupita, New Mexico. Judging from its physiographic expression, the valley appears to have been formerly occupied by a large, through flowing ancestral Coyote Creek. The valley is in fact part of the Coyote-Mora-Quebraditas half-graben trend. The half-graben may have induced local alluviation by east-flowing montane streams, but it probably was not the site of a major southward-flowing Pleistocene river.

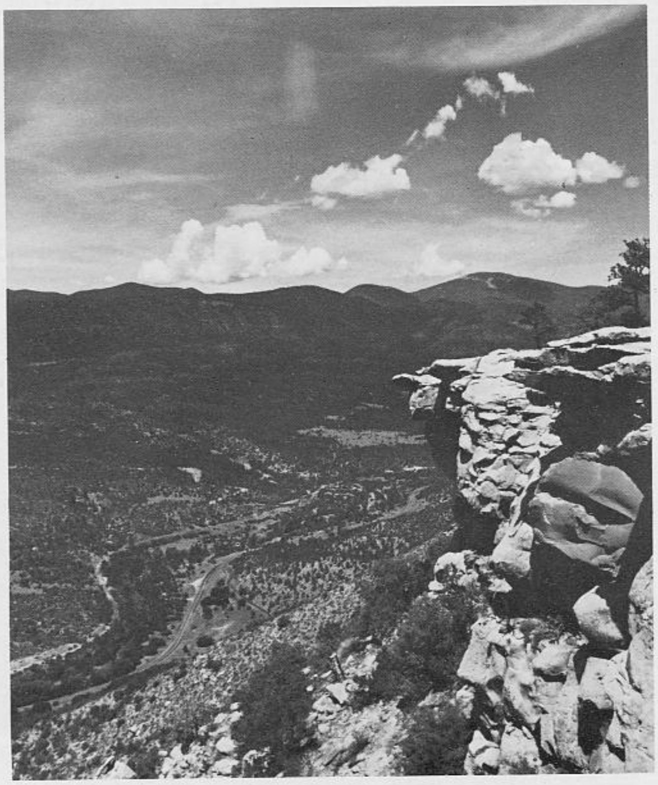


Fig. 6. View west up the canyon of Cimarron Creek from near Cimarron, New Mexico. The canyon is in places more than 2500 ft deep and completely transects the Cimarron Range. Cimarron Creek established its course through the range prior to Pliocene tectonism. Most of Cimarron canyon's relief is the product of Pliocene-Pleistocene epeirogenic uplift and cyclic Pleistocene climatic change.

Osage Plains

The Canadian River system, from the Ogallala feather edge outcrop eastward across Oklahoma to its confluence with the Arkansas River, drains a linear swath of Oklahoma's Osage Plains. Rocks of Pennsylvanian and Permian age, mostly sandstone and shale, underlie the plains and dip gently westward or nothwestward into the Anadarko basin. Outcropping edges of more resistant units give rise to generally south-trending, east-facing escarpments. These are up to 200 ft higher than intervening predominantly shale lowlands. The entrenched courses of the Canadian and North Canadian Rivers usually obliquely transect the topographic grain in terraced, alluvium-filled valleys. Both the alluvium and the wide (10 to 15 mi) sand-dune belts that often occur northeast of the rivers are Pleistocene in age. From the High Plains to Oklahoma City, the parallel courses of the Canadian and North Canadian Rivers are fed almost exclusively by short, low-order ephemeral tributaries. East of the Oklahoma capitol, the Canadian basin broadens to accommodate a denser parallel network of streams before joining the Arkansas River.

CLIMATE/VEGETATION

For purposes of evaluating general basin hydrologic response, climate may be viewed in terms of mean annual precipitation, seasonal precipitation, and mean annual temperature. Vegetation type and distribution reflect the interplay of these climatic variables and thus provide a surrogate measure of basin climate.

Mean annual and mean seasonal values of precipitation and temperature within the Canadian River basin are modulated by the relative prevalence of either polar air from the continental interior or maritime tropical air from the Gulf of Mexico. Altitudinal increases in mean annual temperature, from 39°F near Red River Pass to about 50°F at Las Vegas and Cimarron, New Mexico (NOAA, 1974, p. 801), and decline in mean annual precipitation (Fig. 12), with descent from the Sangre de Cristo Mountains, give way eastward to a more gradual but progressive increase in both values. Under the greater cumulative influence of warm, moist Gulf air circulation, precipitation increases from about 18 in to 42 in per year, and mean annual temperatures increase from 50°F to approximately 64°F between the foot of the southern Rockies and eastern Oklahoma (*ibid.*, p. 801-827). North-south shifts of continental mid-latitude westerlies at the expense of southeasterly air circulation from the Gulf produce a more pronounced seasonal climate in the western portion of the drainage basin. An average duration of one to three months for the relatively "wet" season in northeastern New Mexico lengthens to from seven to ten months in central Oklahoma (Visher, 1954, p. 332). Nearly 80% of annual precipitation on the New Mexico High Plains falls during the warmest six months of the year, mostly in brief torrential thunderstorms generated by strong surface heating and orographic lifting of moist Gulf air westward over higher terrain. In contrast, the more general and abundant rainfall of central and eastern Oklahoma becomes somewhat more localized and sporadic only in late summer and early fall. Based upon the

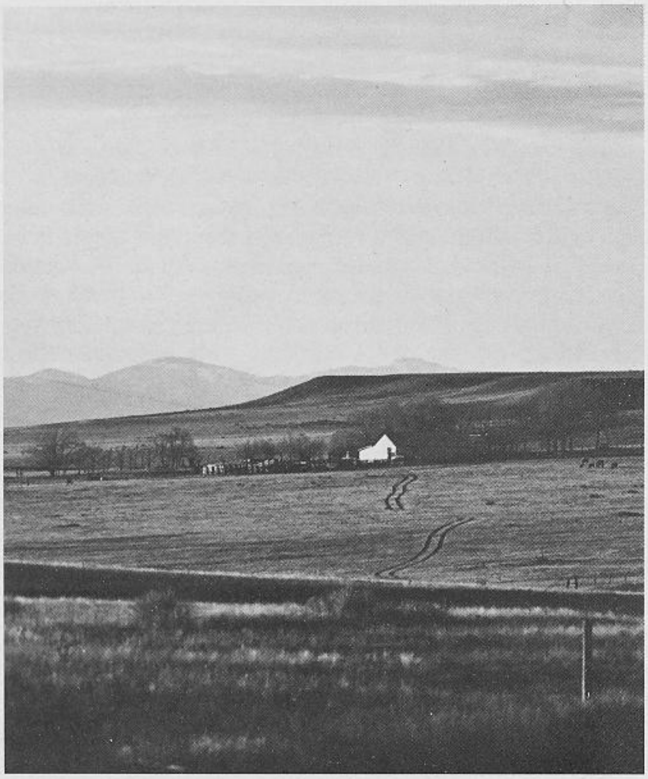


Fig. 9. View looking northwestward along the west-facing Ogallala escarpment near Mills, New Mexico. The valley of the south-flowing Canadian River and the Sangre de Cristo Range are in the distance. Thin Ogallala cover and a less pronounced caliche caprock account for much of the contrast between the western scarp and its east-facing counterpart. The escarpment originated with a headward (northward) migrating ancestral Canadian River breaching the terminal Ogallala surface during late Pliocene-early Pleistocene tectonism.

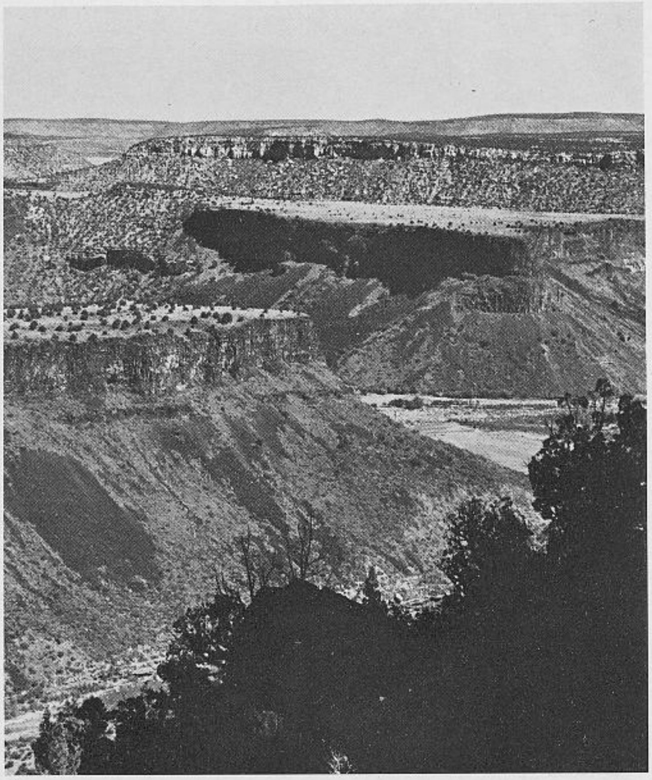


Fig. 10. View northeast of the entrenched Canadian River near Sabinoso, New Mexico. Basalt capping surfaces in the middle distance is part of the Maxson Crater flow. The elevation of this flow relative to the Dakota sandstone uplands along the skyline suggests that at least 65% of Canadian entrenchment occurred prior to middle Pleistocene time. Entrenchment was caused by epeirogenic uplift and climatically induced changes by hydrology and downstream base level.

annual abundance and periodicity of precipitation that it receives, the Canadian River basin descends to the Arkansas River across semi-arid, subhumid, and humid climatic zones.

Altitudinal and meridional climatic variations are mirrored by the range of vegetation types within the Canadian basin. The interval from the crest of the Sangre de Cristo Range to an elevation of about 9500 ft supports a dense forest of Englemann spruce, a variety of firs, and appreciable numbers of lodgepole pine and aspen. This Canadian vegetation zone changes at lower elevations (as low as 6500 ft) to a forested Transition Zone that is composed primarily of yellow pine and Douglas fir, broken only occasionally by grassy meadowlands or "parks" such as Moreno Valley (Hunt, 1974, p. 393). Higher montane forest gives way to pinyon pine—juniper woodland and oak chaparal on the high basalt-capped mesas of the Raton section. To the east, pine, juniper, oak and other trees and shrubs are increasingly restricted to the margins of major water courses. The broad interfluves of the High Plains sustain a dense growth of predominantly blue grama and buffalo grass, distinctive of the vast short grass steppe of central North America (Rumney, 1968, p. 344). At about the one hundredth meridian, or the eastern extent of the High Plains, the semi-arid shortgrass steppe grades into tall grass prairie. Requiring greater and more reliable rainfall, the dominant bluestem and grama of the prairie form a dense mantle over most of the Osage Plains. As the prairie approaches the humid climate of eastern Oklahoma, it gradually accommodates individuals and then groves of blackjack and post oak, which give way near the Arkansas River to oak-hickory forest (Küchler, 1964).

HYDROLOGY

All variables of drainage basin character thus far discussed significantly affect basin hydrologic response. The past record of such response is largely contained in what evidence we have of earlier climate and sedimentation. Consequently, the following discussion of basin hydrology is confined to extrapolations that can readily be made from major aspects of modern climate and sedimentation.

Runoff, sediment yield, and sediment concentration are fundamental expressions of changes in the fluvial system's mode of sediment transport and deposition that accompany regional variations in climate. In the Canadian basin, average annual runoff decreases from a high of approximately 10 in in the Sangre de Cristo Mountains to minimum values of less than 0.25 in on the High Plains, and gradually increases eastward to about 10 in again in eastern Oklahoma (Fig. 13). A comparison of precipitation distribution with that of runoff (Fig. 12) illustrates the simple fact that runoff varies according to the amount of precipitation. Langbein *et al.* (1949) elaborated upon this relationship by incorporating mean annual temperature (Fig. 14). Thus for a given annual rainfall, runoff increases with decreasing temperature, or as the effects of evapotranspiration decline.

Consideration of runoff as a percentage of mean annual precipitation gives some hint of the complexity of basin-wide hydrologic response. Relatively high percentages (up to about 50%) of annual precipitation are dispersed as runoff at higher elevations in the Sangre de Cristo Range. The amount is in accord with trends suggested solely from the relationship between runoff and temperature (Fig. 14), but is probably appreciably enhanced by the orographic effect of montane relief. Downstream meridional increases in both percent age of runoff (up to approximately 20% in eastern Oklahoma) and mean annual temperature undoubtedly reflect greater rainfall during cooler seasons.

The direction and relative magnitude of basin-wide variation in sediment yield can be similarly equated with climatic factors. Figure 15 depicts annual sediment yield as a function of effective precipitation (precipitation required to produce a known runoff), assuming a mean annual temperature of 50° F. The results are based upon data from 90 stations in drainage basins averaging 1500 sq mi each. Elsewhere, peak values of sediment yield also have been demonstrated to occur at an annual precipitation rate of about 12 in (Gregory and Walling, 1973, p. 336), or at between one and 3 in of runoff (Dendy and Bolton, 1976, p. 264). If temperature is taken into consideration, these peak values vary in a predictable fashion (Fig. 16). With higher temperature (and thus higher rates of evapotranspiration), a smaller proportion of precipitation is available to support vegetation, runoff is less (Fig. 14), and peak sediment yield occurs under conditions of greater mean annual precipitation. A plot of selected sites within the Canadian basin according to this graphic relationship (Table 1, Fig. 16) demonstrates that sediment

Fig. 11. View southeast into the rugged inner valley of the Canadian River near Meredith, Texas. Most of the rocks exposed are redbeds of the Permian Quartermaster Formation. Subsurface salt dissolution in older Permian rocks has played a major role in localizing dissection that produced the Canadian breaks.

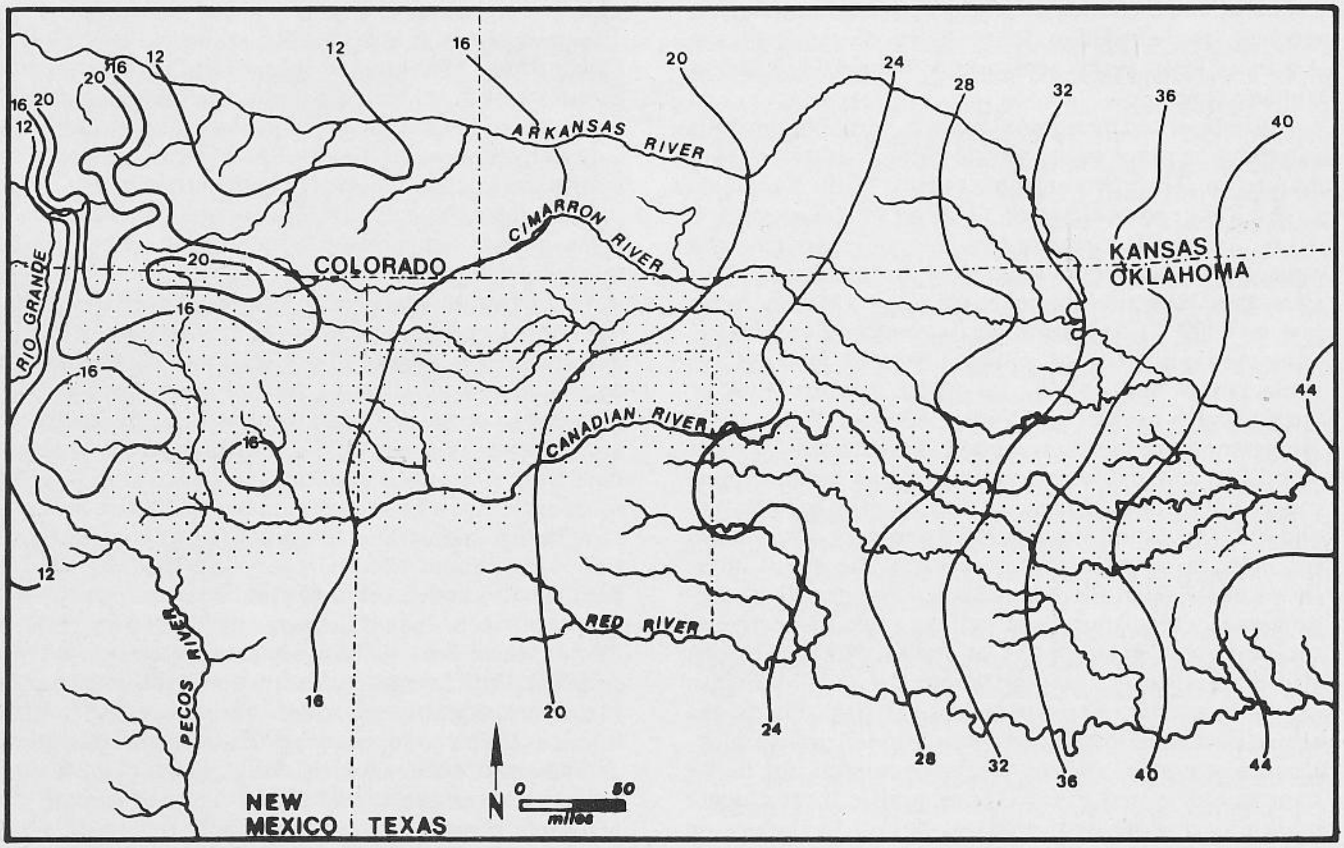


Fig. 12. Mean annual precipitation (inches) map of the Canadian River basin. Eastward and southeastward declining mean annual precipitation within the upper Canadian River basin accompanies decreasing altitude of the Sangre de Cristo Range and Raton Plateau. Farther east, meridional increases in annual rainfall reflect progessively greater proximity to moist Gulf Coast air circulation. Mean annual precipitation, when considered with seasonally occurring precipitation, mean annual temperature, and vegetation type and distribution, provides a climatic basis for evaluating general basin hydrologic response. Data from NOAA, 1974.

yield is approximately the inverse of runoff. About twice as much sediment is contributed per unit area from drained portions of the semi-arid plateaus, plains and valleys of eastern New Mexico and the Texas-Oklahoma Panhandles than from the mountain headwaters or subhumid-humid Osage Plains. Although this disparity is reduced somewhat by the confinement of most semi-arid precipitation to the warmest months, the relative amount of sediment contributed to the Canadian fluvial system is clearly greatest in the region of most diminished and ephemeral runoff.

One additional hydrologic variable that will prove useful in documenting the history of fluvial channel behavior is sediment concentration. Like sediment yield, mean annual sediment concentration also varies systematically with mean annual precipitation and temperature. The same selected Canadian basin sites shown in Figs. 14 and 16 are plotted on curves that show the relationship between sediment concentration and precipitation at different values of mean annual temperature (Fig. 17). As was the case for sediment yield, sediment concentration is greatest in the Pecos Valley and High Plains sections of the Canadian basin, where runoff is most diminished and intermittent.

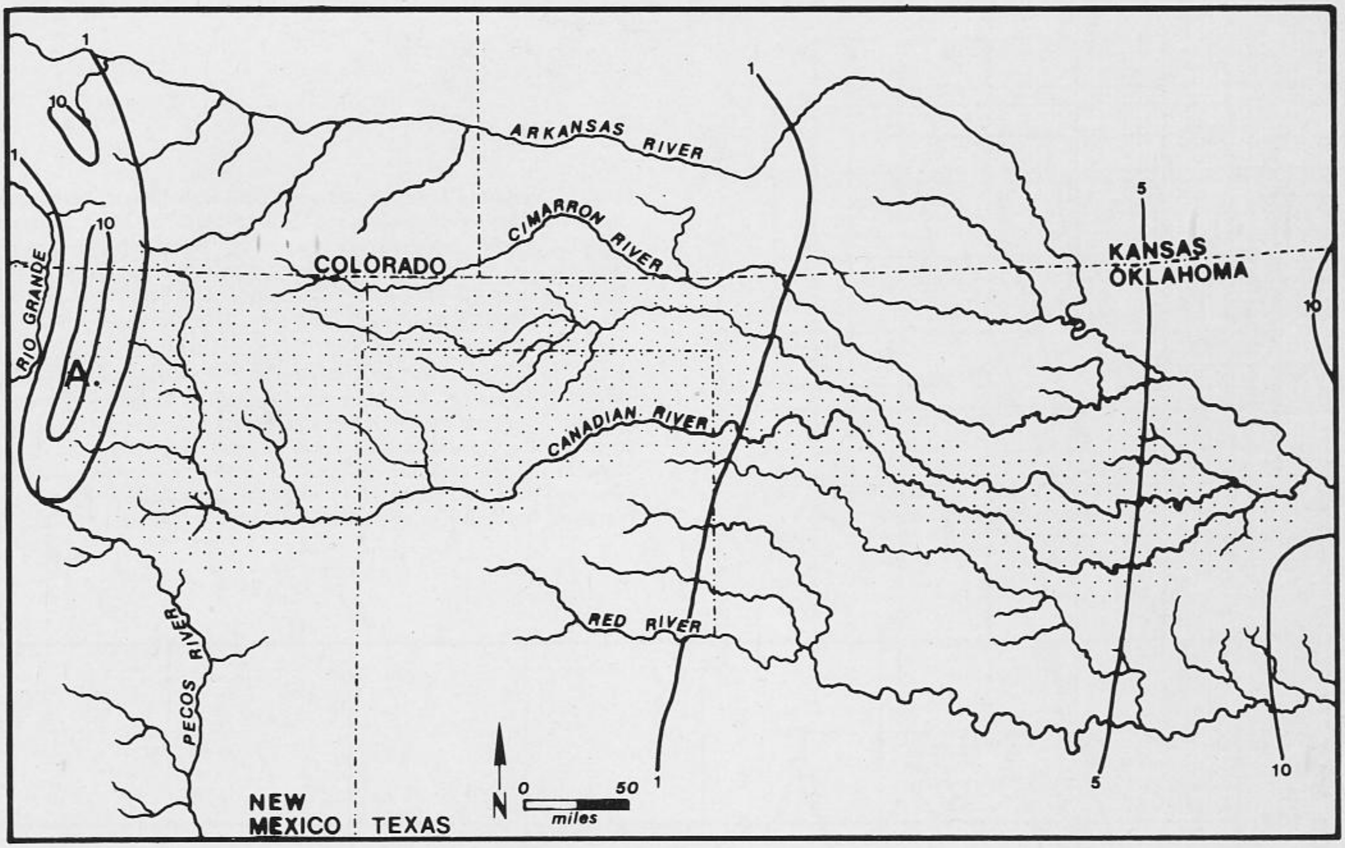


Fig. 13. Mean annual runoff (inches) for the Canadian River basin. Runoff generally varies according to the amount of precipitation (Fig. 12), but it is also strongly influenced by average annual temperature (Fig. 14). The systemic relationship between runoff and climate is especially useful in projecting paleohydrologic response of the fluvial system to climatic change (Fig. 32). Based on Geraghty et al., 1973, Plate 1.

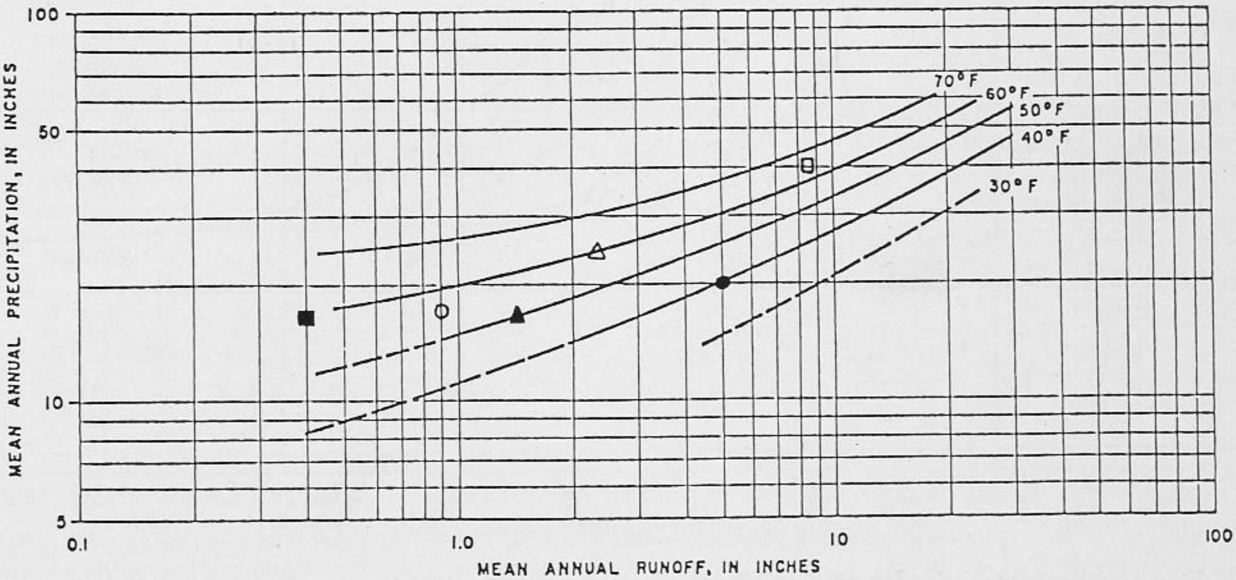


Fig. 14. The effect of temperature on the relationship between mean annual runoff and mean annual precipitation. Symbols: ● Red River, New Mexico; ▲ Las Vegas/Cimarron, New Mexico; ■ Tucumcari, New Mexico; o NW Texas Panhandle; Δ SE Texas Panhandle; □ eastern Oklahoma. The curves are modified to exclude the effects of seasonal rainfall. Evapotranspiration increases with increasing temperature, thereby reducing the amount of runoff generated at a given annual rainfall. Most precipitation falls on the semi-arid High Plains and plateaus of the Canadian basin during the warmest 6 months of the year. Actual basin runoff values are therefore less than those determined from Table 1. The converse is true for areas of less seasonal rainfall, the Sangre de Cristo Range and Osage Plains. From Langbein et al., 1949, p. 8.

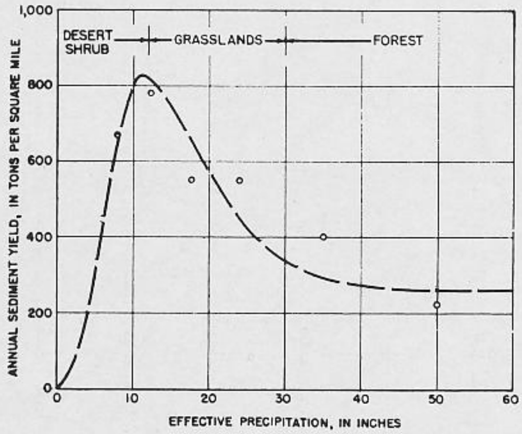


Fig. 15. Variation of annual sediment yield with climate, based upon data from small watersheds in the United States. This curve illustrates how the interplay between precipitation and vegetation affects runoff and erosion. As rainfall increases from zero, more runoff is generated and thus more sediment can be transported. This tendency is opposed by the increasing abundance of vegetation. At precipitation rates higher than 12 in, grass and forest cover are sufficient to progressively reduce sediment yield. From Langbein and Schumm, 1958, p. 40, used with permission.

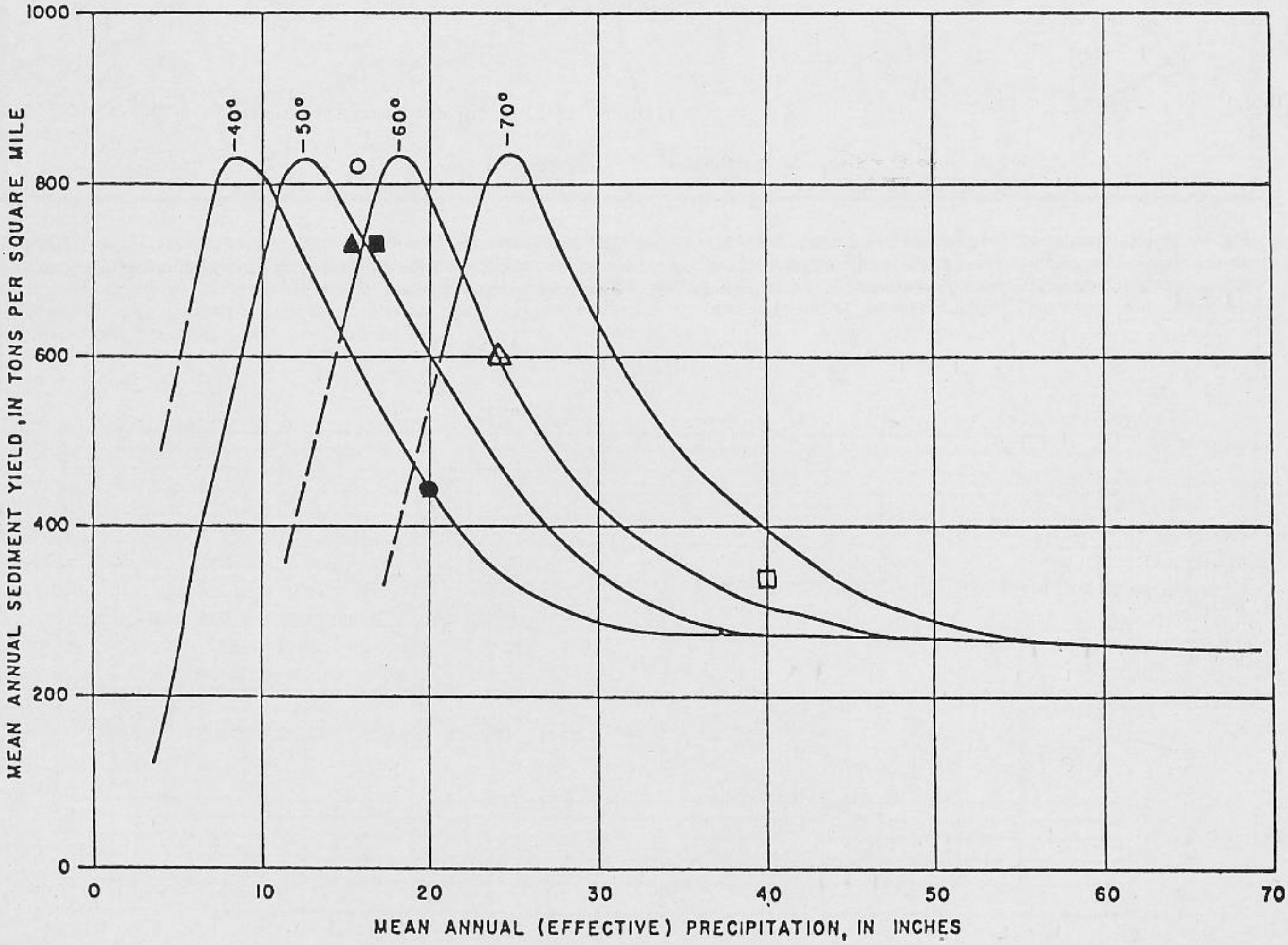


Fig. 16. The effect of temperature on the relationship between mean annual sediment yield and mean annual precipitation. Symbols: ● Red River, New Mexico; ▲ Las Vegas/Cimarron, New Mexico; ■ Tucumcari, New Mexico; o NW Texas Panhandle; Δ SE Texas Panhandle; □ eastern Oklahoma. The curves themselves are useful in estimating the effect of Pleistocene glacial cooling on sediment yield. Since sediment yield is also influenced by local physiography and several other factors, only the direction and relative magnitude of climatically induced change is meaningful. From Schumm, 1965, p. 785 *in* H. E. Wright, Jr., and David G. Frey, eds., The Quaternary of the United States. Copyright (c) 1965 by Princeton University Press. Fig., p. 785, reprinted by permission of Princeton University Press.

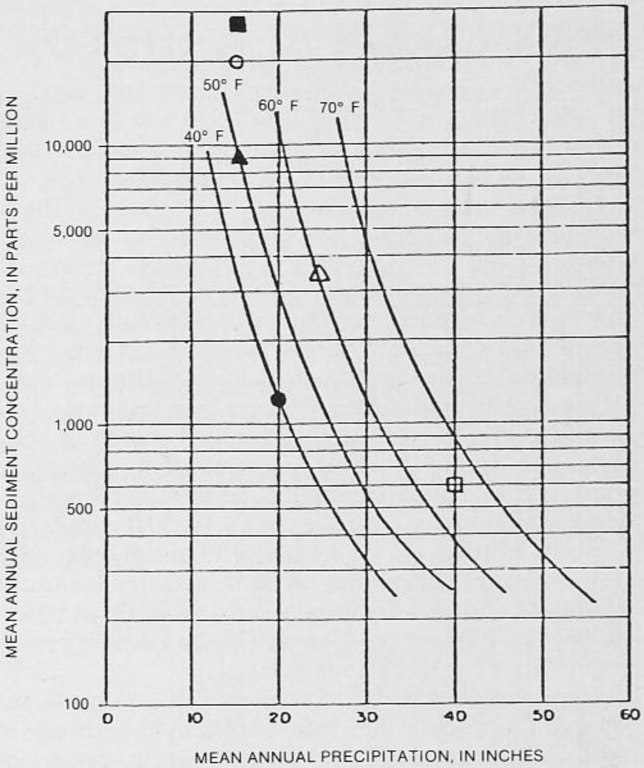


Fig. 17. The effect of temperature on the relationship between mean annual sediment concentration and mean annual precipitation. Symbols: • Red River, New Mexico; ▲ Las Vegas/Cimarron, New Mexico; ■ Tucumcari, New Mexico; o NW Texas Panhandle; Δ SE Texas Panhandle; □ eastern Oklahoma. Dissolved load is not included in sediment concentration values, but its influence on fluvial system behavior is negligible. Like sediment yield (Fig. 16), sediment concentration at a given precipitation rate increases with increasing temperature (i.e., with higher rates of evapotranspiration). From Schumm, 1965, p. 786 *in* H. E. Wright, Jr., and David G. Frey, eds., The Quaternary of the United States. Copyright (c) 1965 by Princeton University Press. Fig., p. 786, reprinted by permission of Princeton University Press.

Table 1. Values for selected climatic and hydrologic variables from representative sites within the modern Canadian River basin.

1	2	3	4	5	6	7	8	9	10
SYMBOL	LOCATION	PHYSIOGRAPHIC SETTING	MAT	MAP	MAR	MAR	MASY	MASY	MASC
•	RED RIVER, NEW MEXICO	SANGRE DE CRISTO RANGE	40	20	>10	5		450	1,200
▲	LAS VEGAS/ CIMARRON, NEW MEXICO	RATON SECTION	50	16	1	>1		725	9,000
■	TUCUMCARI, NEW MEXICO	PECOS VALLEY SECTION	60	16	<1	<1	247-1,643[a]	725	>20,000
o	NW TEXAS PANHANDLE	HIGH PLAINS SECTION	55	16	<1	<1		825	>20,000
Δ	SE TEXAS PANHANDLE	HIGH PLAINS/OSAGE PLAINS SECTION	60	24	1	>2		600	3,500
□	EASTERN OKLAHOMA	OSAGE PLAINS SECTION	65	40	10	>8	921[b]	350	600

1. • Red River, New Mexico; ▲ Las Vegas/Cimarron, New Mexico; ■ Tucumcari, New Mexico; o NW Texas Panhandle; Δ SE Texas Panhandle; □ eastern Oklahoma.
2. The first three data sites are specific towns; the last three are from at least one locale within each region specified.
3. Terms are the names of physiographic subdivisions used in this study.
4. Mean annual temperature (°F); data from NOAA, 1974.
5. Mean annual precipitation (inches); data from Fig. 12.
6. Mean annual runoff (inches); data from Fig. 13.
7. Mean annual runoff (inches); data from Fig. 14.
8. Mean annual sediment yield (tons per square mile); data from Dendy and Champion (1978, p. 38-40). a) range of values tabulated at five irregular intervals between June 1942 and October 1970 for Conchas Reservoir, on the Canadian River west of Tucumcari; major reasons for such variation include short term changes in land use and rainfall; b) value from June 1969 survey at Eufaula Lake, eastern Oklahoma.
9. Mean annual sediment yield (tons per square mile); data from Fig. 16.
10. Mean annual sediment concentration (parts per million); data from Fig. 17. Figures with asterisks plotted off the scale spanned by the curves.

PRE-OGALLALA HISTORY OF THE CANADIAN BASIN REGION

Drainage history of what is now the Canadian basin began with regression of the Late Cretaceous epicontinental sea. Roughly 65 million years separate this event from onset of the Ogallala erosion cycle; Harland *et al.,* (1964, p. 260) give the pre-Pliocene time scale employed in this study. Most of the sedimentary record of basin evolution during this time is contained in continental clastic rocks exposed along the flanks of the Sangre de Cristo Mountains (Fig. 8) and in thick fluvio-deltaic deposits beneath the Gulf Coastal Plain of Texas (Fig. 18). Inferences regarding tectonic activity, landscape character, and paleohydrology supplement the sediment record and help outline a history of the Canadian basin region prior to Ogallala sedimentation.

Final withdrawal of the Cretaceous epicontinental sea during Campanian and Maestrichtian time coincided with the beginnings of Laramide tectonism in what is now the upper Canadian basin. The rising San Luis highland induced eastward and possibly southward retreat of the Late Cretaceous strandline (Reeside, 1957, p. 539; Ash and Tidwell, 1976, p. 198; Fassett, 1976, p. 189). Early major drainage ways were probably consequent upon the newly emergent land surface, tracing the direction of marine regression. Uplifts on the more stable craton of Oklahoma and Texas similarly governed the pattern of continental emergence and early subaerial drainage (Fig. 18).

Laramide orogenesis culminated during late Paleocene-early Eocene time in accelerated uplift of the San Luis highland and its differentiation into modern Rocky Mountain structural elements (Burbank and Goddard, 1937, p. 958-959, Tweto, 1975, p. 31). Large volumes of sediment were transported to adjacent intermontane depressions (Stearns, 1943, p. 319; Berner and Briggs, 1958, p. 1533-1534; Figure 25, profile 1), eastward into the Raton basin (Johnson and Wood, 1956, p. 717; Siems, 1964, p. 167), and southeastward to the Gulf basin (Rainwater, 1967, p. 181). Compressive deformation along the Sierra Grande arch established Raton basin's eastern margin (Baltz and Bachman, 1956, p. 107; Muehlberger *et al.,* 1967, p. 7), restricting eastward sediment dispersal. Cratonic flexures and uplifts farther from the center of orogenic activity probably underwent slight rejuvenation during epeiric uplift of the entire Gulf Coast region (MacNeil, 1966, p. 2358; Fig. 18). Such mild deformation of structures beneath gently dipping epicontinental marine deposits favored development of major river systems that were subsequent to regional structure.

The influence of large scale structures on the location of major drainage ways is most evident where early Tertiary trunk streams entered the Gulf of Mexico. During Laramide tectonism, delta systems of rivers originating in the southern Rocky Mountains were confined to two adjacent areas of the Texas Gulf Coast (Fig. 18). Within these areas, fluvio-deltaic sediments accumulated in successively stacked lobes whose axes of maximum thickness define persistent avenues of cratonic fluvial transport. The location of these axes relative to structure supports the observation that major cratonic river systems tend to avoid positive regional tectonic features and instead follow basin lows (Potter, 1978, p. 17). Locations of Oligocene and modern river systems bear out Potter's generalization and add plausibility to northwestward projections of early and middle Tertiary trunk drainage (Fig. 18).

Laramide orogenic activity waned in middle to late Eocene time, reducing the volume of sediment transported to montane alluvial basins and Gulf Coast fluvio-deltaic systems (Robinson, 1972, p. 236; Fisher *et al.,* 1970, p. 234). Relative tectonic quiescence favored development of a widespread erosion surface. Montane areas in the central and southern Rocky Mountains were reduced to a few isolated highlands rising above a rolling low relief piedmont plain (Epis and Chapin, 1975, p. 52-53). The piedmont merged with plains to the east and southeast. Its surface consisted of extensive pediments separating streams that had broader floodplains, gentler gradients, and conducted higher discharges than modern High Plains rivers (Scott, 1975, p. 231). The late Eocene erosion surface differed most from modern montane border counterparts in having formed under a deep weathering regime promoted by a subtropical climate (Epis and Chapin, 1975, p. 59; Bammel, 1979, p. 29).

Both sedimentologic and climatic conditions within the Canadian basin region changed dramatically during Oligocene time. From Canada to presumably as far south as New Mexico, streams transecting the Rocky Mountain border underwent roughly simultaneous aggradation (Clark, 1975, p. 111). Voluminous outpouring of volcaniclastic debris hastened the process (Scott and Taylor, 1975, p. 4; Fig. 19), but climate was probably the major impetus to abrupt and widespread development of an Oligocene depositional regime (Clark, 1975, p. 115).

Early Tertiary subtropical climate deteriorated rapidly in middle Oligocene time (roughly 30 to 35 million years B.P.) (Savin, 1977, p. 339). Fossil terrestrial flora in western North America document a sharp drop in mean annual temperature (on the order of 18° F or 10° C), a less marked decline in mean annual precipitation, and more pronounced seasonal changes of both temperature and precipitation (Leopold and MacGinite, 1972, p. 186; Wolf, 1978, p. 695). The earliest advent of such continental climatic conditions to the Canadian basin region was in the rain shadow of the Laramide Rocky Mountains, an area coincident with the zone of marked Oligocene fluvial aggradation.

Onset of a middle Oligocene depositional regime can be related to paleohydrologic changes by means of hydrologic relationships, which were introduced in the discussion of the modern Canadian River. Figure 20 summarizes the impact that climatic change and volcaniclastic sedimentation had on the hydrology and depositional regime of middle Oligocene fluvial systems. It is unclear whether diminished, more seasonal precipitation or lower mean annual temperature had the greater influence on hydrologic response. However, if the role of volcaniclastic sedimentation is also considered, then the net effect of hydrologic change was to induce fluvial aggradation.

A depositional regime predominated in the Canadian basin region throughout middle-late Oligocene and Miocene time. The prevalence and intensity of deposition varied according to location within major southeast-trending drainage basins. Aggradation prevailed along the montane border, where climate-induced hydrologic changes, volcaniclastic outflow, and gradient reduction were most pronounced. These conditions diminished both upstream and downstream of the montane border and were accompanied by a corresponding reduction in the magnitude and persistence of fluvial aggradation. Deposition was most voluminous along the lower reaches of Oligocene rivers where their sediment load fed prograding Gulf Coast delta systems (MacNeil, 1966, p. 2363; Galloway *et al.,* 1977, p. 4: Doyle, 1979, p. 21).

Lobate wedges of fluvio-deltaic sediment beneath the modern Texas Gulf Coast are all that remain of Oligocene-Miocene rivers that headed in the southern Rocky Mountains. Axes of maximum thickness within these sediment bodies coincide with those drawn through remnants of earlier Tertiary delta systems (Fig. 18). Major drainage ways evidently continued to follow avenues of long distance sediment transport that had been established during Laramide tectonism. Portions of these avenues were eventually abandoned in favor of more easterly trending master streams like the Canadian. The process of drainage disruption and reintegration is expressed in the Pliocene-Pleistocene history of the Canadian basin.

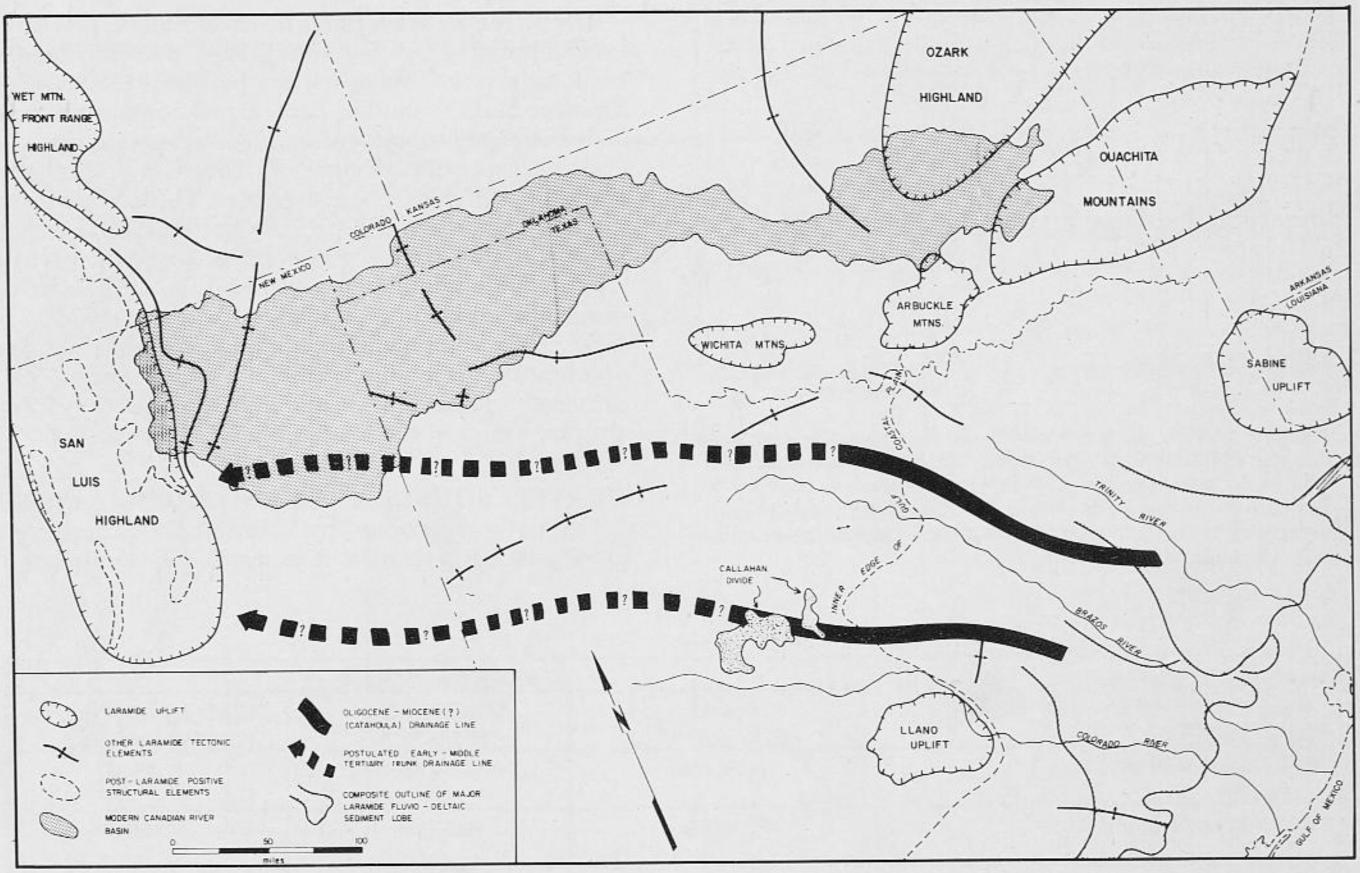


Fig. 18. This map summarizes the major geographic aspects of pre-Ogallala drainage history in the Canadian basin region. Laramide tectonism induced general Gulfward retreat of the Late Cretaceous sea. Early major drainage ways were probably consequent upon the newly emergent land surface. Regional drainage lines became more subsequent to structure in response to continued uplift and structural differentiation of the San Luis Highland and to cratonic emergence of other Laramide tectonic elements. By early Eocene Wilcox deposition, major river systems evidently followed tectonic lows from the southern Rocky Mountain region to the Gulf of Mexico. Vertical accumulation of Wilcox and younger Laramide fluvio-deltaic systems attests to the stability of cratonic avenues of fluvial sediment transport. These avenues persisted into Oligocene-Miocene time (Doyle, 1979, p. 10), and their positions roughly coincide with those of modern Gulf Coast rivers. Northwestward projections of early-middle Tertiary trunk drainage lines are based upon the presumption that major rivers followed paths of tectonic least resistance across the craton. Added support for this argument may rest with lag gravel capping the Callahan Divide. Eastward projections of the High Plains surface pass 600 ft below the top of the divide, suggesting a pre-Ogallala (early-middle Tertiary) age for the high gravel (Epps, 1973, p. 29). Sources: Tectonic elements—Eardley, 1949, p. 681; Rainwater, 1960, p. 99; Burgess, 1976, p. 139; Reeside, 1957, p. 539. Composite outline of major Laramide (Wilcox, Queen City, and Jackson) fluvio-deltaic sediment lobes—Fisher and McGowen, 1969, p. 40; Fisher et al., 1970, p. 236; Guevara and Garcia, 1972, p. 9. Oligocene-Miocene (?) (Catahoula) drainage lines—Galloway et al., 1977, p. 30.

THE OGALLALA EROSION CYCLE

Ogallala sediments and the topography that they obscure permit reconstruction of the proto-Canadian basin in detail sufficient to serve as a point of departure in tracing basin evolution.

The Ogallala Formation consists of a feather edge to more than 500 ft of alluvial sediments derived from uplands west of its present outcrop extent (Fig. 8). Deposition probably began during late Miocene time and continued throughout most of the Pliocene, covering an erosional topography of moderate local relief (Frye, 1970, p. 5). Early descriptive studies inspired speculation that such deposition was the product of valley alluviation (Johnson, 1901, p. 612; Baker, 1915, p. 26-29) or the eastward coalescence of alluvial fans (Plummer, 1932, p. 769). More recent investigations have generally substantiated the valley alluviation hypothesis; a widely adopted stratigraphic classification subdivides the Ogallala Formation into three progressively more areally extensive units. The Valentine Zone represents a basal gravel valley fill, overlain by the more voluminous and finer grained Ash Hollow, and topped by the fine-grained extensive Kimball Zone. The entire sequence often culminates in a caliche caprock. The Ogallala members, previously defined as floral units from a study of the formation in Kansas and Nebraska (Elias, 1942, p. 132-147), have been correlated to Ogallala exposures in the Canadian basin on the basis of physical stratigraphy, plant and molluscan fossils, volcanic ash, and clay mineralogy (Leonard and Frye, 1978, p. 6-7).

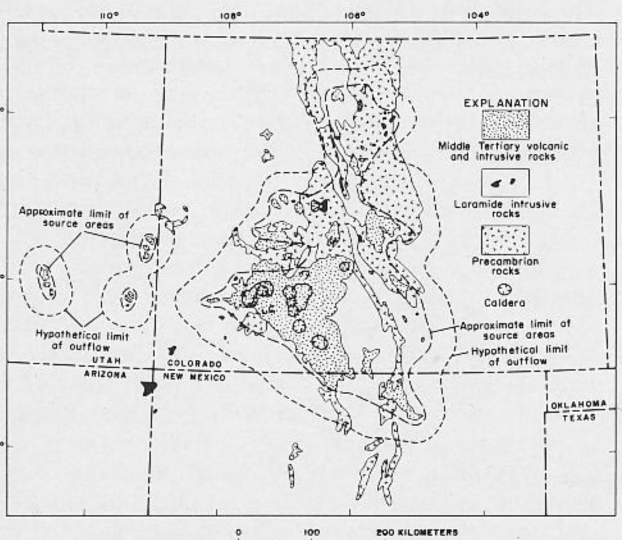


Fig. 19. Map of the southern Rocky Mountains showing the postulated extent of middle Tertiary volcanic field. The modern headwater Canadian basin clearly overlaps with an extensive area once covered by volcanics and volcaniclastic outflow. The late Pliocene limits of southeast drainage roughly coincide with the modern Canadian basin outline (Fig. 26). Adapted from Steven, 1975, p. 78.

The petrologic character, areal distribution, and vertical succession of Ogallala stratigraphic units provide the basis for several lines of inquiry pertinent to Canadian drainage basin evolution. Basal gravel composition and distribution are conspicuous evidence of source area and drainage network configuration. They also support generalizations about the mode and foci of initial sediment dispersal. Subsequent phases of Ogallala sedimentation reflect general and progressive changes in hydrologic regime, landscape, and drainage morphology. Termination of the erosion cycle signals a period of relative quiescence in the evolution of the Canadian fluvial system. The accompanying development of an Ogallala "climax soil," provides a datum against which the relatively catastrophic events of the Pleistocene can be measured.

GRAVEL: SOURCE AREA AND MOBILIZATION

The hiatus represented by Valentine gravel occupying pre-Ogallala topographic lows marks a discontinuity of

MIDDLE OLIGOCENE SECULAR CLIMATIC CHANGE (30-35 MILLION YEARS B.P.)	HYDROLOGIC RESPONSE		
	RUNOFF (SEE FIGURE 14)	SEDIMENT YIELD (SEE FIGURE 16)	SEDIMENT CONCENTRATION (SEE FIGURE 17)
MEAN ANNUAL TEMPERATURE DECLINE	INCREASE	DECREASE	DECREASE
MEAN ANNUAL PRECIPITATION DECLINE	DECREASE	INCREASE	INCREASE
GREATER PRECIPITATION SEASONALITY (DRIER WINTERS)	DECREASE	INCREASE	INCREASE
NET HYDROLOGIC RESPONSE	DECREASE	INCREASE	INCREASE
FLUVIAL SYSTEM RESPONSE	AGGRADATION		

Fig. 20. This chart summarizes the probable impact that climatic change had on the hydrology and depositional regime of middle Oligocene fluvial systems. Note that deducing net hydrologic response solely from qualitative assessments of climatic change is an equivocal exercise. Two other factors were considered in determining hydrologic change: 1) Oligocene volcaniclastic sediment altered the hydrologic regime both by substantially increasing sediment yield and concentration and by its tendency to reduce runoff by absorption; and 2) grasses, which did not appear until middle Miocene time, failed to fill the ecologic void left by the deterioration of subtropical vegetal cover under an increasingly continental climate. Hydrologic response was, therefore, accentuated in the direction indicated on the above chart.

major proportion in the record of Canadian River basin history. For the Sangre de Cristo Range, the presumed source for most of the gravel, the gap is even more substantial. No Ogallala erosional remnants exist and only vestiges of pre-Ogallala Tertiary sediments survive. Nonetheless, the petrologic character and distribution of these sparse deposits, and of the Ogallala gravel itself, indicate the diversity of the area and manner in which coarse clastics accumulated and were subsequently mobilized with initiation of Ogallala sedimentation.

Representative samples of Ogallala and probable Ogallala gravel show metaquartzite to be the most abundant constituent, followed by volcanics (mainly basalt, andesite, and dacite), and limestone (Appendices A and C). These lithologic constituents have their sources in the bedrock of the Sangre de Cristo Mountains, a thin gravel veneer of speculative origin, remnants of a former extensive volcanic and volcaniclastic mantle, and derivatives of early Tertiary basin alluvium.

Quartzose contribution

Scattered thin deposits of mostly well-rounded quartzose gravel on roughly accordant high mountain surfaces are problematic both in their origin and their association with Ogallala sedimentation. Some of the gravel is undoubtedly a lag accumulation from Oligocene age deposits that once mantled the Laramide erosion surface (Scott, 1975, p. 235). The origin of the gravel is discernible by the presence of distinctive volcanic clasts in close proximity to artifacts of a volcanic source area (Locality 40). In most cases, though, gravel composition is neither indicative of its origin nor clearly associated with other similarly occurring deposits. An example is the quartzose material that veneers accordant surfaces on either side of northern Moreno Valley. Some observers regard them as vestiges of the pre-tectonic (late Eocene) erosion surface (Smith and Ray, 1943, p. 920; Clark and Read, 1972, p. 74). However, further reconstruction on the basis of lithologic evidence is impossible because the deposits are not locally derived and do not resemble one another (Localities 39 and 41). These and other sparse high-level quartzose gravel deposits (Robinson, 1977, p. 17) are most useful in the denotation rather than characterization of potential Ogallala source terrain.

More direct evidence of provenance area is contained within the Ogallala gravel itself. Its sizeable metaquartzite fraction (Fig. 21) is highly variable in petrologic texture and accessory mineralogy. Some constituents are of sufficiently distinctive lithology and widespread occurrence to permit an appraisal of source area.

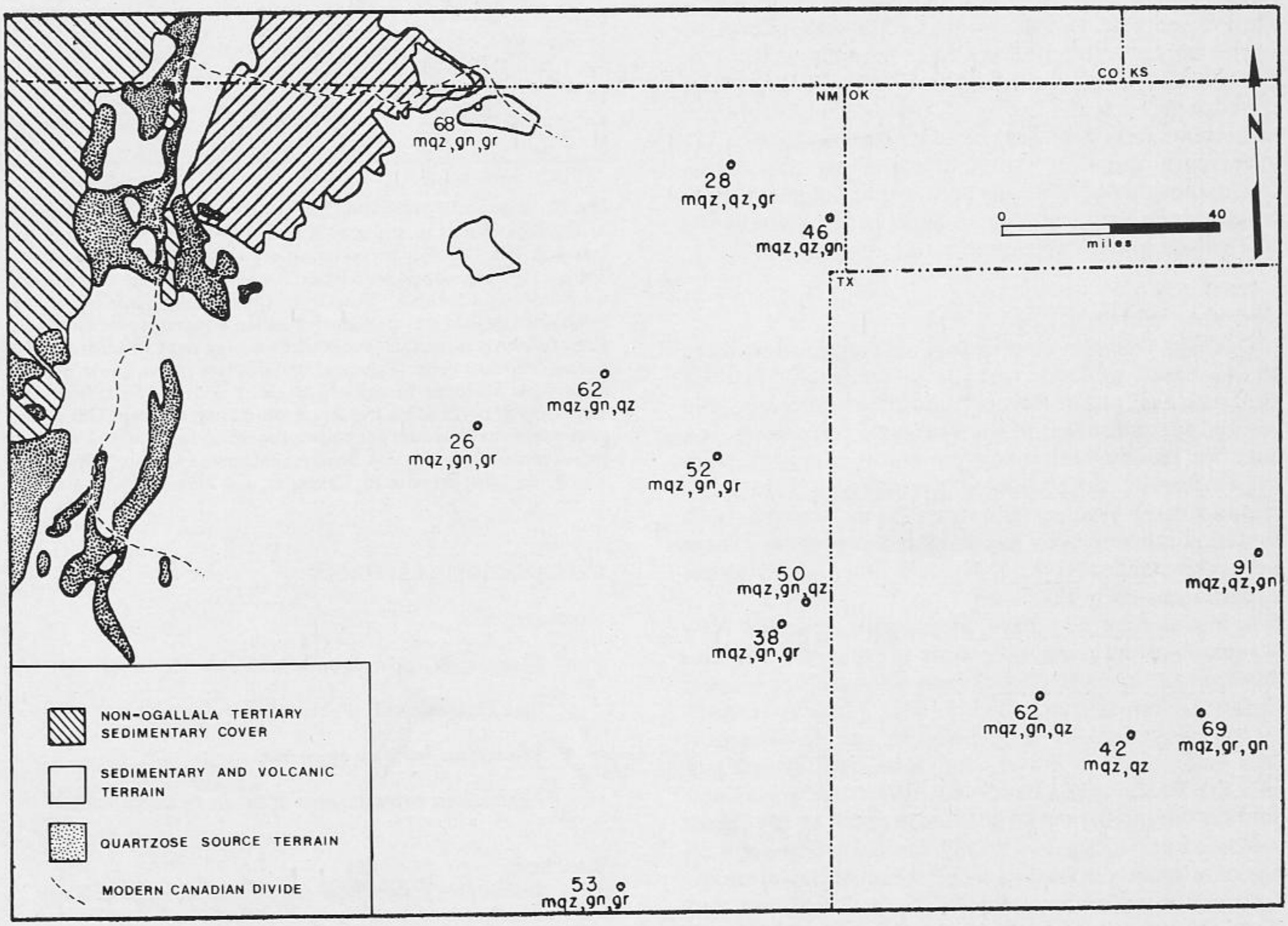


Fig. 21. Map showing the percentage and composition of quartzose constituents in Ogallala and probable Ogallala gravels within the Canadian basin. The small circles denote gravel sample sites (Fig. 1); numbers represent percentages of quartzose constituents and letters indicate dominant quartzose lithology (gn—gneiss, gr—granite, mqz—metaquartzite, qz—quartz). The absence of a pronounced trend toward downstream concentration of durable quartzose clasts is indirect evidence for local sedimentary contribution to Ogallala drainage ways.

Hematitic meta-arkose containing accessory staurolite and kyanite was observed in most Ogallala gravel samples and analyzed in thin sections of clasts from Localities 11, 58, and 97. Middle grade hematitic, quartzofeldspathic metasedimentary rocks (distinguished by the presence of staurolite) of granoblastic texture are widely exposed in the Precambrian terrain of the southern Sangre de Cristo Mountains. The lower quartzite member of the Ortega Formation in the Picuris Range (Montgomery, 1953, p. 9), Ortega Mountains (Lindholm, 1963, p. 8) and other adjacent portions of the Sangre de Cristo Range (Miller *et al.,* 1963, pocket map), muscovite-hematite granulite in the vicinity of Eagle Nest (Clark and Read, 1972, p. 10), and presumably correlative units extending into southern Colorado (Edwards, 1966, pocket map) all contain rocks fitting this description.

More definitive association of distinctive gravel lithology with postulated source area can be made in the case of clasts of sillimanite gneiss. Though never present in great abundance, their occurrence was noted at virtually every Ogallala gravel locality. This ubiquity within the depositional setting is particularly significant when contrasted with the restricted outcrop extent of sillimanite gneiss. Its presence in the Picuris Range (Montgomery, 1953, p. 72) and adjoining southeastern Sangre de Cristo Mountains (Miller *et al.,* 1963, p. 19; Cepeda, 1973, p. 470) is confined to lower stratigraphic positions within the Precambrian Ortega Quartzite. The present outcrop of this unit (which could only have been more restricted in Ogallala time) is a rather narrow zone along the leading edge of thrust and high angle reverse faults east of the structural crest of the Sangre de Cristo Range (Fig. 22). Apparently most structural displacement and consequent exposure of this zone occurred along much of the length of the Sangre de Cristo uplift before termination of Ogallala gravel deposition.

Volcanic contribution

Ogallala volcanic clasts range in composition from olivine basalt to dacite and are quite variable in their abundance (Fig. 23). This petrographic and geographic variability, unlike that of the quartzose component, is a basis for reconstruction of a previously more extensive source terrain. Formation of the volcanic terrain occurred during two periods of extrusive activity, both contemporaneous with Ogallala sedimentation. These were in late Oligocene-early Miocene time and during the late Miocene-early Pliocene.

In the Sangre de Cristo Mountains, near the New Mexico-Colorado line, Oligocene age andesitic breccia, flows, and volcaniclastic rocks rest on an Eocene erosion surface (Pillmore *et al.,* 1973, p. 502). These are unconformably overlain by early Miocene age rhyolitic ash-flow tuff, volcanic gravel, and associated basalt and andesite flows interlayered with quartzose gravel and boulder conglomerate (*ibid.*). Deposition of the upper volcanic interval was essentially contemporaneous with intrusive activity in the Spanish Peaks complex of south-central Colorado (Stormer, 1972a, p. 2445), the Red River-Questa area of northern New Mexico (Kottlowski *et al.,* 1969, p. 279; Pillmore and Laurie, 1976, p. 44), and possibly other intrusions southeast of Raton (Stormer, 1972a, p. 2443; Hayes, 1957, p. 954).

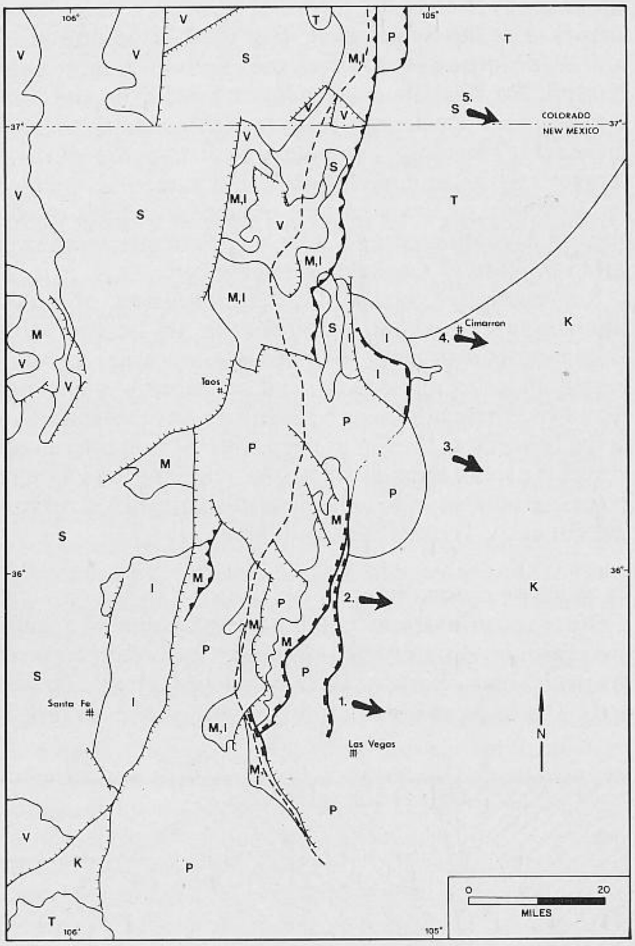


Fig. 22. Map showing montane Ogallala source terrain and inferred foci of Ogallala sediment dispersal within the western Canadian basin (arrows). Numbered dispersal points are keyed to those described in Table 2 (1—Gallinas-Sapello River, 2—Mora River, 3—Ocate Creek, 4—Cimarron Creek, 5—Purgatoire-Cimarron Rivers). Note that quartzitic Ogallala gravel originated within a narrow upthrust zone of Precambrian metamorphic rocks that was even more areally restricted during Pliocene time. Paleozoic sedimentary rocks (now beneath middle-late Pliocene basalts of the Ocate volcanic field) break the continuity of north-south trending Precambrian outcrop. This prominent break may account for some geographic variations in Ogallala gravel composition (Fig. 24). Sources: Bachman and Dane, 1962; Johnson, R. B., 1969; Woodward, Callendar, and Zilinski, 1975.

EXPLANATION OF SYMBOLS

Structures:

Normal fault, hachures on downthrown side

High angle reverse fault, bars on upthrown side

Thrust fault, barbs on upper plate

Approximate structural crest of Sangre de Cristo Range

Rock Units:

s	Sedimentary graben fill of Santa Fe Group and equivalents
v	Pre-Pliocene volcanic and volcaniclastic rocks
t	Early Tertiary basin fill
k	Cretaceous sedimentary rocks
p	Paleozoic sedimentary rocks
i	Precambrian and Tertiary intrusive igneous rocks
m	Precambrian metamorphic rocks

The general sequence of intermediate composition breccia and lava overlain unconformably by intercalated quartzose gravel and relatively more mafic flows is repeated in the Thirtynine Mile volcanic field north of the Canadian basin and along the southeastern margin of the San Juan field to the northwest (Lipman and Mehnert, 1975, p. 126-133). Widespread correspondence among these and other smaller volcanic centers across a post-Laramide erosion surface that was virtually intact prior to Miocene block faulting prompted Steven (1975, p. 78) to postulate the existence of a single large composite field. Aprons of volcaniclastic material coalesced to form an almost continuous volcanic cover over much of south-central Colorado and adjacent northern New Mexico (Fig. 19). Though areas coincident with the extrusive centers of this cover remain, limited representatives of the clastic outflow facies are most indicative of the possible contribution by a composite volcanic field to Ogallala sedimentation.

Relics of clastic outflow from middle Tertiary volcanic source areas are preserved in the western Sangre de Cristo Range and along the margins of the San Luis Basin as Carson Conglomerate (Locality 43), Picuris Tuff (Locality 44), and Los Pinos Formation (Butler, 1971, p. 297), among others. The volcaniclastic units generally consist of water-laid tuffaceous sandstone and conglomerate, which were derived from adjacent San Juan and Sangre de Cristo volcanic highlands and were deposited in subsiding structural depressions. Subsidence accelerated during middle Miocene rifting (Chapin, 1971, p. 191), thus assuring local preservation of the outflow sequence.

Direct evidence of an analogous tectonic/sedimentologic setting along the eastern front of the Sangre de Cristo Range is confined to an extension of the Rio Grande Graben into the upper Arkansas River valley of southern Colorado (Van Alstine, 1968, p. 158). Farther south, the more abbreviated Ogallala sedimentary record is the only indication that volcanic material was dispersed eastward from a center in northern New Mexico (Fig. 23).

Properties of remnant outflow units and derivative volcanic conglomerates, west of the Canadian basin and elsewhere (Lindsey, 1972, p. 22), are applicable to the question of volcanic provenance within the Canadian basin. The volume and size of Ogallala volcanic clasts imply reworking of a former volcaniclastic cover in the New Mexico Sangre de Cristo Range. Such a terrain

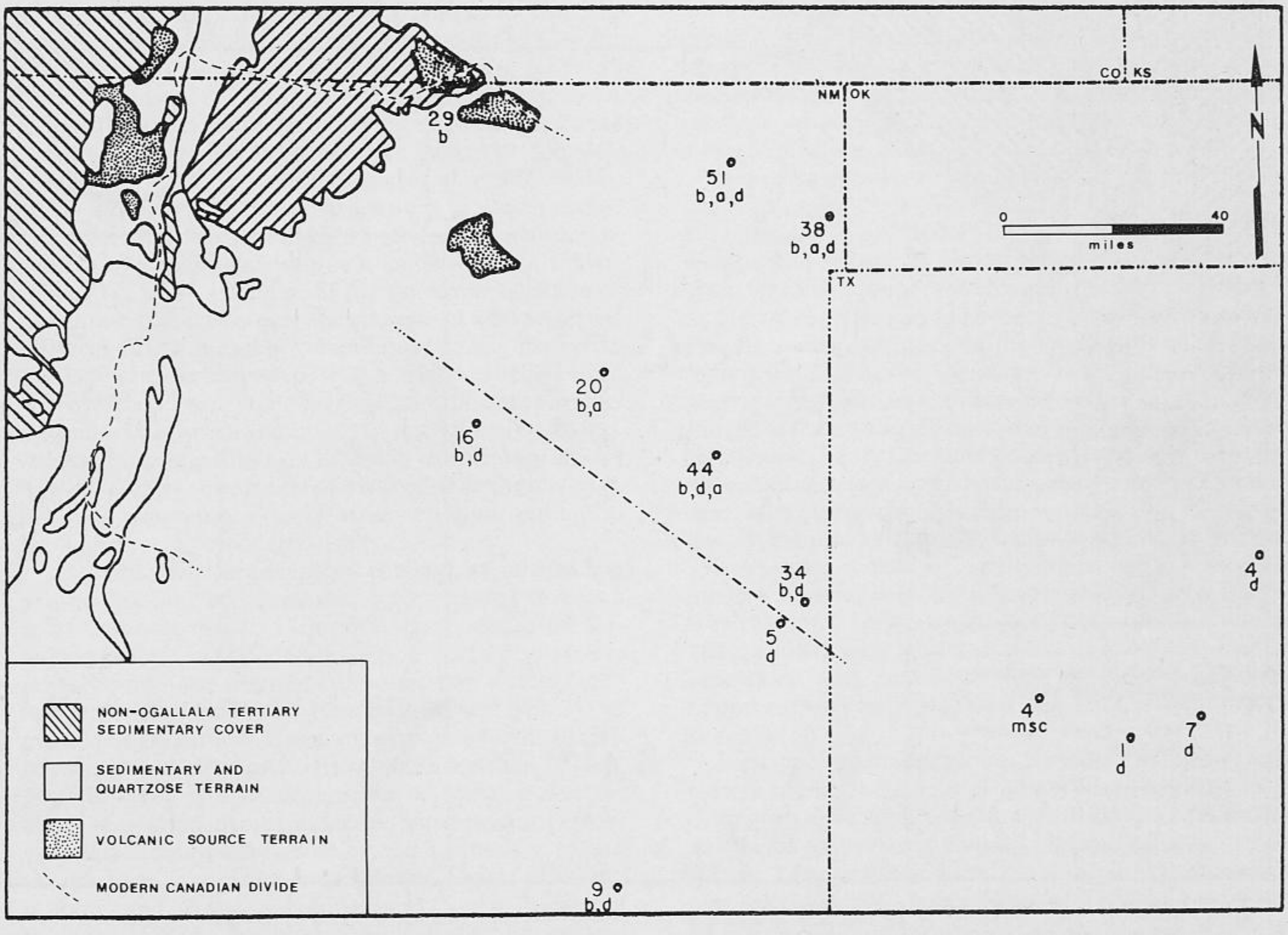


Fig. 23. Map showing the percentage and composition of volcanic constituents in Ogallala and probable Ogallala gravels within the Canadian basin. The small circles denote gravel sample sites (Fig. 1); numbers represent percentages of volcanic constituents and letters indicate dominant volcanic rocks (a—andesite, b—basalt, d—dacite, msc—miscellaneous). The percentage of volcanics increases markedly northeast of the dashed line. This may reflect the presence of a regional Ogallala drainage divide that prevented the southward dispersal of coarse volcanic sediment (Fig. 26).

would characteristically yield an abundance of readily mobilized coarse clastic debris with potential for transport great distances. High percentages of volcanic constituents at several Ogallala gravel sites include rounded cobbles up to 70 cm (27.5 in) in diameter (Locality 12) and exceeding 20 cm (8 in) in diameter nearly 180 mi from the nearest possible source (Locality 115). These clasts and others of local non-volcanic origin (Butler, 1971, p. 296; Montgomery, 1953, p. 52; Locality 43) could have been freighted in a cohesive slurry of poorly sorted tuffaceous sand generated by fluvial dissection of the volcaniclastic terrain. Considering the range of sediment size in the Valentine Zone, even minor amounts of clay, notably present in the basal Ogallala as apparently indigenous montmorillonite (Frye *et al.,* 1974, p. 11), might produce a transporting medium of sufficient density and cohesiveness to accomplish this (Rodine and Johnson, 1976, p. 213). The record of Oligocene-Miocene Catahoula sedimentation along the Texas Gulf Coast attests to the effectiveness of this mechanism over great distances on a low relief surface (Galloway *et al.,* 1977, p. 11, 19, 25).

Resurgent volcanism during basal Ogallala sedimentation supplied an indeterminant but probably sizeable sediment load from a locus of dispersal similar to that for middle Tertiary volcaniclastic outflow (Fig. 23). This approximate overlap in source area introduces uncertainty about the relative contribution of each volcanic interval to Valentine gravel. Olivine basalt in gravel deposited on or basinward of mesas in the Raton volcanic field (Localities 11, 12, 104) is probably Raton Basalt, first extruded at least 7 million years ago (latest Miocene time) (Stormer, 1972a, p. 2443). Volcanics of intermediate to silicic composition were concurrently emplaced on Johnson Mesa (Kudo, 1976, p. 110) and over a broad area farther south, as reflected in deeply eroded plugs, domes, and flows of dacite and hornblende andesite (Fig. 8) (Stormer, 1972b, p. 3300). Such volcanism, being roughly synchronous with initiation of Ogallala sedimentation, could have generated abundant, easily mobilized debris as readily as an older zone of volcaniclastic outflow. More definitive conclusions await detailed petrographic studies of Ogallala volcanic clasts as well as source terrain.

SEDIMENTARY CONTRIBUTION

A change in Ogallala gravel lithology occurs across a

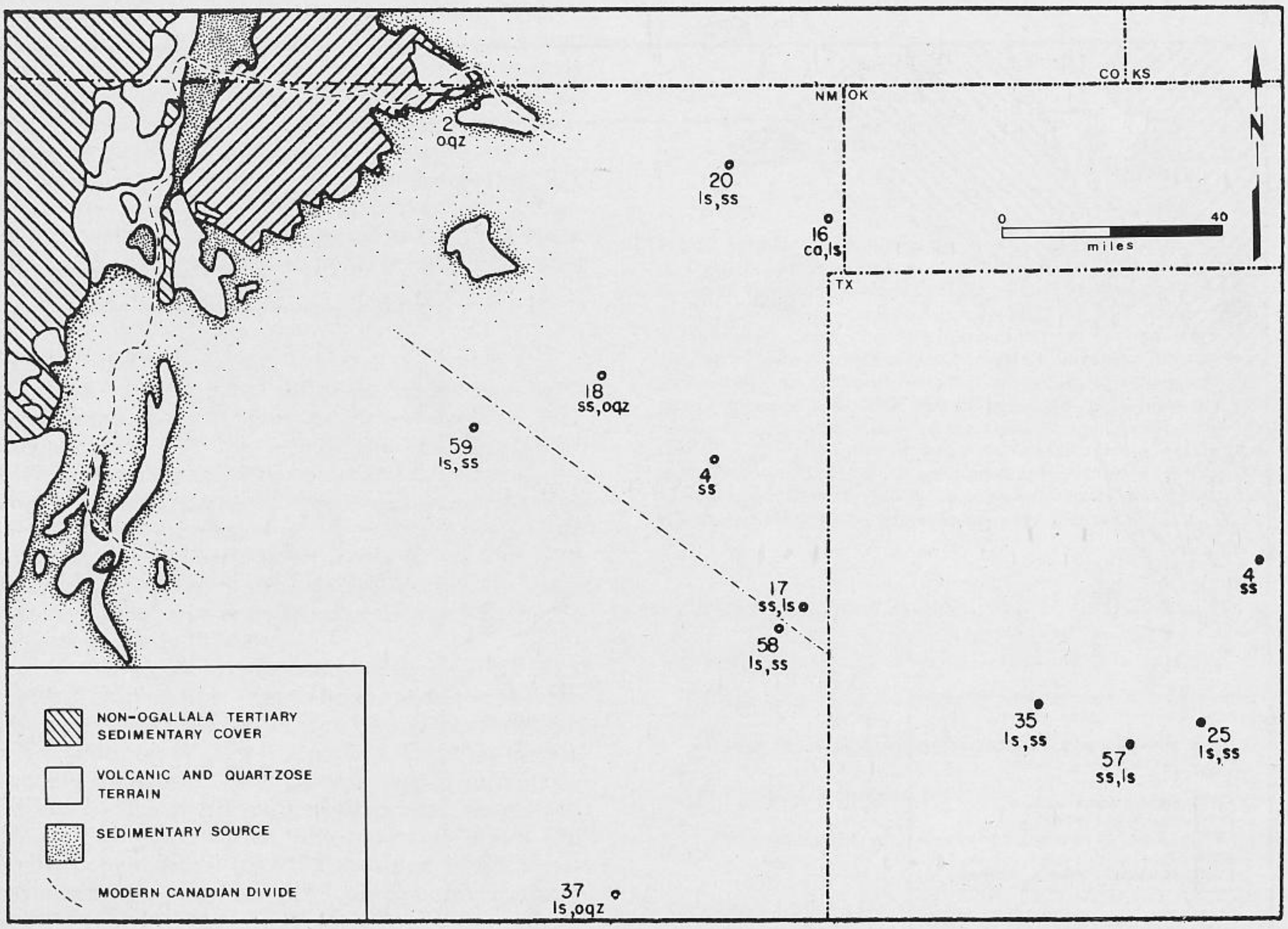


Fig. 24. Map showing the percentage and composition of sedimentary constituents in Ogallala and probable Ogallala gravels within the Canadian basin. The small circles denote gravel sample sites (Fig. 1); numbers represent percentages of sedimentary constituents and letters indicate dominant sedimentary rocks (ca—caliche, ls—limestone, oqz—orthoquartzite, ss—sandstone). The percentage of sedimentary clasts increases markedly southwest of the dashed line. This probably reflects a locus of sediment disposal in a portion of the Sangre de Cristo Range dominated by sedimentary cover.

southeast-trending line separating Localities 80, 81, and 97 from Localities 58 and 96 (Fig. 24). The percentage of sedimentary constituents appreciably increases southwest of the line. If this reflects an absolute increase rather than one resulting from a relative decline in the proportion of quartzose and volcanic clasts, then two explanations of provenance are possible. The locus of sediment dispersal may have been in a portion of the Sangre de Cristo Range dominated by sedimentary cover (Fig. 22). On the other hand, since the cover is continuous eastward, local erosional contribution to Ogallala drainage channels may also be indicated. A major gravel source in plains sedimentary bedrock is inconsistent with the apparent nature of Ogallala sedimentation. Studies of modern stream gravel in the southern Sangre de Cristo Range show that a predominantly quartzose sediment load from headwater tributaries is rapidly diluted by downstream gravel influx of differing lithology (Miller, 1958, p. 30). No similar progressive downstream dilution is evident in Ogallala gravel. In fact, quartzose material may be concentrated downstream (Fig. 21). This sustains the assumption that most of the Ogallala sediment load originated with erosion of a montane source area and was deposited in an alluvial environment relatively unmodified by local stream incision or network extension.

Locally derived sedimentary clasts also help reconstruct the role of plains tributary drainage in Ogallala sedimentation. Specimens of the pelecypods *Gryphea* sp. or *Ostrea* sp., all relatively unabraided, were retrieved from Localities 58, 87, 89, 96, and 112. Their occurrence in basal Ogallala gravel elsewhere in and near the Canadian basin has also been reported by Baker (1915, p. 24), Cronin (1961, p. 37), and Trauger *et al.* (1972, p. 38), generally accompanied by designations of a local source in Cretaceous bedrock. Such reflections of local provenance are by no means uniform, a conclusion also arrived at by Frye *et al.* (1956, p. 8) for the lower Ogallala of northern Kansas. However, the presence of well-preserved Cretaceous fossils and of voluminous but less distinctive subangular to subrounded, friable, clastic cobbles from nearby Triassic bedrock, suggests sediment transport was over short distances and involved negligible reworking. Alluviation along tributary valleys in sedimentary terrain was apparently so episodic or proceeded so rapidly as to preclude voluminous local sediment contribution to through-flowing drainage.

One additional sedimentary component of Ogallala provenance may be represented by gravel that veneers a south-trending ridge on Glorieta Mesa, west of the Canadian basin (Localities 68 and 69). Uncertainty as to the gravel's origin has inspired conjecture that it is an Ogallala remnant (Griggs and Hendrickson, 1951, p. 31) or possibly the residuum of a major eastward-flowing Ogallala stream ancestral to the Rio Grande (Belcher, 1975, p. 39). However, a high proportion of rounded durable clasts of late Paleozoic limestone (dated primarily from included crinoidal debris) indicates a northerly source in the adjacent Sangre de Cristo uplands. Gravel of similar lithology and provenance is preserved 15 mi to the west in the coarse clastic fraction of the Galisteo Formation, which comprises up to 3000 ft of clay to cobble-sized detritus (Disbrow and Stoll, 1957, p. 11). The Galisteo Formation accumulated in an alluvial basin marginal to the Laramide San Luis (Sangre de Cristo) Uplift (Stearns, 1943, p. 312). Its former extent may have included Localities 68 and 69, now reduced to a reworked coarse lag.

A similar process of reduction may also explain apparently exotic gravel lag in the upper Canadian basin (Localities 6, 36 and 39), where the locus of Laramide alluviation was Raton basin. Potential sources of coarse clastic sediment within Raton basin include the Poison Canyon and basal Raton Formations, and possibly younger less extensive alluvial units preserved only in the tectonic "shadow" of Huerfano Park (Johnson, 1961, p. 144-145). Partial erosion and transport of this alluvial sequence to the Ogallala plains occurred when post-Laramide orogenic activity transformed large portions of the basin into a foothill border. Such a border would greatly expand the possible source area of quartzose and sedimentary gravel and finer grained sediment (Fig. 8).

Gravel mobilization

Data presented in preceding pages suggest that most basal Ogallala gravel was derived from a montane source area by corrasion of pre-Tertiary bedrock, reworking of early Tertiary basin alluvial fill, and dissection of middle to late Tertiary volcanic and volcaniclastic cover. Intermittent, highly competent bedload streams deposited the gravel as basal fill in widely dispersed shallow valleys that later received finer grained alluvium. Determining the cause of a discrete pulse of basal Ogallala sedimentation involves weighing the relative importance of climatic change versus tectonic activity (Smith, 1940, p. 88).

Lack of evidence for a prominent climatic shift during late Miocene to early Pliocene time (Vail *et al.*, 1977, p. 87; Savin, 1977, p. 333, 339) indicates climate was only a subordinate factor in initiating the Ogallala erosion cycle. The major impact of climate appears to have been during the extended period between formation of the late Eocene erosion surface and the beginnings of Ogallala sedimentation. In the Canadian basin, this 30 million year interval was one of relative tectonic quiescence. Fluvial and alluvial processes were conditioned by a secular climatic change from late Eocene subhumid subtropical conditions to a late Miocene-early Pliocene climate somewhat warmer and slightly wetter than that of the present (Smith, 1940, p. 78; Leonard and Frye, 1978, p. 15). Vegetation change mirrored this climatic shift as modern montane coniferous forests gradually supplanted tropical floral communities (Leopold and MacGinitie, 1972, p. 164), The advent of more continental climatic conditions also coincided with the middle Miocene appearance of prairie grasses (Elias, 1942, Plate 17; Axelrod, 1981, p. 10).

Tertiary climatic change was accompanied by a degeneration of morphogenetic processes that were conducive during early Tertiary time to the formation of a deeply weathered planar surface of regional extent (Büdel, 1973, p. 208). Climatically induced modification of the surface may have produced a coarse-grained alluvial covermass similar to that which mantled the Zagros Mountains of Iran prior to its deposition as the Pliocene Bakhtiari Conglomerate (Oberlander, 1965, p. 34). Like the Ogallala Formation, the Bakhtiari Conglomerate is a molasse deposit, whose genesis is readily associated with a period of diastrophism.

A syntectonic deposit that is geographically more relevant to early Ogallala sedimentation (the Santa Fe Group) accumulated along the western front of the Sangre de Cristo Range. The tectonic episode, which initiated both Santa Fe and Ogallala sedimentation in northern New Mexico, began about 26 million years ago with subsidence of the San Luis Basin and concurrent Hinsdale basaltic volcanism (Lipman and Mehnert, 1975, p. 125). Potassium-argon dates from numerous Hindsale flows interfingering with the Los Pinos Formation, a volcaniclastic facies equivalent of the Santa Fe Group, document sedimentary accumulation from 25 to 5 million years ago (earliest Miocene to middle Pliocene time) (Butler, 1971, p. 297; Lipman and Mehnert, 1975, p. 130; Fig. 25, profile 1). Little radiometric dating of the Santa Fe Group itself has been done. As with the Ogallala Formation, absolute age is inferred from vertebrate fossil evidence. On this basis, basal low-angle piedmont alluvial fans of the Santa Fe Group are apparently middle Miocene in age (Galusha and Blick, 1971, p. 116). Subsequent steeper and more widespread alluvial fan deposition of late Miocene and early Pliocene age coincides with the most intense interval of tectonic activity (Taylor, 1975, p. 224). This interval also marks the beginning of Ogallala sedimentation, probably in late Miocene time (Frye and Leonard, 1959, p. 19). But where the Santa Fe Group consists principally of syntectonic fans of coarse-grained granitose debris, the lower Ogallala (Valentine Zone) is dispersed as basal valley alluvial fill representing a diverse provenance. These contrasting sedimentary environments reflect a substantial contrast in tectonic setting.

Tectonism essentially involved fragmentation and displacement of the widespread Eocene erosion surface (Scott, 1973, p. 510). Along the western margin of the Sangre de Cristo Range, normal faulting offsets structural blocks by as much as 12,000 m (Scott, 1975, p. 236). The range itself underwent about 1,000 to 1,300 m of epeiric uplift (as indicated by paleobotanic-paleoclimatic data of Axelrod and Bailey, 1976, p. 251), with only local displacement of the pre-tectonic surface. Most deformation of the eastern slope was directed along high-angle reverse or thrust faults (Figs. 3, 22). Widespread truncation of the resultant upthrusts was evidently accomplished before middle Pliocene time, producing a rejuvenated erosion surface that was continuous eastward with the Ogallala plain of alluviation (Scott, 1963, p. 50; Frye, 1970, p. 10).

Contrasting provenance of Santa Fe and Ogallala sediments reflects the general effect that tectonic disruption of the Eocene erosion surface had on the regional drainage patterns. The complex west-facing fault scarp and adjacent graben system that arose from extensional block faulting of the western Sangre de Cristo uplift redirected streamflow centripetally into what had formerly been an Oligocene volcanic plateau (Lipman and Mehnert, 1975, p. 126). Montane sediment contribution to this system was from marginal dissection of granitic crystalline rocks exposed along the fault border (Denny, 1940, p. 688; Galusha, 1974, p. 283). East of the structural divide, there is no indication that drainage was substantially reoriented. The effect of epeiric uplift and reverse faulting on the eastern flank was apparently twofold. First, elevation of the Eocene surface accelerated the degeneration of early Tertiary tropical weathering processes that had originally been paramount in its formation. Second, uplift and reverse faulting promoted excavation and transport of residuum from a broad and lithologically diverse terrain. The result was an etched erosional plain rather than a dissected montane border scarp.

Gravel dispersal

Drainage from the rejuvenated Eocene erosion surface eastward onto depositional plains is believed to have occurred from several points or foci of sediment dispersal (Fig. 22). Entrenched montane Ogallala channels (Scott, 1975, p. 240), assuming they were present, have been appreciably altered by the effects of Pleistocene tectonism and climatic change. The basis for defining proximal Ogallala drainage courses thus rests on interpretation of gravel lithology and relict landscape features. More specifically, dispersal points can be inferred from: (1) Ogallala gravels that reflect dominant contribution from a specific source terrain, (2) diverse indications of paleoslope direction, and (3) incised streams whose entrenchment evidently reflects (in addition to paleoslope trend) antecedence to structural displacement that induced Ogallala sedimentation. Table 2 summarizes this evidence for major foci of Ogallala sediment dispersal.

The nature of the western Ogallala outcrop is an additional though somewhat indirect indication that most Ogallala gravel transport from the mountains was predominantly by means of a few disparate alluvial channels. Leonard and Frye (1975, p. 8) observed regional westward thinning of the Ogallala Formation in east-central New Mexico. A similar thinning trend is also apparent farther north, where only a sparse record of Ogallala deposition exists west of the Canadian River. Two general circumstances may account for this sparsity: (1) the Ogallala may have been truncated westward by later erosion, and/or (2) widespread Ogallala deposition did not extend to the mountains.

Post Ogallala erosion has been considerable on a local scale, as indicated by the magnitude of topographic inversion associated with buttes capped by Pliocene age basalt in the Ocate and Raton volcanic fields (Fig. 43). However, aside from areas along major drainage courses, most denudation between the mountains and the western Ogallala escarpment has entailed stripping of stratiform plains. From the Las Vegas escarpment northward, these plains are mostly comprised of subhorizontal layers of Cretaceous sandstone and shale that display stratigraphic as well as topographic continuity with sub-Ogallala units east of the Canadian River (Fig. 25, profile 2). Only three small Ogallala outliers above the Mora River (Bachman and Dane, 1962) and more widespread (eolian?) fine sand and calcareous debris indicate exotic sediment transport across this surface. The virtual absence of coarse gravel lag on a plain of such diminished relief suggests most Ogallala transport was confined to a few discrete channels. There is, therefore, no reason to doubt that principal drainage outlets from montane areas have persisted since Ogallala time (Smith, 1940, p. 82).

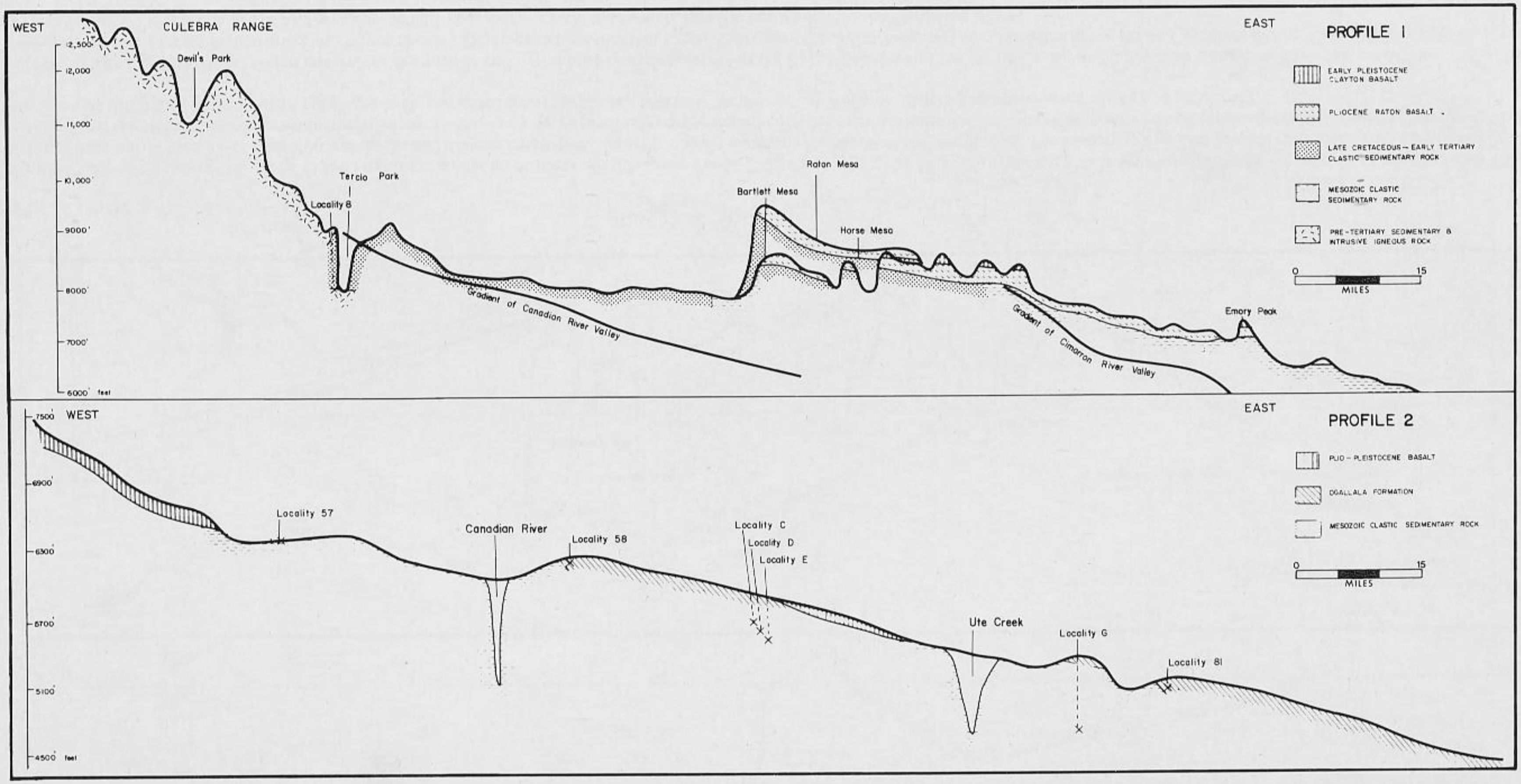


Fig. 25. Projected profiles along selected transects of the upper Canadian basin and Canadian breaks (Fig. 1). Note that stratigraphic thicknesses are diagrammatic. Outcrop limits are adapted from Bachman and Dane, 1962; Texas Bureau of Economic Geology, 1977; and Tweto, 1979. The volcanic sequence in profile 1 is from Muehlberger et al., 1967.

Profile 1. This profile depicts the marked physiographic changes that occur eastward from the crest of the Sangre de Cristo (Culebra) Range to near the eastern limit of the Raton Section. Devil's Park contains volcaniclastic alluvial fill, which accumulated during the tectonic episode that initiated Ogallala sedimentation in the Canadian basin. The Culebra Range rapidly descends to Tercio Park (a breached anticline), and piedmont slopes developed on clastics generated during Laramide orogenesis. Basalt-capped mesas of the Raton Section rise above the montane border. Pliocene-Pleistocene epeirogenic uplift resulted in upwarping of the basalt surfaces and pronounced entrenchment of the Cimarron River.

Profile 2. The subtle transition from Raton to High Plains sections is shown in this transect. Upwarping of Pliocene age basalts in the Ocate volcanic field is an indication of pronounced montane epeirogenic uplift to the west. Farther east, Pliocene-Pleistocene tectonism tended to rejuvenate Paleozoic structural elements. One such element, the Sierra Grande Arch (Fig. 4), may be responsible for steepened Ogallala surface gradients east of the Canadian River. Late Pliocene-early Pleistocene basalt west of Ute Creek is associated with fluvial gravels that are the earliest sedimentary remnant of an ancestral south-flowing Ute Creek (Fig. 4). Several literature localities (C, D, E, and G) represent local early-middle Pleistocene landscape levels.

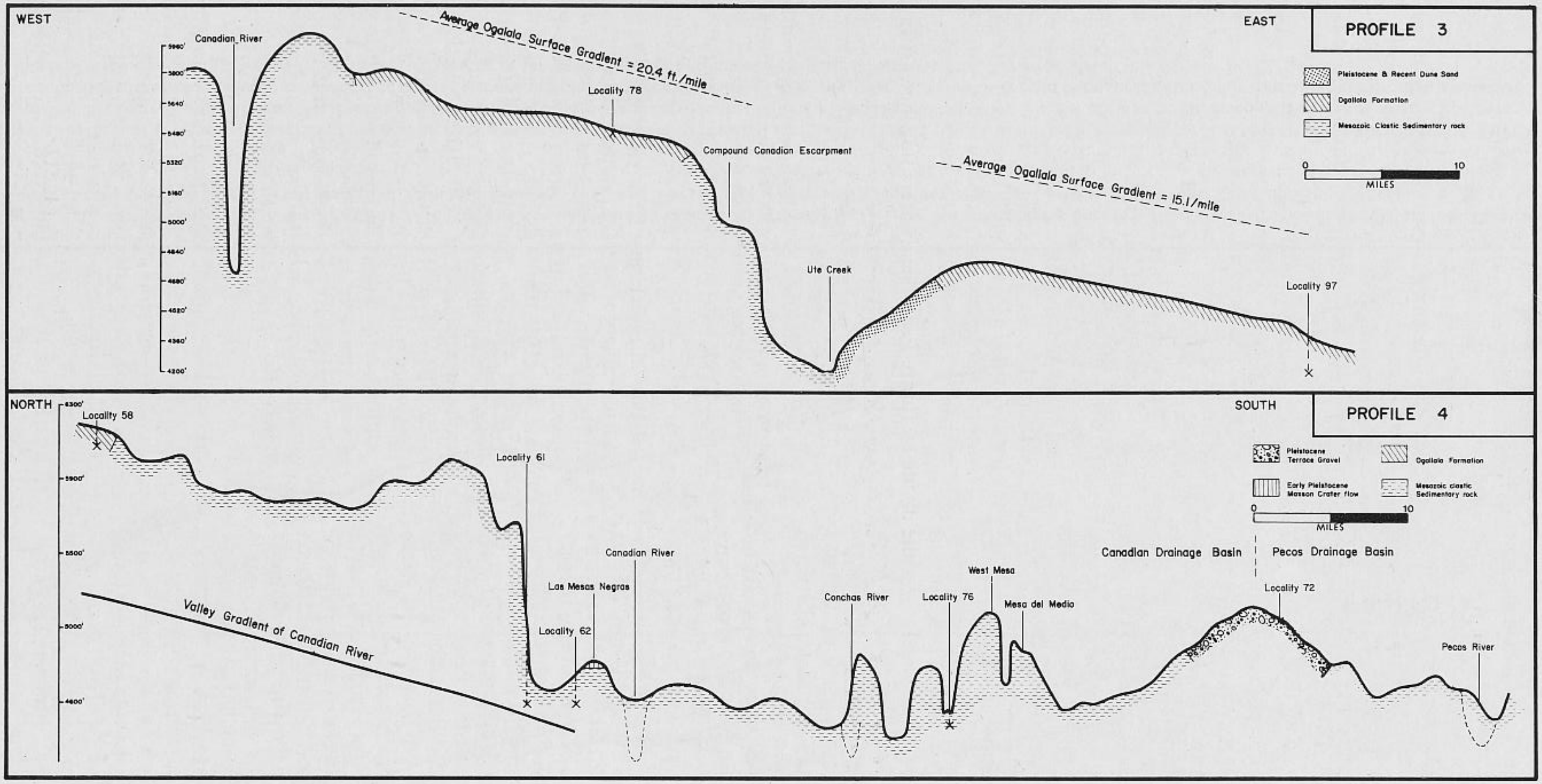


Fig. 25. (continued).

Profile 3. Profile 3 follows the slope of the High Plains near its border with the upper Pecos-Canadian valley. The High Plains surface between the Canadian River and Ute Creek is about 30% steeper than it is farther east. Late Pliocene-early Pleistocene epeirogenic uplift probably accounts for much of the steepening. The Canadian and Ute courses responded similarly to regional uplift. Their late Pliocene courses were modified according to the pattern of deformation until entrenchment stabilized the drainage network. Post-Ogallala gravel at Locality 97 suggests that portions of the Ogallala Formation may have been truncated and redeposited eastward as a result of Pliocene-Pleistocene epeirogenic tilting (Appendix A).

Profile 4. The Canadian escarpment dominates this profile and defines the boundary between the Raton Section and the Pecos-Canadian Valley. The Canadian River incised at least 65% of its valley north of the escarpment during late Pliocene-early Pleistocene time. Farther south, the rugged Canadian bend region culminates in the Pecos-Canadian divide. Gravel capping the divide is evidently early Pleistocene in age and was deposited by ancestral Pecos headwaters flowing eastward into the Canadian River.

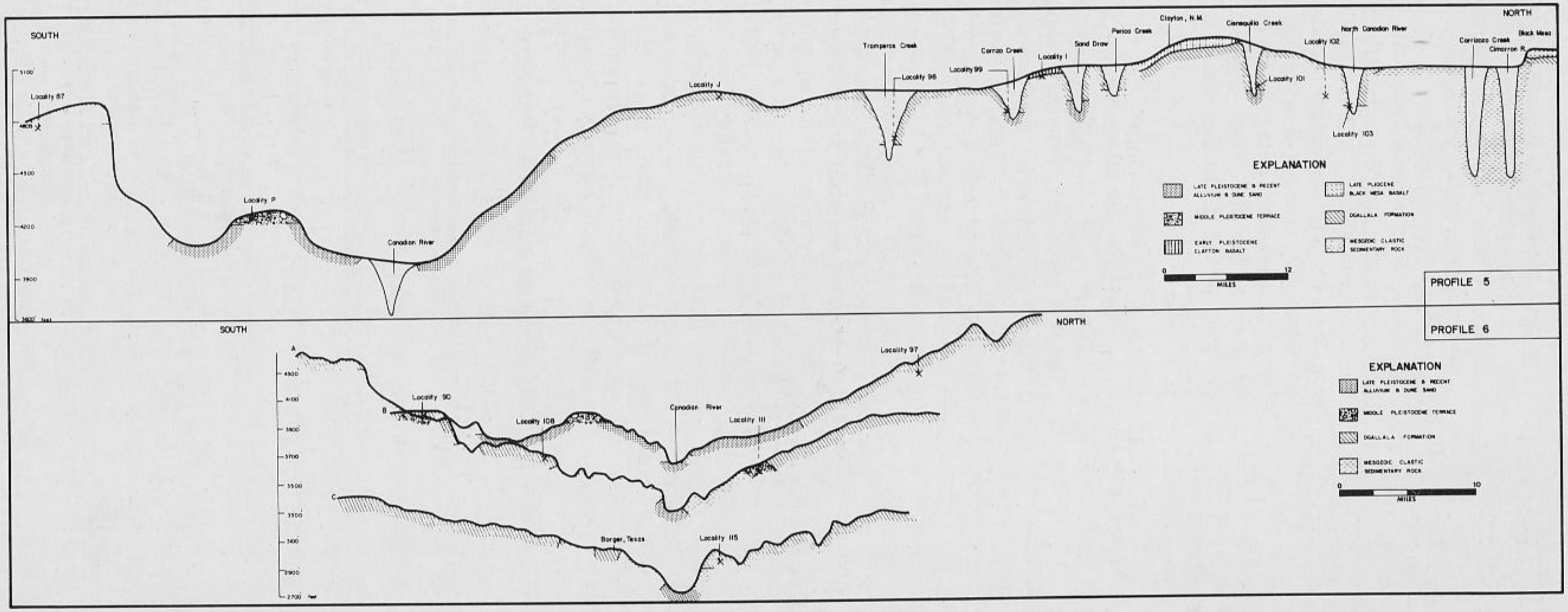


Fig. 25. (continued).

Profile 5. This profile spans the north-south length of the Canadian basin, across the western High Plains border and upper Canadian breaks. Valley profiles of most east-flowing High Plains streams resemble one another, except for those of the Cimarron River, Tramperos Creek, and the Canadian River. Anomalous entrenchment of the Cimarron (and its tributary, Carrizozo Creek) is probably a consequence of its location within a region where several late Pliocene-early Pleistocene drainage controls had maximum impact on the fluvial system. Tramperos Creek apparently differs from adjacent High Plains streams because it drains an area that was underlain by thin inter-channel sediments of the Ogallala Formation. The location and dimensions of the Canadian breaks are attributable in large part to the effects of subsurface evaporite dissolution. Canadian valley excavation had proceeded to at least the level of Locality P by middle Pleistocene time.

Profile 6. This overlay of three Canadian valley profiles illustrates the persistence of the valley's dimensions across the Texas Panhandle. By middle Pleistocene time, the Canadian breaks were almost as wide and about half as deep as they presently are. A precise history of the breaks is not possible until its alluvial chronology has been deciphered. For example, much of what is shown on the profile as Ogallala Formation may be terrace/alluvial gravel reworked from the Ogallala.

OGALLALA SEDIMENTATION AND DRAINAGE NETWORK MORPHOLOGY

Extrapolation of Ogallala drainage network morphology east of inferred proximal montane outlet channels is based largely upon depth-to-bedrock compilations, the distribution of basal Valentine gravel, and Ogallala sand and gravel isolith and percentage trends (Fig. 26). Throughout most of northeastern New Mexico, alluviation began in sharply defined erosional valleys. These valleys trend east and southeastward across a similarly inclined, gently undulating terrain that generally exhibits less than 200 to 300 ft of local relief. Early Ogallala drainage courses ranged in size from small shallow channels transporting sparse, mostly locally derived gravel to major through-flowing rivers that were both depocenters for the greatest volume of coarse montane sediment and conduits for its dispersal beyond the Ogallala alluvial plain.

Not all incipient alluviation was confined to a roughly subparallel fluvial network. Coarse Ogallala sediments and equivalent deposits over much of the Texas Panhandle and adjacent portions of Oklahoma and Kansas were concentrated in locally subsiding surface irregularities produced by groundwater dissolution of Permian evaporites.

Ogallala sedimentation and the question of an ancestral Canadian River

A marked change in the nature of topographic control on Ogallala sedimentation occurs in the vicinity of the New Mexico-Texas line. The subparallel fluvial network prevalent over much of the western Canadian basin gives way to an irregular array of closed solution collapse depressions, the development of which preceded and probably accompanied Ogallala deposition (Dutton *et al.*, 1979, p. 87; Gustavson *et al.*, 1980, p. 30-32; Seni, 1980, p. 5; Figs. 26, 27). Sub-Ogallala topography and the distribution of basal Valentine gravel are thus unreliable bases for projecting an Ogallala drainage network in this area.

A more satisfactory technique for defining Ogallala depositional geometry on the Texas High Plains was adopted by Seni (1980, p. 2). He constructed Ogallala sand and gravel isolith and sand and gravel percentage maps from several thousand water well-drillers' logs. Trends on these maps purportedly define several channels whose network geometry reflects medial and distal fan deposition (Seni, 1979, p. 514, Seni, 1980, p. 14-17; Fig. 26). The characterization of one of the more discrete or apparently through-flowing channels as being the ancestral Canadian is an exercise in conjecture. It also neglects the fact that much Ogallala deposition in this portion of the Canadian basis was by non-fluvial processes.

Laverne Formation and distal Ogallala sedimentation

The pattern of most basal Ogallala deposition in the Canadian basin east of the New Mexico-Texas line was governed by numerous solution collapse depressions (Fig. 26). Earliest stratigraphic record of these depressions is contained in the Laverne Formation, determined from vertebrate fauna to be mostly early Pliocene in age (Kitts, 1965, p. 9). The Laverne Formation crops out discontinuously throughout the eastern Panhandle of Oklahoma and adjacent southwestern Kansas. Its thickness is highly variable, possibly exceeding 500 ft in the subsurface (Byrne and McLaughlin, 1948, p. 72), and consists of gravel to clay-sized (mostly sand) sediment, caliche, and limestone (Schoff, 1956, p. 4). The laterally discontinous beds of sandy, fossiliferous, or carbonaceous limestone are quite distinctive. Dip magnitude (up to several hundred feet per mile) and direction are not areally consistent (*ibid.*, p. 3). The relationship of the Laverne Formation to the presumably younger Ogallala rocks was initially a source of confusion, since contact

Table 2. Bases for Postulating Foci of Ogallala Sediment Dispersal from the Pliocene Montane Border of the Canadian River Basin.

FOCUS OF OGALLALA SEDIMENT DISPERSAL (SEE FIGURE 22)	POST-OGALLALA DRAINAGE EQUIVALENT	EVIDENCE	SUPPORTING DATA
1.	GALLINAS-SAPELLO RIVERS	—EASTWARD INCLINED GRAVEL-DEFENDED PRE-MIDDLE PLIOCENE EROSION SURFACES	P. 54; FIG. 35, SITES 20 & 21
		—DRAINAGE SUPERPOSITION ON PRE-MIDDLE PLIOCENE STRUCTURES	P. 54; FIG. 36
		—WESTERLY PROVENANCE OF PROBABLE MIDDLE PLIOCENE PEDIMENT GRAVEL	FIG. 35, SITES 20 & 21; FIG. 36
2.	MORA RIVER	—SOUTHEAST-INCLINED PRE-MIDDLE PLIOCENE EROSION SURFACE	P. 47; SCHOWALTER, 1969, P. 60
		—DRAINAGE SUPERPOSITION ONTO PRE-MIDDLE PLIOCENE STRUCTURES	P. 53; FIG. 5
		—STABLE PROVENANCE AREA SINCE BEFORE EARLY PLEISTOCENE TIME	P. 54; LOCALITIES 53 & 54
3.	OCATE CREEK	—SOUTHEAST-INCLINED PRE-MIDDLE PLIOCENE EROSION SURFACE	P. 46
		—STREAM ENTRENCHMENT ACROSS STEEPENED MARGIN OF PRE-MIDDLE PLIOCENE EROSION SURFACE	FIG. 39
		—GEOGRAPHIC DISTRIBUTION OF SEDIMENTARY CONSTITUENTS IN OGALLALA GRAVEL	FIG. 22 & 24
		—WESTERLY PROVENANCE OF PROBABLE PLIOCENE AGE GRAVELS	LOCALITIES 46 & 56
4.	CIMARRON CREEK	—DRAINAGE SUPERPOSITION ONTO PRE-LATE MIOCENE STRUCTURES	P. 55, FIG. 6
		—WESTERLY PROVENANCE OF PRE-MIDDLE PLIOCENE PEDIMENT GRAVEL	LOCALITY 33
5.	PURGATOIRE-CIMARRON RIVERS	—WESTERLY PROVENANCE OF PLIOCENE FLUVIAL GRAVEL	LOCALITIES 11-13
		—WESTERLY PROVENANCE OF PROBABLE EARLY PLIOCENE PEDIMENT GRAVELS	LEVINGS, 1951, P. 86
		—EAST-TRENDING LINEARITY OF LATE PLIOCENE BLACK MESA BASALT FLOW	P. 63

between the two units had nowhere been recognized (Myers, 1959, p. 48). Later workers have mapped the Laverne as basal Ogallala in eastern Beaver County, Oklahoma (Marine and Schoff, 1962, plate I) and documented a conformable contact between the two in Ellis County, Oklahoma (Kitts, 1965, p. 9).

The character and distribution of the Laverne Formation, its age, and its association with the Ogallala Formation suggest deposition approximately synchronous with that of the Valentine unit. The Valentine was deposited during incipient stages of valley alluviation; in contrast, the Laverne accumulated in local subsidence depressions formed by subsurface dissolution of Permian evaporites. The major proportion of surface collapse can be attributed to solution of a prominent salt zone in the Flowerpot Shale by eastward-flowing groundwater (Irwin and Mor-

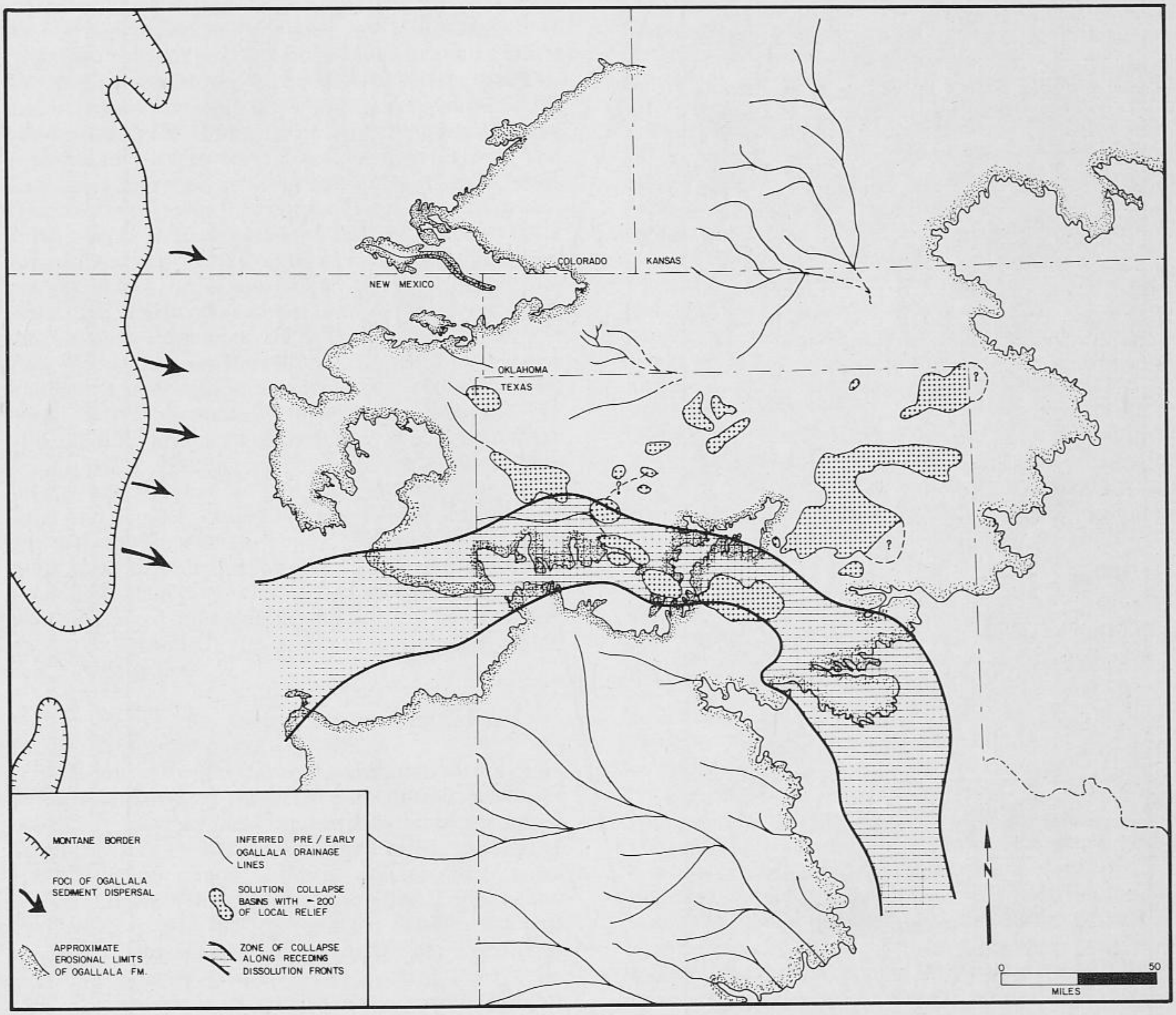


Fig. 26. Postulated network geometry of Pliocene drainage that persisted in the Canadian basin area throughout at least the early stages of Ogallala deposition. Pre/early Ogallala drainage lines are inferred from sub-Ogallala topography, Ogallala gravel occurrence and composition, Ogallala saturated thickness, and outcrop geometry of Pliocene age basalt. Outlines of solution collapse basins are in part derived from Ogallala saturated thickness that is greater than 300 ft. Given Pleistocene sedimentologic and groundwater effects, areas of solution collapse are probably shown as being more extensive than they were during early Ogallala deposition. The zone of early Pliocene collapse above receding dissolution fronts was estimated by projecting the modern collapse zone 15 mi updip. The assumption that dissolution fronts have receded 15 mi since the early Pliocene is roughly consistent with calculations of Pleistocene migration rates. Outlines of major sub-Ogallala physiographic regions can also be summarized from this map. Ogallala sediment was transported from the mountains along a few montane borner rivers that were probably entrenched into Cretaceous marine clastic bedrock. Entrenched valley systems continued southeastward across plateaus or highlands developed mostly on Permian through Cretaceous age clastics. Subsurface evaporite dissolution within what is now the Texas Panhandle produced an irregular karst-like topography on Permian-Triassic bedrock plains. Most through drainage entering the solution collapse terrain was diverted into numerous local basins and troughs. The few streams that exited the terrain probably again followed valleys incised into mostly upper Paleozoic clastic bedrock. The effect that subsurface dissolution had on regional drainage lines precludes identifying the course of a pre/early Ogallala Canadian River. Sources: Pre/early Ogallala drainage lines—Baldwin and Bushman, 1957, p. 16 and 18; Baldwin and Muehlberger, 1959, p. 65; Cronin, 1961, Plate 2, p. 15 and 23; McGovern, 1970, p. 18; Reeves, 1972, p. 109; Schoff, 1939, p. 66; Schoff, 1943, p. 102. Solution collapse areas—Cronin, 1961, Plate 2; Foster et al., 1972, p. 10-12; Seni, 1980, p. 10. Ogallala erosional limits—Dane and Bachman, 1965; Miser, 1954; Moore and Landes, 1937; Tweto, 1979.

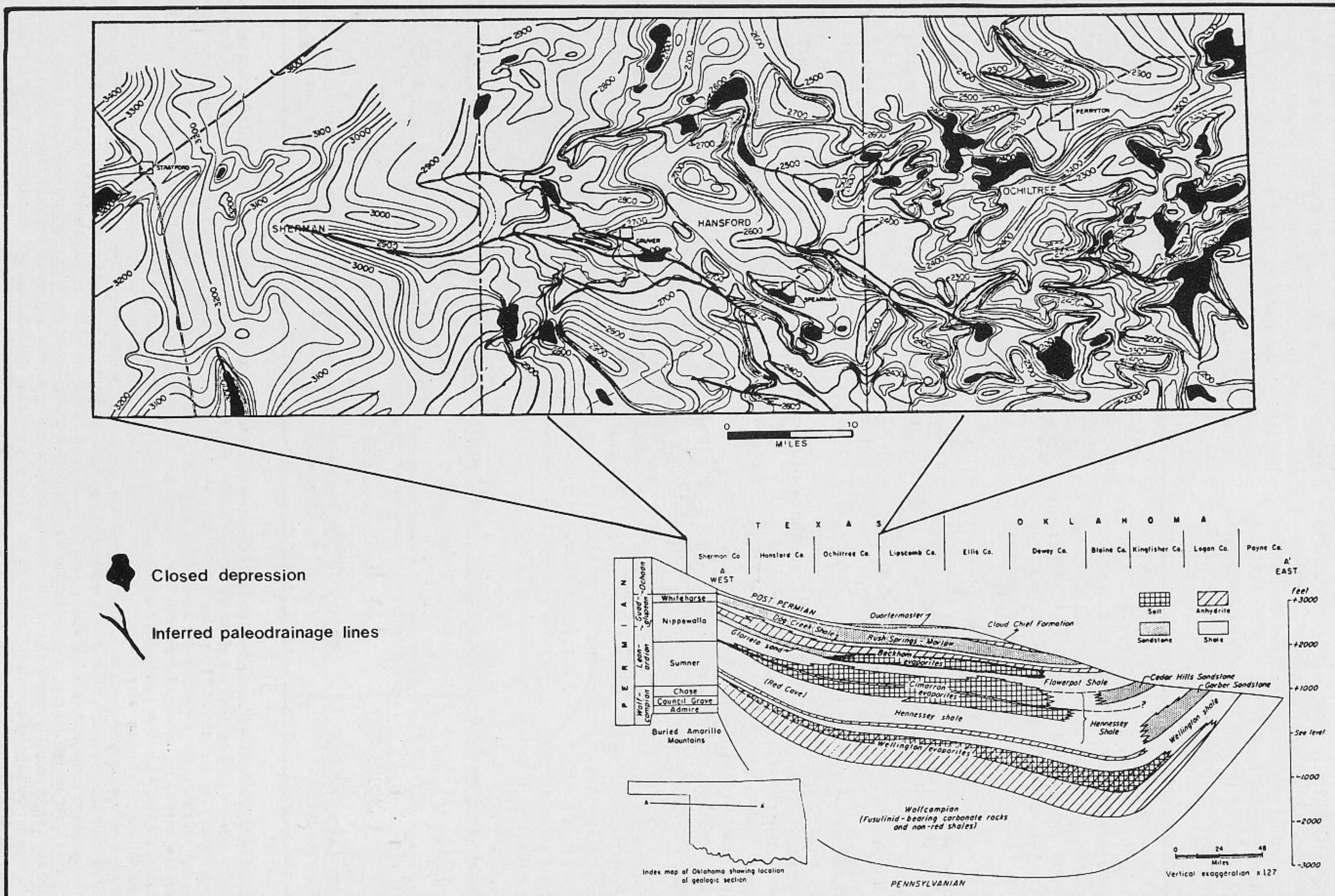


Fig. 27. Generalized subsurface geologic section and sub-Ogallala topographic map demonstrating the effects of subsurface evaporite dissolution on Ogallala deposition. More specifically, the transect displays karst-like sub-Ogallala topography produced by collapse along a westward-receding dissolution front (Fig. 50). The front is within the Flowerpot Salt near its apparent western depositional limit. Adapted from Jordan and Vosburg, 1963, p. 10; North Plains Water Conservation District, 1965, Fig. 27.

ton, 1969, p. 9; Fig. 27). Such activity evidently preceded Laverne alluviation, widely accompanied Ogallala deposition in western Oklahoma (Patrick, 1972, p. 126) and the eastern Texas Panhandle (Seni, 1980, p. 5), and has continued with varying intensity throughout the Pleistocene. Its impact on evolution of the Canadian fluvial system during Pliocene time is evident by comparing typical Valentine gravel with sediment of similar size in the Laverne Formation.

Gravel collected from the Laverne Formation (Locality 117) is predominantly subangular to subrounded. It contains a wide range of lithologic types, including much ferruginous sandstone (often with a surface patina), micritic limestone, shells of *Gryphea,* metaquartzite, and various volcanics. Though more representative of locally exposed rock types than most Valentine gravel, the Laverne does reflect mixing with gravel from western Ogallala source areas. Lesser rounding, greater friability, and the occasional surface patina of locally derived clasts suggest mixing probably occurred in topographic swales peripheral to areas of most active fluvial transport and deposition. Eventual incorporation of these clasts into the Laverne Formation may have involved sporadic sheet-flood transport flow into nearby solution collapse hollows. A somewhat analogous sequence of events has been inferred for sediment-filled hollows, or dayas, in arid and semi-arid parts of the northwest Sahara (Clark *et al.,* 1974, p. 138). In both cases, stratigraphic evidence further suggests that the great bulk of sediment is sand sized and smaller, settled in local ponded depressions, and was supplemented by appreciable eolian deposition. Such local sedimentary in-filling complemented more general Ogallala valley alluviation. Both processes effectively obscured topographic impediments to drainage network migration in the course of producing a coalescent alluvial plain.

Valley alluviation and termination of the Ogallala erosion cycle

Basal Valentine gravel is overlain by deposits of quite different sedimentary character. Sand and lesser quantities of silt and clay make up virtually all of the upper Valentine, Ash Hollow, and Kimball zones. In terms of areal distribution and sediment volume, these units represent most of the Ogallala Formation (Leonard and Frye, 1975, p. 9). The finer grained deposits are also products of fluvial aggradation, supplemented locally by a proportionately greater eolian contribution (Frye, 1970, p. 7; Reeves, 1976a, p. 214). They apparently reflect continued valley alluviation, first by overlapping of gentle side slopes but eventually by inundation of the bedrock topography and formation of a coalescent plain of alluviation (Frye *et al.,* 1978, p. 8).

Details of the process of alluviation are few. Isolated gravel lenses and laminae distributed throughout the upper Ogallala (Localities 86, 87, 89, 107, 112, and 114) are evidently the coarse lag of braided fluvial channels that shifted laterally across their own alluvium. Diminishing evidence of these inferred channels accompanies a general upward decrease in grain size (Frye and Leonard, 1959, p. 16). In addition, deterioration of flora and freshwater molluscan fauna throughout Pliocene time indicates a declining water table and more irregular streamflow, apparently caused by increasing aridity (Frye and Leonard, 1957a, p. 8). Finally, proof that these conditions produced a geomorphically stable alluvial plain lies in the greater prevalence of calcareous silty sand and calcareous pedogenic horizons higher in the Ogallala section.

The presence at several localities (Localities 74, 75, 78, 85, 86, 88, 112 and 118) of disseminated carbonate and caliche horizons within Ogallala sediments that rest upon non-calcareous bedrock indicates prolonged and considerable influx of eolian carbonate dust. Measurements of modern calcareous "desert loess" accumulation (Ruhe, 1967, p. 59) and numerous soil studies throughout eastern New Mexico and west Texas (Reeves, 1970a, p. 355) sustain this conclusion. Furthermore, there is abundant evidence that thick caliche profiles like those found in the upper Ogallala develop on a stable, slowly aggrading surface (Reeves, 1976b, p. 108). The late Pliocene Ogallala plains of northeastern New Mexico and Panhandle Texas-Oklahoma probably were such a surface. Calcareous dust must have been borne by prevailing winds sweeping extensive carbonate exposures to the south and southwest (the wind direction supports sedimentologic and ecologic evidence of semi-aridity). Surface infiltration of dissolved carbonate during intermittent or seasonal wet periods eventually produced the incipient Ogallala "climax soil" or "caprock." Though its present morphology bears the imprint of solution, brecciation, and recrystallization under a cyclically changing Pleistocene climatic regime (Frye and Leonard, 1972, p. 5), the Ogallala caprock does represent an important spatial and temporal datum in Canadian River history.

Under conditions of increasing semi-aridity and diminishing local relief, the Ogallala drainage network, which conveyed perennial flow, was probably constricted to a few major channels. Their orientation conformed to regional surface inclination but was relatively unconstrained by major bedrock topographic irregularities. As a consequence, the abrupt and apparently concurrent onset of Pleistocene tectonic activity and climatic deterioration exerted a major impact on drainage network configuration as well as fluvial regime. The reliability of the Ogallala caprock as a measure of this impact lies in its generally faithful reflection of the terminal Ogallala alluvial plain, a plain that may have persisted essentially unchanged during a hiatus of up to four million years (Boellstorff, 1976, p. 64).

THE PLEISTOCENE CANADIAN RIVER BASIN

The modern Canadian fluvial system has been depicted in terms of basin geology, landscape and drainage network morphology, climate/vegetation, and the hydrologic factors of runoff, sediment yield and sediment concentration. These variables have interacted through time to influence drainage basin morphology. The manner of their interaction is most evident over the time span of the Pleistocene Epoch. Evidence of Pleistocene drainage history is most abundant, both by virtue of its recency and because of the recurrence of intense and cyclic climatic change. In fact, the Pleistocene and Holocene Canadian River bears a prevailing overprint of climatically induced cyclicity. All other variables influencing the fluvial system have been conditioned by cyclic change of climate to such a degree that some preliminary discussion of its impact is necessary.

Pleistocene cyclic climatic change in the region of the Canadian basin began with a major episode of cooling sometime after cessation of Ogallala deposition. Precise dating of this cooling, which is postulated to have been a global event (Frakes, 1979, p. 236), is the subject of debate. For purposes of this study, the date is placed at between 2.5 and 3.0 million years B.P., based largely upon fission-track ash dates for the southern mid-continent region (Boellstorff, 1978, p. 70). Cooling signalled the onset of the first of four prolonged periods of climatic reversal that correspond to major glacial advances in North America. These reversals varied in length and intensity and each was punctuated by several intervals of greater climatic severity, the timing of which roughly coincides with minor readvances of the North American ice sheets. Evidence for the succession of "cool" glacial and intervening "warm" interglacial periods in the vicinity of the modern Canadian basin is found chiefly in relict cryogenic deposits of the Sangre de Cristo Range, in an intensively studied fragmentary biostratigraphic record from alluvial deposits of the High Plains, and in a somewhat more continous biostratigraphic record from the Gulf of Mexico.

The distribution of alpine glacial landforms and a variety of relict cryogenic deposits in the southern Rocky Mountains have been the basis for several estimates of the magnitude of full-glacial snowline, permafrost, and timberline depression (Leopold, 1951, p. 152; Antevs, 1954, p. 182; Richmond, 1965, p. 225; and Brackenridge, 1978, p. 22). These estimates have in turn been the major source for estimates of the magnitude of full-glacial cooling. Brackenridge's (1978, p. 22) conclusion that mean annual cooling during the last glacial maximum (27,000-13,000 years B.P.) was about 7° to 8° C (13° F) is accepted as being reasonable for the Canadian basin. A similar degree of full-glacial cooling for the region has also been postulated using different lines of reasoning (Bachuber, 1976, p. 566; Gates, 1976, p. 1142).

Pleistocene deposits of the High Plains section contain the only dateable fossil-sediment record within the Canadian basin. For quite some time, this record was presumed to correlate well with the glacial chronology of the upper Midwest (Frye, Swineford, and Leonard, 1948, p. 501). However, such regional correlations were based on the concept of a Pearlette Ash datum of late Kansan or Yarmouthian age. Izett *et al.* (1972, p. 571), Boellstorff (1976, p. 48), and others have since demonstrated that at least six ashes originating from three widely scattered volcanic sources may be present on the southern Great Plains. Dating of these ashes, largely by the fission-track method, has provided an absolute time frame for the High Plains Pleistocene sedimentary record (Fig. 28).

Ongoing solution subsidence on the southern High Plains was largely responsible for the accumulation and preservation of deposits containing the most complete sequence of late Pliocene and Pleistocene continental vertebrate and molluscan faunas yet recorded (Taylor, 1960, p. 18). Intensive study of this faunal record, particularly in southwestern Kansas and adjacent Oklahoma, has documented the marked cyclic climatic changes of the Pleistocene. The usefulness of this faunal evidence for the study of the Pleistocene Canadian is twofold. First, relative values for paleotemperature and effective precipitation can be deduced from comparisons with modern conditions. Second, the lithologic setting of the faunal record gives some indication of the nature of sedimentation during a specific climatic interval.

In general, glacial periods were marked by lower temperatures and greater effective precipitation than today. Accumulation of lacustrine silt and sand was more common, as was the deposition of coarser grained alluvial sand and gravel. The greatest contrast between Pleistocene full glacial and present conditions roughly coincides with deposition of sediments containing the Cudahy local fauna (Fig. 28) about 600,000 years ago (the classic "Kansan" of Frye and Leonard, 1965 and others). Early Pleistocene and post-Kansan (middle to late Pleistocene) glacial intervals were somewhat less severe.

Interglacial temperatures and effective precipitation were comparable to those of the southern High Plains today. Playa lake sedimentation accounts for preservation of most of the interglacial fossil record. Erosional stability prevailed over most of the region, as evidenced by widespread soil development.

The most continuous record of Pleistocene climatic change affecting the Canadian basin is contained in sediments deposited in the Gulf of Mexico. Paleotemperature curves based on the occurrence of planktonic foraminifers and calibrated to a time scale for geomagnetic reversals provide a continuous record of relative temperature change since the late Pliocene (Fig. 28). The curves corroborate and add some coherence to the more discontinuous continental sedimentary sequence.

PLEISTOCENE PALEOHYDROLOGY: A MODEL

As was evident from the discussion of modern Canadian River basin hydrology, there is a systematic relationship between climate and hydrology. From this relationship, it is possible to infer values of mean annual runoff, sediment yield, and sediment concentration from climatic variables of mean annual temperature and precipitation. Furthermore, because there is a close similarity between modern and Quaternary vegetation, one can use the climate-hydrology relationship to postulate both hydrologic and more general fluvial response to Pleistocene climatic change.

Curves first developed by Langbein and Schumm (1958) can be used in a manner suggested by Schumm (1965) to postulate the effects of cyclic Pleistocene climatic change on the Canadian fluvial system. These postulations, while expressed in quantitative terms, are useful only as indicators of the direction and relative order of magnitude of paleohydrologic response.

As mentioned previously, Brackenridge's (1978, p. 37) conclusion that mean annual cooling during the last glacial maximum was about 7° to 8° C (13° F) is considered valid for the Canadian basin. Citing the divergence of published glacial lake-budget calculations, Brackenridge further determined that uniform cooling alone could account for paleolake levels, without the need for postulating appreciably higher precipitation rates (Brackenridge, 1978, p. 34). The following paleohydrologic reconstruction is therefore based on the assumption that the climate during the last glacial maximum was not a pluvial episode in the classic sense (Antevs, 1954, p. 182). Instead, an approximate 13° F cooling was probably accompanied by a 25% to 50% reduction of evaporation rates (Leopold, 1951, p. 163; Reeves, 1965, p. 185-187; Reeves, 1966, p. 642; Galloway, 1970, p. 255), but by no appreciable change in the amount of annual precipitation.

The effect of a 13° F full glacial cooling on mean annual runoff, sediment yield, and sediment concentration is shown in Table 3. The selected sites are the same as those used to document modern Canadian basin hydrology. Postulated values for runoff during the last glacial maximum show the greatest departure from present rates. Runoff was apparently greater by up to about 300% over the Raton and High Plains sections, with a lesser but still substantial increase occurring over the rest of the basin. Sediment yield generally appears to have been slightly less throughout the basin (by 20 to 30%). Sediment concentration was diminished by a somewhat greater amount (60 to 80%) basinwide.

The preceding quantification of Pleistocene paleohydrologic response contains several biases. The magnitude of full glacial cooling is presumed to have been uniform over the entire Canadian basin, though data collected for the Climap project (a simulation of ice-age climate using a global atmospheric model) suggest cooling over the southern High Plains may have been only about two-thirds of the assumed amount (Gates, 1976, p. 1142). If the Climap data are correct, the magnitude of hydrologic response to Pleistocene climatic change over the High Plains would have more closely resembled the Osage Plains than the plateau region to the west. The seasonal occurrence as well as amount of precipitation is considered to have been similar to present conditions. If precipitation during Pleistocene glaciation had been concentrated during the summer months (as suggested by Dillon, 1956, p. 168-169), the departure from present hydrologic conditions would have been somewhat less. Finally, there is considerable opportunity for bias in the climate-hydrology curves themselves. Records used to compile the curves were sometimes few in number and were usually assembled for drainage basins affected to some extent by human agency. Variations in land use comprise a particularly significant possible source of error, as indicated by discrepancies between plotted and measured values for some hydrologic variables (Table 1).

Despite their great potential for error, paleohydrologic reconstructions using Schumm's curves do carry the weight of empirical rather than *a priori* speculation. They also provide a point of departure in postulating the more general response of the fluvial system to cyclic Pleistocene climatic change.

RESPONSE OF THE CANADIAN FLUVIAL SYSTEM TO PLEISTOCENE CLIMATIC CHANGE

With the onset of the first period of Pleistocene glacial cooling, the Canadian fluvial system began to display regional hydrologic variation that was similar in magnitude to that of the modern river. The development of a more contrasting hydrologic character was also accompanied by pronounced regional differences in the fluvial system's response to climatic deterioration.

Fluvial processes in the montane headwater region of the Canadian differed most significantly from the rest of the fluvial system during glacial cooling. Paleohydrologic reconstructions using Schumm's curves fail to account for this disparate response because full glacial mean annual temperatures were depressed too near the freezing point of water (Table 3). During glacial periods, the Rocky Mountains south of latitude 37° N were capped by alpine ice masses of very limited areal extent (Ray, 1940, p. 1891-1901; Richmond, 1963, p. 121-125). This is corroborated by estimates of regional snowline depression during the last glacial maximum (Brackenridge, 1978, p. 24-25). Although the direct effect on the Canadian basin of alpine glaciation was negligible, far more extensive periglacial conditions had a major impact on the fluvial environment. The magnitude of postulated depression of full glacial timberline gives a rough idea of the area of heightened periglacial influence in the Canadian basin (Fig. 29). Most of the southern Sangre de Cristo Range and adjoining uplands of the Raton section may have been above timberline during the last glaciation. This area would have been affected by greatly intensified mechanical weathering and mass wasting, accompanied by a comparatively slight change in runoff (Fig. 30). The resulting increase in sediment yield (possibly by as much as 150%, based on estimates by Corbel, 1959, p. 24) and concentration would have induced widespread aggradation of montane streams. In effect, the onset of glacial climate would have generated a sediment reservoir in the Canadian headwaters. Drainage of this reservoir, along with subsequent incision and extension of head-

SUMMARY OF LATE CENOZOIC FAUNAL, CLIMATIC, AND LITHOLOGIC SEQUENCES IN SOUTHWESTERN KANSAS AND ADJACENT OKLAHOMA (ADAPTED FROM TAYLOR, 1960, P. 15 AND BAYNE, 1976, P. 11 & 13)

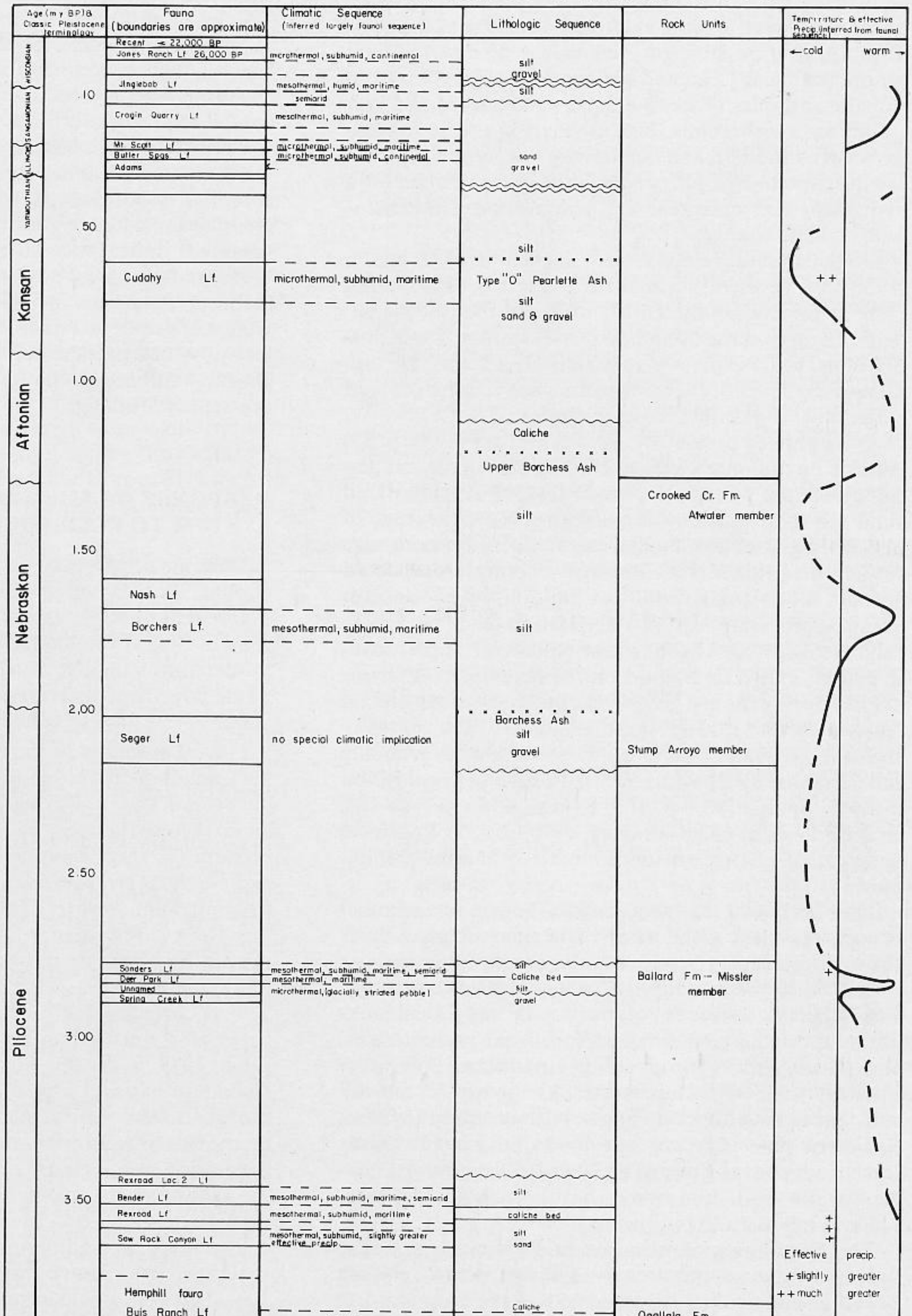
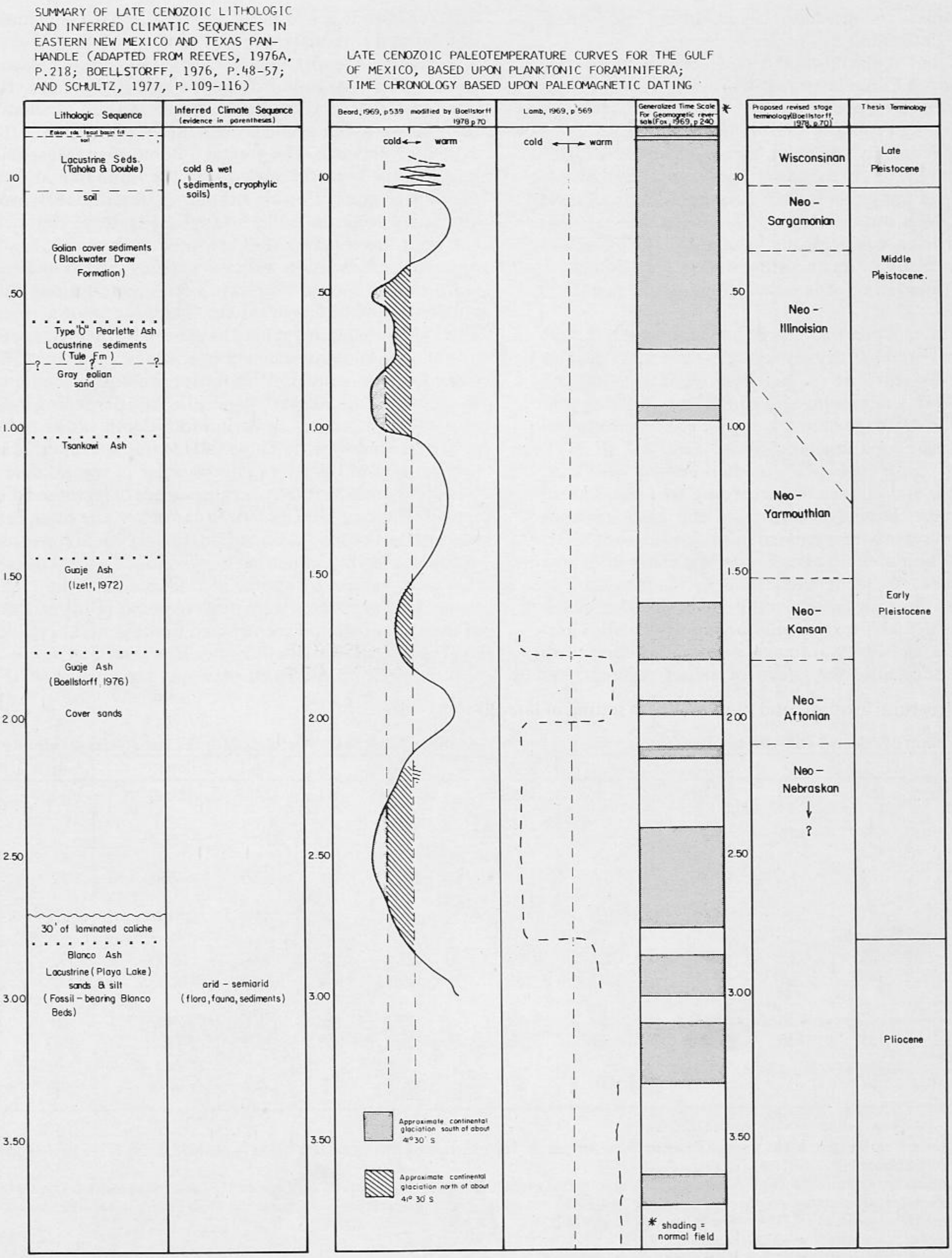


Fig. 28. This chart summarizes the varied record of Pleistocene climate and sedimentation that exists within the region of the Canadian River basin. The record is presentable within an absolute time frame on the basis of published correlations to fission track and potassium-argon dated ash layers of the mid-continent and to



the potassium-argon dated magnetic polarity epochs of the Gulf of Mexico. However, scattered "absolute" dates serve only to bracket particular stratigraphic sequences and therefore all time boundaries should be considered approximate.

water streams, would have begun during the waning stages of glaciation.

The advent of glacial climate had a markedly different impact on the Canadian downstream from the region of pronounced periglacial activity. As shown in Table 3, glacial cooling produced sharply increased runoff and a modest decline in sediment yield and concentration throughout the rest of the basin. The magnitude of hydrologic change was greatest over the semi-arid plateau and plains sections, but the nature of the change was such that stream incision was probably basinwide. The pattern as well as intensity of downcutting during glacial climatic episodes varied in accordance with regional differences in climate.

Study of modern fluvial systems and world climate reveals that drainage density is greatest and most variable in markedly seasonal or semi-arid climates (Gregory, 1976, p. 294). Under semi-arid conditions, differing portions of the drainage network appear to respond to different climatic parameters. What Gregory (p. 311) termed a "basic network" is occupied by perennial streamflow and is variable according to mean annual precipitation. Drainage density of the basic network tends to increase with increased rainfall, since the greater runoff per unit area necessitates greater channel volume per unit area. An "expanded network," characterized by ephemeral flow, responds more to seasonal climatic events, particularly to precipitation intensity. In this portion of the network, drainage density decreases with increased rainfall as the effects of denser vegetal cover (i.e., transpiration and moisture retention) become more pronounced (Stoddart, 1969, p. 195).

In accordance with Gregory's analysis, waxing glacial climate over the semi-arid plateau and High Plains sections would have caused an increase in the Canadian's basic network, but would have induced contraction of the expanded network. The greater volume of runoff would largely have been channeled into the Canadian and its major perennially flowing tributaries. Because increased discharge would be concentrated along these channels and their dense network of low-order tributaries, headward stream extension, valley deepening, and associated scarp retreat should also have been greatest along this portion of the drainage system. The process of accelerated valley enlargement may have been further enhanced by changes in major channel profile and behavior. The Canadian and its major tributaries probably accommodated greater discharges by widening and deepening their channels and increasing their width-depth ratios (Leopold and Maddock, 1953, p. 5-8). Major lateral shifts in the thalwegs of the rivers (on the order of several miles) also apparently occurred during periods of increased discharge (Sharps, 1969, p. 69). In summary, the basic network of the full glacial Canadian fluvial system consisted of streams having somewhat deeper, much wider courses that were subject to appreciable lateral diversion. The major stream courses were disposed toward net erosion of their channels and contributed to the general excavation and expansion of alluvial valleys (Fig. 31).

In contrast to the basic network, the portion of the

Table 3. Values of selected climatic and hydrologic variables for the Canadian River basin postulated for the last glacial maximum.

1	2	3	4	5	6	7	8	9	10	11
LOCATION	MAT	MAR	MAR	%Δ	MASY	MASY	%Δ	MASC	MASC	%Δ
●	27	>10	—	—	—	—	—	—	—	—
▲	37	4	+3	300	525	-200	28	<2500	>-6500	72
■	47	>2	>+1	>100	700	-25	3	6000	>-14,000	>70
o	42 (46)	3 (>2)	>+2 (>+1)	>200 (>100)	600 (675)	-225 (-150)	27 (18)	4000 (6000)	-16,000 (-14,000)	80 (70)
Δ	47 (51)	>5 (4.5)	>+3 (<+2.5)	>150 (<50)	425 (500)	-175 (-100)	29 (17)	>1100 (1500)	-2400 (-2000)	69 (57)
□	52	14	>+5	>60	275	-75	21	250	-350	58

1. ● Red River, New Mexico; ▲ Las Vegas/Cimarron, New Mexico; ■ Tucumcari, New Mexico; o NW Texas Panhandle; Δ SE Texas Panhandle; □ eastern Oklahoma.
2. Mean annual temperature (° F); figures reflect the assumption that average full glacial temperatures were some 13° F cooler than today's. Figures in parentheses (for all columns) were derived assuming 33% (4° F) less mean annual temperature decline over the High Plains, in accordance with conclusions inferred from CLIMAP data (Gates, 1976, p. 1142).
3. Mean annual runoff (inches); values based on Fig. 13.
4. Departure of mean annual runoff (inches) from modern values. Note that this and subsequent values are unrecorded for the first location (Red River, New Mexico). Mean annual temperature was depressed below the freezing point of water and thus beyond the range of curves shown in Figs. 14, 16, and 17.
5. Percentage departure of mean annual runoff from modern values.
6. Mean annual sediment yield (tons per square mile); values based on Fig. 16.
7. Departure of mean annual sediment yield (tons per square mile) from modern values.
8. Percentage departure of mean annual sediment yield from modern values.
9. Mean annual sediment concentration (parts per million); values based on Fig. 17.
10. Departure of mean annual sediment concentration (parts per million) from modern values.
11. Percentage departure of mean annual sediment concentration from modern values.

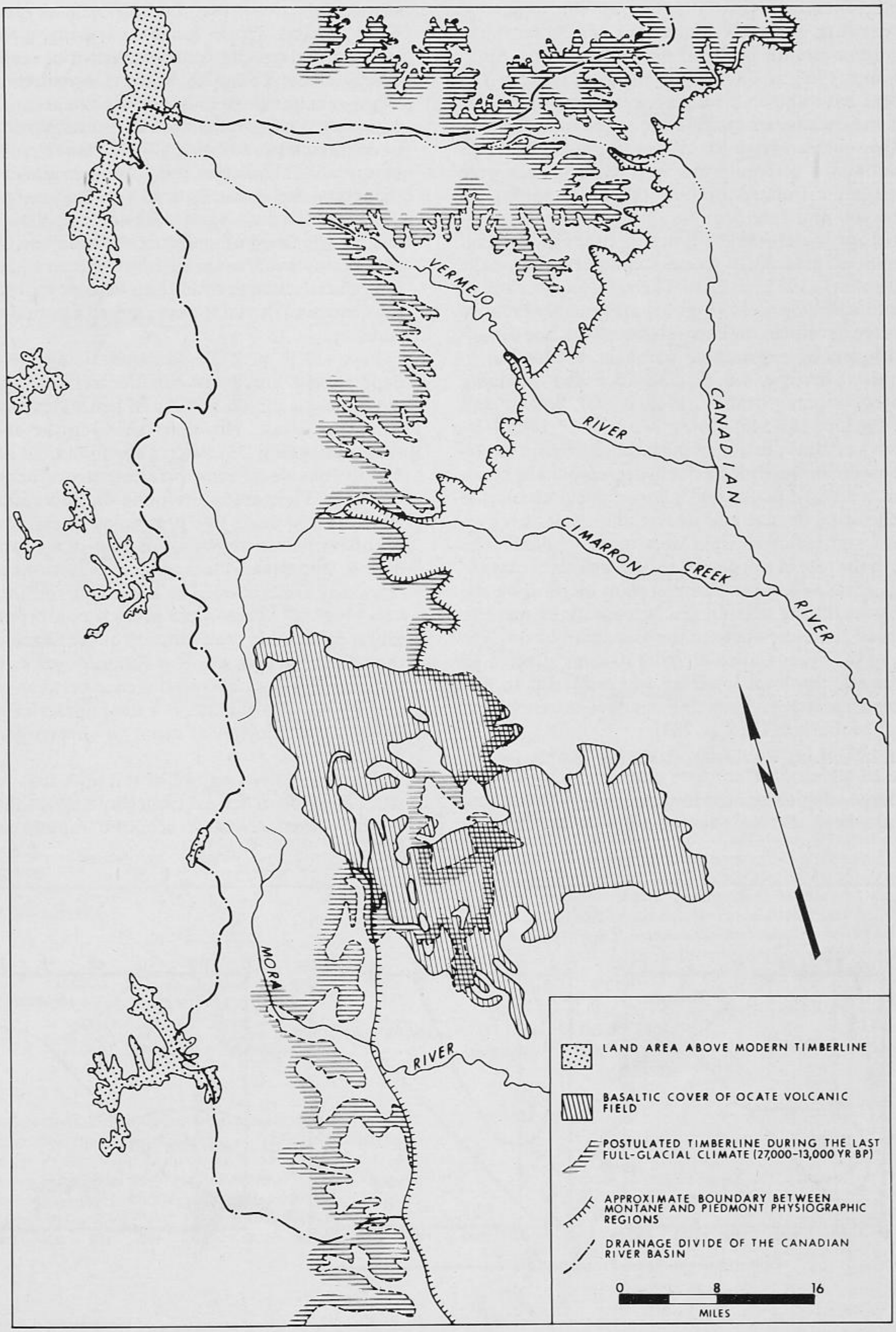


Fig. 29. Map of the montane border of the Canadian basin showing modern and postulated last full-glacial timberlines. The latter is determined from a best-fit curve plotted by Brackenridge (1978, p. 25). Timberline during the last glacial maximum (27,000 to 13,000 years B.P.) is inferred to have been at an elevation of from 2250 to 2300 m (about 7,500 ft).

semi-arid Canadian basin drained by the expanded stream network probably underwent far more subtle physiographic modification during glacial cooling. Studies by Kapp (1965, p. 232), Brackenridge (1978, p. 35), and others have shown that grass-covered divides and wooded stream courses typified the vegetation distribution of the southern High Plains during glacial maxima. The lower limits of coniferous woodland species were depressed an estimated 700 m (2300 ft), owing to increased soil moisture brought on by cooler temperatures (*ibid.*, p. 37). This vegetation shift probably entailed forestation of previously treeless ephemeral drainage ways (Wendorf, 1975, p. 259). The resulting decline in runoff and sediment yield (Fig. 15) presumably reduced the drainage density of the expanded network and diminished the zone of appreciable sediment production to grass-covered divides, where landslides and slumping would predominate (Strahler, 1940, p. 300; Watson and Wright, 1963, p. 545-546).

The Osage Plains portion of the Canadian basin generally underwent far less full glacial hydrologic change than the more semi-arid plains and plateau provinces to the west. Vegetation change and its attendant role in reducing runoff and sediment yield were more subdued. The increase in the rate of full glacial runoff was also substantially less (Table 3). As a result, stream incision on the Osage Plains during waxing glacial conditions was less pronounced than elsewhere in the Canadian basin. The distance of the lower Canadian from streams affected by glacio-eustatic sea level lowering was sufficient to discount this as a factor enhancing channel entrenchment (Fisk and McFarlan, 1955, p. 285).

The aim of the foregoing discussion has been to use the evidence of Pleistocene climatic change to construct a model of hydrologic response to such change. This model has in turn been the basis for postulating the climate-related behavior of the fluvial system as summarized in Figs. 31 and 32. In general, waxing glacial climate induced widespread alluviation in the montane headwaters of the Canadian River. Downstream, the same change initiated stream entrenchment and headward extension, valley excavation and enlargement, and more frequent and pronounced lateral channel migration. The nature and intensity of this fluvial response varied with the regional climatic setting. Waning glacial conditions promoted the flushing of sediment from montane alluvial basins. The flood of sediment accentuated valley alluviation that was active throughout the rest of the basin. As interglacial climatic conditions became more established, the Canadian fluvial system entered a period of erosional stability.

Frye (1973, p. 278), in summarizing the Pleistocene depositional history of the Central Interior Province, envisioned a similar pattern of fluvial response to cyclic climatic change. His chart showing the succession of these cycles (Fig. 33) reflects abandonment of the notion of only four glaciations. No alternative scheme for subdividing the Pleistocene has found wide acceptance, though Frye favored using five protracted interglacial intervals of soil formation as a basis for time-stratigraphic classification. The broad Pleistocene subdivisions adopted for this study are bracketed by three such soil-forming intervals (Fig. 33). These time periods conform as much to major episodes in the evolution of the Canadian River as they do to the succession of climatic cycles. This reflects not only the close correspondence between river history and Pleistocene climate, but the impracticality of correlating a specific fluvial event to shorter term climatic episodes.

The generalized nature of the time scale used in this study should not detract from the fact that changes in the fluvial system probably occurred rapidly and episodi-

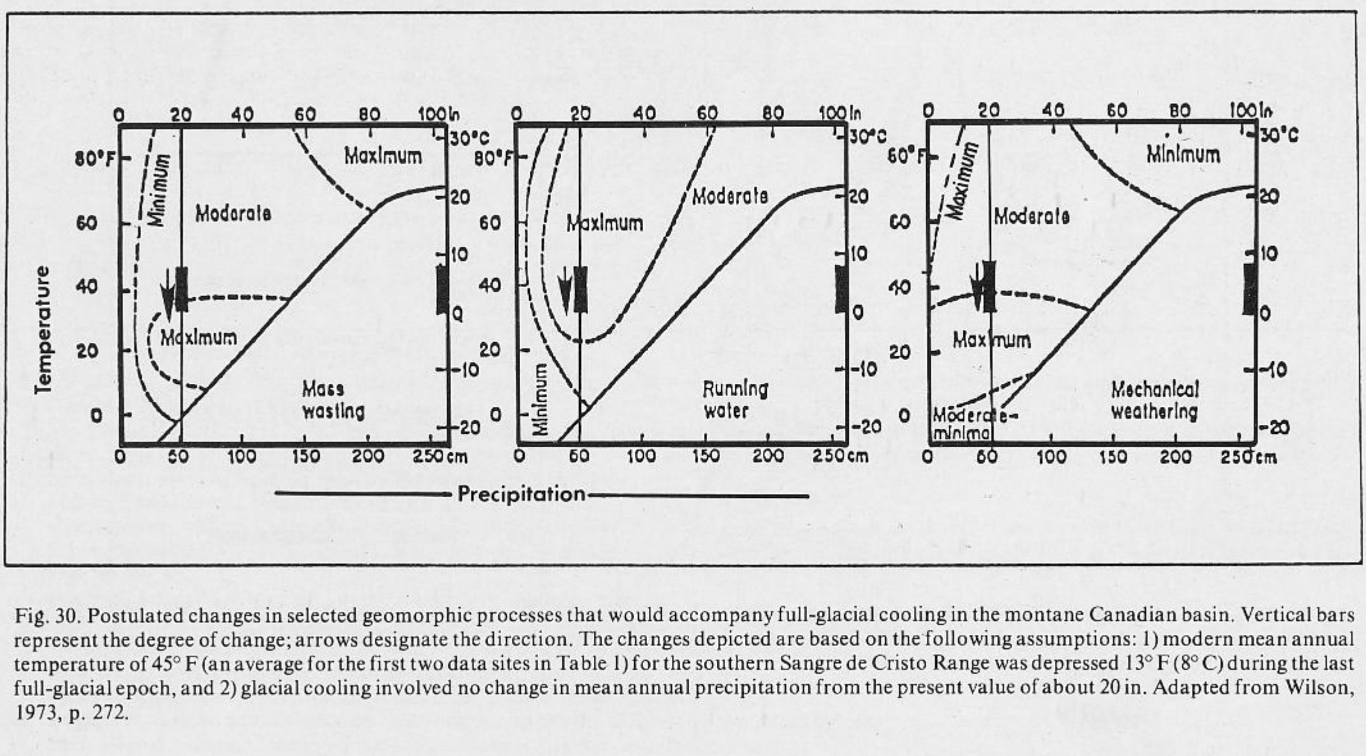


Fig. 30. Postulated changes in selected geomorphic processes that would accompany full-glacial cooling in the montane Canadian basin. Vertical bars represent the degree of change; arrows designate the direction. The changes depicted are based on the following assumptions: 1) modern mean annual temperature of 45° F (an average for the first two data sites in Table 1) for the southern Sangre de Cristo Range was depressed 13° F (8° C) during the last full-glacial epoch, and 2) glacial cooling involved no change in mean annual precipitation from the present value of about 20 in. Adapted from Wilson, 1973, p. 272.

cally. Studies of Holocene fluvial history reveal that major readjustments in stream morphology occur in rapid response to progressively changing environmental conditions (Schumm, 1977, p. 78). Climatic change, as opposed to tectonic or eustatic events, appears to be paramount in inducing a river system to exceed a threshold of stability (Knox, 1975, p. 195). Sudden and rather marked modifications of the Canadian fluvial system would thus have centered around periods of waxing and waning glacial climate. This process of abrupt fluvial adjustment and its apparent primary association with changing climate will be alluded to in succeeding discussions.

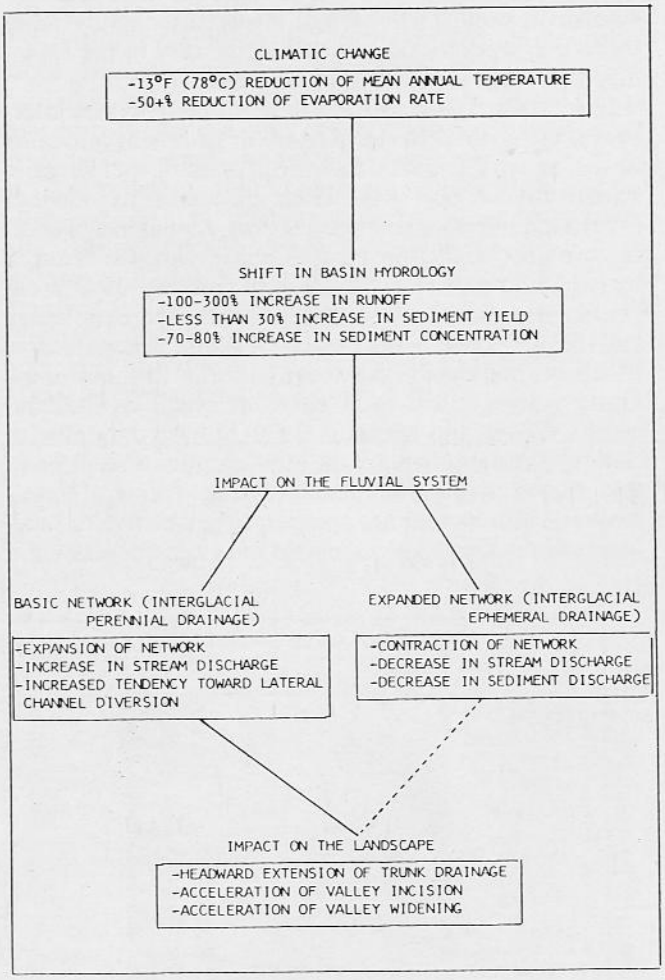


Fig. 31. This flow chart summarizes the postulated response of semiarid plains drainage to a shift toward Pleistocene full glacial conditions. Changes are expressed relative to modern conditions, which resemble those of waxing interglacial periods (Richmond, 1972, p. 321). The pattern of fluvial response to climatic change was probably similar on the more easterly sub-humid Osage Plains, though the magnitude of response was less.

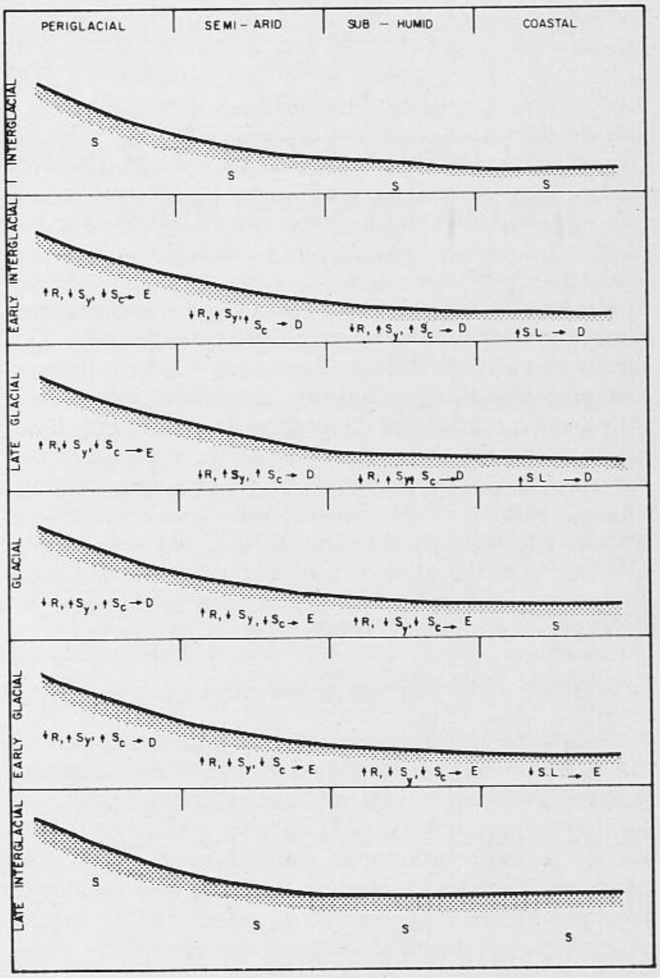


Fig. 32. Scheme for paleohydrologic response of the fluvial system to Pleistocene climatic shifts. Changes in key hydrologic variables during a given climatic interval are shown as causing either net erosion or net deposition, depending upon the climate and the physiographic region in which the changes take place. A simplified model of cyclic Pleistocene climatic change is shown; the apparent waxing and waning of each major glacial epoch is actually the cumulative effect of many short-term oscillations (Fig. 33). Symbols: S—stability, D—net deposition, E—net erosion, R—runoff, Sy—sediment yield, Sc—sediment concentration, S.L.—sea level. Adapted from Schumm, 1965, p. 790-792.

*Processes active in the coastal zone presumably did not directly affect the Canadian fluvial system.

PLEISTOCENE DRAINAGE EVOLUTION OF THE MONTANE BORDER OF THE CANADIAN BASIN

The late Pliocene landscape over most of northeastern New Mexico was a broad, stable plain of low relief. The plain had achieved stability during the period of relative tectonic quiescence that followed most Ogallala sedimentation and preceded late Pliocene-early Pleistocene structural activity. In the eastern part of the region, a widespread pedocal soil developed on the terminal Ogallala alluvial surface. This constructional plain gave way westward to interspersed areas of erosional topography. Further west, the eastern front of the Sangre de Cristo Range was flanked by a predominantly erosional piedmont plain (Frye *et al.,* 1978, p. 13).

EVIDENCE OF PLEISTOCENE RIVER HISTORY

Pleistocene drainage history within and marginal to the southern Sangre de Cristo Range must largely be inferred from the vertical succession and landscape position of erosion surfaces and from the areal distribution of surface bedrock formations and structures. Most remnants of Pliocene-Pleistocene montane and piedmont erosion surfaces are preserved as gravel- and/or basalt-capped outliers. Some of these outliers are present in the southern Sangre de Cristo Mountains, but most occur immediately east of the mountain front. They are often referred to as "pediments," though many are evidently not the exclusive result of pedimentation. Several gravel samples were collected from alluvium veneering all of the so-called pediment levels that have been identified in the upper Canadian basin. Many of the erosion surfaces are capped by stream-rounded gravel derived from montane crystalline and Paleozoic sedimentary bedrock terrain to the west (Localities 7, 14, 31, 32, 34, 50, 52, 57, and 64-66). Some gravel is clearly of local origin and shows little evidence of fluvial transport (Localities 8, 27, 36, and 38). A few sample sites identified in the literature as pediments are more likely stream terraces (Localities 16, 30, and 51).

Distinguishing pediments from terraces based upon their mode of formation is often an exercise in conjecture. The use of the term "pediment" will here be applied in a morphologic rather than a genetic sense. Pediments are surfaces that slope away from the mountain front or an adjacent highland. They usually do not occupy the valleys of major streams. Pediments that do lie adjacent to modern trunk drainage are not graded to that drainage.

The foregoing definition helps show the advantages of using pediment rather than terrace remnants to document drainage history. Terraces in the montane upper Canadian basin are all less than 250 ft above local base level. Pediments of apparent Pleistocene age occur at elevations up to approximately 500 ft above nearby modern drainage. With one exception, all dated basalts cover pediment rather than terrace surfaces. Furthermore, terraces are more apt to reflect local changes in drainage regime than pediments. For this reason, writers have frequently discouraged the long distance correlation of terrace levels (Ritter, 1978, p. 272). Pediments are also admittedly subject to local base level changes, but studies by several workers suggest that in the case of the Canadian basin this is a secondary influence (Fig. 34).

Several authors have described, correlated, and interpreted the geological significance of pediment remnants in the upper Canadian basin. Surfaces in the Vermejo Park-Raton region have been discussed by Levings (1951) and Pillmore and Scott (1976). A relative chronology of Pliocene-Pleistocene erosional events was deduced by Ray and Smith (1941) and Smith and Ray (1943) from pediments and related surfaces within Moreno Valley and the plains east of the Cimarron Range. The extensive basalt-capped erosion surfaces that comprise much of the Ocate volcanic field received scant attention until recently. O'Neill and Mehnert (1980) utilized a number of radiometric dates to place the physiographic evolution of this region within an absolute time frame. Gravel-covered surfaces that are apparently correlative to pediments in the Ocate volcanic field have been described in

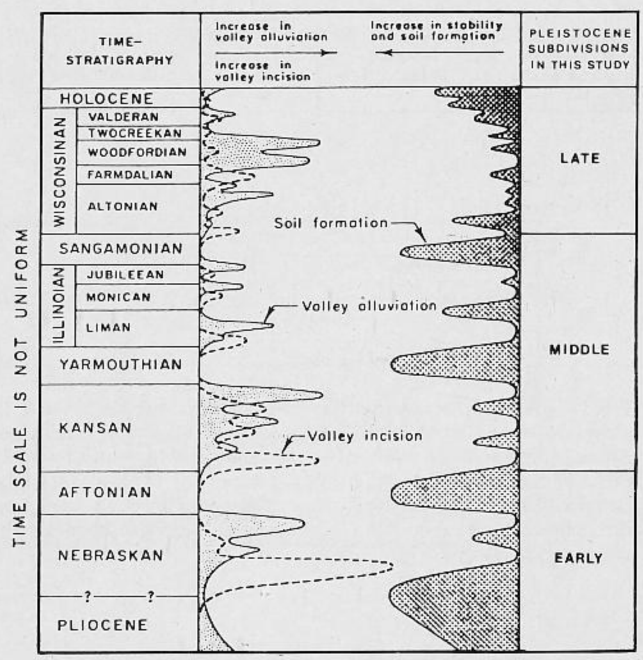


Fig. 33. Generalized curves showing average Pleistocene conditions in the continental interior for intensities of valley incision, valley alluviation, and soil formation. The relative intensities of processes depicted here are considered representative for the Canadian basin. Notice 1) the implied abandonment of the notion of four-fold Pleistocene glaciation and 2) that most fluvial incision—and presumably network stabilization—occurred during early and early-middle Pleistocene glacial epochs. Adapted from Frye, 1973, p. 278.

the Las Vegas region by Baltz *et al.* (1956) and Lessard and Bejnar (1976). Little has yet been done to interpret these erosional remnants in the context of regional physiographic evolution.

The evidence of fluvial history contained in widely scattered relict erosion surfaces is most instructive when tied to an absolute chronology that is applicable basin-wide. This involves correlation of disparate surfaces to a few dated ones that are mostly located in the Ocate region. Criteria that are most useful in correlating pediment levels include the following: absolute elevation and elevation above local and regional base level; nature of the soil, gravel, or basalt veneer; and the direction and gradient of surface slope. No combination of characteristics is wholly reliable in making detailed regional correlations of erosion surfaces because of appreciable local variation in surface geology and in structural and drainage history. In the case of the Canadian basin, these criteria do permit the tentative correlation of erosion surface remnants that apparently originated during the same general time interval. Figures 35 and 36 illustrate five groups of erosion surfaces ranging in age from late Miocene (?) to late Pleistocene (?). Age assignments are inferred from radiometric dates of basalt flows in the Raton and Ocate volcanic fields (Fig. 37). The three youngest groups are most pertinent to the Pleistocene history of the Canadian River.

THE PRE-PLEISTOCENE (LATE PLIOCENE) LANDSCAPE

In the course of succeeding discussions, it will become apparent that drainage of the montane border of the Canadian basin was less affected by Pleistocene events than was drainage in most other parts of the basin. A first step toward arriving at this conclusion is to depict the tectonic-geologic setting and drainage morphology of the pre-Pleistocene (late Pliocene) landscape. Only two areas along the montane border of the Canadian basin contain evidence sufficient to reconstruct pre-Pleistocene physiography. Ocate volcanic field, by virtue of its dated volcanic cover, provides the most complete picture. The area south of the Ocate volcanic field, within the watershed of the Mora River, permits an adequate but less comprehensive portrayal of the late Pliocene landscape.

OCATE VOLCANIC FIELD: DRAINAGE SETTING

The physiographic character of the pre-Pleistocene landscape along the montane border is best known in the vicinity of the Ocate volcanic field. Most radiometric dates of basalts in the field fall between 4.1 and 5.7 million years B.P. Flows of this age collectively overlie a gently southeast-inclined erosion surface of low relief that had formed by middle Pliocene time. Drainage

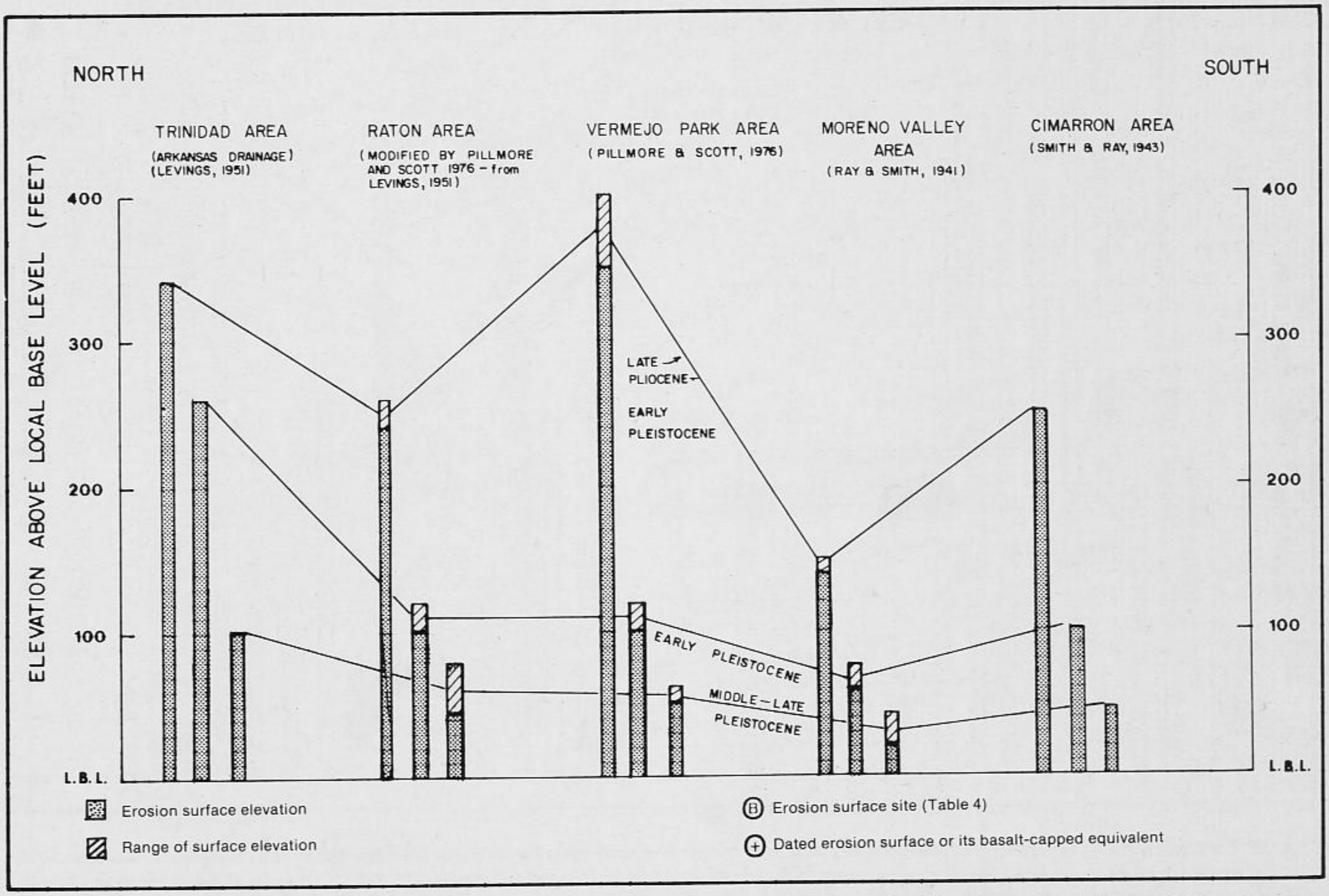


Fig. 34. A diagram showing a summary of several physiographic studies of the montane border north of the Ocate volcanic field. The diagram shows both the regional equivalence of Pleistocene pediment levels and their approximate absolute ages as inferred from basalt dates in the Ocate and Raton volcanic fields. Although the correspondence between surfaces is demonstrated here in terms of elevation above local base level, the correlation of pediment levels is also based upon nature of soil, gravel, or basalt veneer, and direction and gradient of surface slope. Adapted from Pillmore and Scott, 1976, p. 117.

across much of the erosion surface was probably consequent. The areal extent of middle Pliocene basalts and underlying fluvial gravels would suggest that stream flow was through broad, shallow valleys trending southeastward across a gently rolling erosional plain.

A markedly different drainage setting is preserved near the margins of the relict surface, where there is evidence of regional structural deformation. The western edge of the erosion surface was fragmented by north-south trending down-to-west normal faults. By middle Pliocene time, faulting had caused partial dispersion of southeast drainage along the north-south trending Coyote-Mora-Quebraditas half-graben (Fig. 38). Pre-middle Pliocene deformation near the eastern boundary of the remnant erosion surface produced a zone of abnormally high gradient across which major streams were apparently entrenched (Fig. 39). This oversteepened zone is not related to the steep dip of strata forming the Creston. The prominence of the latter feature as a major topographic barrier to drainage post-dates the middle Pliocene surface, as evidenced by gently southeast-inclined basalts and pediment remnants of middle Pliocene age resting on the bevelled edge of the Creston's steeply inclined strata (Figs. 35, 36). East of the zone of oversteepened gradient, sparse evidence indicates that pre-late Pliocene drainage had been superposed onto structural elements that predate late Miocene-early Pliocene tectonism.

In summary, drainage in the vicinity of the Ocate volcanic field prior to late Pliocene tectonism had been disrupted by widespread volcanism. Areas not covered by basalt flows were drained by southeast-flowing streams. These may have been tributary to relatively few trunk drainage courses that were incised across the montane-plains border and superposed onto plains struc-

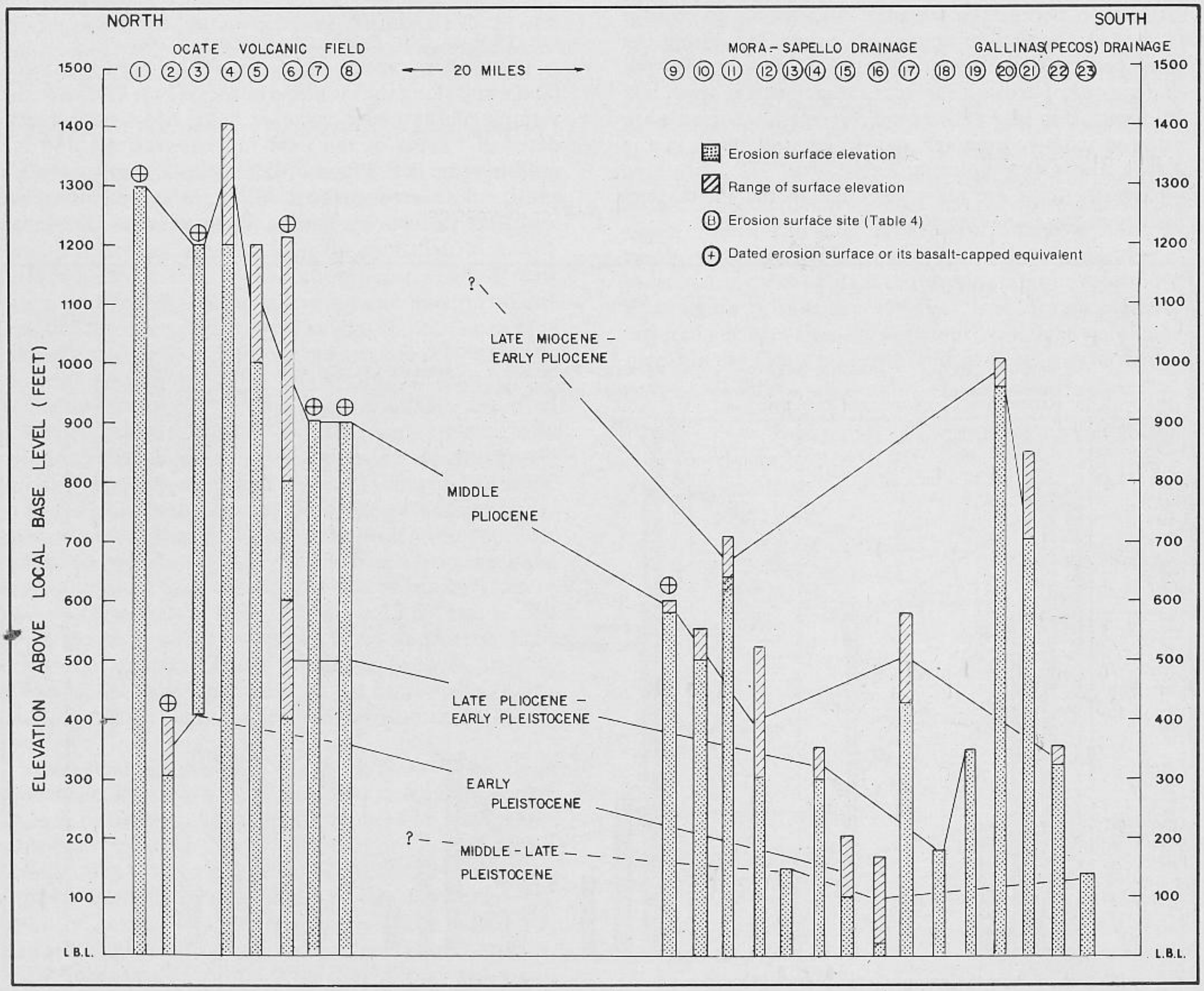


Fig. 35. Diagram showing correlation of selected pediment and related erosion surface levels located within and south of the Ocate volcanic field. Absolute ages are based upon dated basalts and thus establish only minimum ages for underlying surfaces. For this reason, and because of the paucity of Pleistocene radiometric dates, the time interval that brackets each group of equivalent surfaces is necessarily broad. The succession of such intervals is consistently reflected both north (Fig. 34) and south of the Ocate volcanic field, despite differences in the criteria used for erosion surface correlation and despite the fact that several shorter term erosional episodes may be included in one time period. This regional correspondence of erosion surface levels obliges two observations: 1) prolonged but discrete periods of intermittent erosion surface formation and subsequent dormancy have occurred within the upper Canadian basin and 2) these periods are compelling indication that climatic change exerted a primary influence on erosion surface development.

tural elements. The Mora River was apparently the largest of these drainage ways, since it was the probable outlet for montane drainage diverted southward along the Coyote-Mora-Quebraditas half-graben trend (Fig. 7).

Ocate volcanic field: tectonic setting

On the northern edge of the Ocate volcanic field, the elevation difference between the middle Pliocene surface and one of probable late Pliocene age is from 400 to 600 ft—or roughly the difference between the late Pliocene and modern landscape levels (Fig. 35, sites 6 through 8). The apparent degree of landscape lowering during the middle to late Pliocene, in the absence of evidence for climatically induced downcutting, would suggest that tectonism accelerated during late Pliocene time. The timing of structural activity apparently coincides with uplift of the Sangre de Cristo Range in southern Colorado, during which extensive canyon cutting and displacement of once continuous depositional surfaces occurred (Scott, 1975, p. 236).

In the Ocate region, tectonism had a more subtle impact on landscape and drainage character. The available evidence suggests that the structural configuration of the middle Pliocene erosion surface around the Ocate volcanic field was not appreciably altered by Pliocene-Pleistocene tectonism. Middle Pliocene age basalts, lying across normal faults bounding the east side of Coyote Creek, have not been displaced by subsequent fault movement (O'Neill and Mehnert, 1980, p. 25). Middle Pliocene flows overlying faults east of the Creston are similarly undisturbed (Johnson, 1974). Elevation differences between erosion surfaces in the vicinity of the Creston are essentially the same as those between analogous levels along the Coyote-Mora-Quebraditas half-graben trend. None of these surfaces exhibits anomalous slope that could be attributed to local faulting. Therefore, epeirogenic uplift must have accounted for most Pliocene-Pleistocene tectonic activity along this portion of the mountain front.

Mora River basin: physiographic setting

South of the Ocate volcanic field, only scattered remnants of the middle Pliocene erosion surface are preserved. All of these gravel-covered outliers are inclined southeastward and some overlie the Creston and related structural features. Middle Pliocene drainage in the Mora basin apparently resembled that of the Ocate region in consisting of a parallel network of southeast-flowing streams. This drainage system was superimposed onto structures whose outlines had been established prior

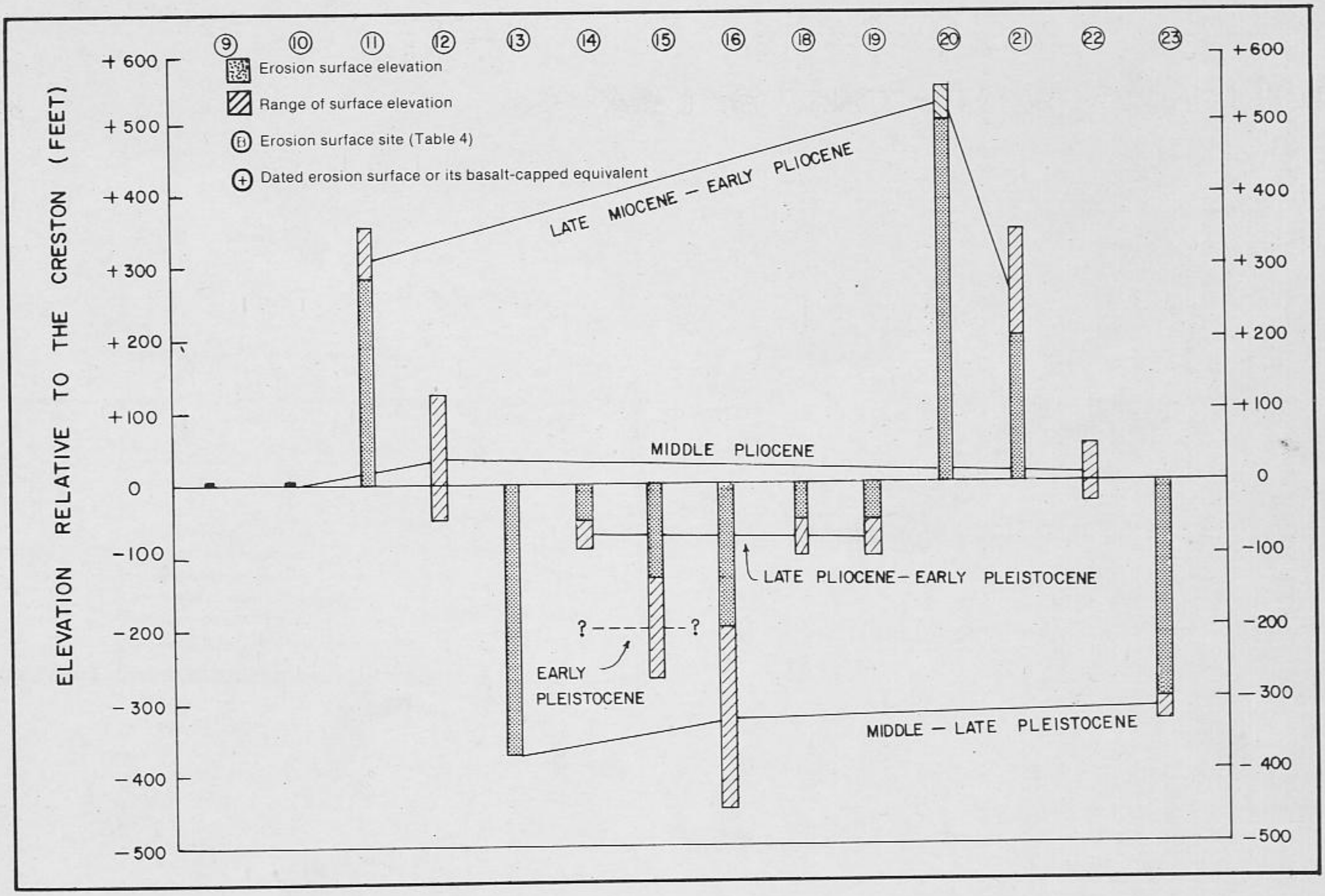


Fig. 36. Diagram illustrating correlation of selected erosion surface levels south of the Ocate volcanic field based solely upon their elevation relative to the Creston. Note that in most cases (especially sites 18, 19, and 22) the correspondence between surfaces of similar age is less ambiguous than that depicted in Fig. 35. The Creston is apparently more satisfactory than local base level as a datum for regional physiographic correlation. This is not surprising if one considers that denudation rates along drainage ways are probably far more susceptible to regional variation than those along the crest of a prominent hogback ridge.

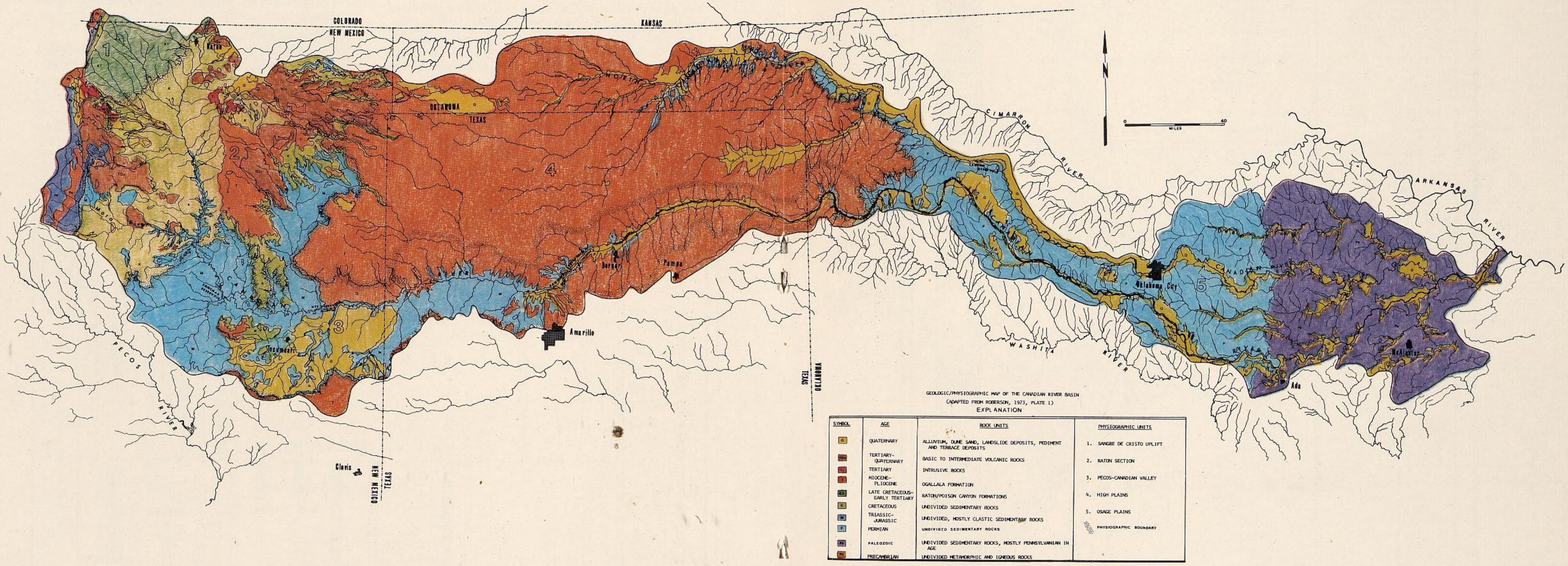


Fig. 8. Geologic/physiographic map of the Canadian River basin. Adapted from Roberson, 1973, Plate 1.

NAME	LOCATION	AGE (MILLION YEARS B.P.)
	Cerro del oro 36° 04', 105° 55'	0.81 ± 0.14
	vent plug 2 mi NW of Yates, NM. NW SE NW NW Sec. 14, T22N, R 28E	1.2
	Maxson Crater, 35° 53', 104° 52'	1.37 ± 0.15
Emery Peak Basalt	Road cut, NM Hy 325, Sec 6, T 30N, R 29E, Union Co.	
Sierra Grande Andesite	NE 1/4 Sec 19, T29N, R29E, Union Co.	1.8 ±0.1
Clayton Basalt, Gaps flow	W 1/2 Sec 6, T28W, R 32 E, Union Co.	1.9 ± 0.5
	Wagon Mound (lower mesa) 36° 03', 104° 42'	2.2 ± 0.3
Clayton Basalt	Road cut N.M. 370 W 1/2 Sec. 22, T25N, R35E, Union Co.	2.5 ± 0.8
	Charette Mesa, 36° 01', 104° 42'	3.07 ± .34
Late Basalt	Road cut I 25 @ Wagon Mound, 35° 59.5' N, 104° 42.5' W	3.3 ± 0.3
	Road cut 6 mi SE of Yates, NM. NE NE NE Sec 13, T21N, R29E	3.4 (avg)
Late Raton Basalt	Bartlett Mesa, 36° 51' 32" N, 104° 24' 55" W, Colfax Co. &	3.5 ± 0.2
	White Peak, 36° 07', 105° 02'	±1.2
	Guadalupita Valley 36° 04', 105° 17'	3.83 ± 0.46
*	Uracca Mesa 36° 24' 25", 104° 59' 18"	4.3 ± 0.1
	Guadalupita Valley 36° 04', 105° 17'	4.53 ± 0.18
Basalt	Coyote Cr. 9 mi south of Black Lake, 36° 12.0' N, N 5° 13.7' W	4.71 ± 0.3
	Cerro Vista 36° 08', 105° 26'	5.74 ± 0.34
	Las Mesas del Conjelon 36° 00' 104° 42'	5.94 ± 0.40
Early Raton Basalt	Johnson Mesa, lowest flow, NW 1/2 Sec 20, T31N, R25E, Colfax Co.	7.2 ± 0.3
Red Mtn. Dacite **	Cunningham Butte, sec. 31, T30N, R24E Colfax Co.	8.2 ± 0.8
	Sierra Montuosa, 36° 14', 105° 09'	8.34 ± 0.5

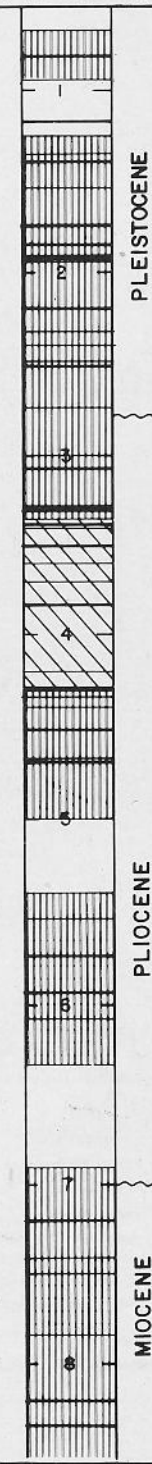


Fig. 37. Summary of potassium-argon dates for volcanics in the Canadian River basin. Shading represents ranges of individual dates. Overlap of more than two date ranges is shown by diagonal lines. Sources: Hussey, 1971, p. 45; Stormer, 1972a, p. 2445; Trauger, 1973, p. 7; O'Neill and Mehnert, 1980, p. 11.

*Several flows of this age are present in the Ocate region (O'Neill and Mehnert, 1980, p. 11).
**Age may be anomalous due to excess argon in dated hornblende. Stratigraphic relations suggest that Red Mountain Dacite extrusion was contemporaneous with that of Clayton basalts (Kudo, 1976, p. 109).

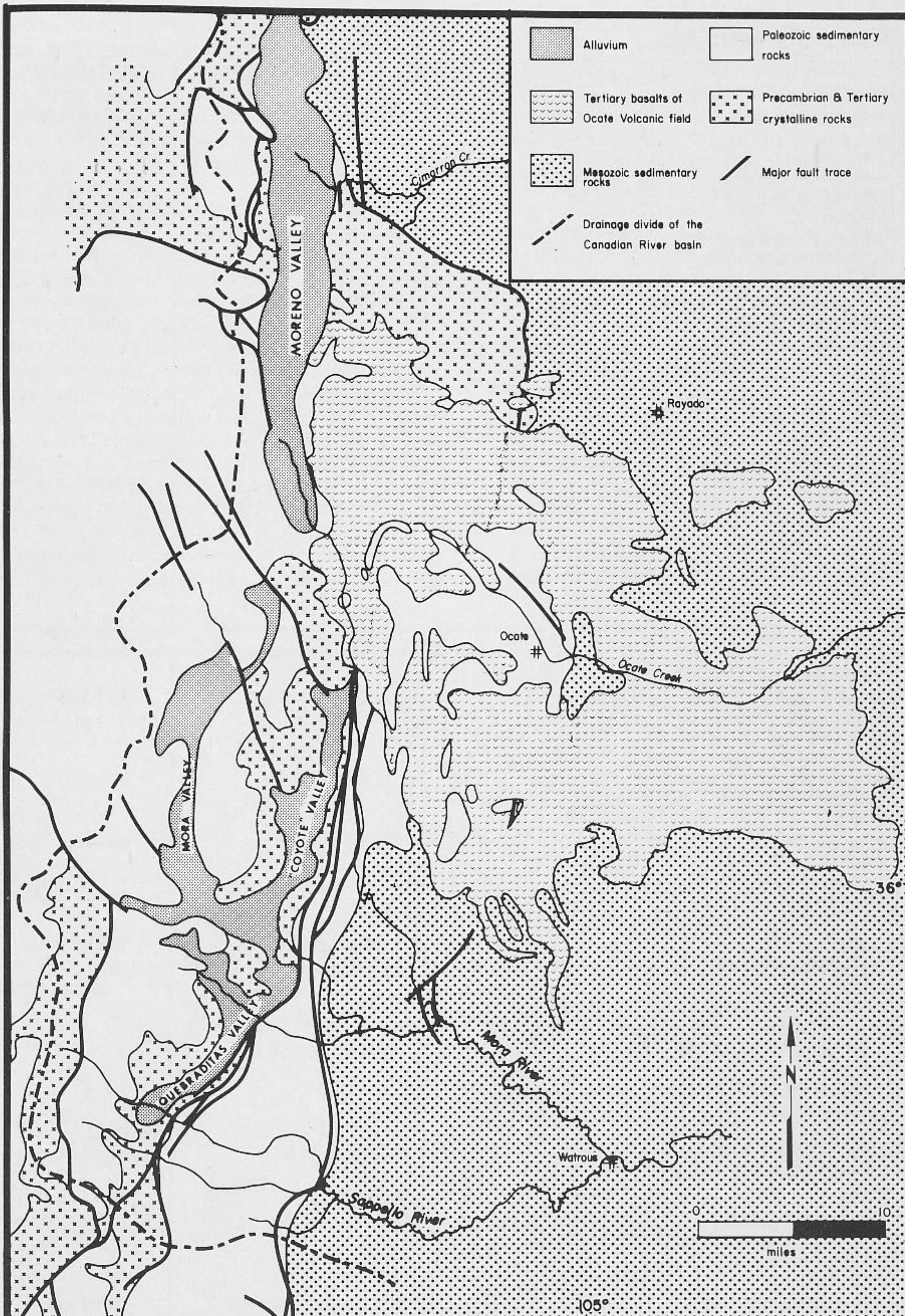


Fig. 38. Map of a portion of the montane Canadian basin showing major surface structural and physiographic features. Middle Pliocene age basalts of the Ocate volcanic field overlie a gently southeast-inclined erosion surface. The western edge of the erosion surface was fragmented before middle Pliocene time by down-to-west normal faults, producing the north-south trending Coyote-Mora-Quebraditas half-graben. The distribution relative to structure of alluvium filling the half-graben and more northerly Moreno Valley is one argument against ancestral south-flowing through drainage. Adapted from Dane and Bachman, 1965.

Table 4. Key to Erosion Surface Sites

SITE NO.	SURFACE LOCATION	SURFACE AGE (M.Y.B.P.) IF DATED (FIGURE 37), OR CLOSELY CORRELATIVE (≈) TO A DATED SURFACE (FIGURE 36)	ELEVATION ABOVE LOCAL BASE LEVEL (FT.) OR REFERENCE SURFACE	ELEVATION RELATIVE (±) TO CRESTON (FT.) IF APPLICABLE (SEE FIGURE 36)
1	URRACA MESA (SAMPLE LOCALITY 33)	4.3±0.1	1300 (RAYADO CR.)	—
2	GRAVEL-CAPPED BUTTES S. OF RAYADO CR. (T25N, RL9E)	≈ 2.2	300-400 (RAYADO CR.)	—
3	RAYADO-GONZALITOS MESA (SAMPLE LOCALITY 34)	4.5±0.3	800 (SITE NO. 2)	—
4	SAME	SAME	1200-1440 (RAYADO CR.)	—
5	SAME	SAME	1000-1200 (SWEETWATER CR.)	—
6	SAME	SAME	400-600 (BUTTES IN N¼ T23N,R19E 3.1 M.Y.R.P.)	—
7	APACHE MESA (SE¼ T23N, R14E)	≈ 4.1-4.3	900 (SWEETWATER CR.)	—
8	SAME	SAME	400 (CHARETTE MESA S½ T23N, R20E (3.1 M.Y.B.P.)	—
9	WOLF CR. BASALT, LA MESA (36°23'N. 105°09'W)	4.2±0.3	575-600 (COYOTE CR.)	0?
10	SAMPLE LOCALITY 50	≈ 4.2	500-550 (COYOTE CR.)	0
11	OLD PEDIMENT (TP) OF BALTZ & O'NEILL (1980A) SOUTH OF LA CUEVA LAKE	—	635-705 (MORA R.)	285(+) 355(+)
12	HIGH PEDIMENTS (Q TG, Q TP) OF BALTZ & O'NEILL (1980A&B) S. OF LA CUEVA LAKE	—	300-520 (MORA R.)	50(-)-125(+)
13	SAMPLE LOCALITY 52 (QAP OF BALTZ & O'NEILL, 1980A)	—	140 (MORA R.)	375(-)
14	PEDIMENTS (QP, QPG) of BALTZ & O'NEILL (1980 A&B) ALONG CRESTON BE-TWEEN MORA & SAPELLO RIVERS	—	300-350 (MORA R.)	50(-)-85(-)
15	SAME	—	100-200 (MORA R.)	103(-)-270(-)
16	YOUNG PEDIMENTS (QAP) of BALTZ & O'NEILL (1980 A&B) ALONG CRESTON BETWEEN MORA & SAPELLO RIVERS	—	20-170 (MORA R.)	200(-)-450(-)
17	HIGH PEDIMENTS (QTG) OF BALTZ & O'NEILL (1980 A&B) ABOVE MONTANE SAPELLO R. TRIBUTARIES E SE OF ROCIADA	—	425-575 (SAPELLO R.)	—
18	SAMPLE LOCALITY 64 (QPG OF BALTZ & O'NEILL, 1980B)	—	175 (SAPELLO R.)	50(-)-100(-)
19	SAME	—	175 (SAPELLO R.)	50(-)-100(-)
20	HIGH LEVEL PEDIMENT (QTP OF DANE & BACHMAN, 1962) 10 MILES E NE OF LAS VEGAS	—	950-1000 (GALLINAS R.)	500(+)-550(+)
21	PEDIMENT SURFACE 3-5 MILES EAST OF LAS VEGAS	—	700-850 (GALLINAS R.)	200(+)-350(+)
22	SAMPLE LOCALITY 65	—	325-350 (GALLINAS R.)	25(-)-50(+)
23	SAMPLE LOCALITY 66	—	115-140 (GALLINAS R.)	300(-)-325(-)

to middle Pliocene time. Unlike the Ocate area, drainage was not disrupted by post middle Pliocene volcanism.

In the Mora basin, pediments of probable late Pliocene-early Pleistocene age are about 50 to 100 ft lower than the top of the Creston (Fig. 36). Drainage superposition was therefore well advanced by this time. The Creston was enough of a topographic barrier to southeast drainage to be a locus of piedmont alluviation, much as it is today (Fig. 5).

The physiographic importance of the other major barrier to southeast drainage—the Coyote-Mora-Quebraditas half-graben trend—has been the subject of some discussion. Several workers have inferred this feature to be the eastern valley margin of an ancestral Coyote Creek (Baltz and Read, 1956, p. 71; Mercer and Lappala, 1970 and 1972; Clark and Read, 1972). During the Pleistocene Epoch, major portions of Coyote Creek were presumably pirated by headward-migrating tributaries of the ancestral Mora and Sapello Rivers. Only general reference to channel deposits, barbed tributaries, and windgaps has been forwarded as evidence of this piracy (Bugh, 1968, p. 47). Instead of citing specific evidence, most investigators have simply repeated the assertion that much of the Coyote-Mora-Quebraditas half-graben trend was formerly occupied by a large through-flowing Pleistocene river (Mercer and Lappala, 1970, p. 15; *ibid.*, 1972, p. 23; Clark and Read, 1972, p. 103). In some areas, the half-graben trend does resemble a fluvial valley (Fig. 7), but this morphology, like that of Moreno Valley to the north, may have arisen more from the activity of alluvial rather than fluvial processes.

Development of north-south trending structural lows within the southern Sangre de Cristo Range began prior to middle Pliocene time. The barrier that these sags must have posed to eastward drainage is not in itself compelling evidence that they were eventually occupied by a major through-flowing subsequent drainage course. In fact, there are several phenomena that favor an alternative scenario for Pleistocene montane drainage.

Instead of delineating the course of an ancestral Coyote Creek, the Coyote-Mora-Quebraditas half-graben trend may have controlled local drainage that was integrated to east-southeast flowing montane trunk streams. The series of prominent west-facing fault scarps along the trend could have posed a barrier to eastward drainage sufficient to induce accumulation of extensive alluvial fill without appreciably diverting headwater tributaries of the ancestral Mora and Sapello Rivers. Several lines of evidence give credence to this drainage picture. Numerous seismic refraction bedrock profiles across the purported valley of ancestral Coyote Creek show little or no evidence of dissection by a major through-flowing stream

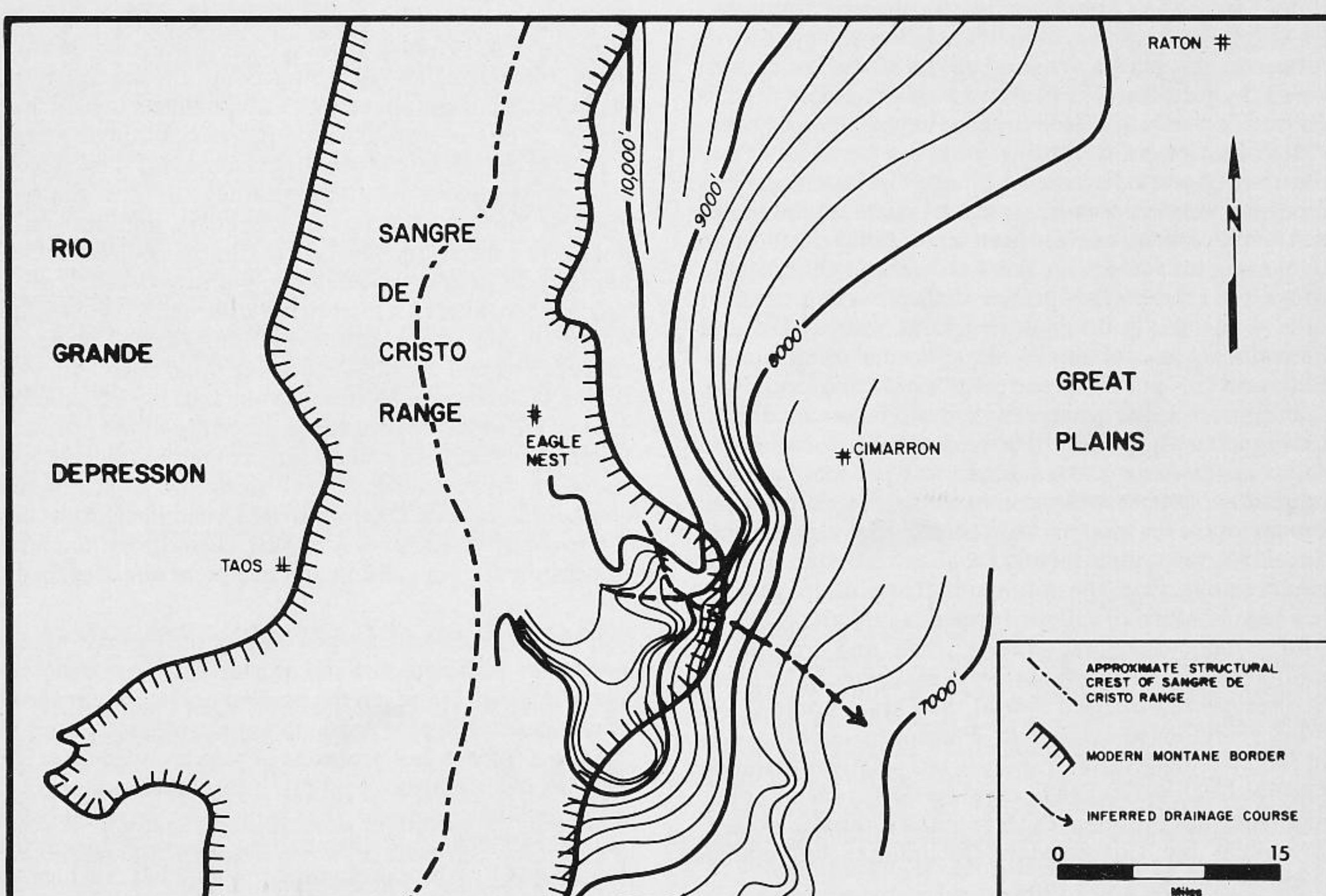


Fig. 39. Structure contour map of the middle Pliocene erosion surface along the montane border of the Canadian basin. The surface has been reconstructed from remnants that underlie or are correlative with from 4 to 5 million year old basalts in the Ocate volcanic field. Contour lines (200-ft contour interval) are approximately located. Note that pre-middle Pliocene deformation has produced a zone of steep gradient across which drainage entrenchment has evidently occurred. The inferred drainage lines roughly coincide with the modern position of Rayado Creek. Modified from O'Neill and Mehnert, 1980, p. 24.

(Mercer and Lappala, 1970). Extensive gravel-defended pediments of apparent middle Pliocene age (Fig. 35, site 17) have been cut into divides adjacent to montane tributaries of the Sapello River (Baltz and O'Neill, 1980b). These erosion surfaces are evidence that eastward drainage persisted after there was appreciable topographic relief along the half-graben to the west. East of the mountains, markedly contrasting terrace levels above the Mora River do not reflect piracy of a major south-flowing montane drainage course by headwater Mora tributaries. Instead, representative samples of terrace gravels (Localities 53 and 54) document unroofing of the Precambrian core area that presently lies within the montane Mora watershed. The dated Maxson Crater flow (1.4 million years B.P.), approximately 15 mi downstream from the sample localities, intersects the river at a level similar to that of the higher Mora terrace. Therefore, the Mora system appears to have remained unaffected by substantial headwater piracy since before the end of early Pleistocene time.

If one discounts the likelihood of major stream piracy along the Coyote-Mora-Quebraditas half-graben trend, then several plausible statements can be made regarding Pleistocene drainage of the Mora basin. Montane alluviation was probably concentrated along the half-graben trend, upstream of west- and northwest-facing fault scarps. Drainage outlets to the structural valleys, like those across the Creston, consisted of a few southeast-flowing streams. Breaches in both the hogback and more westerly fault scarps are now occupied (from north to south) by the Mora River, Rito Cebolla, and the Sapello River. These three trunk streams have apparently persisted along essentially their present courses since before the onset of pre-Pleistocene drainage superposition. Surface structure had a more profound effect on low-order tributaries. Numerous folds and minor faults, in addition to those associated with the Creston and the Coyote-Mora-Quebraditas half-graben, influenced development of a crude trellis drainage network both within and immediately east of the montane border (see maps by Baltz and O'Neill, 1980a and 1980b; and Johnson, 1975).

In summary, the general pattern of Pleistocene fluvial sediment transport from the montane Canadian basin south of the Ocate volcanic field was probably already established prior to Pleistocene climatic deterioration. Precursors to the modern Mora River, Rito Cebolla, and Sapello River were evidently the major avenues of sediment removal from the mountains. These drainage ways headed in alluvial valleys formed along the Coyote-Mora-Quebraditas half-graben trend and exited the montane region through narrow breaches in the Creston. Sediment was dispersed east of the Creston onto a low relief piedmont alluvial plain. Pleistocene modification of this system of fluvial transport was chiefly in response to episodic climatic change, continued epeirogenic uplift, and recurrent subsidence (Mercer and Lappala, 1972, p. 27) along the Coyote-Mora-Quebraditas half-graben trend.

PEDIMENTS AND PLEISTOCENE DRAINAGE MODIFICATION

Active pediments are essentially piedmont erosion surfaces that are stable when the rates of sediment supply and sediment removal are in equilibrium (Cooke and Warren, 1973, p. 207). Multiple pediment levels indicate intermittent episodes of disequilibrium during which drainage across the erosion surface is diverted laterally and/or vertically. The result is "deactivation" or abandonment of the pediment surface, often beneath a protective mantle of alluvial gravel. The lack of evidence for substantial diversion of Pleistocene drainage courses away from pediment surfaces suggests that vertical drainage diversion—or stream incision—was the most important cause of pediment abandonment in the upper Canadian basin. Three major episodes of downcutting are indicated by the similar succession of Pleistocene pediment levels in several montane and piedmont areas (Figs. 34, 35).

Periodic downcutting and consequent pediment abandonment along the montane border of the Canadian basin are attributable to some combination of four possible circumstances: 1) downstream base-level adjustment due to stream piracy, 2) local differences in bedrock resistance to erosion, 3) intermittent epeirogenic uplift, or 4) episodic climatic change. Piracy-induced lowering of base level has played an important role in the Pleistocene drainage evolution of piedmont regions where the physiographic character is quite similar to that of the Canadian montane border (Ritter, 1972, p. 92; and Hunt *et al.*, 1953, p. 191-204). However, the process would have had too localized an effect to account for the apparent widespread correspondence of Canadian basin pediment levels. If this correspondence represents roughly synchronous stages of pediment development, then steady state adjustment of piedmont drainage to local geology (Denny 1967, p. 102) was of secondary importance in pediment formation. The fact that most pediment remnants occur in areas of relatively uniform bedrock geology further favors an historical rather than steady state interpretation of pediment evolution. There is evidence that epeirogenic uplift, which accelerated during middle to late Pliocene time, continued well into the Pleistocene Epoch. However, epeirogenesis probably would not have induced intermittent and roughly contemporaneous episodes of stream entrenchment along the length of the southern Sangre de Cristo Range. Cyclic Pleistocene climatic change thus appears to have been the major cause of periodic stream incision and pediment abandonment.

There is no direct evidence linking the formation of a particular pediment surface to a given Pleistocene climatic interval. However, the number and apparent age of Pleistocene pediment levels do appear to correspond to the most intense and protracted episodes of Pleistocene climatic deterioration (Fig. 28). If this correspondence is more real than apparent, then it implies that roughly 1/3 to 1/2 of Pleistocene downcutting occurred during the first major Pleistocene climatic reversal. Several lines of evidence point to the second such reversal (the classic "Kansan" of Frye and Leonard, 1965, and others) as having been the most intense. In light of this, the more pronounced impact of the earlier glacial cycle on the fluvial system might therefore indicate a relatively more intense period of epeirogenesis.

A CLIMATIC MODEL OF PEDIMENT FORMATION

The causes of episodic stream entrenchment and consequent pediment abandonment can be explained in terms of the previously proposed model of Pleistocene paleohydrology. While this approach is admittedly speculative, it does provide some insight into the possible processes of Pleistocene drainage modification in the upper Canadian basin.

The most pronounced physiographic transition within the Canadian basin is that between the southern Sangre de Cristo Range and the piedmont plateau and High Plains sections. The obvious contrasts in drainage and landscape morphology and their effect on fluvial sedimentation were accentuated by Pleistocene climatic change. This is reflected in the apparent depression of timberline during the last full glacial epoch to near the base of the mountain front (Fig. 29). This lower level also probably coincided with the approximate boundary between montane and plains zones of paleohydrologic response (Fig. 32).

As pointed out earlier, waxing glacial conditions evidently favored net fluvial deposition in montane basins and drainage ways, while inducing net erosion along stream courses east of the mountains. The converse would have occurred during waning glaciation. Pediment abandonment through piedmont stream incision was therefore most likely during periods of base-level disequilibrium caused by waxing glacial climate. The advent of full glacial conditions, combined with reduced piedmont stream sediment yields (Fig. 32), would have promoted base-level stabilization and the cutting of a new, lower erosion surface. A flood of montane-derived sediment probably accompanied waning glaciation, thereby tending to convert the new pediment surface into a piedmont alluvial plain. Under these conditions, wide dispersal of alluvial debris by laterally shifting streams would be common and changes in piedmont drainage network geometry more probable.

The timing of pediment-related drainage events with respect to Pleistocene climatic change would have been somewhat different for pediments formed in montane alluvial basins. Waxing glacial conditions would have caused burial of a pediment surface beneath thick, locally derived alluvium. Stream incision into the resulting alluvial blanket and the subsequent cutting of a lower pediment surface were more likely during waning glacial climate.

PLEISTOCENE MODIFICATION OF MONTANE BORDER DRAINAGE

Evidence of Pleistocene montane and piedmont drainage history is insufficient to verify the preceding scenario for pediment development. What relict erosion surfaces and their physiographic setting do indicate is that Pleistocene drainage modification in the upper Canadian basin was climate-related and that it varied according to the nature of the montane-piedmont transition. Differences today along this zone of marked physiographic change are essentially those that affected the Pleistocene fluvial system.

UPPER CANADIAN-VERMEJO RIVER DRAINAGE

Most of the montane and piedmont region north of Cimarron Creek is drained by a parallel network of subsequent streams. The southeast-flowing drainage is entrenched into a stripped structural plain developed on southeast-dipping continental clastics (Fig. 8). Small montane basins or "parks" have formed near the upper limits of the plain. Most of the parks contain pediment and/or terrace remnants that are covered with up to several tens of feet of silt- to boulder-sized alluvium (Pillmore and Scott, 1976, p. 111). The coarser fraction on surfaces near the Canadian-Rio Grande divide is dominated by angular clasts of local provenance. Further east, in Vermejo Park, erosional surfaces are capped with rounded gravel that was probably reworked from older (middle Tertiary?) alluvial deposits (Locality 9). The concentration of alluvium in these basins suggests that they were centers of montane sediment accumulation and dispersal during the Pleistocene. Gravel on the few low terraces that are preserved downstream from the parks is mostly locally derived, indicating little downstream storage of montane sediment (Localities 15 through 24).

The montane-piedmont transition occurs along the contact between gently southeast-dipping erosional plains developed on continental clastics to the northwest and on marine shale to the southeast (Fig. 8). The juncture of the two surfaces is marked by a 1000-ft escarpment, into which drainage courses have been deeply incised. In contrast to areas farther south, there is little or no evidence of previous episodes of pedimentation at the base of the mountain front. Only Wisconsinan (?) and Holocene age fan deposits of local provenance are present along this zone (Hunt, 1977). The limited availability of coarse alluvial debris apparently precluded preservation of pediment surfaces beneath a protective gravel veneer. The only surfaces in the area that can be considered pediments rather than terraces are those that extend southward from the base of basalt-capped mesas of the Raton Plateau. The gravel on these pediments has come from volcanics and Ogallala-equivalent gravels capping the adjacent mesas (Locality 14).

In summary, there is no evidence to suggest that the network geometry of streams draining the montane-piedmont region north of Cimarron Creek was appreciably altered during the Pleistocene Epoch. Pleistocene drainage modification apparently amounted to progressive stream entrenchment with little generation of durable gravelly bedload material.

CIMARRON CREEK DRAINAGE

The drainage setting of Cimarron Creek is unique within the upper Canadian basin. The creek heads in Moreno Valley, the largest montane alluvial basin in the southern Sangre de Cristo Range. It then flows eastward through a narrow canyon incised deeply into Precambrian fault blocks and middle Tertiary intrusive bodies, whose structural attitude had been established prior to late Miocene time (Fig. 6). The canyon opens east of the Cimarron mountain front onto a pedimented shale plain.

The succession of pediment levels in this area implies that landscape denudation during middle to late Pliocene time was five times as great as that which occurred during Pleistocene time (Fig. 34 and Fig. 35, site 1). This is in marked contrast to the Ocate volcanic field immediately to the south, where less than twice as much downcutting apparently occurred during the earlier time interval (Fig. 35, sites 2, 3, and 6). As is the case in the volcanic field, the absence of fault displacement of middle to late Pliocene basalts (Wanek *et al.,* 1964) south of Cimarron Creek suggests that accelerated downcutting was the result of epeirogenic uplift rather than fault movement. The apparent timing of uplift is such that Cimarron Creek was probably entrenched along its present montane course prior to the onset of Pleistocene climatic deterioration.

Moreno Valley was the single largest center of montane alluviation during Pleistocene time. Some workers (Ray and Smith, 1941; Smith and Ray, 1943; Clark and Read, 1972) have attributed this alluviation to a southward-flowing ancestral Coyote Creek, though the distribution and provenance of so-called fluvial gravels apparently precludes through-flowing drainage. Instead, sedimentation appears to have been confined to Moreno Valley, except for the dispersal of sediment basinward via Cimarron Creek. An average of 50 ft of mostly gravel-sized alluvium reportedly overlies bedrock in Moreno Valley (Goodknight, 1973, p. 43). However, no adequate assessment can be made of the Pleistocene drainage history of Moreno Valley and its relationship to that of Cimarron Creek without more detailed subsurface data.

The montane-piedmont transition near Cimarron Creek occurs along a 1000- to 1500-ft escarpment separating montane crystalline and clastic rocks from the pedimented shale plain to the east. In contrast to montane drainage farther north, Cimarron Creek transported abundant coarse-grained sediment to the montane border. As a consequence, several pediment surfaces have been preserved near where Cimarron Creek emerges onto the piedmont shale plain (Smith and Ray, 1943, Plate 2; Wanek *et al.,* 1964). Gravels mantling the surfaces are roughly divisible into two suites, based on rounding and provenance: 1) subrounded to well-rounded quartzitic and indurated clastic alluvium derived from the upper Cimarron watershed, and 2) subangular to subrounded metamorphic and intrusive igneous debris shed off the adjacent Cimarron Mountain front. Sparse sampling (Localities 30 through 32) suggests that the relative proportions of these two suites may represent the approximate lateral limits of bedload material transported by the Pleistocene Cimarron Creek. If so, Cimarron Creek appears to have been responsible for the eastward transport of gravel found on erosion surfaces between it and Cimarroncito Creek to the south. It is evident from the distribution of pediment levels that coarse fluvial sediment was dispersed over a lateral distance of approximately 4 mi sometime during early to middle Pleistocene time. If such dispersion was accomplished by a laterally migrating Pleistocene Cimarron Creek, then the intervening pediments should more properly be termed "terraces." Significantly, they are mapped as such by Wanek *et al.* (1964).

In conclusion, the montane course of Cimarron Creek, like montane trunk streams to the north, remained essentially unchanged throughout Pleistocene time. Drainage modification consisted mostly of progressive and probably episodic entrenchment. At the base of the mountain front, the Pleistocene Cimarron Creek may have undergone limited lateral diversion. The vertical succession of erosion surfaces that give evidence of this diversion is remarkably similar to the sequence found in Moreno Valley (Fig. 34). This congruence is apparent despite regional differences in the effects of epeirogenic uplift, thus lending additional credence to a climatic model of Pleistocene pedimentation.

Mora River drainage

As previously discussed, the essential outline of the montane border drainage network within the Mora River basin had been established prior to the end of Pliocene time. Modification of the system during Pleistocene time entailed progressive and probably episodic stream incision. The apparent magnitude of Pleistocene downcutting shows gradual local variation throughout the southwestern montane Canadian basin, but it differs markedly across the Canadian-Pecos divide. A pediment preserved on the divide (Locality 64) lies 175 ft above local base level in the Canadian basin (Sapello River), but it lies nearly twice that height above nearby Pecos tributary drainage (Fig. 35, sites 18 and 19). The discrepancy is a local expression of the general base level/gradient advantage of the southward-flowing Pecos system over east-trending Canadian tributaries. This is the result of Pecos drainage down the south-plunging Sangre de Cristo synclinorium and related tectonic features (Kelly, 1972a, p. 1849). In effect, a broad 90° (east-to-south) shift in the orientation of regional structural gradient occurs across the Canadian-Pecos divide.

This shift has undoubtedly induced some drainage exchange between the Canadian and Pecos fluvial systems, but the extent of the exchange is unclear. Bugh (1968) analyzed drainage network and basin morphometry as a means of documenting the geomorphic evolution of the southeastern Sangre de Cristo Range. He envisioned a network of parallel streams draining a northeast-inclined late Pliocene (Ogallala) surface. During early Pleistocene (?) time, much of this network was supposedly pirated by eastward-flowing resequent tributaries of the ancestral Mora and Sapello rivers (Bugh, p. 65-67). Though Bugh's conclusions are plausible, his substantiation of them is so general as to permit only isolated and tentative proof of former stream piracy.

This writer found the Gallinas River to be the only likely instance of Canadian trunk drainage (i.e., that transecting the Creston) having been diverted by south-flowing Pecos tributaries. A right angle bend (elbow of capture ?) in the Gallinas River just east of the Creston coincides with the upstream end of an apparent paleovalley. This valley roughly parallels Interstate 25 northeastward to an intersection with the Sapello River (Santa Fe 1:250,000 sheet). An estimate of the timing of drainage diversion must await verification that the valley contains fluvial deposits and that these deposits define a depositional surface that can be projected to adjoining active drainage ways.

The most commonly cited evidence of substantial drainage exchange between the Pecos and Canadian fluvial systems involves the region of the Canadian "bend," from 40 to 50 mi east-southeast of Las Vegas. The genetic significance of this postulated elbow of capture and the more general question of large-scale Canadian-Pecos piracy will be addressed in the following section.

PLEISTOCENE EVOLUTION OF THE PLAINS OF THE CANADIAN BASIN

EVIDENCE OF PLEISTOCENE RIVER HISTORY

Evidence for the evolution of Canadian plains drainage differs in some important respects from that for the montane border. Though datable basalt flows and volcanic ashes are more widespread on the plains, fewer absolute age determinations have been made. Most geomorphic events related to plains drainage history are recorded in depositional rather than erosional sequences. However, the dating of these events still relies heavily on the vertical succession and landscape position of underlying erosion surfaces. A more complex array of factors influences erosion surface formation east of the piedmont, and regional correlations are less reliable.

The physical characteristics and physiographic setting of Pleistocene age fluvial and alluvial deposits are the most direct evidence of plains river history. Analyses of gravel collected from terraces flanking the Canadian River and its major plains tributaries and from other alluvial surfaces provide a record of changing provenence, network configuration, and hydrologic regime. This record is augmented by consideration of the extent, structural attitude, and physiographic setting of late Pliocene and Pleistocene age basalt flows, volcanic ashes, and selected dated literature localities.

More subtle and generalized aspects of the plains Canadian basin are also useful in deciphering Pleistocene drainage history. The distribution and structural attitude of Ogallala and sub-Ogallala sedimentary units had a profound influence on network morphology, especially prior to and during the first Pleistocene glaciation. Vestiges of cyclic Pleistocene climatic change, as discussed previously, imply a variety of responses by the Canadian fluvial system.

The evidence briefly cited above can be used to outline four large-scale events that have had significant though varying impact on the plains fluvial system. These events are: 1) cyclic climatic change, 2) epeirogenic movement along regional tectonic features, 3) subsurface dissolution of Permian age evaporites, and 4) drainage superposition onto structurally deformed late Paleozoic sedimentary rocks. The procession of these events within the differing physiographic settings of the Raton, High Plains, Pecos-Canadian Valley, and Osage Plains sections accounts for most Pleistocene Canadian River basin history east of the Rocky Mountains (Fig. 8).

IMPACT OF PLEISTOCENE CLIMATIC CHANGE ON THE SEMI-ARID CANADIAN BASIN

Further mention of the Canadian fluvial system's response to cyclic Pleistocene climatic change is unnecessary except to emphasize points that are relevant to later discussions. Figure 31 summarizes the possible impact of waxing glaciation on semi-arid plains drainage. The onset of glacial conditions induced shifts in basin hydrology that had far greater consequences for fluvial history than did any other stage of cyclic Pleistocene climatic change. The temporal subdivisions of the Pleistocene begin with the three most profound climatic reversals. These reversals, manifested in episodes of markedly accelerated network extension and modification, are most evident on the semi-arid plains of the Canadian basin. In the absence of contrary evidence, the fact that many changes in the semi-arid fluvial system appear to be episodic is sufficient argument for the major impact of cyclic climatic change.

An apparent contradiction in Figure 31 suggests some shortcomings in generalizing paleohydrologic response. Waxing glaciation is postulated to have caused a markedly higher increase in sediment concentration than in sediment yield. One explanation for this discrepancy is that both modern and full glacial sediment concentration values reflect only the sediment load along perennially flowing trunk drainage. In contrast, modern sediment yield measurements include substantial contribution from the ephemeral expanded network. During maximum glaciation, sediment is stored in the "expanded" drainage network.

The scope of modern sediment yield/concentration measurements poses another difficulty in interpretation. A study of a drainage basin spanning semi-arid physiographic zones in south-central Alberta that are analogous to those of the Canadian River reveals that roughly 2% of the drainage area, a region of badlands, supplies about 90% of the total suspended sediment load for the basin (Campbell, 1977, p. 165). Therefore, generalizing sediment yield for landscapes such as the High Plains or Canadian breaks may be misleading. Such regional figures fail to account adequately for proportionally small areas of steep valley and escarpment slope that undergo the most consequential changes in rates of erosion and sediment production. These areas, rather than a whole basin or physiographic province, are more precisely the subject of paleohydrologic projections summarized in Figure 31.

DRAINAGE EVOLUTION OF THE RATON-HIGH PLAINS SECTIONS

Controls on Development of the Pleistocene Drainage Network

The Ogallala erosion cycle came to an end on the High Plains under conditions of increasing aridity and diminishing local topographic relief. The few perennially flowing streams that persisted until the end of the Pliocene were not entrenched and stream valleys were much shallower than their modern counterparts. Drainage was consequent upon an essentially featureless eastward and southeastward-inclined terminal Ogallala alluvial surface that probably resembled the modern pre-settlement

High Plains (Dalquest, 1975, p. 46). This drainage setting has prompted the conclusion that streams shifted laterally across the alluvial plain without regard to former valley positions (Leonard and Frye, 1975, p. 8). While lateral channel diversion was undoubtedly commonplace, the subtle topography of the terminal Ogallala surface did influence stream position.

Pleistocene entrenchment has preserved numerous clues to the nature of late Pliocene topographic controls on Pleistocene drainage. Modern incised stream courses are frequently situated over pre-Ogallala drainage divides or bedrock highs (Frye and Leonard, 1957a, p. 4; Frye and Leonard, 1963, p. 23; Marine and Schoff, 1962, p. 15). The cause of this localized entrenchment is usually attributed to greater erosional susceptibility of areas with thin Ogallala cover (Reeves, 1970b, p. 65). While this may partially explain entrenchment, it does not adequately account for the localization of drainage over Ogallala thins prior to entrenchment.

The distribution of entrenched Pleistocene stream courses can frequently be linked to the pattern of late Ogallala sedimentation. Major sub-Ogallala bedrock highs persisted as drainage divides throughout Ogallala sedimentation. As the Pliocene landscape developed into a coalescent alluvial plain, the former bedrock divides became sites of Ogallala interfan and interchannel deposition. These areas tended to form post-Ogallala topographic lows where Pleistocene and Holocene lacustrine sediments were preferentially deposited (Reeves, 1970b, p. 65; Seni, 1980, p. 23). Such ponded drainage would have been integrated into through-flowing streams during the early stages of entrenchment. Significantly, most trunk drainage and major reentrants on the southern High Plains coincide with what are identified as Ogallala interfan and interchannel areas (Fig. 40).

Another prominent Ogallala physiographic feature, the caliche caprock, probably had a very subdued influence on early Pleistocene drainage development. Most researchers believe that the terminal Ogallala caliche profile initially formed under aggrading conditions in a semi-arid climate. The indurated caprock so prominent today probably evolved through several Pleistocene climatic reversals during which extensive solution and reprecipitation occurred (Schultz, 1977, p. 14). The Ogallala caliche caprock was probably far less of an obstacle to incipient stream entrenchment, drainage network extension, and scarp retreat during late Pliocene-early Pleistocene times than it is today.

The prolonged Pliocene-Pleistocene interval of widespread landscape stability that fostered initial caprock development ended with the roughly concurrent onset of the first Pleistocene climatic reversal and pronounced tectonic activity. Of the two phenomena, tectonism had a far more substantial impact on the evolution of early Pleistocene drainage network geometry. Students of the High Plains have consistently observed that modern plains surface gradients are probably much higher than they were during Ogallala deposition (Collins, 1949, p. 1022; Frye and Leonard, 1972, p. 7; Leonard and Frye, 1975, p. 9; Frye *et al.*, 1978, p. 13; and others). Pleistocene tilting and warping is further cited as a chief cause of post-Ogallala drainage reorientation and entrenchment (Frye and Leonard, 1952, p. 187; Doering, 1958, p. 771-773; Baldwin and Muehlberger, 1959, p. 69; Reeves, 1970b, p. 68). A more precise definition of the tectonic influence on early Pleistocene drainage requires examination of the nature of epeirogenic movement. Four major aspects of epeirogenesis, each having a unique impact on the Canadian fluvial system, have been identified. They are 1) uplift of the Sangre de Cristo Range, 2) rejuvenation of pre-Ogallala bedrock structural elements, 3) displacement along deep-seated fractures, and 4) volcanic upwarping.

The elevation and inclination of various dated basalt surfaces in the Raton and Ocate volcanic fields are the best evidence of uplift along the southern Sangre de Cristo Range. The magnitude of Pliocene-Pleistocene dissection in both regions is greater than that which can be accounted for by climatic reversals alone, thus indicating a tectonic cause (Fig. 41). Projected profiles across the volcanic fields show progressively greater upwarping toward the western margin of Pliocene age basalts (Fig. 25, profiles 1 and 2). Montane uplift may also be evidenced by downstream gravel deposition (Schultz, 1969, p. 23-27; Scott, 1975, p. 242-243; Localities F and I), although proof of tectonically induced sedimentation is usually tenuous.

The evidence is far less tenuous in demonstrating that Pliocene-Pleistocene rejuvenation of Paleozoic structural elements has substantially influenced drainage network geometry and valley morphology. Recurrent movement along sub-Ogallala bedrock structures has long been postulated as affecting Pleistocene physiographic modification of the High Plains (Reed and Longnecker, 1932, p. 6; Baldwin and Muehlberger, 1959, p. 79; Cronin, 1961, p. 34; Trauger and Bushman, 1964, p. 33). The most prominent and areally extensive epeirogenic feature within the upper Canadian basin is the northeast-southwest trending Sierra Grande uplift. This assymetric arch parallels the Rocky Mountain front for almost the length of the Canadian watershed and has a comparatively abruptly dipping western flank. The pattern of drainage entrenchment relative to the axis of the Sierra Grande arch (Fig. 42) is such that the structure may have acted as a hinge, east of which the High Plains were tilted east-southeastward (Fig. 25, profile 2). A similar tectonic mechanism apparently governed late Ogallala and Pleistocene fluvial sediment dispersal in a closely analogous setting along the Chadron-Cambridge arch of western Nebraska (Stanley, 1971, p. 69).

In addition to causing entrenchment by increasing stream gradient, uplift along the Sierra Grande arch and some smaller scale structures also may have contributed to appreciable post-Ogallala reorientation of New Mexico High Plains drainage. The consequences of this reorientation are displayed in the north-south courses of the Canadian River and Ute Creek and in the semi-radial network of High Plains streams between Ute Creek and the Cimarron River. Evolution of this drainage will be discussed in succeeding pages.

Epeirogenesis on the High Plains involved rejuvenation of faulted as well as folded pre-Ogallala bedrock structures. LANDSAT/air photo imagery and drainage network analyses of the New Mexico-Texas High Plains outline hundreds of lineaments that are oriented north-

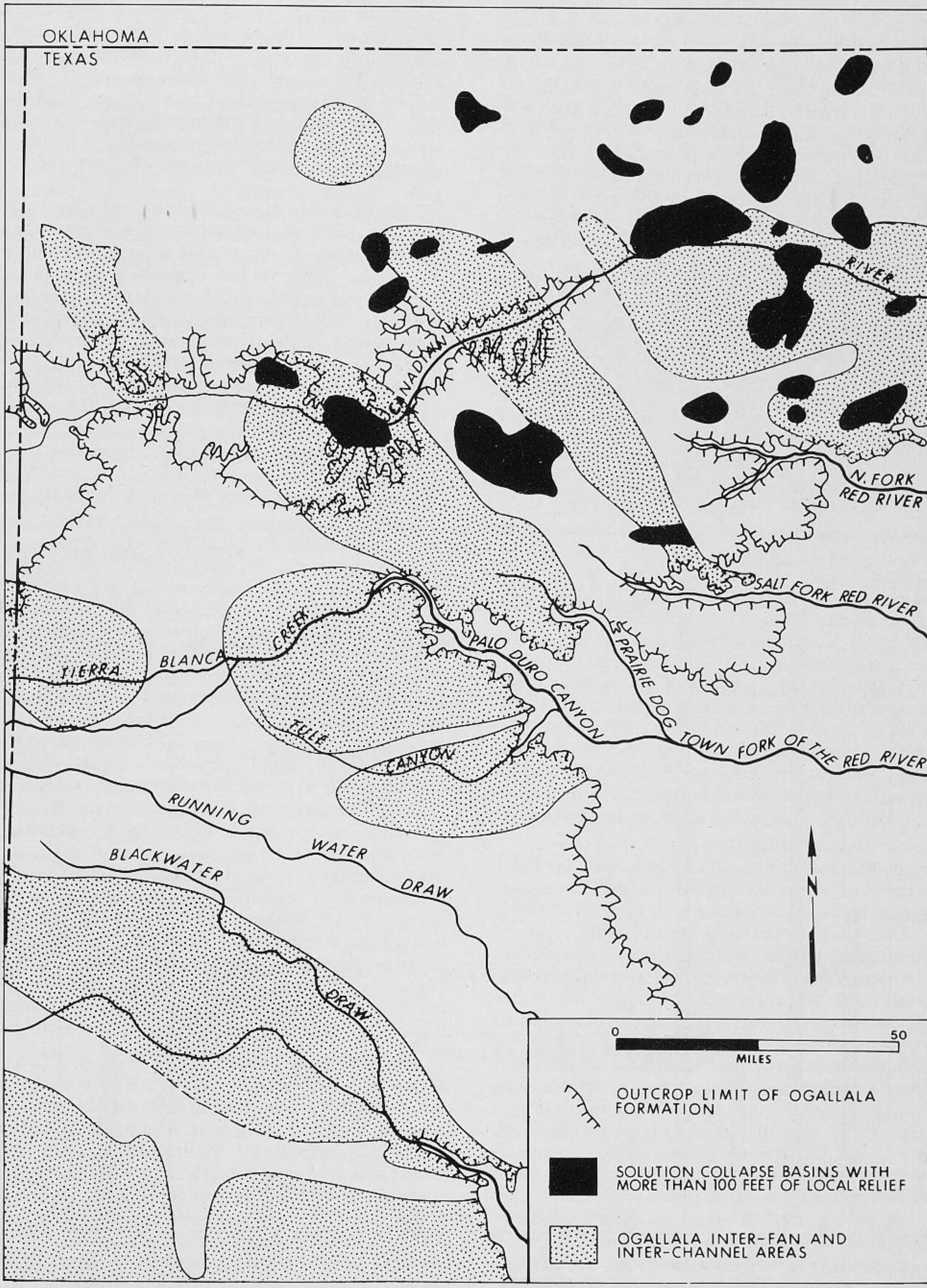


Fig. 40. Map showing the relationship of Ogallala depositional geometry to Pleistocene network geometry. Several High Plains streams and most major reentrants along the Caprock escarpment coincide with bedrock highs represented by Ogallala interfan and inter-channel areas. Eastward-flowing fresh groundwater may have been concentrated against several pre-Ogallala bedrock highs that extend across the Canadian breaks. Such concentrated flow may in turn have accelerated the process of evaporite dissolution in the area (Fig. 50). Adapted from Seni, 1980, p. 9 and 17.

south, northeast-southwest, and northwest-southeast (Reeves, 1970b, p. 68; Gustavson *et al.*, 1978, p. 413; Finley and Gustavson, 1981, p. 33). The lineament trends appear to coincide with those of joint systems in Permian bedrock (Reeves, 1970b, p. 59) prompt the observation that lineaments mirror deep-seated basement structural trends or similarly oriented regmatic shear zones (Reeves, 1970b, p. 68; Gustavson *et al.*, 1978, p. 413). Pliocene-Pleistocene epeirogenesis resurrected these deep fracture trends to the extent of inducing localized alignment of stream channels, playa lakes, and valley and scarp segments on the Canadian High Plains (Finch and Wright, 1970, p. 56; Dutton *et al.*, 1979, p. 80).

Volcanic upwarping in northeastern New Mexico is associated with a conjunction of epeirogenic events that affected Canadian drainage evolution. Raton volcanic field lies at the end of a major belt of Quaternary volcanism that extends northeastward across the state of New Mexico. The belt circumscribes and is closely associated with a linear dome having a diameter of roughly 200 km (125 mi) and rising up to a kilometer above the surrounding countryside (Suppe *et al.*, 1975, p. 408). The Raton section has long been recognized as a site of doming (Fenneman, 1931, p. 38-39), the history of which is displayed in the succession of basalt-capped surfaces (Fig. 25, profile 1; Fig. 41). Alignment of volcanic centers within the section implies that they occur along fractures. The fractures may be tensional features produced by Pliocene-Pleistocene uplift along or west of the Sierra Grande arch (Baldwin and Muehlberger, 1959, p. 83). Tectonic influences on drainage history, at least in the Raton section, involve contemporaneous montane uplift, rejuvenation of paleostructures, and recurrent volcanism.

The conjunction of tectonic events in the Raton section is an aspect of a geographically more widespread concurrence in the timing and duration of pronounced Pliocene-Pleistocene uplift. Initial upwarping throughout the upper Canadian basin clearly postdates incipient calichification of the terminal Ogallala alluvial surface. This fact is supported by the occurrence of abraded caliche clasts in sediments deposited during the first post-Ogallala cycle of erosion (Localities 97, 102 and K). Elevation differences between erosion surfaces capped by Pliocene age basalts in the Ocate volcanic field further suggest that once late Pliocene uplift began, it accelerated quite rapidly (Fig. 41).

Pronounced upwarping continued into early Pleisto-

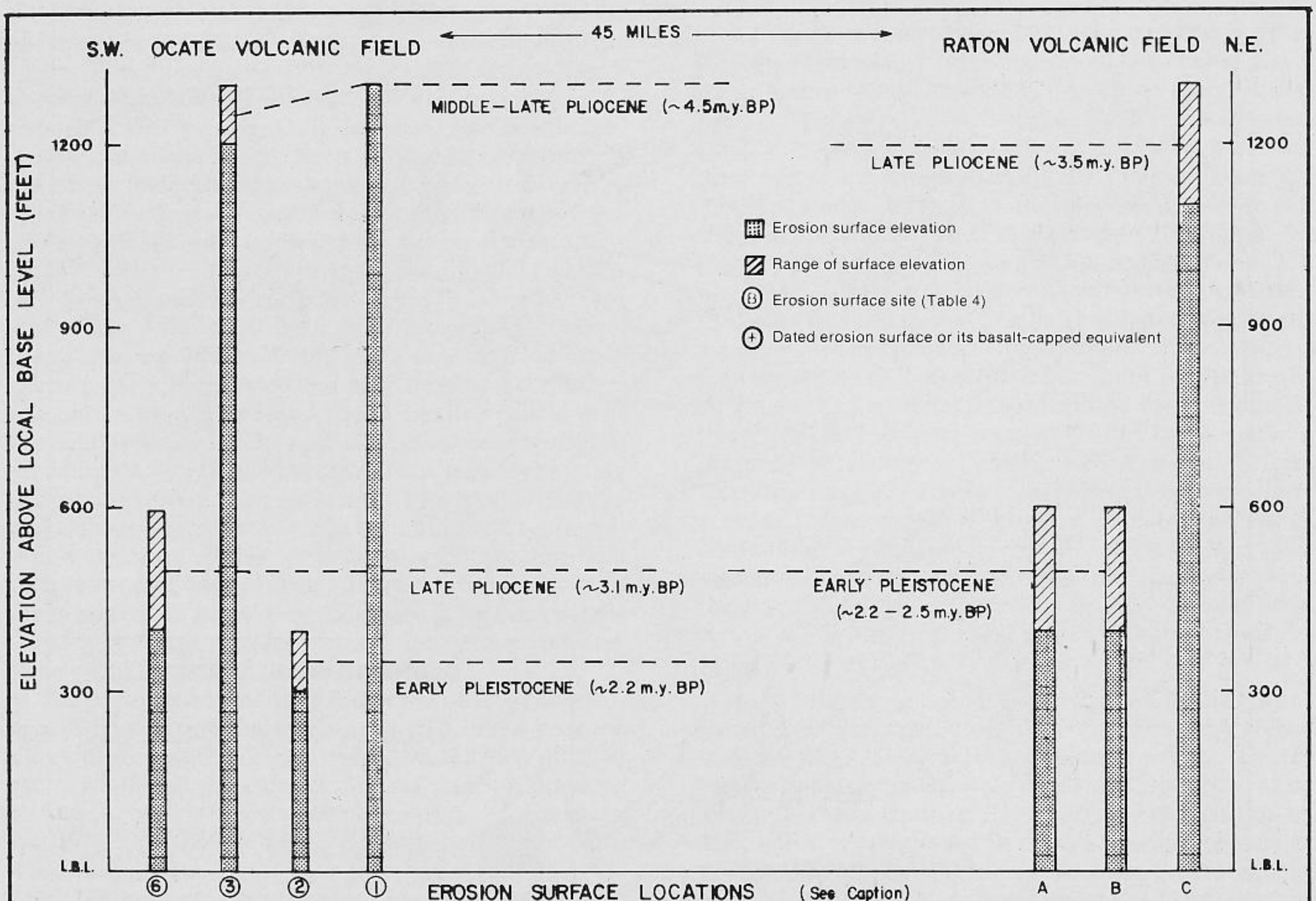


Fig. 41. Diagram showing the elevations above local base level of selected erosion surfaces located within the Ocate and Raton volcanic fields. Numbers for erosion surface locations in the Ocate volcanic field correspond to those listed in Table 4. Lettered locations in the Raton volcanic field are as follows: A. Clayton Basalt-capped Black Mesa (T30N, R24E, sec 22); B. Clayton Basalt-capped surface on Johnson Mesa and equivalent surfaces surrounding Clayton volcanic vents to the southeast; C. Late Raton Basalt-capped Bartlett Mesa and equivalent levels on Horse Mesa and Little Mesa. Relative erosion surface elevations within and between the volcanic fields illustrate two points: 1) once late Pliocene uplift began, it proceeded quite rapidly; and 2) the greater amount of late Pliocene-early Pleistocene downcutting in the Raton volcanic field probably reflects more pronounced upwarping in that area.

cene time, though evidence of this in the Raton volcanic field is complicated by the effects of initial Pleistocene climatic deterioration. Roughly 50% of Pleistocene denudation in the Raton area evidently occurred prior to the end of the first Pleistocene climatic reversal (Fig. 28, 41). While this proportion is comparable to or somewhat greater than that determined for the Ocate volcanic field, the absolute amount of landscape lowering is substantially larger (Fig. 41). The two regions closely resemble one another in physiographic setting and in their probable responses to climatically induced hydrologic changes. In light of this, the far more pronounced downcutting in the Raton section is probably attributable to early Pleistocene epeirogenic uplift.

Pronounced upwarping in the upper Canadian basin apparently abated as rapidly as it began. Gradients of linear early Pleistocene basalt flows paralleling several High Plains streams (Fig. 42) differ little from those of modern drainage courses. The similarity affirms negligible middle-late Pleistocene tilting. Some later Pleistocene epeirogenic movement in northeastern New Mexico is attested to by Holocene earthquake activity in the region (Northrop and Sanford, 1972, p. 149). However, the evident parallelism of early Pleistocene and modern stream courses demonstrates that such movement has merely augmented climatically induced incision, rather than appreciably altering preexisting drainage patterns.

Figure 43 briefly summarizes the nature, regional extent, and timing of major controls on post-Ogallala drainage development in the Raton-High Plains sections of the Canadian basin. This synopsis supports the preliminary conclusion that drainage network geometry and, to some extent, valley morphology probably assumed close to their present form during a relatively brief but eventful time interval spanning the Pliocene-Pleistocene boundary. Consequent drainage courses on the low relief terminal Ogallala alluvial plain were susceptible to appreciable lateral diversion. Diversion intensified under the influence of late Pliocene epeirogenic tilting, upwarping, and basement fold and fracture rejuvenation. The upper Canadian drainage network changed dramatically as formerly consequent streams were reoriented subsequent to structure. The new drainage pattern rapidly stabilized as continued tectonism and the onset of early Pleistocene glaciation caused widespread entrenchment. Evidence presented in succeeding pages for the development of particular drainage ways will further substantiate and develop this scenario.

Evolution of eastward-flowing plains drainage

Most of the northern limit of eastward-flowing plains drainage in the Canadian basin coincides with the divide between the North Canadian River and the Cimarron River, a major tributary of the Arkansas. Major features of both the upper Arkansas and Cimarron valleys clearly demonstrate that little Pleistocene drainage exchange has occurred between the Arkansas and Canadian watersheds. The evidence is more ambiguous concerning such exchange farther downstream.

The course of the upper Arkansas River across the Colorado High Plains has deviated little since late Pliocene-early Pleistocene deposition of Nussbaum gravel (Scott, 1975, p. 243). Nussbaum alluvium was dispersed across an erosion surface sloping southward from the Platte-Arkansas divide to the Arkansas River. The difference in elevation between this surface and the projected base of the Ogallala Formation increases progressively southward to a maximum of over 1000 ft near the Arkansas River (Soister, 1967, p. 43). The upper Arkansas had therefore carved a broad alluvial valley by early Pleistocene time. Since deposition of the Nussbaum Formation, changes in the direction of upper Arkansas drainage have been restricted to slight southward migration under the force of south-flowing tributaries (Sharps, 1969, p. 70).

Farther east, Arkansas River history has been the subject of conflicting interpretations. Subsurface drilling in western and central Kansas has delineated what Frye and Leonard (1952, p. 194) identify as sedimentary bodies deposited by three discrete early Pleistocene fluvial systems. Drainage from each of the systems exited the state to the south, presumably to a confluence with either an ancestral Cimarron or Canadian River. Integration into an ancestral Arkansas River purportedly occurred in middle Pleistocene (Kansan) time by a process of "divide spill-over" on a rapidly alluviating surface (*ibid.*, p. 191).

More detailed studies of subsurface alluvial sequences contradict the notion that early Pleistocene southward-flowing outlets to the Arkansas watershed were not integrated into an east-flowing master stream until middle Pleistocene time. Late Pliocene (post-Ogallala)-early Pleistocene subsurface salt dissolution in southwestern Kansas produced a broad area of subsidence across which the southeast-trending ancestral Arkansas and Cimarron rivers flowed. Their distinctive record of cutting and refilling ends with deposition of thick lacustrine silt-clay containing abundant early Pleistocene ostracods (Gutentag, 1963, p. 614-615; McGovern, 1970, p. 17). This evidence of an early Pleistocene regional shift from fluvial to lacustrine sedimentation, in the Arkansas-Canadian divide region reaffirms the likelihood that drainage exchange predates the early Pleistocene.

The upper Cimarron River poses more direct evidence that negligible Arkansas-Canadian drainage exchange occurred during Pleistocene time. Frye and Leonard (1957b, p. 7), in discussing trunk drainage of the southern High Plains, observed that adjacent High Plains canyons are indicative of independent drainage systems. This is clearly the case for the Cimarron River. When compared to east-flowing plains tributaries of the Canadian River, the Cimarron is far more deeply entrenched (Fig. 25, profile 5). The pronounced canyon of the Cimarron is devoid of early to middle Pleistocene age alluvial terraces and contains late Pleistocene deposits that are substantially lower than those along adjacent drainage courses. Frye *et al.* (1978, p. 15) believed the foregoing observations were evidence that Cimarron canyon developed quite rapidly and quite recently (in late Pleistocene time). They further proposed that earlier Pleistocene drainage in the Cimarron area may have flowed northward from near a paleodivide separating the ancestral Arkansas and Canadian watersheds.

Late Pliocene and early Pleistocene age basalt flows support a quite different account of Cimarron River history. Extrusion of early Pleistocene age Emory Peak Basalt (Fig. 37) clearly dammed the deeply incised headwater canyon of the Cimarron (Muehlberger *et al.*, 1967,

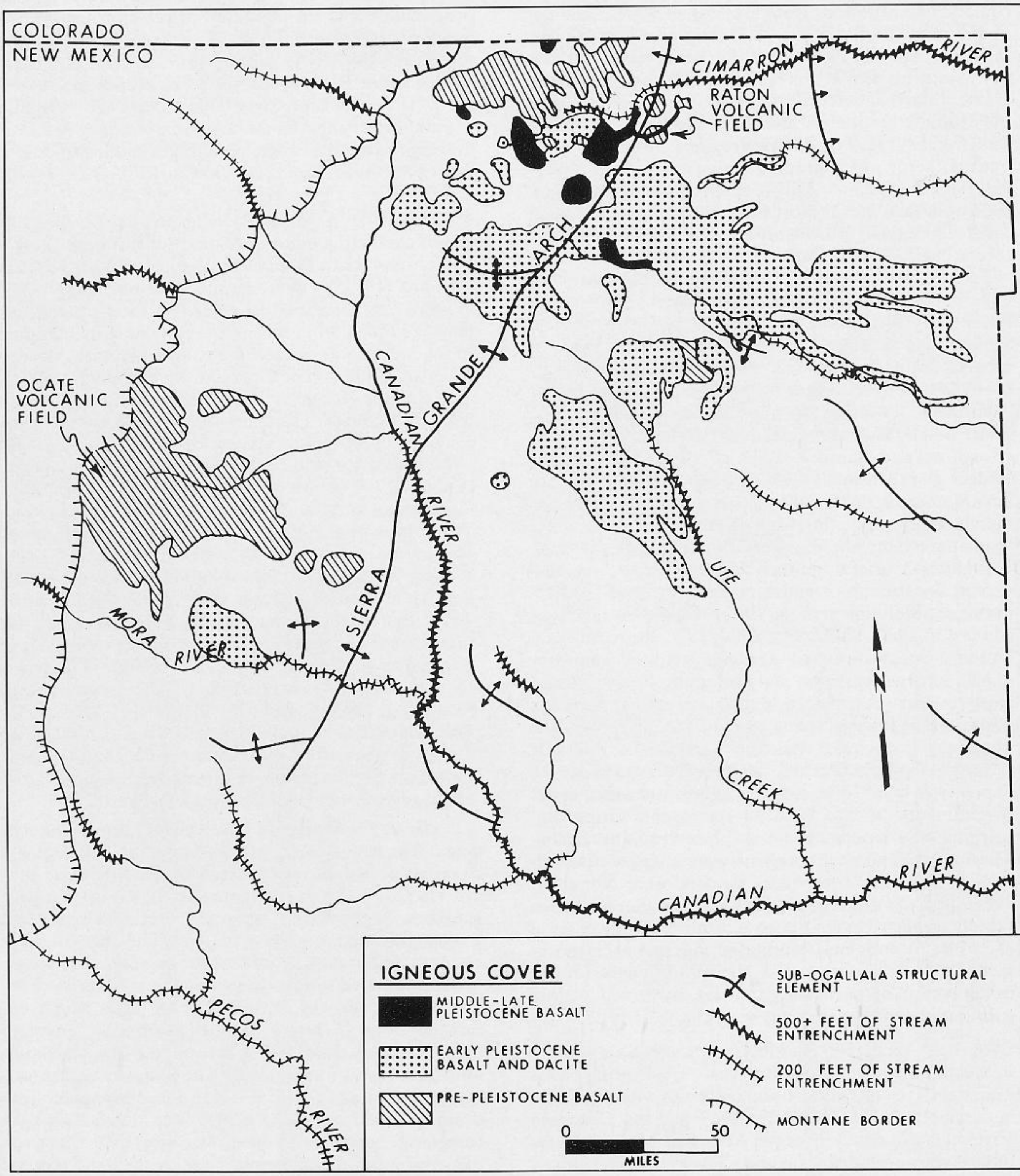


Fig. 42. Map showing the pattern of Canadian network entrenchment relative to the area of igneous activity and the axes of major sub-Ogallala structural elements. The network geometry and entrenchment pattern of east- and south-flowing Canadian plains drainage are evidence of movement along sub-Ogallala structures, particularly the Sierra Grande arch. A portion of the arch coincides with the center of Pleistocene volcanic upwarping of the Raton volcanic field. This implies a genetic relationship between volcanism and epeirogenesis. Sources: Volcanic cover—Dane and Bachman, 1965; Muehlberger et al., 1967, p. 16-17; O'Neill and Mehnert, 1980, p. 31. Entrenchment—1:250,000 topographic maps. Structural elements—Baldwin and Muehlberger, 1959, p. 81; Baltz, 1965, p. 2043; Doeringsfeld et al., 1956, pocket; Griggs, 1948, p. 2; Krisle, 1959, p. 113; Neiler, 1956, p. 145; Wanek, 1962; Wood et al., 1953; Woodward and Snyder, 1976.

p. 36). The basalt now crops out near river level, some 1150 ft below an early (?) Pliocene age Raton Basalt-capped mesa 2 mi to the northwest. Farther downstream, a probable late Pliocene age (Scott, 1968) linear flow atop Black Mesa borders the north side of the modern Cimarron for over 15 mi in northeastern New Mexico and western Oklahoma (Fig. 25, profile 5). The existence of quartzose Ogallala gravel beneath the basalt (*ibid.;* Miser, 1954; and Locality 106) means the paleodrainage course traced by Black Mesa could be either a relic of earlier Ogallala deposition or the result of later flow along an interchannel swale on the terminal Ogallala surface.

The history of the upper Cimarron River is suggested by Figure 43. The Cimarron's present course, which may partially coincide with that of an Ogallala or early post-Ogallala stream, was established by late Pliocene time. Epeirogenic uplift and volcanism during the late Pliocene and early Pleistocene promoted course stabilization by inducing stream entrenchment. The first episode of Pleistocene climatic deterioration augmented entrenchment such that by the end of the first glacial period the headwater Cimarron had become incised to near its present level.

Proof of the existence of a late Pliocene ancestral Cimarron River discounts Pleistocene drainage exchange between the Canadian and Arkansas systems but fails to address the question of Cimarron entrenchment. Explanation of Cimarron canyon's great depth and lack of early or middle Pleistocene age alluvial terraces must take into account several factors. Anomalous entrenchment is probably a consequence of the Cimarron watershed being situated in a region where several late Pliocene-early Pleistocene drainage controls had maximum impact on the fluvial system. Cimarron River headwaters extend to near the probable center of upwarping in Raton volcanic field (Fig. 42). The stream transects the crest of the Sierra Grande arch and trends down its eastern flank along a course that probably underwent minimal reorientation during structural movement (significantly, the gradient on Black Mesa is 60% greater than that of the Cimarron valley bottom). The Cimarron River also drains a region that, by virtue of its altitude and extensive basaltic cover, probably experienced the most intense climate-related paleohydrologic changes to affect semi-arid plains drainage (Figs. 29, 31).

The absence of early to middle Pleistocene age alluvial terraces in Cimarron canyon may result from the lack of a gravelly alluvial mantle sufficiently thick or durable to assure their preservation. Transport of montane-derived

FACTOR CONTROLLING DRAINAGE DEVELOPMENT	IMPACT OF CONTROL ON DRAINAGE DEVELOPMENT	TIME INTERVAL DURING WHICH DRAINAGE CONTROL IS MOST PRONOUNCED (TIME SCALE = MILLION YEARS B.P.)	BASIN AREA WHERE DRAINAGE CONTROL IS MOST PRONOUNCED
		LATE PLIOCENE / EARLY PLEISTOCENE / MIDDLE-LATE PLEISTOCENE	
CLIMATICALLY INDUCED CHANGES IN PALEOHYDROLOGY	SEE FIGURE 31		SEMI-ARID PLATEAUS AND PLAINS
TERMINAL OGALLALA DEPOSITIONAL TOPOGRAPHY	LOCALIZATION OF LATE/POST OGALLALA CONSEQUENT DRAINAGE		OGALLALA INTER-FAN AND INTER-CHANNEL AREAS (PRE-OGALLALA BEDROCK DIVIDES)
EPEIROGENIC UPLIFT OF SANGRE DE CRISTO RANGE	ENTRENCHMENT OF MONTANE BORDER STREAMS		MONTANE BORDER
REJUVENATION OF PRE-OGALLALA BEDROCK STRUCTURAL ELEMENTS	-DRAINAGE REORIENTATION SUCH THAT STREAMS FLOW SUBSEQUENT TO STRUCTURE IN A SUBRADIAL/SUBPARALLEL NETWORK -ENTRENCHMENT OF STREAM CHANNELS, PLAYA LAKES AND VALLEY AND SCARP SEGMENTS		SIERRA GRANDE ARCH
DISPLACEMENT ALONG PRE-OGALLALA BEDROCK FACTORS	LOCAL ALIGNMENT OF STREAM CHANNELS, PLAYA LAKES, AND VALLEY AND SCARP SEGMENTS		BASIN-WIDE BUT PROBABLY CONCENTRATED IN AREAS OF GREATEST TECTONIC ACTIVITY
VOLCANIC UPWARPING	DRAINAGE REORIENTATION SUCH THAT STREAMS FLOW SUBSEQUENT TO UPWARP IN A SUBRADIAL NETWORK -ENTRENCHMENT OF STREAMS DRAINING THE CREST AND FLANKS OF THE UPWARP	3 2 1	RATON VOLCANIC FIELD

Fig. 43. Summary of the nature, timing, and regional extent of major factors controlling post-Ogallala drainage development in the Raton and High Plains sections of the Canadian basin. Drainage network geometry and, to an exent, valley morphology probably assumed essentially their modern form during an eventful time interval spanning the Pliocene-Pleistocene boundary.

quartzose alluvium by the Ogallala Cimarron evidently ended with the onset of Pliocene volcanism. No Pleistocene age quartzose gravel is found within Cimarron canyon, with the exception of some which has been reworked from Ogallala gravel deposits beneath nearby basalt flows (Localities 105 and 106). Had early-middle Pleistocene terraces been gravel capped, the mantle would have consisted of easily eroded clasts of locally derived Mesozoic age fine clastics (Fig. 8).

New Mexico-High Plains drainage between the Cimarron River and Ute Creek forms a semi-radial network that heads along or east-southeast of the crest of the Sierra Grande arch (Fig. 42). The streams are incised into a low relief surface mantled by Ogallala sediments which are appreciably thinner than they are farther east on the Texas Panhandle. Areally extensive Clayton Basalt flows were extruded across this surface, preserving a record of early Pleistocene drainage and its subsequent modification.

The cover of early Pleistocene age Clayton Basalt (Fig. 37) extends east-southeastward across the northeast corner of New Mexico and surrounds several Ogallala inliers. Topographic relief between the inliers and bordering basalt is negligible, except where topographic inversion has occurred along modern drainage courses. Gravel which caps some of the inliers is devoid of clasts from the surrounding basalt (Locality A). Wells drilled into a few of the Ogallala "islands" also failed to encounter basalt (Baldwin and Muehlberger, 1959, p. 74). Thus Clayton Basalt overlying the northeastern New Mexico High Plains may consist of a series of partially coalescent linear flows separated by discrete Ogallala-defended divides. Near the downslope limits of volcanic cover, more isolated linear flows parallel the courses of several modern plains streams. Based upon the regional morphology of Clayton Basalt flows, northeastern New Mexico during early Pleistocene time was probably drained by a shallowly incised, subparallel network of streams. Drainage flowed down the southeastern flank of the Sierra Grande arch in a pattern nearly identical to that of the modern fluvial system. Streams had probably shifted from a more easterly Ogallala flow direction (*ibid.*, p. 78) during late Pliocene rejuvenation of the Sierra Grande arch.

Stream valley deepening and widening promoted early Pleistocene network stabilization and accounted for most changes in the middle-late Pleistocene High Plains fluvial landscape of northeastern New Mexico. These changes were approximately uniform throughout the region, with the exception of Tramperos Creek. Besides its anomalous degree of entrenchment (Fig. 25, profile 5), Tramperos Creek differs most from other southeast-flowing plains drainage in that its headwaters have exhumed an extensive area of sub-Ogallala bedrock (Fig. 8). Sediment removal from the broad watershed has been accomplished by a dendritic stream network that contrasts sharply with adjacent narrow drainage systems of low tributary density. This contrast is reflected in higher percentages of quartzose (reworked Ogallala) constituents for terrace gravels along the more constricted watersheds (compare Locality 98 with Localities 99 and 104). Tramperos Creek is apparently no older than adjacent drainage courses (Locality H, Fig. 1), so it must have been subject to the same Pliocene-Pleistocene drainage controls (Fig. 43). Of these controls, Ogallala thickness and depositional setting are most likely to initiate contrasting drainage systems within a region of relatively uniform physiography, structure and climatic history. Lower Tramperos Creek (also called "Major Long Creek" and "Punta de Agua Creek") apparently lies over an Ogallala interchannel area (Seni, 1980, p. 17); this relationship may continue upstream into New Mexico. The case of Tramperos Creek suggests that Ogallala depositional geometry may have been particularly important in the early development of streams draining plains areas of shallow Ogallala cover.

Evolution of southward-flowing plains drainage: Ute Creek

The southward flow of the Canadian River and Ute Creek is one of the most anomalous aspects of the New Mexico-High Plains drainage network. The place of these rivers in the regional drainage pattern has inspired allusions to stream piracy as a major agency in their development (Plummer, 1932, p. 770; Baldwin and Muehlberger, 1959, p. 85; Roberson, 1973, p. 133-136; and others). Piracy has been involved in the evolution of south-flowing streams, but only in conjunction with several other important factors. Drainage controls generalized in Fig. 43, in concert with base level changes along the east-flowing Canadian, also affected the evolution of southward drainage. The accounts of Ute Creek and Canadian drainage development contribute to the larger picture of plains fluvial system evolution as summarized in Figures 44 to 46.

Late Pliocene-early Pleistocene age basalt flows are associated with fluvial gravels at Localities 79 and 82 and are the earliest evidence of an ancestral south-flowing Ute Creek. Basalts at both localities flowed along broad, shallow, post-Ogallala/pre-early Pleistocene drainage ways that parallel the modern Ute Creek channel.

Farther downstream, remnants of ancestral Ute Creek drainage are quite different. Locality 83 lies within an extensive area west of lower Ute Creek known as the "Gravel Hills." The hills are subjacent to and several hundred feet below the crest of the east-facing Canadian escarpment (Fig. 25, profile 3). They reportedly consist of up to 200 ft of gravelly "channel deposits," which are related to several nearby physiographic features, and suggest deposition near the end of the first post-Ogallala erosional period (Trauger *et al.*, 1972, p. 17). Gravel composition differs from upstream Ute Creek localities in the preponderance of quartzose constituents and virtual absence of volcanics (Appendix C). Gravel Hills alluvium is presumably derived from the reworking of sediment southwest of the line indicated in Figure 23.

The composition of gravel capping a second terrace level of lower Ute Creek (Locality 95) reflects a Gravel Hills rather than upper Ute Creek source. Unless the abundance of upstream gravels has been substantially diluted by the introduction of alluvium farther downstream, local provenance of the lower Ute Creek terrace gravel implies recent (late Pleistocene ?) development of the modern course of lower Ute Creek (Fig. 46). An abrupt bend in Ute Creek approximately 10 mi upstream of its confluence with the Canadian may be an elbow of capture, an explanation consistent with evidence cited by Spiegel (1972, p. 118).

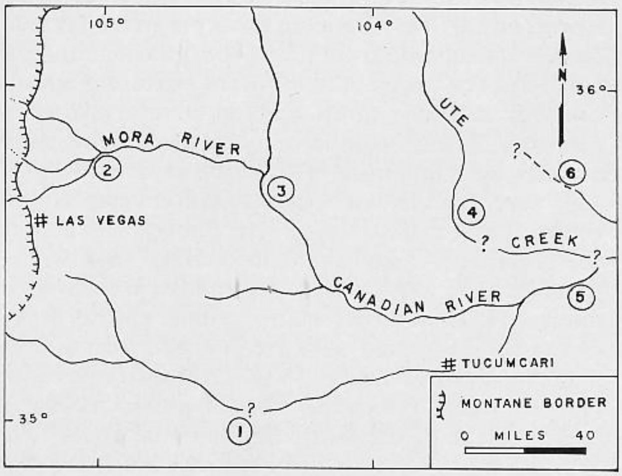


Fig. 44. Map of the postulated High Plains/Pecos-Canadian Valley fluvial network during late Pliocene-early Pleistocene time. 1) Course of the ancestral Pecos River is uncertain. Here it is shown as a headwater tributary of the Canadian system, though there is no evidence against a southward confluence with Portales River. Uncertainty lies in the former dimensions of Pajarito Creek. The underfit Canadian tributary presently heads along the Canadian-Pecos divide. 2) Montane drainage through Gallinas River, now a Pecos headwater tributary, flowed into the Mora system. The additional discharge probably promoted Mora River entrenchment. 3) The Mora and south-flowing Canadian Rivers occupied essentially their modern courses. At least 65% of entrenchment had taken place before middle Pleistocene time. 4) Upper Ute Creek already occupied its present course. Lower Ute Creek may have also assumed its modern position, given the probability that the east-facing Canadian escarpment had begun to develop. Doubt regarding the provenance of gravels along lower Ute Creek precludes specifying a lower Ute Creek-Canadian relationship. 5) The east-flowing Canadian follows a lowland on the terminal Ogallala surface formed above a southward-receding dissolution front (Fig. 50). 6) A sizeable southeastward-flowing stream may have persisted on the Ogallala surface, as evidenced by gravels at Locality 97.

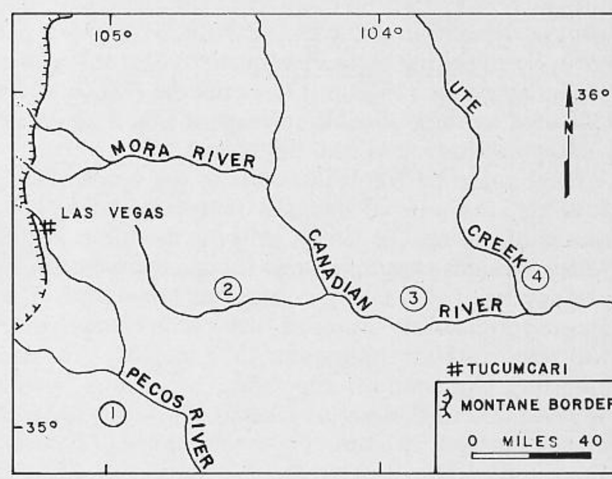


Fig. 45. Map of the postulated High Plains/Pecos-Canadian Valley fluvial network during middle Pleistocene time. 1) Montane tributary drainage of the future Pecos River clearly joined eastward-flowing Canadian drainage. Farther south, the Portales River was being beheaded by a headward (northward) migrating ancestral Pecos River. 2) A gradient advantage down the Sangre de Cristo synclinorium resulted in piracy of Mora headwaters by the south-flowing ancestral Gallinas River. 3) Entrenchment of the Mora-Canadian continued, possibly as a result of lowered Canadian base level accompanying heightened discharge from the ancestral Pecos River. 4) Ute Creek persisted along roughly its present course, though uncertainty over the provenance of the lower Ute Creek gravels fosters similar uncertainty as to the dimensions of the Ute Creek watershed during middle Pleistocene time. Gravel composition does suggest that Ute Creek did not enter the east-flowing Canadian near their present confluence. 5) The Canadian River may have flowed somewhat south of its present course, through a proto-Canadian Valley. The valley was nearly as wide as the modern breaks and approximately half as deep.

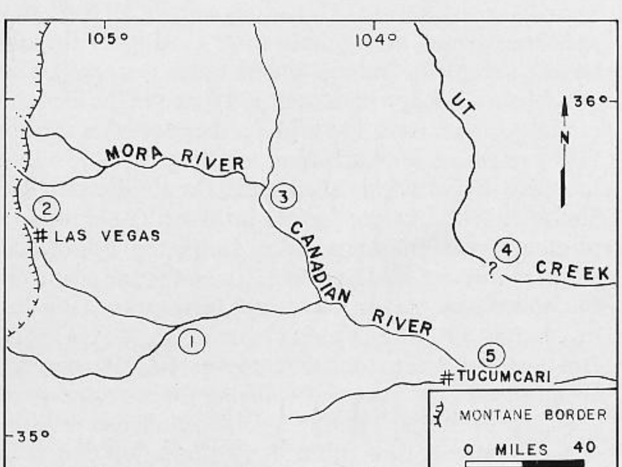


Fig. 46. Map of the postulated High Plains/Pecos-Canadian Valley fluvial network during late Pleistocene-Holocene time. 1) The ancestral Pecos River, after beheading the middle Pleistocene Portales River, continued to migrate headward (northward) until it had integrated its present montane headwaters. 2) Lowering Canadian base level continued to induce widespread incision and valley excavation. Most evidence of a former Pecos-Canadian connection was removed. 3) The east-flowing Canadian shifted to its present course while incising to roughly twice the depth of the middle Pleistocene master stream. Approximately half the excavation of the Canadian breaks also took place after middle Pleistocene time. 4) Lowering of base level along the Canadian also induced headward migration of a south-flowing Canadian tributary and its capture of lower Ute Creek.

The development of upper Ute Creek appears to have followed the scenario outlined for other plains drainage and depicted in Figure 43. South-southeastward-flowing upper Ute Creek predates Pliocene-Pleistocene basalt extrusion and thus probably reflects tectonically induced reorientation of southeast-flowing late Ogallala drainage (Fig. 26). This observation is supported by the apparent subsequence of upper Ute Creek to the eastern limb of the Sierra Grande arch. Continued Pliocene-Pleistocene epeirogenesis and early Pleistocene climatic deterioration eventually induced network stabilization through stream entrenchment (Fig. 25, profile 2).

Ancestral lower Ute Creek apparently also realigned itself according to the pattern of late Pliocene tectonism. This is implied by a steepened Ogallala surface gradient west of the river as shown in Fig. 25, profile 3. Profile 3 also depicts the broad, deeply incised, and markedly asymmetric lower Ute Creek valley. This prominent feature probably originated with regional uplift, but assumed much of its present dimensions during Pleistocene episodes of altered hydrologic regime and associated downstream base-level changes.

Most of the relief along the Canadian escarpment west of Ute Creek and within Ute Creek valley itself developed prior to deposition of the Gravel Hills. The Gravel Hills are evidently either early Pleistocene in age, as suggested by Trauger *et al.* (1972, p. 17), or middle Pleistocene, as indicated by their possible correspondence with erosion surfaces of that age (Localities M and N).

If the reported 200-ft thickness of the Gravel Hills is accurate, the alluvial deposits represent more than a means of dating Ute Creek valley excavation. A thick valley fill consisting of coarse fluvial sediment implies prior cycles of alternating incision and alluviation. There are several possible causes of such cyclic changes in fluvial sedimentation (Schumm, 1977, p. 203). The most plausible explanation, supported by factors such as downstream thickening of alluvial fill in the Canadian breaks (Speigel, 1972, p. 119), is the change of base level along the master stream. The alternation of Canadian River incision and alluviation during Pleistocene climatic reversals and periods of upstream drainage diversion would have influenced Ute Creek entrenchment, lower Ute Creek alluviation (i.e., the Gravel Hills), and possible piracy near the Ute Creek-Canadian confluence (Figs. 45, 46). This theme of base level change along the east-flowing Canadian and its impact on tributary drainage will be further developed in subsequent discussions.

EVOLUTION OF SOUTHWARD-FLOWING PLAINS DRAINAGE: CANADIAN RIVER

A genetic explanation of the south-flowing Canadian River, like that of Ute Creek, must account for both its anomalous trend and the spectacular entrenchment of the lower north-south reach (Fig. 10). Previous authors have devoted exclusive attention to the upper Canadian's peculiar network geometry. Given the obvious montane provenance of Ogallala gravels, it has seemed indisputable that the north-south Canadian evolved through headward (northward) migration and beheading of east-flowing montane drainage (Plummer, 1932, p. 770). Several apparently related phenomena support this interpretation. Both an elbow of capture along the Canadian southwest of Raton (Fig. 1) and the right angle juncture of the river with several of its montane tributaries imply stream piracy. The Canadian flows progressively farther from the mountain front on its southward course. This may reflect its progressive eastward migration under the force of montane uplift and/or tributary discharge, assuming the more southerly course is older (i.e., assuming headward migration) (Robinson *et al.*, 1964, p. 137-138). Lateral Canadian channel migration may have been constrained on the east by late Pliocene uplift of the Sierra Grande arch and Chico Hills (Baldwin and Muehlberger, 1959, p. 85). More erosive bedrock and thinner former alluvial mantle along the north-south Canadian, compared with areas to the west and east, might have also facilitated south-flowing drainage development. Finally, the upper Canadian network is a near mirror image of the upper South Platte River, whose course also apparently evolved through headward migration and successive stream piracy in a similar setting along the Colorado Piedmont (Pearl, 1971, p. 25).

The foregoing observations resemble one another in that they are plausible assertions made without the support of a sedimentary or erosional record. The absence of such a record is itself a source of speculation. The limited distribution of channel-bound Ogallala sediment may have assured the removal of fluvial deposits and underlying erosion surfaces from the dominantly erosional late Pliocene landscape. In any event, there are indications of more youthful drainage changes. The evidence is in the form of 1) upper Canadian gravels, which can be used to infer the timing of network reorientation, and 2) a dated basalt flow, which aids in establishing the age and probable causes of Canadian entrenchment.

Several gravel samples were collected from various terrace levels (Localities 15-18, 25 and 26) flanking the Canadian above its confluence with its first major montane tributary (Vermejo River). Composition of this gravel can be explained by erosion of bedrock areas both west and east of the upper Canadian. There is apparently no sedimentary evidence that the upper Canadian exhumed alluvium contained in obliquely trending Ogallala drainage channels. Nor is there any indication that upper Canadian provenance changed as a result of progressive northward piracy by the Canadian of Pleistocene montane drainage.

The similarity in composition of gravels mantling different terrace levels at the same river locality (Localities 25 and 26) suggests the Canadian watershed (i.e., provenance area) has been stable since cutting of the oldest terrace sampled. The age of the older terrace (Locality 26), which lies approximately 300 ft above the Canadian, can only be inferred. The high surface occupies the broad valley of the upper Canadian, a setting similar to that of Locality 16, which has been mistakenly identified as a pediment. If the major factors influencing pediment and terrace formation are similar along the upper north-south reaches of the Canadian, which they appear to be in this specific case, then the terrace level at Locality 26 can be equated with Raton area pediment surfaces at equivalent elevations above local base level (Fig. 34). Accepting this premise, the gravel at Locality 26 is probably early Pleistocene in age. The upper Canadian River has, therefore, undergone no significant reorientation of drainage, so far as can be discerned from terrace gravel composition, since early Pleistocene time.

A dated basalt flow within the canyon of the lower Mora River constitutes a time stratigraphic datum that can be used to deduce the timing and probable causes of Mora and Canadian River entrenchment. Basalt that parallels the Mora River for over 50 mi is dated at 1.4 million years B.P. near its source in Maxson Crater (Fig. 37). For roughly the lower 40 mi of its length, the early Pleistocene age flow is confined to the entrenched valley of the lower Mora. Figure 47 depicts the gradient of this flow as compared to the gradient of the Mora River and the crest of adjacent Dakota Sandstone uplands.

The Dakota uplands are part of a widespread stripped structural plain into which both the Mora and south-flowing Canadian have been deeply incised. The surface of the plain roughly coincides with the level of the late Pliocene landscape, judging from an extensive late Pliocene age basalt flow (Charette Mesa) overlying the surface just 15 mi north of the Mora River (Fig. 37). If the Dakota uplands flanking the Mora represent a minimum elevation of the late Pliocene landscape, then at least 65% of Mora and Canadian River entrenchment occurred during latest Pliocene and early Pleistocene time (Fig. 25, profile 4). The causes of entrenchment probably correspond to those for Ute Creek and eastward-flowing plains drainage during the same time interval (Fig. 43). The role of Pliocene-Pleistocene tectonism is graphically supported by coincidence of the upstream limit of Canadian River entrenchment with the axis of the Sierra Grande arch (Fig. 42). Early Pleistocene waxing glacial conditions promoted incision by altering Mora and Canadian River hydrology and by lowering base level downstream along the east-flowing Canadian (Fig. 31).

Gradients of the Maxson Crater flow and Mora River suggest that regional uplift played a minor role in middle-late Pleistocene entrenchment. If east and southeastward tilting did occur, it should be reflected in higher gradients on older time-stratigraphic surfaces. Nearly the reverse is true in the case of the Mora canyon. For three-fourths of the distance measured, the average gradient of the Maxson flow and the Mora are almost identical (Fig. 47). In the lower 10 mi of its course, the Mora River gradient is appreciably steeper than that of the early Pleistocene basalt surface. The abrupt steepening evidently reflects nickpoint migration, the result of a late (?) Pleistocene episode of climatically induced base-level lowering along the east-flowing Canadian. Similar instances of lowered Canadian base level earlier in the Pleistocene are presumed to have also augmented entrenchment by the Mora and south-flowing Canadian. If there is evidence of

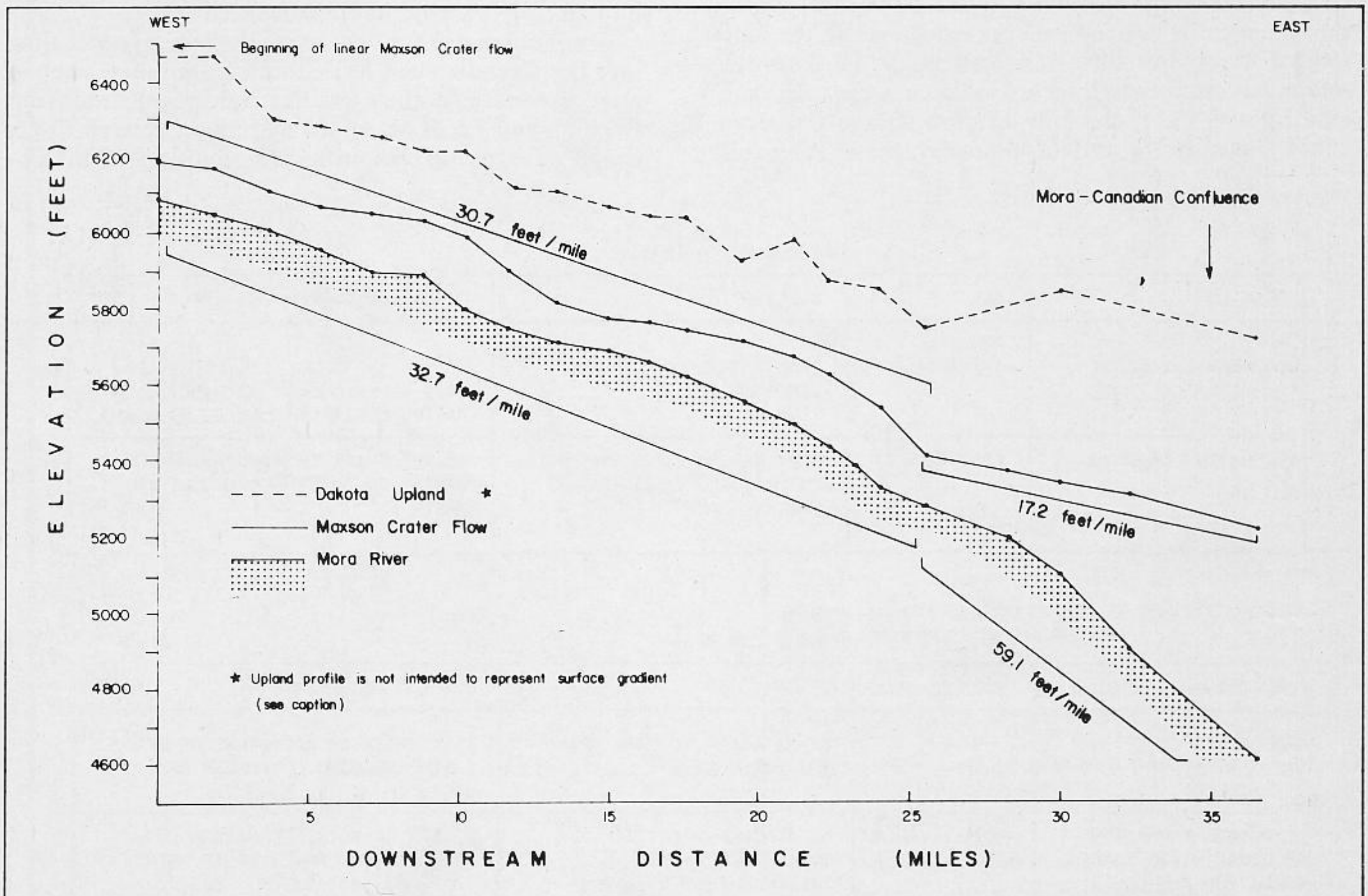


Fig. 47. Chart showing the elevations and average gradients of the Mora River and the early Pleistocene Maxson Crater basalt flow, with a profile of the late Pliocene Dakota upland. Measurements were taken from 1:24,000 scale maps of a 37 mi reach of the entrenched lower Mora River from the upstream limit of the linear Maxson Crater flow eastward to the confluence of the Mora with the Canadian River. The upland profile is derived from elevations taken at points adjacent to those measured for the lower surfaces. Distances between points are thus diagrammatic and are an unreliable basis for calculating surface gradient. The gradient of a projected profile along the upland north of and paralleling the Mora canyon in this area is approximately 33.5 ft per mile.

rising base level, like that found along lower Ute Creek and the Canadian breaks, it is submerged beneath Conchas Reservoir.

DRAINAGE EVOLUTION OF THE PECOS-CANADIAN VALLEY

Development of the Canadian bend

The upper Canadian shifts from a southward- to eastward-flowing stream through an abrupt right angle bend east of a relatively low portion of the Canadian-Pecos divide (Fig. 8). This striking network anomaly is the most obvious indication of former drainage exchange between the Canadian River and an adjacent fluvial system. Several writers have cited the morphology of the Canadian bend region and alignment of the south-flowing Canadian and Pecos Rivers as signifying that the upper Canadian was once a headwater tributary of the ancestral Pecos (Thomas, 1972, p. 28; Roberson, 1973, p. 136; Leonard and Frye, 1975, p. 12; and Gustavson *et al.*, 1980, p. 33). However, compelling morphologic traits notwithstanding, several arguments can be made against a former Canadian-Pecos confluence and in favor of an alternative interpretation.

No evidence exists along the Pecos-Canadian divide in the vicinity of the Canadian bend to suggest that upper Canadian drainage previously joined the Pecos. None of the ephemerally drained valleys through which the thalweg of a pre-diversion Canadian might have flowed retain the sedimentary record of such a past. In fact, exotic gravel was found only on a low terrace of Cuervo Creek (Locality 76), and its preponderance of Paleozoic limestone is clear indication of a western (Pecos) rather than northern (Canadian) provenance (Figs. 48, 49). An elongate lowland circumscribed by Triassic Santa Rosa Sandstone (Bachman and Dane, 1962) extends westward to the Pecos from the Canadian bend, further suggesting Pecos drainage was formerly channeled eastward into the Canadian.

A gravel-veneered Pecos-Canadian divide southwest of the Canadian bend is the highest barrier a postulated ancestral Canadian-Pecos connection would have had to cross (Fig. 25, profile 4). The surface thus bears the earliest sedimentary record of such a connection. Projected profiles along the divide reveal at least two topographic sags that could be interpreted as windgaps. These possible remnants of abandoned channels are underlain by an areally extensive pediment or terrace surface (Dane and Bachman, 1965). Gravel samples from this surface (Localities 72 and 73) contain characteristic upper Pecos basin carbonates (Fig. 48) and other lithologic constituents denoting Pecos provenance (Localities 67, 70, and 71). The gravel-capped divide between the Pecos and the Canadian bend is evidently early Pleistocene in age, given the probable age of Locality T and the divide's elevation relative to nearby Ogallala and middle Pleistocene (Locality S) surfaces. Fluvial gravels were deposited on the divide by future Pecos headwaters flowing eastward into an early Pleistocene Canadian River (Fig. 44).

A minimum age for continued Pecos headwater flow into the Canadian can be deduced from gravel-capped erosion surfaces in the Canadian bend region and from the timing of Pecos headward migration. Cuervo Creek drains an extensive erosion surface southwest of the Ca-

UPPER CANADIAN BASIN

FORMATION	AGE	DESCRIPTION	OUTCROP OCCURRENCE
NIOBRARA FORMATION FT. HAYS LIMESTONE	CRETACEOUS	GRAY, THIN-BEDDED MARINE LIMESTONE	UP TO 350' THICK; 25-55' OF FT. HAYS LIMESTONE IN NORTHERN RATON BASIN, 10-20' IN LAS VEGAS BASIN
GREENHORN LIMESTONE	CRETACEOUS	GRAY MARINE LIMESTONE WITH INTERBEDDED CALCEROUS TO CHALKY SHALE	30-50; THICK IN NORTHERN RATON BASIN; 20-60' THICK IN LAS VEGAS BASIN

UPPER PECOS BASIN

FORMATION	AGE	DESCRIPTION	OUTCROP OCCURRENCE
SAN ANDRES LIMESTONE	PERMIAN	DENSE LIGHT TO DARK GRAY EARTHY LIMESTONE	150' THICK IN SOUTHERN LAS VEGAS BASIN, WEDGING OUT NORTH OF LAS VEGAS
LA POSADA FORMATION (EQUIVALENT TO SANDIA FORMATION AND LOWER GRAY LIMESTONE OF MADERA FORMATION	PENNSYLVANIAN	MOSTLY NON-MICRITIC BIOSPARUDITE WITH ABUNDANT FOSSILS AND FOSSIL FRAGMENTS	27-67% OF TOTAL FORMATION OUTCROP IS CARBONATE, UP TO APPROXIMATELY 1000' THICK. BEST EXPOSED IN UPPER PECOS VALLEY.

Fig. 48. Chart showing the lithologic contrast between major carbonate provenance areas of the upper Pecos and upper Canadian drainage basins. The determination that an outcropping carbonate unit is a major sediment contributor is based upon both the outcrop area of the unit (Fig. 49) and the extent (in terms of percentage) to which it is represented in downstream/downslope Pleistocene age gravel. Data compiled from Miller et al., 1963, p. 22-38; Bachman and Dane, 1962.

nadian bend that is probably middle Pleistocene in age, based upon dating of Locality S (Appendix B). Gravel, which mantles a low terrace of Cuervo Creek (Locality 76), was probably concentrated from the surrounding erosion surface. Carbonates from Locality 76, as mentioned previously, are clearly derived from the modern Pecos headwater region of the southern Sangre de Cristo Mountains. This watershed was therefore part of Canadian drainage for at least a portion of middle Pleistocene time.

The Pecos River incorporated its upper drainage through headward (northward) migration and capture of east-flowing montane drainage. The process was promoted by a gradient advantage of the lower Pecos (Leonard and Frye, 1975, p. 11), north-south structural alignment (Frye and Leonard, 1972, p. 6; Kessler, 1972, p. 167), and the integration of trains of coalescent solution collapse sinks (Morgan, 1942, p. 32; Kelly, 1972b, p. 45-46). The timing of Pecos headward migration into the ancestral Canadian basin is best defined by the probable age of Pecos-Portales River piracy. This well documented event took place in the vicinity of Fort Sumner, New Mexico, and involved southward diversion of a major montane tributary of the ancestral Brazos River, the Portales River (Baker, 1915, p. 54; Reeves, 1972, p. 113-114). The oldest terrace found both above and below the point of capture is middle Pleistocene (Kansan) in age (*ibid.*, p. 114). Integration of more upstream ancestral

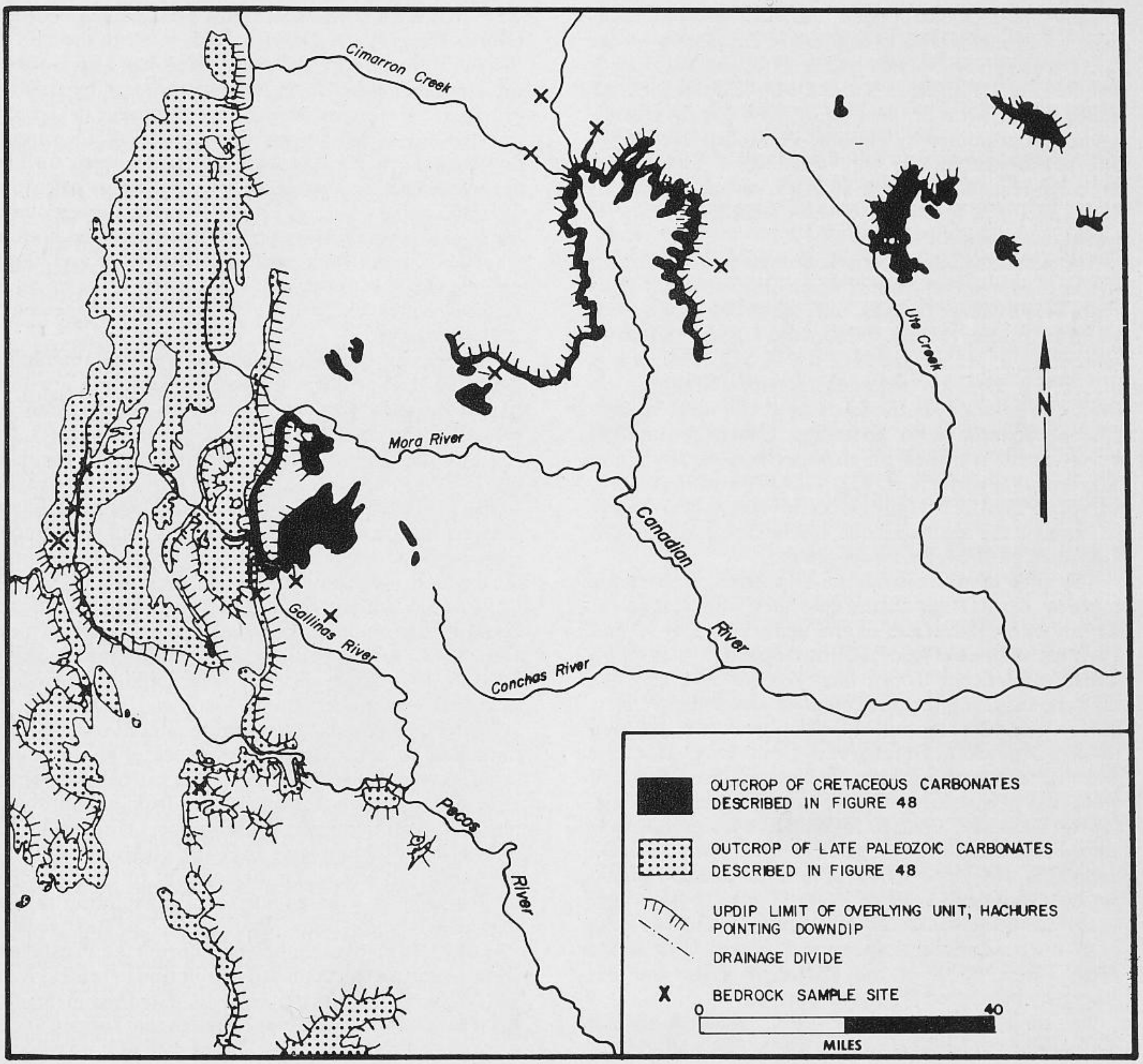


Fig. 49. Map of portions of the upper Pecos and Canadian drainage basins showing the approximate outcrop area of carbonate formations described in Fig. 48. The lithologic distinction between late Paleozoic and Cretaceous age carbonates parallels a geographic contrast in outcrop region. From the outcrop geometry of overlying units, it is apparent that the area of exposed Paleozoic limestone was formerly more restricted whereas that of Cretaceous carbonates was greater. Sites (other than sample localities) where limestone bedrock was studied are also shown. Their distribution reflects an effort to assess the range of carbonate types contributing to downstream/downslope Pleistocene age gravels.

Canadian drainage by the Pecos must therefore be a middle Pleistocene or later event.

The timing of Canadian-Pecos drainage exchange probably had a direct impact on downstream changes in the Canadian fluvial system. Added discharge from Pecos headwater tributaries would have augmented pronounced upper Canadian, Ute Creek, and Canadian breaks entrenchment/excavation during waxing early and possibly middle Pleistocene glacial episodes. The abrupt reduction in discharge accompanying middle or late Pleistocene piracy may account for backfilling along the Canadian breaks and lower Ute Creek.

Evaporite dissolution and evolution of the Canadian breaks

East of the Canadian bend, the river enters a broad, deep valley that retains its impressive dimensions across northeastern New Mexico and most of the Texas Panhandle (Fig. 25, profiles 5 and 6). Development of the valley began with termination of the Ogallala erosion cycle, was promoted by Pliocene-Pleistocene tectonism, and accelerated rapidly with Pleistocene climate- and drainage-related hydrologic changes. An additional pervasive factor in formation of the Canadian "breaks" is subsurface evaporite dissolution.

The effects of dissolution have been frequently noted in the Pecos-Canadian Valley region. Widespread occurrence of subsidence troughs, collapse basins, and smaller solution features (Myers, 1959, p. 66; Trauger and Bushman, 1964, p. 31; Speigel, 1972, p. 118; and Gustavson *et al.*, 1980, p. 33) attest to the general impact of subsurface evaporite solution on the landscape. The more specific role of dissolution in governing Canadian drainage development is evident in cross-sections by Irwin and Morton (1969), Morton (1973), Gustavson *et al.* (1980, p. 6), and in Fig. 50. To fully assess this role, it is necessary to examine the regional scope, mechanics, and timing of Canadian basin evaporite dissolution.

The zone of active evaporite dissolution beneath the modern Texas High Plains coincides with a series of abrupt inclined surfaces at the updip limits of several Permian salt beds (Fig. 51) (Gustavson *et al.*, 1980, p. 35). These surfaces, or fronts, have receded in a step-like manner, the stratigraphically highest salts having undergone the most extensive lateral (downdip) dissolution (*ibid.*, p. 6; Fig. 50). The migrating fronts have left in their wake intraformational solution breccias, the collapse of which has produced a rolling or karst-like surface topography (Bachman, 1980, p. 55-56). Such a topography is widespread beneath the Canadian breaks and adjacent areas (Fig. 40). Up to 1000 ft of solution-related regional surface subsidence, 25 to 60% of which may have occurred during Pleistocene time (Gustavson *et al.*, 1980, p. 9), has produced a steeper, more easterly slope to the High Plains north of the Canadian River and has markedly influenced the river's position.

The timing and areal extent of Canadian basin salt dissolution is contingent upon the nature and rate of groundwater movement. The chief source of fresh groundwater beneath the High Plains is the Ogallala aquifer, especially in areas like the Canadian breaks, which underlie coarse channel deposits (Shepherd and Owens, 1981, p. 89). In regions both within and marginal to the High Plains, fluvial sandstones of the Triassic upper Dockum Group are also conduits of fresh groundwater to adjacent salt beds (Gustavson *et al.*, 1980, p. 35). Downward water migration to Dockum Sandstone aquifers and salt horizons is inhibited in northwestern Oklahoma and northeastern New Mexico by overlying Cretaceous shale and clay (Myers, 1959, p. 66) and throughout the area of salt occurrence by impermeable lacustrine units within the Dockum Group (Gustavson *et al.*, 1980, p. 37). For this reason, regional fracture trends are probably important avenues of fresh water percolation and thus represent zones of accelerated dissolution (Fig. 50).

Both surface and sub-Ogallala topography also affect the pattern and rate of dissolution. Ogallala groundwater movement follows the eastward slope of the pre-Ogallala topography, except where it is focused toward drainage ways that have been incised into pre-Ogallala bedrock (North Plains Water District, 1965, p. 8). In the case of the south-flowing Canadian, incision has also isolated the Ogallala aquifer from possible recharge by streams draining the Rocky Mountains. Recharge is largely through downward percolation of local surface runoff. Groundwater within the Ogallala aquifer tends to flow over closed paleotopographic lows and across paleotopographic highs (*ibid.*, p. 12-13). Flowing fresh groundwater, the most efficient agent of subsurface dissolution, would be concentrated against paleodivides and along discrete Ogallala drainage courses. These areas would in turn be the most likely sites of both incipient and accelerated dissolution.

Independent but complementary views of the timing and rate of Pleistocene evaporite dissolution are supported by local products of solution collapse and by general estimates of horizontal dissolution rates. In southwestern Kansas and adjacent Oklahoma, the middle Pleistocene (Kansan) Meade Formation (Reeves, 1976a, p. 218) and correlative alluvial deposits in solution subsidence basins are more widespread and voluminous than deposits of similar origin laid down at other times during Pleistocene time (Frye and Leonard, 1965, p. 209). Coincidence of the most intense Pleistocene climatic reversal with pronounced solution collapse is also evident along the Canadian River, where solution collapse chimneys are associated with probable middle Pleistocene (Kansan) age terraces (Gustavson *et al.*, 1980, p. 33).

Estimated horizontal dissolution rates have a different time connotation than local evidence of solution collapse. Gustavson *et al.* (1980, p. 36) calculated average rates of dissolution front migration from annual solute loads of several streams draining the Llano Estacado. Solute loads for drainage over the present dissolution zone (Fig. 50) and within or adjacent to the Canadian breaks yield an average horizontal dissolution rate of 3.35 mi per million years. Walters (1977, p. 7) arrived at a rate of 2 to 4 mi per million years during the Pleistocene from a study of Permain salt dissolution in central Kansas. Walters' estimate derives from dated sediments filling a subparallel succession of basins that formed above a receding dissolution front. In the case of both calculations, too many indeterminant factors influence long term dissolution rates to permit more than rough estimates. With this in mind, dissolution fronts underlying the Canadian breaks have apparently receded only 6 to 12 mi since the beginning of the Pleistocene Epoch.

Pleistocene salt dissolution apparently triggered widespread vertical collapse without involving appreciable lateral migration of shallower dissolution fronts. Most regional subsidence evidently occurred during glacial episodes, when higher effective moisture would enhance infiltration and dissolution (Bachman, 1980, p. 96). Since shallow dissolution fronts had already receded from much of the region (Fig. 50), deeper salt horizons were involved in the process (Dutton *et al.*, 1979, p. 88; Gustavson *et al.*, 1980, p. 6; Fig. 51). Fresh groundwater percolation to deeper salts was enhanced by faulting in the Meade Basin and Canadian breaks (Fig. 50), and by more voluminous recharge beneath the Canadian channel (Gustavson *et al.*, 1980, p. 9). The combination of regional vertical solution subsidence and essentially stationary shallow dissolution fronts has important ramifications for the Pleistocene evolution of the Canadian breaks.

Evolution of the Canadian breaks

Ogallala sediment was transported and deposited across the Texas Panhandle through several alluvial channels and by various non-fluvial processes. The eventual product was a broad alluvial plain that was continuous with the terminal Ogallala surface farther west. The Texas Panhandle plain differed from its upslope counterpart in its greater depth to bedrock and in the extensive solution collapse of that bedrock.

Evaporite dissolution, which preceded and accompanied Ogallala sedimentation, undoubtedly slowed with a progressively declining late Pliocene water table (Frye and Leonard, 1957a, p. 5). Renewed solution activity probably accompanied heightened early Pleistocene groundwater recharge. This, combined with eastward Pliocene-Pleistocene epeirogenic tilting, strongly influenced the course of consequent drainage across the low relief terminal Ogallala alluvial surface. On the eastern Texas Panhandle plain, widespread vertical subsidence arising from deep salt dissolution evidently augmented tilting (Gustavson *et al.*, 1980, p. 9) and directed ancestral Canadian flow oblique to Ogallala drainage (Figs. 26, 40). Renewed collapse along shallow dissolution fronts more immediately controlled early Pleistocene Canadian channel development across the western Texas Panhandle and eastern New Mexico. The coincidence of modern Canadian channel position with shallow dissolution fronts in this area is evidence of a genetic relationship (Gustavson *et al.*, 1980, p. 5; Fig. 50).

Several factors favored development of an incised Canadian channel over shallow dissolution fronts. The late Pliocene position of the fronts—virtually the same as the modern position—probably defined a linear zone of collapse on the otherwise featureless terminal Ogallala surface. The fronts also partially coincide with pre-Ogallala bedrock highs (Fig. 40) and thus fresh groundwater flow would have been concentrated against them. Integration of an ancestral Canadian channel along the linear collapse sag would have further focused groundwater infiltration. In effect, establishment of the Canadian channel probably accelerated the process of dissolution and assured channel stabilization.

Excavation of the Canadian breaks after early Pliestocene channel stabilization is documented by samples collected from the Canadian valley near the New Mexico-Texas line. Gravels from Localities 90 through 94 are separable into two groups on the basis of lithology and physiographic setting. Two samples (Localities 90 and 91) represent alluvium capping an extensive erosion surface within the Canadian valley that is probably middle Pleistocene (Kansan) in age (Fig. 25, profile 5; Fig. 1, Localities O, P, and Q). Most of the alluvium appears to be Paleozoic limestone of upper Pecos provenance, rather than the product of reworking quartzose-rich Ogallala gravel (Localities 86 and 96). Two other samples (Localities 93 and 94) are of gravels on differing Canadian terrace levels 200 ft or more below the middle Pleistocene surface. The percentage of clastics at Localities 93 and 94 is less than that of Canadian terrace gravel at Locality 84, a few miles upstream of Ute Creek. Composition of the downstream gravels is attributed to an influx of quartzose gravel from Ute Creek, and to a lesser degree to erosion of locally exposed Triassic sandstone by the Canadian and lower Ute Creek. Gravel composition at Locality 92 is a mixture of the two groups, resulting from dissection of both middle Pleistocene and younger erosion surfaces south of the Canadian.

Several inferences can be drawn from Canadian breaks samples and their physiographic setting. The extensive middle Pleistocene (Kansan) erosion surface that apparently once spanned the width of the Canadian breaks in eastern New Mexico was probably cut by a large, through flowing river the upper reaches of which drained what is now the Pecos headwater region. Not only was the middle Pleistocene valley nearly as wide as the modern breaks, but relief between it and middle Pleistocene surfaces marginal to the breaks (Fig. 25, profile 5; Localities J and P) is roughly 600 ft. This is about half the depth to which the modern Canadian has incised itself below flanking Ogallala/middle Pleistocene uplands. The flood of quartzose gravel into the Canadian via Ute Creek evidently post-dates middle Pleistoçene (Kansan) excavation of the Canadian breaks. If Ute Creek was a tributary to the Canadian during middle Pleistocene time, it apparently entered the Canadian downstream from its present confluence (Fig. 45).

The middle to late Pleistocene history of the Canadian breaks is one of cyclic incision and alluviation. Erosion-surface evidence of these cycles is concealed beneath deep alluvial fill (Reed and Longnecker, 1932, p. 83; Evans and Meade, 1945, p. 500; Spiegel, 1972, p. 118; Fig. 25, profile 6). Most of the alluvium is derived locally from voluminous Ogallala sand and gravel concentrations (Localities 107 through 115). Redeposition of the sediment has been in response to climatically induced base level changes along the breaks and by upstream hydrologic and drainage changes (such as Pecos-Canadian piracy) within the Canadian system. More detailed appraisal of cyclic cutting and backfilling must await absolute dates from the alluvial fill.

DRAINAGE EVOLUTION OF THE OSAGE PLAINS

Controls on development of the Pleistocene drainage network

Pleistocene drainage of the Osage Plains has developed under conditions differing from those that controlled evolution of High Plains drainage to the west. The role of

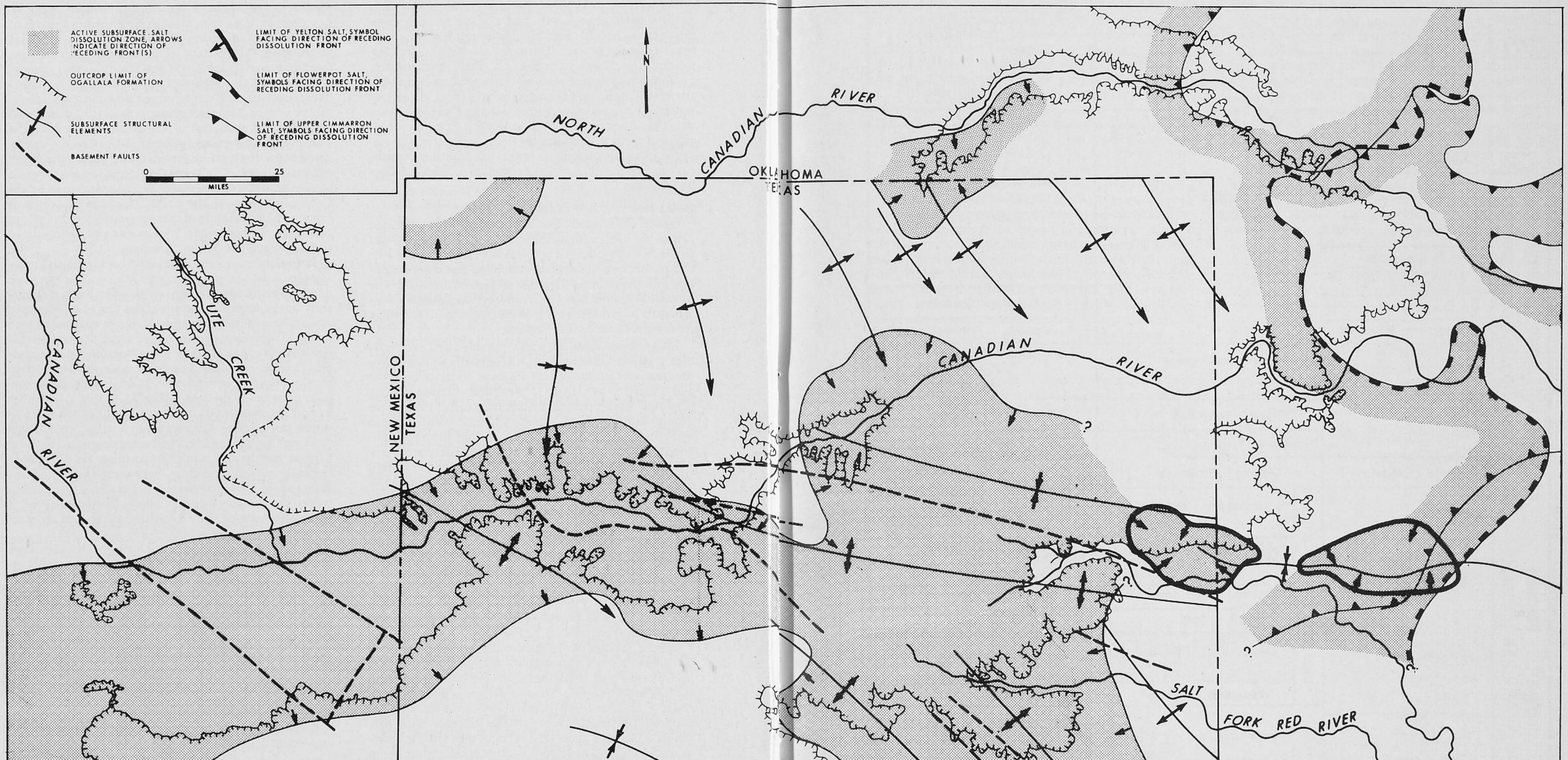


Fig. 50. Map of the Canadian breaks and High Plains border showing the relationship of subsurface structure and the modern fluvial landscape to the pattern of Permian evaporite dissolution. As is evident along the plains border, the stratigraphically highest salts have undergone the most extensive lateral (downdip) dissolution. Several south-plunging anticlines across the northern Texas Panhandle have focussed salt dissolution toward the Canadian Valley. Basement faults along the valley extend upward as fracture zones in overlying rocks. These fracture zones are probable conduits for fresh water percolation and may thus represent areas of accelerated dissolution. Sources: Dissolution zones—Foster et al., 1972, p. 10-12; Gustavson et al., 1980, p. 8; Jordan and Vosberg, 1963, Plate III; Morton, 1973. Structural elements—Gustavson et al., 1980, p. 3; Jordan and Vosberg, 1963, Plate III. Basement faults—Dutton et al., 1979, p. 12; Foster et al., 1972, p. 20.

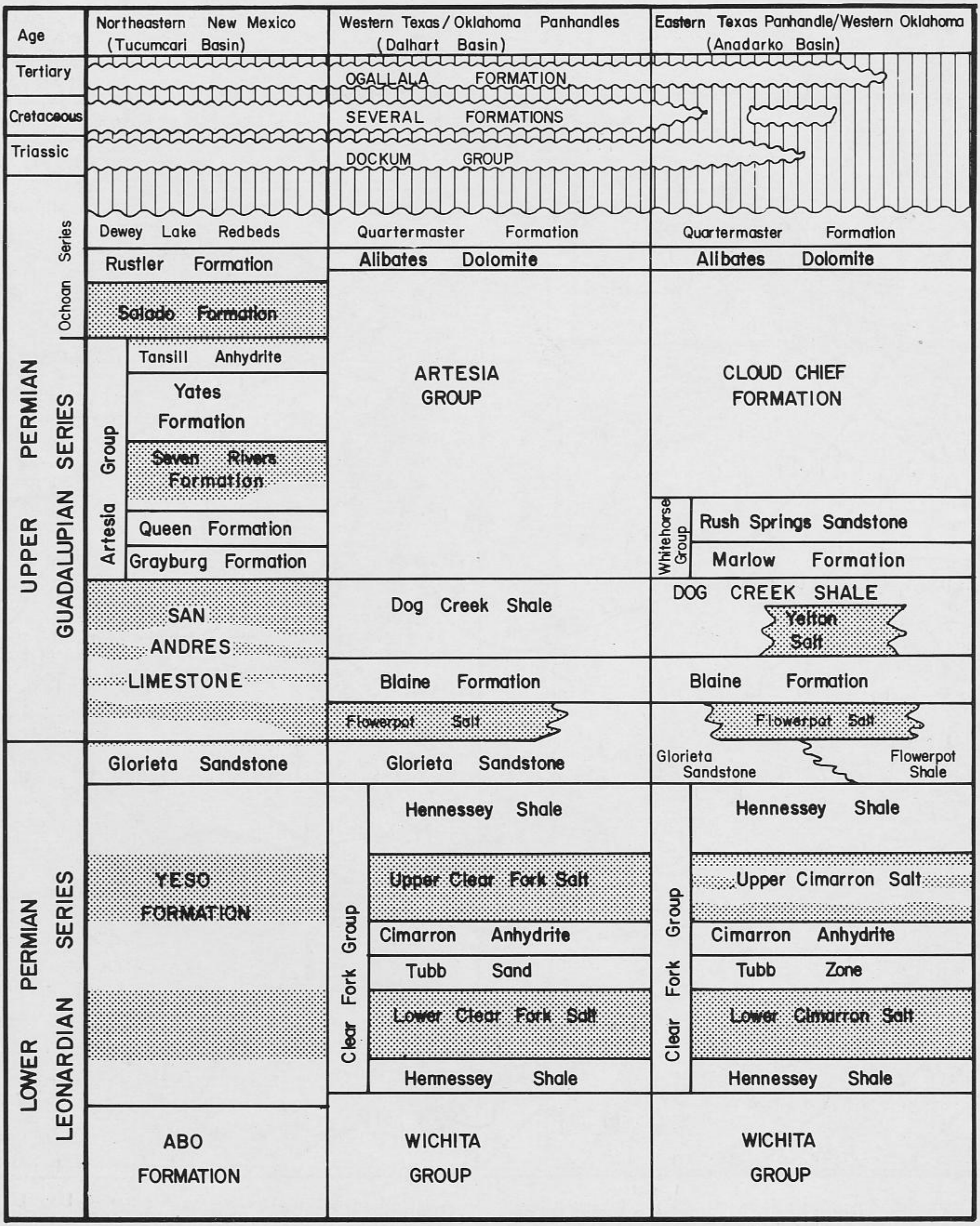


Fig. 51. Stratigraphic nomenclature chart of Permian and younger strata underlying the Canadian breaks. All salt horizons, with the exception of the Lower Clear Fork-Lower Cimarron salts, have undergone dissolution, which has resulted in regional surface subsidence. Salts above the upper Clear Fork-Upper Cimarron have receded along discrete dissolution fronts that have controlled development of the Canadian valley in northeastern New Mexico and the western Texas Panhandle. Adapted from McKee et al., 1967, Table 1; Gustavson et al., 1980, p. 4.

tectonism was reduced to subtly expressed eastward epeirogenic tilting. Permian evaporite dissolution locally influenced landscape and drainage morphology near the High Plains border (Fay, 1958, p. 58; Myers, 1960, p. 10; Meyers, 1962a, p. 13; Myers, 1962b, p. 174; Fig. 50), but its effects were negligible east of the modern limits of dissolution. Two large-scale events account for most widespread changes in Osage Plains drainage: 1) drainage superposition from an eastward-inclined Ogallala alluvial and erosional plain onto structurally deformed late Paleozoic sedimentary rocks and 2) cyclic Pleistocene climatic change.

Drainage superposition and network adjustment subsequent to structure are obvious from the relationship of modern drainage pattern to structure (Miser, 1954; Brown, 1967, p. 140). A record of the process of structural adjustment during the Pleistocene is recorded in the morphology and physiographic setting of gravel-capped terraces and other erosion surfaces. These landscape features also document the impact of Pleistocene climatic reversals on the Osage Plains fluvial system. The magnitude of climatic change and attendant altered hydrology was less than for semi-arid plains farther west. The pattern of change remained the same (Fig. 31) and significantly accelerated the development of subsequent drainage during discrete time intervals. This periodicity of fluvial response aids in deciphering the sequence of drainage events and their placement within an absolute time frame.

Dating of Pleistocene drainage events on the Osage Plains of Oklahoma is hampered by an absence of absolute age determinations. The situation will undoubtedly be remedied as the fission-track method is applied to volcanic ashes that are found in several fluvio-lacustrine sequences throughout the state (Ham and Burwell, 1949, p. 43). For the time being, ash occurrence alone remains useful as a reference point in dating fluvial system changes. Most ashes in the Canadian basin of Oklahoma are preserved in high terrace deposits. Vertebrate remains and molluscan fauna found in some of the deposits establish a Pleistocene age for them (*ibid.,* p. 8; Kitts, 1959, p. 15). The ashes are petrographically similar to those classified as "Pearlette"—previously thought to be a reliable late Kansan datum (Frye and Leonard, 1965, p. 207). Absolute dating of Pearlette-type ashes in southwestern Kansas has yielded ages ranging from about 0.6 to 2.0 million years B.P. (Boellstorff, 1976, p. 48). The most intense Pleistocene climatic reversal, the classic Kansan, occurred during this time span (Fig. 28). Relief between Pearlette ash-bearing high terraces and adjacent lower terrace levels along the Osage Plains Canadian is significantly greater than that between any other successive erosion surfaces (Kitts, 1959, p. 15; Fay *et al.,* 1962, p. 89; Alexander, 1965, p. 21). Thus Pearlette-type ash occurrence is apparently reliable evidence that high terrace deposition predates the waxing stages of initial middle Pleistocene glaciation.

Evolution of Osage Plains drainage

The Pleistocene drainage history of the Osage Plains, like that of areas farther west, follows termination of the Ogallala erosion cycle. The terminal Ogallala alluvial plain apparently changed character a short distance east of its present limits. High, probable pre-Pleistocene bed-

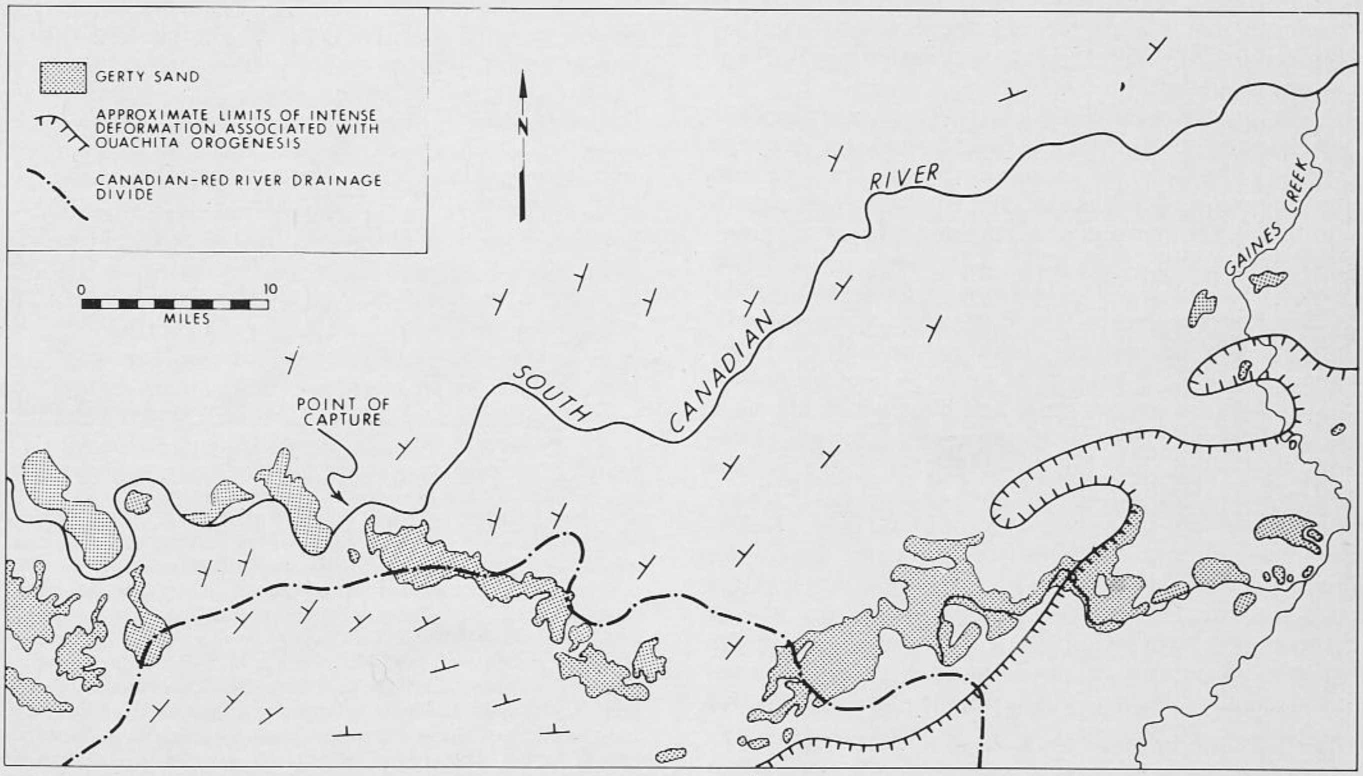


Fig. 52. Map showing the extent of Gerty Sand cover and its relationship to modern drainage pattern and regional bedrock structure. Gerty Sand trend defines a former channel of the South Canadian River. The paleochannel is presumably early Pleistocene in age, based upon contained Pearlette ash and landscape position (not the channel's trend relative to the Canadian-Red River divide). Early Pleistocene superposed trunk drainage was pirated by a headward migrating subsequent tributary, probably during waxing middle Pleistocene (Kansan) glacial climate. The sequence and timing of tributary capture is quite similar to that involving the meander-like bends of the Canadian farther upstream (Fig. 53). Adapted from Miser, 1954.

rock divides exist in western Oklahoma, some substantially above the projected base of the Ogallala (Fay, 1959, p. 6; Kitts, 1959, p. 24; Fay *et al.*, 1962, p. 94 and 99). Their presence suggests that the Ogallala had ceased to be a blanket deposit in the area. Intermittent Ogallala divide cover and/or channel fill must have extended much farther eastward, as evidenced by the widespread occurrence of gravel lag on some of the highest Osage Plains bedrock surfaces (Ries, 1954, p. 88; Weaver, 1954, p. 83; Kitts, 1959, p. 14; Markas, 1965, p. 37). In fact, many of these remnant surfaces may have been a part of an eastern erosional equivalent to the Ogallala alluvial plain, termed the "Pawhuska Rock Plain" (Ham, 1939, p. 36).

Initial post-Ogallala incision into the Ogallala alluvial/erosional plain probably accompanied eastward Pliocene-Pleistocene epeirogenic tilting and early Pleistocene climatic change (Fig. 43). The result of early incision was drainage network superposition onto structurally deformed late Paleozoic bedrock along the northeastern flank of the Anadarko basin, the west-dipping Central Oklahoma platform, and the Ouachita fold belt (Fig. 4). The level to which superposition proceeded is marked by the highest levels of Pleistocene terrace development. These high terraces are up to several hundred feet below bedrock/Ogallala-defended divides on the western Osage Plains (Kitts, 1959, p. 15; Howery, 1960, p. 50; Mogg *et al.*, 1960, p. 17-18; Fay *et al.*, 1962, p. 94), but are frequently coincident with regional drainage divides farther east (Webb, 1957, p. 35-37; Wood and Burton, 1968, p. 25). Widespread occurrence of Pearlette ash in fluvio-lacustrine deposits capping the highest Pleistocene terraces (Oakes and Knechtel, 1948, p. 63; Kitts, 1959, p. 15; Fay *et al.*, 1962, p. 89; Alexander, 1965, p. 21) is evidence that the degree of superposition that they represent was achieved prior to the onset of middle Pleistocene glaciation.

The time period preceding waxing middle Pleistocene glacial climate was evidently one of prolonged drainage stability and/or pronounced alluviation. Pearlette ash-bearing terrace deposits and their equivalents are significantly thicker than alluvium covering other erosion surface levels (Kitts, 1959, p. 15; Kitts, 1965, p. 16; Wood and Burton, 1968, p. 25). This may partially explain their widespread occurrence. The most conspicuous and well-preserved Pleistocene high-terrace remnant is the Gerty Sand. Gerty Sand consists of up to 50 ft of unconsolidated siliceous gravel, sand, and clay, which mantle a discontinuous eastward-sloping erosion surface (Hendricks, 1937, p. 365; Locality 119). The sand's sinuous 90-mi long trend defines a former channel of the Canadian River across the eastern Osage Plains (Fig. 52). The channel is evidently early Pleistocene in age, based upon reported Pearlette-type ash occurrences within it (Ham and Burwell, 1949, p. 43) and finer grained equivalents (Oakes and Knechtel, 1948, p. 63). The degree of the channel's preservation, in comparison to other Pleistocene fluvial deposits, is strong argument for a distinctive pre-middle Pleistocene episode of drainage stability/alluviation.

At least one student of the Osage Plains has observed that the advent of middle Pleistocene glaciation was accompanied by "radical changes in stream channels" (Fay, 1959, p. 11). The process of "radical change" involved lateral channel shift, stream incision, and headward tributary migration and piracy. All are events that were promoted by a shift toward Pleistocene full glacial conditions (Fig. 31). The net result of climatically induced drainage changes was to accelerate the process of network adjustment to late Paleozoic bedrock structure. Both process and results are exemplified by the case of the bends of the Canadian.

The Canadian River inscribes three huge meander-like bends as it crosses the High Plains-Osage Plains border (Fig. 8). The bends originated with drainage superposition from the eastward-inclined Ogallala plain onto generally southwest-dipping Permian bedrock (Harris, 1970, p. 95). Superposition has been followed by progressive

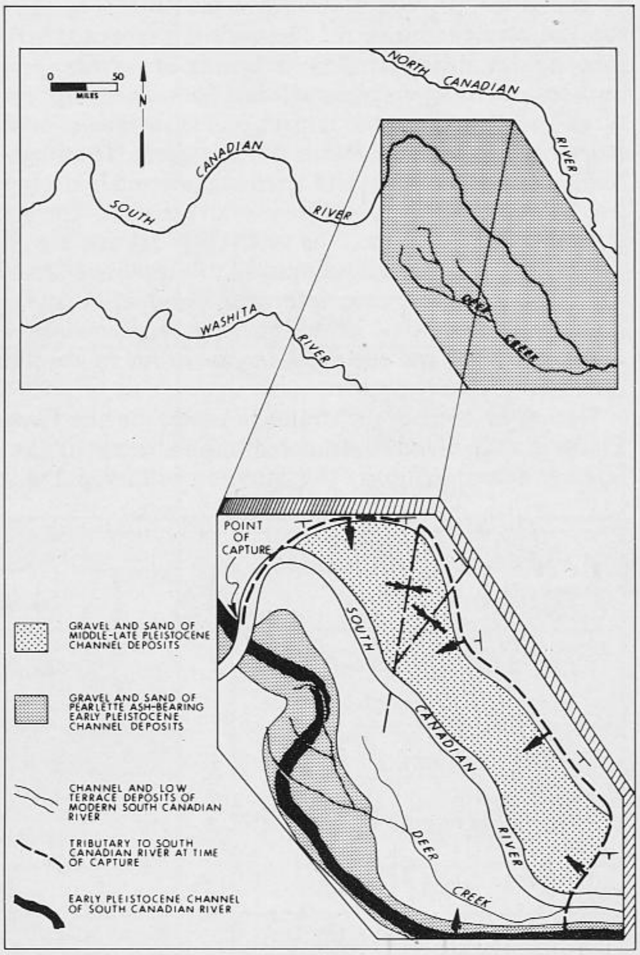


Fig. 53. Pleistocene deposits and paleodrainage map of the third meander-like bend of the South Canadian River. Arrows show the direction of channel shift after piracy. Prior to piracy (early Pleistocene), a tributary of the South Canadian trended east and southeastward, following the northeastern edge of a south-plunging syncline. The tributary joined the Canadian near the master stream's present confluence with Deer Creek. The pirating tributary worked headward along strike of the eastern and northern flank of the syncline and was accelerated by local solution collapse (Fay, 1959, p. 10). Piracy of the Canadian evidently occurred during waxing middle Pleistocene (Kansan) glaciation, assuming the Pearlette Ash-bearing terrace flanking the older Canadian channel is early Pleistocene in age. Diversion of the Canadian into its former tributary was followed by downdip (southeastward) lateral migration of the new master stream. This migration progessively accentuated curvature of the most downsteam meander-like bend of the Canadian. The abandoned channel of the South Canadian is now occupied by an underfit stream, Deer Creek. Adapted from Fay, 1959, p. 4 and 7.

downstream network adjustment to Permian structure. The bend farthest downstream not only exhibits the greatest degree of drainage subsequence, but bears the most complete record of its development (Fig. 53). The modern network evolved during waxing middle Pleistocene (Kansan) glaciation through a combination of headward tributary migration, stream piracy, and lateral channel shift. The timing and process of accelerated middle Pleistocene adjustment of superposed drainage to bedrock structure has been repeated to varying degrees throughout the Osage Plains (Fay, 1965, p. 91).

An extensive reach of the lower Canadian River assumed its present course in a manner similar to that of the meander-like bends. The sinuous ancestral Canadian course traced by the Gerty Sand was evidently abandoned during the onset of middle Pleistocene glaciation, judging from the sand's age and landscape position (Hendricks, 1937, p. 372; Tanner, 1956, p. 31). Abandonment resulted from piracy of the superposed ancestral Canadian by a former subsequent tributary of the same river, much the way it did farther west (Fay, 1959, p. 11; Figs. 52, 53).

The progressive development of subsequent drainage that advanced so rapidly during waxing middle Pleistocene (Kansan) glaciation has continued at a lesser pace to the present day. Probable climatic-induced cycles of accelerated drainage adjustment to structure are most evident in the physiographic setting of Pleistocene terrace deposits. On the western Osage Plains, terraces reflect the progressive downdip lateral shift of the Canadian and North Canadian Rivers (Fig. 54). Throughout the Osage Plains, formerly superposed trunk drainage continued to be modified by an ever-increasing number and length of low order subsequent tributaries.

CONCLUSIONS

1. Given the landscape scale and time span being considered, the Cenozoic history of the Canadian River basin is best depicted in terms of changing surface geology, landscape and drainage network morphology, climate/vegetation, and hydrology.
2. Drainage history of what is now the Canadian basin began with regression of the late Cretaceous epicontinental sea during early stages of Laramide tectonism. The rising San Luis Highland and other cratonic uplifts governed the pattern of continental emergence and early subaerial drainage. By early Eocene time, major river systems extended southeastward from the southern Rocky Mountains to the Gulf of Mexico. These rivers tended to avoid positive regional tectonic flexures and instead followed basin lows. Relative tectonic quiescence in late Eocene time favored development of an extensive erosion surface. The surface formed under a deep weathering regime promoted by a subtropical climate. Both sedimentologic and climatic regime changed dramatically during Oligocene time. Voluminous outpouring of volcaniclastic debris and a rapid shift to more continental climatic conditions induced widespread fluvial aggradation. Deposition was most pronounced along the montane border and Gulf Coastal portions of major southeast-trending drainage basins. Avenues of fluvial sediment transport within these Oligocene-Miocene basins were essentially those that had been established during Laramide tectonism.
3. Ogallala sediments and the topography that they obscure permit the earliest detailed reconstruction of the proto-Canadian basin. Most basal gravel of the Ogallala formation within the Canadian basin area was derived from the Sangre de Cristo Range of northern New Mexico. Specific lithologic constituents of Ogallala gravel indicate a sediment source in Precambrian quartzose and Paleozoic sedimentary bedrock, early Tertiary basin alluvial fill, and middle-late Tertiary volcanic and volcaniclastic cover. Basal Ogallala sedimentation was triggered by late Miocene-early Pliocene epeirogenic uplift and reverse faulting. Tectonism induced stripping of a coarse-grained alluvial covermass from a climatically modified Eocene erosion surface.
4. Initiation of the Ogallala erosion cycle evidently did not involve substantial reorientation of regional drainage. Most Ogallala sediment was transported from the mountains along a few entrenched stream-courses. These disparate alluvial channels trended east and southeastward across northeastern New Mexico. Ogallala drainage of the Texas Panhandle and adjacent portions of Oklahoma was largely directed into an irregular array of collapse depressions formed by subsurface dissolution of Permian evaporites. East of the zone of dissolution, early Ogallala streams probably again flowed through discrete fluvial valleys.
5. Basal Ogallala sedimentation marked the initial stage of progressive valley and basin alluviation. Finer grained fluvial, lacustrine, and eolian deposits subsequently filled fluvial valleys and collapse basins to the extent of producing a coalescent plain of alluviation. Development of the alluvial plain ended with formation of a caliche soil under conditions of increasing aridity and tectonic/erosional stability. Perennial drainage across the terminal Ogallala plain was probably restricted to a few consequent streams, the courses of which were relatively unconstrained by major bedrock topographic irregularities.
6. The systematic relationship between modern climate and hydrology permits hypothetical reconstruction of the Canadian fluvial system's hydrologic response to Pleistocene climate change. In general, waxing glacial climate is believed to have induced widespread alluviation in the montane headwaters of the Canadian River. Downstream, the same climatic change would have initiated stream entrenchment and headward extension, valley excavation and enlargement, and more frequent and pronounced

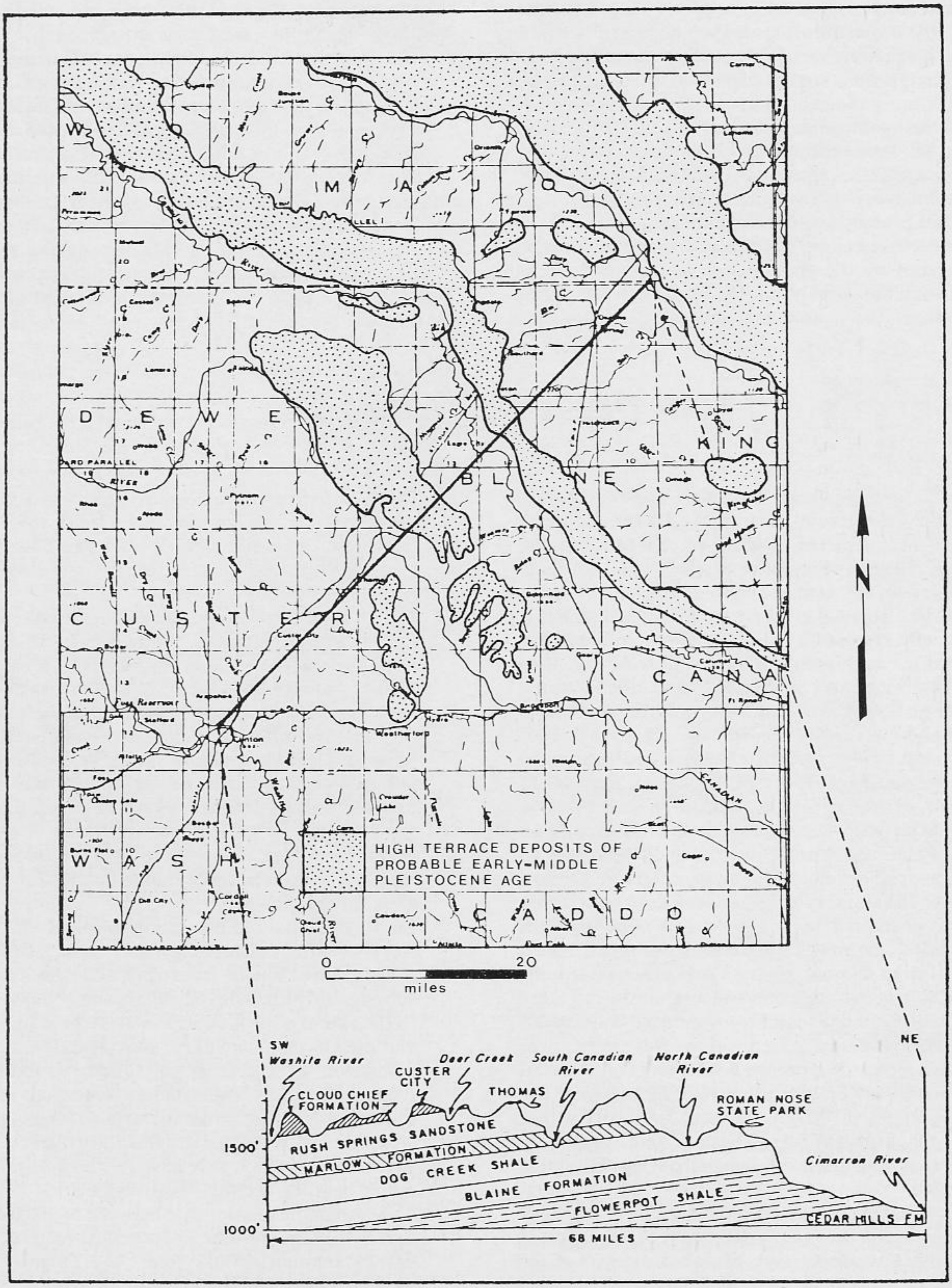


Fig. 54. Geologic cross-section across the western Osage Plains Canadian basin. Trunk drainage in this area consists of strike streams with courses that have migrated laterally downdip throughout much of the Pleistocene. Adapted from Miser, 1954; Fay, 1959, p. 5.

lateral channel migration. Waning glacial climate probably promoted flushing of sediment from montane alluvial basins and hastened valley alluviation on the plains to the east. As interglacial conditions became more established, the Canadian fluvial system entered a period of erosional stability.

7. Pre-Pleistocene (late Pliocene) physiography of the montane border of the Canadian basin is decipherable only for the region within and south of the Ocate volcanic field. Most of the Ocate region was a southeastward-inclined erosion surface during Pliocene time. The surface was drained by consequent trunk streams occupying essentially their modern positions. These major avenues of montane sediment transport headed in alluvial valleys that formed during pre-middle Pliocene fragmentation of the erosion surface. Trunk drainage exited the montane region through narrow breaches in the Creston. Sediment dispersal east of the Creston was onto a low relief piedmont alluvial plain. Late Pliocene modification of this system of fluvial transport was restricted to entrenchment caused by epeirogenic uplift.
8. Relict erosion surfaces and their physiographic setting indicate that Pleistocene drainage modification of the Canadian montane border was chiefly in response to cyclic climatic change and epeirogenic uplift. Montane border trunk streams, having already established their modern courses, underwent progressive and episodic entrenchment.
9. Streams draining the Raton-High Plains sections of the Canadian basin assumed essentially their modern courses during a relatively brief but eventful time interval spanning the Pliocene-Pleistocene boundary. Consequent drainage of the low-relief terminal Ogallala alluvial plain was susceptible to appreciable lateral diversion. Diversion intensified under the influence of late Pliocene epeirogenic tilting, upwarping, and basement fold and fracture rejuvenation. The upper Canadian plains drainage network changed dramatically as formerly consequent streams were reoriented subsequent to structure. The new drainage pattern rapidly stabilized as continued tectonism and the onset of early Pleistocene glaciation caused widespread entrenchment.
10. The drainage divide between eastward-flowing Raton Plateau-High Plains streams of the Arkansas and Canadian watersheds predates late Pliocene-early Plesitocene tectonism. Immediately north of the divide, tectonism and early Pleistocene climatic change caused entrenchment of the Cimarron River to near its present level. Entrenchment was far less pronounced along eastward- and southeastward-flowing Canadian tributaries between the Cimarron River and Ute Creek. These tributaries form a semiradial network that originated with late Pliocene rejuvenation of the Sierra Grande arch. Continued epeirogenic tilting and early Pleistocene climatic change caused stream incision sufficient to stabilize the network. Most changes in the fluvial landscape after network stabilization were confined to stream-valley deepening and widening brought on by middle-late Pleistocene climatic reversals.
11. The south-flowing Ute Creek and upper Canadian River established their anomalous courses in accordance with the pattern of late Pliocene epeirogenic uplift. Ute Creek followed essentially its modern course before the end of the Pliocene. The broad, deep valley of lower Ute Creek originated with late Pliocene regional uplift, but its present dimensions are largely the result of basin hydrologic changes during Pleistocene climatic reversals. Climate-related hydrologic shifts also indirectly affected Ute Creek by inducing downstream base level fluctuations along the east-flowing Canadian. Base-level change promoted Ute Creek entrenchment, lower Ute Creek alluviation, and possible piracy near the Ute Creek-Canadian confluence. The north-south reach of the upper Canadian paralleling the montane border probably evolved through headward (northward) migration and beheading of east-flowing montane drainage. Epeirogenic uplift, bedrock erosiveness, and pirated tributary discharge controlled the process, which was essentially completed by early Pleistocene time. At least 65% of south-flowing Canadian and Mora River entrenchment occurred during late Pliocene-early Pleistocene time. The causes of entrenchment coincided with those for Ute Creek. Tectonism was the major impetus to early (late Pliocene-early Pleistocene) incision. Climatically induced basin hydrologic changes and related downstream base level lowering were responsible for most Pleistocene entrenchment.
12. The montane headwaters of the Pecos River formerly flowed eastward into the Canadian River near where the latter inscribes a south-to-east right angle bend. The connection between fluvial systems existed at least as long ago as early Pleistocene time and persisted into the middle Pleistocene. Sometime during or shortly after middle Pleistocene time, the Pecos River incorporated its upper drainage through headward (northward) migration and capture of east-flowing montane drainage. The process was promoted by a gradient advantage of the lower Pecos, north-south structural alignment, and the integration of trains of solution collapse sinks. Besides producing the Canadian bend, Pecos-Canadian piracy probably also abruptly reduced discharge into the Canadian fluvial system. Such reduction may help explain downstream episodes of valley incision/excavation and alluviation.
13. Development of the broad east-west-trending Canadian valley began with the termination of the Ogallala erosion cycle, was promoted by Pliocene-Pleistocene tectonism, and accelerated during Pleistocene climate- and drainage-related hydrologic changes. However, the most important factor in the valley's evolution was subsurface dissolution of Permian evaporites. Since Pliocene time, several hundred feet of solution-related regional surface subsidence has produced a steeper, more easterly slope to the High Plains north of the Canadian River and has markedly influenced the river's position. The pattern and rate of dissolution were affected by 1) the nature and rate of groundwater movement and 2) surface and sub-Ogallala topography and structure. Subsurface salt dissolution accelerated with height-

ened groundwater recharge during early Pleistocene time. Solution apparently triggered widespread vertical collapse without involving appreciable lateral migration (only 6 to 12 mi) of shallow dissolution fronts. On the eastern Texas Panhandle plain, vertical solution subsidence augmented eastward epeirogenic tilting and redirected Canadian flow. Early Pleistocene Canadian channel development across the western Texas Panhandle and eastern New Mexico was more immediately controlled by renewed collapse along shallow dissolution fronts. Late Pliocene-early Pleistocene development of the river over the fronts was favored by low topographic relief and the concentration of groundwater flow along the zone of dissolution. By middle Pleistocene time, the Canadian valley was almost as wide and about half as deep as the modern breaks. The middle-late Pleistocene history of the Canadian breaks is one of cyclic incision and alluviation.

14. Most widespread changes in Osage Plains Canadian drainage during the Pleistocene are attributable to 1) drainage superposition from an eastward-inclined Ogallala alluvial and erosional plain onto structurally deformed late Paleozoic sedimentary rocks and 2) cyclic Pleistocene climatic change. The process of drainage network adjustment to late Paleozoic bedrock structure involved stream incision, lateral channel shift, and headward tributary migration and piracy. Progressive development of subsequent drainage proceeded most rapidly during waxing middle Pleistocene (Kansan) glaciation and has continued at a lesser pace to the present day.

APPENDIX A

SAMPLE LOCALITIES*

LOCALITY

1. (37°45′N, 105°04′W, Trinidad Sheet) Roadcut 100 yd west of Farisita, Colorado, on north side of Colorado Highway 69. Setting: Low terrace along Huerfano River consisting of reworked Eocene Farisita conglomerate. Description: Diverse gravel mostly metaquartzite, granite, and intermediate volcanics; subrounded to well rounded; maximum cobble observed: 60 cm.
2. (37°05′N, 105°19′W, Trinidad Sheet) Roadcut along San Francisco Creek approximately 2 mi southeast of Lavalley, Colorado. Setting: Exposed fault blocks of either Santa Fe Group or Vallejo Formation on west side of Culebra Range. Description: Diverse sample mostly leucogranite-granite gneiss, quartz diorite, quartz mica schist; subrounded to well rounded; maximum cobble diameter observed: 30 cm.
3. (36°58′N, 105°30′W, Raton Sheet) Roadcut on north side of New Mexico Highway 196 approximately 3 mi southeast of Costilla, New Mexico. Setting: Early Tertiary sediment(?) (McKinlay, 1956). Description: Sample of 15 cm lacustrine(?) limestone ledge in 7 m interval of alternating red shale and fine sandstone. Ledge dipping SE 30°.
4. (36°58′N, 105°30′W, Raton Sheet) Roadcut approximately 3.5 mi east of Costilla, New Mexico, on New Mexico Highway 196. Setting: Tuff of Amalia Formation overlain by Tertiary-Quaternary basalt and underlain by Precambrian rock. Description: Diverse sample mostly miscellaneous extrusives, pink-white granite-granite gneiss, quartzite gneiss; subrounded to rounded; maximum cobble diameter observed: 40 cm.
5. (36°54′N, 105°25′W, Raton Sheet) Streamcut approximately 5 mi southeast of Amalia, New Mexico, off New Mexico Highway 196 about 0.25 mi north of road. Setting: Semiconsolidated Tertiary gravel (McKinlay, 1956) overlain by Tertiary basalt(?) and underlain by Precambrian rock(?). Description: Representative sample (Appendix C); subangular to subrounded; maximum cobble diameter observed: 20 cm.
6. (36°54′N, 105°08′W, Raton Sheet) South and southeast sides of Adams Lake on Vermejo Ranch, New Mexico. Setting: Pediment gravel resting on Raton/Poison Canyon Formation with Ash Mountain Rhyolite and Vermejo Sandstone in close proximity. Description: Diverse sample mostly epidotitic metaquartzite, quartz, quartzite gneiss; subangular to subrounded; maximum cobble diameter observed: 1 m (rhyolite). Ledge of Raton/Poison Canyon a medium-coarse-grained arkose with clasts mostly quartz, gray metaquartzite; subangular to rounded; maximum cobble diameter observed: 5 cm.
7. (37°05′N, 105°02′W, Trinidad Sheet) Approximately 5 mi south of Stonewall, Colorado, in roadcut on road to Tercio, 0.5 mi north of Vallejos Creek. Setting: Streamcut approximately 50 ft above Vallejos Creek exposes gravelly alluvium on Barilla pediment equivalent developed on Cretaceous shale. Description: Representative sample (Appendix C); rounded to well rounded.
8. (37°03′N, 105°01′W, Trinidad Sheet) Off-road exposure approximately 1.5 mi south of Tercio townsite, approximately 10 mi south of Stonewall, Colorado. Setting: Two angular boulders of Raton conglomerate near top of Beshoar Pediment developed on Cretaceous shale exhumed near axis of Tercio Anticline. Description: Clasts in conglomerate mostly angular to subrounded milky quartz (some chalcedonic) and gray-black chert; maximum pebble diameter: 2 cm.
9. (36°54′N, 104°59′W, Raton Sheet) Off-road exposure approximately 2 mi east of Vermejo Park Headquarters on the north side of Vermejo River. Setting: First and second terrace level of Vermejo River developed on Vermejo/Trinidad Sandstone. Description: Representative sample (Appendix C); subrounded to rounded; maximum cobble diameter observed: 40 cm.
10. (37°13′N, 104°25′W, Trinidad Sheet) Gravel pit 0.5 mi west of the junction of U.S. Highway 160 and 350, east of Trinidad, Colorado. Setting: Approximately 40 ft of gravel at Nussbaum Formation with widely disseminated caliche cement. Description: Diverse gravel sample mostly metaquartzite and basalt; subrounded to rounded; maximum cobble diameter observed: 30 cm.
11. (36°56′N, 104°16′W, Raton Sheet) Off-road exposure approximately 5 mi east of Yankee, New Mexico, north of New Mexico 72 on the north-northwest edge of Johnson Mesa. Setting: At least 6 m of horizontal and cross-bedded sand and overlying massive gravel and sand on top of Tertiary basalt. Description: Representative sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 30 cm (basalt).
12. (36°54′N, 104°16′W, Raton Sheet) Off-road exposure 0.5 mi west of Towndrow Peak on Johnson Mesa, 6.5 mi southeast of Yankee, New Mexico. Setting: High quartzose gravel of Lee (1912) approximately 50+ ft thick, underlain and overlain by basalt. Description: Diverse gravel sample from caliche-cemented sand matrix; sand in places displays horizontal to low-angle festoon cross-bedding. Gravel dominantly metaquartzite, quartz diorite gneiss, intermediate volcanics; subrounded to rounded; maximum cobble diameter observed: 70 cm (dacite porphyry).
13. (36°56′N, 104°19′W, Raton Sheet) Off-road exposure below small basalt-capped butte approximately 0.5 mi south of Yankee, New Mexico, off New Mexico Highway 72. Setting: Gravel accumulating on and downhill from Quaternary basalt capping Cretaceous Vermejo/Trinidad Sandstone. Description: Diverse gravel mostly

*Conversion Factors: 1 in = 2.5 cm; 1 ft = 0.3 m; 1 yd = 0.9 m; 1 mi = 1.61 km.

metaquartzite, meta-arkose, and quartzite gneiss; rounded; maximum cobble diameter observed: 50 cm.

14. (36° 50'N, 104° 20'W, Raton Sheet) Roadcut approximately 7 mi southeast of Raton, New Mexico, on north side of U.S. Highway 64/87. Setting: Gravel on Beshoar surface developed on Pierre/Niobrara. Description: Diverse gravel from top of surface dominantly metaquartzite, basalt, and quartz mica schist: subangular to subrounded.
15. (36° 53'N, 104° 33'W, Raton Sheet) Off-road exposure approximately 9 mi west of junction of New Mexico 555 and I-25. Setting: Low (second?) terrace level of Canadian River developed on Vermejo or Raton Sandstone. Description: Diverse gravel collected from top of terrace level almost all locally derived sandstone; subrounded; maximum cobble diameter observed: 8 cm.
16. (36° 49'N, 104° 27'W, Raton Sheet) Roadcut approximately 3 mi south of Raton, New Mexico, on west side of I-25. Setting: Probable second terrace level of Canadian River developed on Pierre/Niobrara. Description: Diverse gravel from top of surface primarily fine-grained well indurated sandstone, orthoquartzite, and basalt; subrounded to rounded.
17. (36° 48'N, 105° 28'W, Raton Sheet) Crossing of Canadian River by U.S. Highway 85/64 about 8 mi south of Raton, New Mexico. Setting: Probable first terrace level on east side of Canadian River developed on Pierre/Niobrara. Description: Diverse gravel from surface consisting mostly of subangular orthoquartzite and siltstone.
18. (36° 48' N, 104° 28'N, Raton Sheet) Roadcut approximately ½ mi southwest of Locality 17 on southwest side of U.S. Highway 85/64 about 8.5 mi south of Raton, New Mexico. Setting: Probable second terrace level of Canadian River developed on Pierre/Niobrara. Description: Diverse gravel consisting mostly of subangular to subrounded fine sandstone and orthoquartzite.
19. (36° 40'N, 104° 33'W, Raton Sheet) Off-road exposure near crossing of Eagletail Ditch and U.S. Highway 85 about 5 mi south of junction with U.S. 64 south of Raton, New Mexico. Setting: Ditch cut in sediment developed on Pierre/Niobrara. Description: Diverse sample consisting mostly of quartz, metaquartzite, and orthoquartzite; rounded to well rounded.
20. (36° 41'N, 104° 35'W, Raton Sheet) Streamcut along Crow Creek at its crossing by U.S. Highway 64 approximately 11 mi northeast of Colfax, New Mexico. Setting: Sand from bank of Crow Creek. Description: Sand mostly medium to fine grained, angular to subangular quartz, rock fragments, coal, and mica flakes.
21. (36° 36'N, 104° 45'W, Raton Sheet) Vermejo River at its crossing by U.S. Highway 64 near townsite of Colfax, New Mexico. Setting: Second terrace level on south side of Vermejo River. Description: Representative sample of terrace gravel (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 10 cm.
22. (36° 36'N, 104° 45'W, Raton Sheet) Vermejo River at its crossing by U.S. Highway 64 near townsite of Colfax, New Mexico. Setting: Fourth terrace level on south side of Vermejo River developed on Pierre/Niobrara. Description: Sand and ant-bed sample; sand mostly medium to fine grained; subangular to subrounded quartz and rock fragments; coal notably absent.
23. (36° 30'N, 104° 34'W, Raton Sheet) Off-road exposure near crossing of Vermejo River by I-25 approximately 3 mi south of Maxwell, New Mexico. Setting: First terrace level on south side of Vermejo River developed on Pierre/Niobrara. Description: Diverse sample mostly sandstone, orthoquartzite, metaquartzite; subangular to rounded.
24. (36° 30'N, 104° 34'W, Raton Sheet) Off-road exposure approximately 0.5 mi north of Locality 23 on north side of Vermejo River near its crossing by I-25. Setting: Second terrace level on north side of Vermejo River developed on Pierre/Niobrara. Description: Diverse gravel mostly locally derived sandstone, some metaquartzite, granite; subrounded to rounded.
25. (36° 32'N, 104° 32'W, Raton Sheet) Roadcut 1 mi east of Maxwell, New Mexico on road to Chico. Setting: Second terrace level east of the Canadian River developed on Pierre/Niobrara. Description: Representative sample (Appendix C); subrounded to rounded; maximum cobble diameter observed: 20 cm for volcanics and 15 cm for quartzose cobbles.
26. (36° 32'N, 104° 27'W, Raton Sheet) Roadcut 4.5 mi east of Maxwell, New Mexico, on road to Chico. Setting: High pediment (third?) terrace level on east side of Canadian River developed on Pierre/Niobrara. Description: Diverse sample consisting mostly of metaquartzite, basalt, quartz mica schist; subrounded; maximum cobble diameter collected: 10 cm.
27. (36° 32'N, 104° 29'W, Raton Sheet) Roadcut approximately 8 mi east of Maxwell, New Mexico, on road to Chico. Setting: Pediment surface (Griggs, 1948) developed on Pierre/Niobrara. Description: Diverse gravel sample consisting of volcanics, monzonite porphyry, and slickenside from pediment surface; no quartzose clasts present; angular to subangular.
28. (36° 20'N, 104° 30'W, Raton Sheet) Canadian River at its crossing by New Mexico Highway 56 approximately 0.5 mi west-northwest of Taylor Springs. Setting: Second terrace level on west side of Canadian River developed on Graneros Shale. Description: Representative sample of terrace gravel (Appendix C); subrounded to well rounded; maximum cobble diameter collected: 20 cm for a cobble of dacite porphyry.
29. (36° 30'N, 104° 53'W, Raton Sheet) Roadcut approximately 3 mi east of Cimarron on New Mexico Highway 58. Setting: High terrace level on north side of Cimarron Creek. Description: Ant-bed sample consisting mostly of subangular to subrounded quartz, metaquartzite, igneous rock and shell fragments.
30. (36° 31'N, 104° 57'W, Raton Sheet) Roadcut about 4 mi west of Cimarron, New Mexico, on the north side of Highway 64, approximately 1 mi west of Philmont Scout Ranch boundary. Setting: Rayado Pediment along Cimarron Creek, consisting of about 2 m of gravel resting on Pierre/Niobrara. Description: Representative gravel sample (Appendix C); rounded to well rounded; maximum cobble diameter observed: 30 cm.
31. (36° 29'N, 104° 58'W, Raton Sheet) Off-road exposure approximately 0.5 mi northwest of Philmont Scout Ranch Headquarters off New Mexico Highway 21 on Horse Ridge. Setting: Cimarroncito Pediment cut in Pierre/Niobrara and covered by at least 6 m of gravel. Description: Diverse sample consisting mostly of pink-white granite, andesite, mafic schist and gneiss; subrounded to rounded; maximum cobble diameter observed: 50 cm.
32. (36° 27'N, 104° 58'W, Raton Sheet) Roadcut approximately 1.5 mi south-southwest of Philmont Scout Ranch Headquarters off New Mexico Highway 21. Setting: Philmont Pediment cut in Pierre/Niobrara and covered by approximately 6 m of gravel. Description: Representative gravel sample (Appendix C); subangular to subrounded.
33. (36° 25'N, 104° 58'W, Raton Sheet) Off-road exposure on east flank of Urraca Mesa about 10 mi south of Cimarron, New Mexico. Setting: Gravel from beneath basalt resting on Pierre/Niobrara (?) approximately 25-30 m from crest of mesa. Description: Diverse sample consisting mostly of quartz diorite gneiss, milky quartz and pink granite; subangular to subrounded; maximum cobble diameter observed: 25 cm.
34. (36° 20'N, 104° 54'W, Raton Sheet) Off-road exposure on north side of Ravado Mesa south of New Mexico Highway 199 and about 6 mi west of Miami, New Mexico. Setting: Quaternary basalt capping Pierre/Niobrara; gravel collected from beneath basalt. Description: Diverse sample consisting mostly of pink granite-granite gneiss, smoky-milky quartz; subangular to subrounded; maximum cobble diameter observed: 15 cm.
35. (36° 32'N, 105° 10'W, Raton Sheet) Roadcut approximately 7 mi east of Eagle Nest, New Mexico, on north side of U.S. Highway 64. Setting: First terrace of Cimarron Creek in vicinity of Precambrian and Tertiary intrusives. Description: Diverse sample consisting mostly of rhyolite (?) porphyry, medium-grained sandstone, hornfels; subangular to subrounded; maximum cobble diameter observed: 50 cm (sandstone).
36. (36° 33'N, 105° 19'W, Raton Sheet) Off-road exposure on low ridge along west side of Moreno Valley approximately 3 mi west of Eagle Nest, New Mexico. Setting: Downslope accumulation of debris on Dakota Formation from indurated Sangre de Cristo Formation conglomerate. Description: Diverse sample mostly metaquartzite and quartz; subangular to subrounded.
37. (36° 36'N, 105° 17'W, Raton Sheet) Gravel pit along Moreno Creek approximately 1 mi south of Elizabethtown townsite on west side of New Mexico Highway 38. Setting: Near east flank of Scully Mountain, a Tertiary intrusive; sample from quaternary alluvium of Moreno Valley floor. Description: Diverse sample consisting mostly of quartz mica schist, metaquartzite, pink granite, monzonite porphyry; subrounded to well rounded; maximum cobble diameter observed: 25 cm.
38. (36° 37'N, 105° 17'W, Raton Sheet) Gravel pit on east side of New Mexico Highway 38 at townsite of Elizabethtown, 7 mi north of Eagle Nest. Setting: Downslope gravel accumulating from first through third pediments of Ray and Smith (1941) on east side of

Moreno Valley. Description: Diverse sample consisting mostly of monzonite porphyry, metaquartzite, chert, orthoquartzite, trap; subangular to subrounded.

39. (36°40′N, 105°16′W, Raton Sheet) Off-road gravel-veneered surface on Mills Divide on Moreno Ranch east of New Mexico Highway 38, 11 mi north of Eagle Nest. Setting: Lag gravel on mid-Tertiary (?) surface. Description: Representative sample (Appendix C); subangular to well rounded; maximum cobble diameter observed: 15 cm.
40. (36°41′N, 105°22′W, Raton Sheet) Roadcut approximately 4 mi southeast of Red River, New Mexico near crest of Old Red River Pass. Setting: Indeterminant thickness of gravel veneering high, low-relief surface developed on Tertiary intrusives. Description: Diverse sample consisting mostly of leucogranite, magnetic quartz, mica schist, andesite porphyry, metaquartzite; subrounded to rounded; maximum cobble diameter observed: 40 cm.
41. (36°41′N, 105°25′W, Raton Sheet) Off-road exposure approximately 3 mi south of Red River, New Mexico, near small prospect above Placer Creek. Setting: Sparse lag gravel on high low-relief surface (mid-Tertiary?) developed on Tertiary volcanics overlying an undifferentiated Pennsylvanian and Precambrian rock. Description: Diverse sample consisting mostly of coarsely crystalline pink-white granite-granite gneiss, metaquartzite, and quartz; subrounded to rounded; maximum cobble diameter observed: 50 cm.
42. (36°42′N, 106°15′W, Aztec Sheet) Roadside exposure on north side of U.S. Highway 64 south of Brazos Peak and Brazos Box. Setting: Gravel-veneered high surface along crest of Nacimiento Uplift; area surrounded by outcrop of Precambrian metamorphics, Tertiary volcanics, and Carson Conglomerate. Description: Representative sample (Appendix C); subangular to rounded; maximum cobble diameter observed: 50 cm.
43. (36°41′N, 106°07′W, Aztec Sheet) Roadcut in Tusas River valley on north side of U.S. Highway 64, 11 mi west of Tres Piedras, New Mexico. Setting: 15 ft of presumed Carson Conglomerate consisting largely of interstratified tuff, tuffaceous conglomerate, and mudflow debris. Description: Diverse sample consisting mostly of basaltic-andesitic volcanics, chert; subrounded to rounded.
44. (36°24′N, 105°22′W, Raton Sheet) Roadcut on north side of U.S. Highway 64 on road to Eagle Nest, New Mexico, approximately 3.5 mi southwest of the crest of Palo Flechado Pass. Setting: Picuris Tuff on southeast side of Capulin Peak and just west of an exposure of Precambrian rock, surrounded by Pennsylvanian age strata. Description: Diverse sample consisting mostly of basalt-andesitic volcanics, some tuffaceous; subrounded to well rounded.
45. (36°12′N, 105°05′W, Raton Sheet) Roadcut approximately 3 mi northwest of Ocate on west side of New Mexico Highway 120. Setting: Bachman's Las Feveras Formation exposed beneath basalt in valley floored largely by Sangre de Cristo Formation. Description: Representative sample (Appendix C); subangular to subrounded; maximum cobble diameter observed: 20 cm.
46. (36°11′N, 105°14′W, Raton Sheet) Off-road exposure on basalt-capped butte east of Coyote Creek State Park campground off New Mexico Highway 38 about 5 mi north of Guadalupita. Setting: Quaternary basalt overlying undifferentiated Pennsylvanian sandstone, limestone and conglomerate, east of Rincon Range. Description: Diverse sample consisting mostly of fine-grained white to gray butte; subrounded to well rounded; maximum cobble diameter observed: 20 cm.
47. (36°11′N, 105°15′W, Raton Sheet) Roadcut approximately 0.25 mi north of entrance to Coyote Creek State Park on New Mexico Highway 38 about 5 mi north of Guadalupita. Setting: Low terrace of Coyote Creek on west side of road overlain by Quaternary basalt. Description: Representative sample (Appendix C); subangular to subrounded; maximum cobble diameter observed: 20 cm.
48. (36°05′N, 105°15′W, Raton Sheet) Bar ditch in broad alluvial valley just off New Mexico Highway 38 about 11 mi north of Mora. Setting: Sample from contact between Precambrian of Rincon Range and Quaternary alluvium of ancestral Coyote Creek valley. Description: Diverse sample consisting mostly of white-pink quartz mica schist, micaceous quartzite-granite gneiss, quartz; subangular to subrounded; maximum cobble diameter observed: 50 cm.
49. (36°00′N, 105°19′W, Santa Fe Sheet) Roadcut off New Mexico Highway 38 2.5 mi north of Mora. Setting: Precambrian-Quaternary alluvium flanking southeast edge of Rincon Range in ancestral Coyote Creek valley. Description: Diverse sample consisting mostly of white-pink quartz mica schist, micaceous granite gneiss, quartz; subangular to subrounded; maximum cobble diameter observed: 30 cm.
50. (35°57′N, 105°15′W, Santa Fe Sheet) Roadcut about 2 mi north of Rainsville on east side of New Mexico Highway 21. Setting: Quaternary/Tertiary pediment resting on Dakota Formation just east of the Creston. Description: Representative sample (Appendix C); subangular to subrounded; maximum cobble diameter observed: 1 m.
51. (35°59′N, 105°14′W, Santa Fe Sheet) Gravel pit along New Mexico Highway 21 approximately 1.25 mi north-northwest of Rainsville, New Mexico. Setting: Terrace resting on Dakota Sandstone just east of the Creston, near a breach in vertically dipping Dakota Sandstone. Description: Representative sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 50 cm.
52. (35°55′N, 105°15′W, Santa Fe Sheet) Roadcut approximately 3 mi south of La Cueva, New Mexico, on New Mexico Highway 3. Setting: About a meter of gravel atop Dakota Sandstone immediately east of areally extensive Precambrian outcrop. Description: Representative sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 20 cm.
53. (35°53′N, 105°12′W, Santa Fe Sheet) Roadside exposure along Mora River about 2 mi west of Golondrinas on New Mexico Highway 161. Setting: First terrace level along Mora River developed on Dakota or Greenhorn Limestone. Description: Diverse sample consisting mostly of smoky metaquartzite and quartz; rounded to well rounded.
54. (35°50′N, 105°04′W, Santa Fe Sheet) Roadside exposure approximately 0.5 mi west of Locality 55 (6.5 mi west of Watrous) on high (second or third) terrace level of Mora River on north side of Highway 161. Setting: High terrace level of Mora River developed on Dakota Sandstone. Description: Diverse sample consisting mostly of milky-gray metaquartzite, white-smoky metaquartzite gneiss; subrounded to well rounded; maximum cobble diameter observed: 60 cm.
55. (35° 50′N, 105°04′W, Santa Fe Sheet) Roadside exposure near unnamed ephemeral tributary of Mora River about 6 mi northwest of Watrous, New Mexico on south side of New Mexico Highway 161. Setting: High Mora River terrace consisting of at least 3 m of gravel capping a butte of Dakota/Greenhorn Limestone. Description: Diverse sample consisting mostly of gray metaquartzite, metaquartzite gneiss, microcrystalline limestone, quartz mica schist; rounded to well rounded; maximum cobble diameter observed: 60 cm.
56. (36°00′N, 104°43′W, Raton Sheet) Roadcut on east side of I-25 about 100 ft south of Wagon Mound exit. Setting: Sequence approximately 3 m thick consisting of cobble lag resting on Quaternary basalt; basalt underlain by cross-bedded and massively bedded sand and gravel, which in turn overlie Carlile Shale. Description: Representative sub-basalt gravel sample (Appendix C).
57. (36°05′N, 104°39′W, Raton Sheet) Roadside exposure approximately 1.7 mi east of Levy, New Mexico off I-25. Setting: Low relief undulating surface on Pierre/Niobrara just northwest of area mapped as Quaternary/Tertiary pediment gravel (Bachman and Dane, 1962). Description: Diverse sample of subrounded milky quartz.
58. (36°06′N, 104°15′W, Raton Sheet) Gravel pit on east side of New Mexico Highway 39, 8 mi south of Colfax County line, north of Roy, New Mexico. Setting: Ogallala overlying Carlile Shale (covered). Description: Representative gravel sample (Appendix C); subrounded to rounded; maximum cobble diameter observed: 20 cm for basalt and 15 cm for quartzose cobble.
59. (35°55′N, 104°21′W, Santa Fe Sheet) Roadcut on west side of Canadian River at its crossing by New Mexico Highway 120, west of Roy. Setting: First terrace level developed on Dakota Sandstone. Description: Representative gravel sample (Appendix C); subrounded to well rounded.
60. (35°55′N, 104°21′W, Santa Fe Sheet) Roadcut approximately 0.5 mi west of Canadian River on New Mexico Highway 120. Setting: Third (?) terrace level of Canadian River developed on Jurassic age sandstone. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter collected: 15 cm (dacite porphyry).
61. (35°43′N, 104°24′W, Santa Fe Sheet) Roadcut along Canadian River on east side of road about 0.5 mi north of Sabinoso, New Mexico. Setting: First terrace level of Canadian River just south of its confluence with Mora River: terrace is developed on Chinle Formation. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter

observed: 20+ cm.

62. (35° 40′N, 104° 23′W, Santa Fe Sheet) Roadcut approximately 3 mi south of Sabinoso, New Mexico, on Highway 56. Setting: Third terrace level of Canadian River developed on Chinle Formation. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 20 cm.
63. (35° 34′N, 104° 46′W, Santa Fe Sheet) Gravel pit approximately 6 mi northwest of Trujillo on west side of New Mexico Highway 65/104. Setting: Area of numerous shallow sinks developed on caliche-capped Dakota Sandstone surface of the Las Vegas Plateau. Description: Caliche sample yields insoluble residue of subangular to subrounded; fine to very fine-grained sand, silt and clay; most sand grains frosted.
64. (35° 44′N, 105° 15′W, Santa Fe Sheet) Roadcut approximately 7 mi north of Las Vegas on the west side of New Mexico Highway 3. Setting: Quaternary/Tertiary pediment gravel resting on Canadian-Pecos divide; pediment developed on Pierre/Niobrara. Description: Diverse sample consisting mostly of pink granite-granite gneiss, microcrystalline limestone, metaquartzite; subrounded; maximum cobble diameter observed; 15 cm.
65. (35° 37′N, 105° 14′W, Santa Fe Sheet) Gravel pit on top of unnamed butte about 0.5 mi west of New Mexico Highway 3, 1 mi north of Las Vegas. Setting: At least 10 meters of gravel overlying Camp Luna Surface (?) developed on Greenhorn Limestone/Graneros Shale. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 50 cm.
66. (35° 36′N, 105° 15′W, Santa Fe Sheet) Off-road exposure approximately 0.5 mi off New Mexico Highway 65 west of Las Vegas in gravel quarry above town. Setting: About 4 m of gravel exposed overlying Camp Luna Surface cut in Carlile Shale; eastward-dipping erosion surface abuts against Creston west of Las Vegas. Description: Diverse sample consisting mostly of quartz diorite gneiss, pink granite-granite gneiss, metaquartzite-meta-arkose, limestone; subrounded to well rounded; maximum cobble diameter observed: 50 cm.
67. (35° 36′N, 105° 28′W, Santa Fe Sheet) Roadcut approximately 0.5 mi east of Pecos River off I-25. Setting: Channel fill on second (?) Pecos terrace level cut into Sangre de Cristo Formation. Description: Representative sample (Appendix C) from top of terrace deposit in caliche-cemented gravel; subrounded to well rounded; maximum cobble diameter observed: 30 cm.
68. (35° 24′N, 105° 40′W, Santa Fe Sheet) Off-road exposure 7 mi south of Rowe, New Mexico, about 1.5 mi west of New Mexico Highway 34. Setting: Gravel veneering north-south-trending Dockum-defended ridge. Description: Diverse sample consisting mostly of microcrystalline limestone, diorite (?), pink granite-granite gneiss, metaquartzite; subangular to subrounded; maximum cobble diameter observed: 10 cm.
69. (35° 19′N, 105° 40′W, Santa Fe Sheet) Roadcut approximately 12 mi south of Rowe, New Mexico, off New Mexico Highway 34. Setting: Ridge of Dockum capped by coarse lag gravel. Description: Representative sample (Appendix C); subrounded to rounded; maximum cobble diameter observed: 15 cm.
70. (34° 57′N, 104° 36′W, Fort Sumner Sheet) Roadcut approximately 1.5 mi east of Santa Rosa on north side of New Mexico Highway 56. Setting: High gravel covered terrace level above east side of Pecos River cut into Chinle/Santa Rosa. Description: Diverse sample consisting mostly of pink granite, microcrystalline limestone, metaquartzite; rounded to well rounded; maximum cobble diameter collected: 10 cm.
71. (34° 57′N, 104° 34′W, Fort Sumner Sheet) Roadside exposure approximately 3 mi east of Santa Rosa at an abandoned stock pond along new Mexico Highway 156. Setting: Near western edge of pediment surface developed on Chinle (Bachman and Dane, 1962). Description: Indurated caliche-cemented gravel containing microcrystalline limestone (showing pisolitic structure), metaquartzite, chert, granite; subrounded; maximum pebble diameter observed: 6 cm.
72. (34° 57′N, 104° 28′W, Fort Sumner Sheet) Roadcut 9 mi east of Santa Rosa, New Mexico, on southern side of New Mexico Highway 156. Setting: High Pecos terrace (?) level cut into Chinle. Undulatory bedrock surface overlain by approximately 1 m of basal gravel grading upwards into at least 2 m of caliche-cemented sand and pebbles with interspersed cobbles. Description: Representative gravel sample (Appendix C); subangular to rounded; maximum cobble diameter observed: 15 cm.
73. (34° 57′N, 104° 25′W, Fort Sumner Sheet) Roadcut on north side of New Mexico Highway 156 approximately 15 mi east of Santa Rosa and 2.75 mi east of Locality 72. Setting: About 1 m of caliche-cemented rounded alluvial gravel overlying "pediment" surface (Bachman and Dane, 1962) cut in Chinle. Description: Representative gravel sample (Appendix C); maximum cobble diameter observed: 30 cm.
74. (35° 02′N, 104° 23′W, Santa Fe Sheet) Off-road exposure on top on unnamed mesa 1 mi east of Cuervo, New Mexico, and about 0.75 mi south of I-40. Setting: Approximately 2 m of reworked Chinle with disseminated caliche nodules overlain by approximately 5 m of caliche-cemented sand; base of sand contains gravel lenses. Description: Representative gravel sample (Appendix C); subangular to subrounded; maximum cobble diameter observed: 10 cm.
75. (35° 14′N, 104° 14′W, Santa Fe Sheet) Off-road exposure on top of Mesa Rica about 2 mi east of townsite of Isidore, east of New Mexico Highway 129. Setting: Less than 3 m veneer of caliche, mapped as Ogallala, (Bachman and Dane, 1962), overlying Dakota Formation at top of mesa. Description: Caliche contains pisolites of microcrystalline limestone, pebbles of limonitic sandstone and siltstone, and medium-fine subangular-subrounded quartz sand.
76. (35° 18′N, 104° 19′W, Santa Fe Sheet) Roadside exposure at crossing Cuervo Creek on north side of New Mexico Highway 104. Setting: Low gravel-covered terrace level along east side of Cuervo Creek cut into Chinle. Description: Representative gravel sample (Appendix C); subrounded to rounded; maximum cobble diameter observed: 10 cm.
77. (35° 19′N, 104° 24′W, Santa Fe Sheet) Off-road exposure approximately 7 mi south-southeast of Variadero about 0.25 mi northeast of New Mexico Highway 104. Setting: Caliche-cemented pea gravel-defended terrace level cut in Chinle above an unnamed ephemeral creek just north of Pino Creek. Description: Sample of limestone pebble conglomerate within the Chinle; clasts mostly quartzite and claystone-sandstone.
78. (35° 45′N, 103° 57′W, Tucumcari Sheet) Railroad cut approximately 3 mi south of Mosquero, New Mexico, on west side of right-of-way of abandoned Mosquero Branch of Southern Pacific Railroad. Setting: Southern edge of Ogallala 'outcrop' extending south from Mosquero on top of Dakota-capped Canadian escarpment. Description: Sample of caliche-cemented sand; sand comprised of medium to fine-grained, subangular to subrounded quartz grains.
79. (36° 18′N, 103° 56′W, Dalhart Sheet) Roadcut west of crossing of Ute Creek on south side of U.S. Highway 56 about 2.5 mi east of Gladstone, New Mexico. Setting: Gravel on first terrace level of Ute Creek, underlain by basalt, which in turn overlies the Ogallala Formation. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 25 cm for basalt and 15 cm for quartzose clast.
80. (36° 13′N, 103° 51′W, Dalhart Sheet) Roadcut on north side of New Mexico Highway 120, 1 mi east of its crossing of Ute Creek. Setting: Crest of valley edge of Ute Creek on Ogallala Formation; creek entrenched in Dakota Formation. Description: Diverse Ogallala gravel sample consisting mostly of metaquartzite, volcanics, metaquartzite gneiss; subrounded to well rounded; maximum cobble diameter observed: 15 cm.
81. (36° 00′N, 103° 51′W, Dalhart Sheet) Roadcut on south side of New Mexico Highway 102, 12.5 mi east of Bueyeros. Setting: Contact of Ogallala Formation and underlying Jurassic Morrison Formation. Description: Diverse gravel sample from over 5 m of cross-bedded Ogallala sand and gravel. Sample consists mostly of metaquartzite, metaquartzite gneiss, miscellaneous volcanics, and quartz mica schist; rounded to well rounded; maximum cobble diameter observed: 30 cm for basalt and 20 cm for quartzose cobble.
82. (35° 54′N, 103° 42′W, Tucumcari Sheet) Roadside exposure 5 mi north of junction of New Mexico Highway 65 and New Mexico Highway 102 on west side of New Mexico Highway 102. Setting: Quartzose pebbles interspersed with basalt debris at the toe of slope flanking basalt-capped butte. Quartzose gravel evidently channel lag of ancestral Ute Creek resting on Morrison and Santa Rosa Sandstone. Description: Diverse gravel sample consisting mostly of metaquartzite, quartz, subrounded to well rounded; maximum cobble diameter observed: 10 cm.
83. (35° 26′N, 103° 39′W, Tucumcari Sheet) Roadside exposure approximately 1 mi east of Blackwell Ranch on dirt road west of New Mexico Highway 39. Setting: Gravel-veneered ridge that is

roughly continuous to Gravel Hills on the north; trends approximately north-south, from 1 to 1.5 mi east of crossing of Carros Creek. Description: Representative gravel sample (Appendix C); subangular to well rounded.

84. (35° 18′N, 103° 57′W, Tucumcari Sheet) Roadside exposure approximately 17 mi west of Tucumcari on north side of New Mexico Highway 104. Setting: Low terrace level of Canadian River developed on San Rafael Group (?). Description: Representative gravel sample (Appendix C); rounded to well rounded.
85. (34° 55′N, 104° 04′W, Fort Sumner Sheet) Roadcut on northeast side of New Mexico Highway 156, 1 mi west of Ima. Setting: Less than 3 m of Ogallala calichified pack sand overlying Dakota Sandstone at edge of Caprock Escarpment. Description: No quartzose cobbles observed.
86. (34° 50′N, 103° 45′W, Clovis Sheet) Roadcut at Caprock Escarpment 0.25 mi north of Ragland on west side of New Mexico Highway 18. Setting: Dockum Formation overlain by 8 m of basal Ogallala gravel and sand, in turn overlain by an undetermined thickness of Ogallala sand and caliche. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter: 30 cm for tabular clast of micritic limestone.
87. (34° 55′N, 103° 27′W, Clovis Sheet) Roadcut on west side of New Mexico Highway 88 at edge of Caprock Escarpment approximately 7 mi southeast of Norton, New Mexico. Setting: Near contact between Ogallala Formation and underlying Chinle Formation. Gravel scattered in laminae throughout at least 20 m of exposed Ogallala sand. Description: Sparse diverse Ogallala cobble sample consisting mostly of pink, gray, white metaquartzite.
88. (34° 59′N, 103° 22′W, Clovis Sheet) Roadcut approximately 7 mi south of San Jon, New Mexico, on the west side of New Mexico Highway 39. Setting: Contact between Ogallala and underlying Dakota Sandstone at the edge of the Llano Estacado. Description: Sample of highly indurated calcite-silica-cemented quartz arenite; this is only material (besides pack sand) consisting basal Ogallala Formation.
89. (34° 57′N, 103° 06′W, Tucumcari Sheet) Roadcut on edge of Caprock Escarpment about 9.5 mi north of Bellview on west side of New Mexico Highway 93. Setting: Undetermined thickness of Ogallala Sand and gravel overlying Dockum (?) Formation. Description: Representative gravel sample (Appendix C); subrounded to rounded; maximum cobble diameter observed: 20 cm.
90. (35° 04′N, 103° 06′W, Tucumcari Sheet) Roadside exposure approximately 4 mi south of Endee on west side of New Mexico Highway 93 near its crossing of Arroyo del Puerto. Setting: Extensive dissected terrace surface with abraded limestone and quartzose gravel mapped as Quaternary alluvium and bolson deposits overlying Chinle (Bachman and Dane, 1962). Description: Representative gravel sample (Appendix C); subangular to rounded; maximum cobble diameter observed: 20 cm.
91. (35° 19′N, 103° 18′W, Tucumcari Sheet) Roadside exposure about 2 mi east of New Mexico Highway 39 and 5 mi southeast of Logan on east side of Tuscocoillo Creek.* Setting: Low terrace level above canyon on north side of pediment surface around Porter, New Mexico. Description: Representative gravel sample (Appendix C); subangular to rounded.
92. (35° 21′N, 103° 24′W, Tucumcari Sheet) Roadside exposure on west side of Revuelto Creek approximately 2 mi east of U.S. 54 on New Mexico Highway 39, about 2 mi south of where Revuelto Creek enters the Canadian River. Setting: Probable first terrace level on west side of Revuelto Creek, resting on southward-dipping Santa Rosa Sandstone. Description: Diverse sample consisting mostly of buff, gray, magnetitic-sericitic metaquartzite, microcrystalline limestone, chalcedonic quartz; subrounded to well rounded; maximum cobble diameter collected: 10 cm.
93. (35° 21′N, 103° 25′W, Tucumcari Sheet) Roadcut on south side of Canadian River about 0.75 mi south of Logan, New Mexico, on the east side of U.S. 54. Setting: Gravel-capped second terrace level of Canadian River cut into Santa Rosa Sandstone. Description: Representative gravel sample (Appendix C); subrounded to well rounded.
94. (35° 21′N, 103° 25′W, Tucumcari Sheet) Roadcut on north side of Canadian River about 0.5 mi south of Logan, New Mexico, along west side of U.S. 54/New Mexico 39. Setting: Gravel-capped third (?) terrace level on north side of Canadian River developed on Santa Rosa Sandstone. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 10 cm.
95. (35° 24′N, 103° 30′W, Tucumcari Sheet) Roadside exposure on east side of Ute Creek near its crossing by a gravel road 4 mi west of New Mexico Highway 39. Gravel road-highway intersection is 3 mi north-northwest of Logan, New Mexico. Setting: Gravel-capped second terrace level of Ute Creek cut in Chinle Formation; surface mapped as Quaternary/Tertiary pediment (Dane and Bachman, 1962). Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 30 cm (indurated sandstone flag).
96. (35° 31′N, 103° 15′W, Tucumcari Sheet) Roadside exposures in gravel pit on northwest side of U.S. Highway 54, 10.5 mi southwest of Nara Visa, New Mexico. Setting: At least 8 m of trough to planar cross-bedded Ogallala sand and gravel. Exposure is evidently near base of the Ogallala Formation. Description: Representative gravel sample (Appendix C); subrounded to rounded; maximum cobble diameter observed: 25 cm for a tabular sandstone clast.
97. (35° 36′N, 103° 07′W, Tucumcari Sheet) Roadcut on southeast side of U.S. Highway 54, 1.8 mi southwest of Nara Visa, New Mexico. Setting: At least 3 m of gravelly sand and sand overlain by 3 m of gravel. The entire sequence is underlain by an indeterminant thickness of clean quartz and presumed to be Ogallala Formation (Trauger, *et al.*, 1972). Description: Diverse gravel sample consisting mostly of metaquartzite, granite, metaquartzite gneiss, miscellaneous volcanics; rounded to well rounded; maximum cobble diameter observed: 20 cm.
98. (36° 05′N, 103° 12′W, Dalhart Sheet) Roadcut approximately 0.25 mi north of Tramperos Creek at its crossing by New Mexico Highway 18. Setting: Terrace level of Tramperos Creek; stream has cut through Ogallala into underlying Dakota Formation. Description: Diverse gravel sample consisting mostly of metaquartzite, sandstone, basalt, quartz mica schist; subrounded to well rounded; maximum cobble diameter observed: 60 cm for subrounded sandstone cobble and 15 cm for quartzose cobble.
99. (36° 15′N, 103° 11′W, Dalhart Sheet) Roadcut at crossing of Carrizo Creek by New Mexico Highway 18, 13.5 mi south of Clayton. Setting: Gravel-capped first terrace level of Carrizo Creek; stream has cut through Ogallala into underlying Dakota Formation. Description: Diverse gravel sample consisting mostly of metaquartzite, metaquartzite gneiss, sandstone, volcanics; subrounded to well rounded; maximum cobble diameter observed: 30 cm for basalt and 20 cm for quartzose cobble.
100. (36° 21′N, 103° 28′W, Dalhart Sheet) Roadcut on southwest side of Carrizo Creek at its crossing by U.S. Highway 56, approximately 17.5 mi southwest of Clayton, New Mexico. Setting: Apparent first terrace level on Carrizo Creek; stream has cut through Ogallala into Dakota Formation. Description: Diverse terrace gravel sample consisting mostly of metaquartzite, orthoquartzite, basalt, metaquartzite gneiss; subrounded to well rounded; maximum cobble diameter observed: 20 cm.
101. (36° 35′N, 103° 08′W, Dalhart Sheet) Roadside exposure on north side of Cienequilla Creek near its crossing by New Mexico Highway 18, 3.5 mi south of Seneca. Setting: Sparse quartzose and basalt gravel-veneered hill on Ogallala Formation. Description: Diverse gravel sample consisting mostly of basalt-andesite, metaquartzite; subrounded to rounded; maximum cobble diameter observed: 25 cm.
102. (36° 40′N, 103° 04′W, Dalhart Sheet) Roadside exposure approximately 2 mi south of crossing of North Canadian River by New Mexico Highway 18. Setting: Sample from Ogallala (?) on rise before descent into North Canadian valley, Ogallala overlies Greenhorn Limestone/Graneros Shale and Dakota (?) Formation. Description: Diverse gravel sample consisting mostly of basaltic-andesitic volcanics, metaquartzite, metaquartzite gneiss; subrounded to rounded; maximum cobble diameter observed: 20 cm.
103. (36° 42′N, 103° 04′W, Dalhart Sheet) Roadside exposure on south side of North Canadian River at its crossing by New Mexico Highway 18. Setting: Two terrace levels along river, both cut into Dakota Sandstone. Both terrace levels veneered with gravel predominantly composed of sandstone. Description: Ant-bed sample

*The name of this creek is spelled here as shown on USGS topographic map 1:250,000 Tucumcari Sheet. Spelling given in Pearce, 1965, is Tuscococillo.

collected from second terrace level.

104. (36°47′N, 103°23′W, Dalhart Sheet) Roadside exposure approximately 5 mi southeast of Guy townsite along New Mexico Highway 370. Setting: Ogallala Formation overlying Greenhorn Limestone/Graneros Shale (?). Description: Diverse sample consisting mostly of volcanics, metaquartzite, metaquartzite gneiss, granite; subrounded to well rounded; maximum cobble diameter observed: 25 cm for quartzose clast.

105. (36°59′N, 103°24′W, Dalhart Sheet) South side of Cimarron River at its crossing by New Mexico Highway 325, 4.5 mi east of its junction with New Mexico Highway 370. Setting: Low second (?) terrace level on Cimarron River, developed on Triassic redbeds. Description: Diverse sample consisting mostly of metaquartzite, metaquartzite gneiss, orthoquartzite, quartz mica schist; quartzose fraction subrounded to well rounded. Most terrace gravel is basalt or sandstone.

106. (36°57′N, 102°57′W, Dalhart Sheet) Roadside exposure along west side of Oklahoma Highway 18, 4.5 mi north of Kenton, Oklahoma. Setting: Sparse quartzose gravel from toe of colluvial slope at base of eastern limit of Black Mesa. Ogallala Formation mapped as cropping out beneath basalt capping Black Mesa (Miser, 1954). Description: Diverse gravel sample consisting mostly of metaquartzite; subangular to subrounded; maximum cobble diameter observed: 10 cm.

107. (35°15′N, 102°47′W, Tucumcari Sheet) Off-road exposure south of I-40 along Agua de Piedra Creek, 5 mi west of Adrian, Texas. Setting: Western edge of Caprock Escarpment exposing contact between the Ogallala Formation and underlying Triassic Dockum Group. Description: Diverse gravel sample consisting mostly of buff, white, gray and black metaquartzite and chert; subangular to well rounded; maximum cobble diameter observed: 15 cm.

108. (35°24′N, 102°20′W, Tucumcari Sheet) Texas Sand and Gravel, Inc. gravel quarry , 2 mi west of Highway 385 and about 12 mi north of Vega, Texas. Setting: Exposure of at least 7 m (base not seen) of basal Ogallala gravel. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 20 cm.

109. (35°28′N, 102°15′W, Tucumcari Sheet) Roadcut on west side of U.S. Highway 385, 3 mi south of its crossing of the Canadian River. Setting: High rise closest to Canadian River; high terrace level of Canadian. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 20 cm.

110. (35°32′N, 102°16′W, Tucumcari Sheet) Roadcut at Old Tascosa, Texas townsite on north side of Canadian at its crossing by U.S. Highway 385. Setting: High terrace level of Canadian River with at least 25 ft of braided stream terrace gravel exposed on top of Dockum redbeds. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 7 cm.

111. (35°36′N, 102°18′W, Tucumcari Sheet) Roadcut approximately 6 mi north of Cal Farley's Boys Ranch on west side of U.S. Highway 385/87 on divide above East Cheyenne Creek. Setting: Gravel-capped high terrace level of Canadian River cut by Cheyenne Creek, an ephemeral southward-flowing tributary; terrace developed on Dockum redbeds. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 7 cm.

112. (35°15′N, 102°04′W, Tucumcari Sheet) Gravel pit on west side of Texas FM 2381, approximately 5 mi north of Bushland, Texas. Setting: About 3 m of basal Ogallala gravel exposed overlying Dockum redbeds. Description: Diverse gravel sample consisting mostly of metaquartzite, metaquartzite gneiss, microcrystalline limestone; subrounded to well rounded; maximum cobble diameter observed: 20 cm.

113. (35°18′N, 101°50′W, Amarillo Sheet) Burrow pit on east side of U.S. Highway 285, 5 mi north of Amarillo, Texas city limits. Setting: Highest promontory before descent into Canadian River valley, supporting undetermined thickness of Ogallala or reworked Ogallala high terrace gravel. Description: Representative gravel sample (Appendix C); subrounded to well rounded; maximum cobble diameter observed: 15 cm.

114. (35°44′N, 101°39′W, Amarillo Sheet) Roadside exposures along Texas FM 1913, 20 airline mi southeast of Dumas, Texas, on the north side of Blue Creek. Setting: Sample 114a is from east roadside exposure of Ogallala gravel lag resting on 8+ m of horizontal to low-angle cross-bedded, medium to coarse-grained Ogallala sand. Entire Ogallala sequence overlies Permian age redbeds. Sample 114b is gravel from cut on west side of road exposing gravel-filled channel cut into Ogallala sand. Description: Representative gravel samples from localities of 114a and 114b (Appendix C); subangular to rounded; maximum cobble diameter observed: 20 cm.

115. (35°46′N, 101°21′W, Amarillo Sheet) Roadside exposure on bluff on north side of Texas FM 2277 and Canadian River, 4 mi downstream of its crossing by State Highway 15/152. Setting: At least 10 m of planar to festoon cross-bedded, medium to coarse-grained sand capped by a gravel log. Sequence is either lower Ogallala Formation or reworked Ogallala terrace material near its contact (not exposed) with underlying Permian Quartermaster Formation. Description: Diverse gravel sample consisting mostly of metaquartzite, gneiss, and volcanics; subrounded to rounded; maximum cobble diameter observed: 20 cm (dacite porphyry).

116. (36°44′N, 101°38′W, Perryton Sheet) Roadcut on unnumbered paved road to Goodwell, Oklahoma, 3 mi south of U.S. Highway 64. Setting: One to 1.5 m sequence of indurated coarse basal Ogallala sandstone/pebble conglomerate overlying Dakota Sandstone. Description: Conglomerate dominantly caliche-cemented coarse to very coarse-grained sand comprised of subangular to subrounded quartz and friable to well indurated limonitic sandstone with lesser amounts of chert, metaquartzite, magnetite, feldspar, and volcanics; maximum pebble diameter collected: 4 cm (basalt and limonitic sandstone).

117. (36°37′N, 99°56′W, Woodward Sheet) Roadcut on south side of U.S. Highway 270/Oklahoma Highway 3, 2 mi west of its junction with U.S. Highway 283. Locality is 6 airline mi southwest of Laverne, Oklahoma. Setting: One and 1.5 m exposure of Laverne Formation consisting of friable, medium to coarse-grained, horizontally bedded sand. Upper 40 cm is limonitic. Pebbles sparsely distributed throughout, many along apparent horizontal laminae. Description: Representative pebble sample (Appendix C) and diverse pebble sample collected. Diverse sample consists mostly of hematitic fine-grained sandstone, gray-white quartz-metaquartzite, and buff microcrystalline limestone; subangular to subrounded; maximum pebble diameter observed: 5 cm.

118. (36°08′N, 99°16′W, Woodward Sheet) Roadside exposure on east side of Oklahoma Highway 34, 1.25 mi south of Vici, Oklahoma. Setting: At least 12 m of Ogallala sand exposed in roadside draw. Basal contact covered. Gravel not found in place but collected from downslope accumulations along upper 3 to 4 m of exposure. Description: Representative gravel sample (Appendix C); subrounded to rounded; maximum cobble diameter observed: 10 cm.

119. (34°54′N, 96°58′W, Ardmore Sheet) Roadside exposure on east side of U.S. Highway 177, 7 mi south of Asher, Oklahoma. Setting: High surface south of Canadian River capped by undetermined thickness of red clayey sand containing scattered quartzose pebbles and cobbles. Surface veneer mapped as Gerty sand (Miser, 1954). Description: Diverse gravel sample consisting mostly of white, buff, and gray fine-grained metaquartzite; subangular to subrounded; maximum cobble diameter observed: 10 cm.

APPENDIX B

LITERATURE LOCALITIES

Locality

Sediments of most of the following literature localities are middle Pleistocene (Kansan) in age. Dating is based upon paleosoil and alluvial stratigraphy and physiographic setting.

A. (36° 35′N, 103° 22′W, Dalhart Sheet) Region surrounding T27N, R33E, Section 12 on Rabbit Ear Mesa is an inlier of the Ogallala Formation that is surrounded by Clayton Basalt. The surface of the inlier is covered with gravel derived from the Precambrian core of the Sangre de Cristo Range, but no outcrops or clasts of basalt are found in the area (Baldwin and Muehlberger, 1949, p. 74).

B. (35° 56′N, 104° 23′W, Santa Fe Sheet) Undescribed middle Pleistocene (Kansan) sample locality in T20N, R24E, Section NW¼ (Frye *et al.*, 1978, p. 27).

C. (36° 02′N, 104° 00′W, Dalhart Sheet) Mitchel West Section of Frye *et al.* (p. 27 and 32) (T21N, R28E, Section 19, NW SW: Roadcuts along New Mexico Highway 120). 9.5 ft of late Pleistocene (Wisconsinan) sand and silt overlies 15.5 ft of middle Pleistocene (Illinoian and Kansan?) sand and silt containing two buried soils.

D. (36° 03′N. 104° 00′W, Dalhart Sheet) Martinez West Section of Frye *et al.* (p. 14 and 27) (T21N, R28E, Section 18, NW SE: Roadcuts along New Mexico Highway 120). Early to middle Pleistocene age basin deposits are approximately 45 ft thick and consist mostly of clayey sand.

E. (36° 03′N, 103° 58′W, Dalhart Sheet) Martinez Section of Frye *et al.* (p. 14 and 27) (T21N, R28E, Section 17, NE SE). Middle Pleistocene (Kansan) sand, silt, and clay contains at least one buried soil.

F. (36° 18′N, 103° 58′W, Dalhart Sheet) Several wells in the vicinity of Gladstone, New Mexico (T24N, R28E) reportedly encountered basalt of depths of between 20 and 67 ft beneath 'upland deposits.' The basalt is believed to be continuous with that cropping out along the west side of Ute Creek canyon, southeast of Gladstone (Baldwin and Muehlberger, 1959, p. 74-75).

G. (36° 00′N, 103° 37′W, Tucumcari Sheet) Undescribed middle Pleistocene (Kansan) sample locality in T20N, R31S, Section 2, NW¼ (Frye *et al.*, 1978, p. 27).

H. (36° 10′ N, 103° 18′W, Dalhart Sheet) Pinabetitos Creek Section of Frye *et al.* (p. 27 and 32) (T22N, R34E, Section 4, SE NE: Roadcut and creek bank). Late Pleistocene (Wisconsinan) lowest terrace is overlain by 3 ft of gravelly sand. Middle Pleistocene (Kansan?) higher terrace is covered with 8 ft of gravel and sand fining upward to clayey sand.

I. (36° 18′N, 103° 09′W, Dalhart Sheet) Several wells drilled south of Clayton, New Mexico in T24N, R36E, Section 19 and adjacent sections penetrated basalt beneath from 20 to 40 ft of 'Ogallala-like' material (Baldwin and Muehlberger, 1959, p. 74).

J. (35° 52′N, 103° 18′W, Tucumcari Sheet) Hayden South Section of Frye *et al.* (1978, p. 15 and 27) (T19N, R34E, Section 22, NE NW: Gullies adjacent to road). 'Typical' middle Pleistocene (Kansan) deposits; 25 ft of sand, caliche cemented at top, overlie about 27 ft of partially calichified gravelly to clayey sand.

K. (35° 21′N, 103° 14′W, Tucumcari Sheet) Sand Springs Station Northeast Section of Frye *et al.* (p. 13) (T15N, R35E, Section 20 SE SE). An area of remnant deposits is situated physiographically below undissected Ogallala upland and topographically above extensive Kansan age deposits. Deposits are considered to be early Pleistocene (Nebraskan) in age based upon stratigraphic position. They consist of coarse channel gravels that grade upward into alternating sand and gravel containing clasts of Ogallala caliche-cemented sand. The sequence is capped by a deep pedocal soil. These remnant deposits may mark the position of an ancestral Canadian River. Clay mineral composition at this locality is distinctly different than that of older Ogallala and younger Pleistocene age deposits and indicates a detrital source to the west (*ibid.*, p. 14).

L. (35° 24′N, 103° 23′W, Tucumcari Sheet) Logan Northeast Section of Frye *et al.* (p. 27 and 31) T14N, R33E, Section 36, NE SE: Railroad cut). 4 ft of late Pleistocene (Wisconsinan) age sand overlie 5.2 ft of middle Pleistocene (Illinoian and/or Kansan) age sand and silt containing two paleosoils. This interval overlies 3 ft of caliche-cemented sand, which in turn caps a 5-ft sequence of gravel and sand. Clasts are evidently reworked Ogallala Formation and include pebbles and cobbles of Ogallala-type caliche. The gravel and sand rest on Triassic sandstone.

M. (35° 24′N, 103° 32′W, Tucumcari Sheet) Undescribed middle Pleistocene (Kansan) sample locality in T14N, R32E, Section 33, SE¼ (Frye *et al.*, p. 27).

N. (35° 24′N, 103° 34′W, Tucumcari Sheet) Undescribed middle Pleistocene (Kansan) sample locality in T14N, R32E, Section 32, NW¼ (Frye *et al.*, p. 27) .

O. (35° 18′N, 103° 37′W, Tucumcari Sheet) Undescribed middle Pleistocene (Kansan) sample locality in T12N, R31E, Section 2, NE NE (Frye *et al.*, p. 27).

P. (35° 10′N, 103° 16′W, Tucumcari Sheet) Undescribed middle Pleistocene (Kansan) sample locality in T11N, R35E, Section 18, SW SW (Frye *et al.*, p. 27).

Q. (35° 13′N, 103° 37′W, Tucumcari Sheet) Adberg Station Section of Frye *et al.* (p. 27 and 31) (T11N, R30E, Section 35, SW¼: Railroad cuts). 9 ft of middle Pleistocene (Kansan) gravelly sand contain a buried (?) soil.

R. (35° 12′N, 103° 44′W, Tucumcari Sheet) Tucumcari North Section of Frye *et al.* (p. 27) (T11N, R 30E, Section 2, NW SW). Apparent middle Pleistocene age (evidently younger than Kansan but older than Wisconsinan) sand section contains two buried soils.

S. (35° 09′N, 104° 15′W, Santa Fe Sheet) Newkirk North Section of Frye *et al.* (p. 27) (T11N, R25E, Section 25, SW¼). Middle Pleistocene (Kansan) sand and?

T. (34° 57′N, 104° 36′W, Fort Sumner Sheet) Santa Rosa East Section of Leonard and Frye (1975, p. 11) (T8N, R22E, Section 4, NE¼). Earliest Pleistocene age terrace gravels overlie Ogallala Formation.

APPENDIX C

LITHOLOGIC PERCENTAGES OF REPRESENTATIVE SAMPLES

Sample Locality Number	Lithologic Type*						
	1	2	3	4	5	6	Total
5	8(2) mqz	19(5) gn,sc	0	0	38(10) gr	35(9) a?	100(26)
7	25(8) mqz	41(13) gn,sc	9(3) ss	0	22(7) gr	3(1) tr	100(32)
9	43(50) mqz	5(6) gn	34(40) ss	0	6(7) gr	11(13) b,a?	99(116)
11	41(17) mqz	15(6) gn	2(1) oqz	0	12(5) gr,qz	29(12) b	99(41)
21	25(23) mqz	2(2) gn	57(53) ss,oqz	0	9(8) gr	8(7) d?	101(93)
25	20(24) mqz, hf	0	36(44) ss,oqz	21(25) ls	1(1) gr	22(27) b	100(121)
28	26(25) mqz, hf	9(9) gn	39(38) oqz,ss	13(13) ls	5(5) gr	8(8) b,d	100(98)
30	40(35) hf,mqz	3(3) gn	25(22) ss	5(4) ch	9(8) qz,do	18(16) a	100(88)
32	20(15) mqz	38(29) gn,sc	4(3) ss	3(2) ls	21(16) gr,qz	14(11) b	100(76)
39	75(77) mqz	20(20) gn	0	0	5(5) qz	0	100(102)
42	91(86) mqz	6(6) gn,sc	0	0	0	3(3) b	100(95)
45	25(17) mqz	3(2) gn	1(1) sts	1(1) ls	1(1) gr	68(46) b	99(68)
47	30(16) mqz	28(15) sc,gn	28(15) oqz	0	4(2) qz	9(5) b	99(53)
50	16(6) mqz	34(13) sc,gn	18(7) ss,sts	3(1) ch	29(11) qz,gr	0	100(38)
51	40(20) mqz	34(17) sc,gn	14(7) oqz	2(1) ch	4(2) qz	6(3) b	100(50)
52	46(31) mqz	30(20) gn	6(4) ss,oqz	0	15(10) qz	3(2) r?	100(67)
56	33(31) mqz	8(4) gn	37(33) ss	4(2) ch	6(3) gr	12(6) b	100(49)
58	16(17) mqz	6(7) gn	18(19) ss,oqz	41(44) ls	4(4) gr	16(17) b,d	101(108)
59	24(46) mqz	2(3) gn	48(90) ss,oqz	13(24) ls	2(4) gr	11(21) d,b?	100(88)
60	25(36) mqz,hf	1(2) gn	49(72) ss,oqz	12(18) ls	2(3) gr	10(15) d	99(146)
61	28(17) mqz	16(10) gn	16(10) ss,oqz	7(4) ls	3(2) gr	30(18) b	100(61)
62	31(30) mqz,hf	2(2) gn	32(31) ss,oqz	6(6) ls	3(3) gr	27(26) b,d	101(98)
64	8(7) mqz	5(4) gn	24(20) ss,oqz	2(2) ls	58(49) gr	4(3) d?	101(85)
65	14(12) mqz,hf	28(25) gn	7(6) ss	18(16) ls	22(19) gr,qz	11(10) b,tr	100(88)
66	12(17) mqz,hf	13(18) gn	7(10) ss,oqz,sts	18(24) ls	42(58) gr,do	7(10) b?,tr	99(137)
67	34(28) hf,mqz	8(7) gn	8(7) ss	25(21) ls	24(20) gr,qz	0	99(83)
69	15(14) mqz	3(3) gn	14(13) oqz	55(51) ls	10(9) qz,gr	2(2) b?	99(92)
70	9(13) mqz	3(4) gn	14(20) ss,oqz	47(66) ls	24(34) gr	2(3) d	99(140)
72	24(19) mqz	0	14(11) ss,oqz	60(47) ls,ch	1(1) gr	0	99(78)
73	6(10) mqz	4(7) gn	9(15) ss,oqz	68(111) ls	13(21) gr	0	100(164)
74	6(1) mqz	0 ss	72(13) ls	17(3) ls	6(1) qz	0	101(18)
76	15(10) mqz	7(5) gn	16(11) ss	56(38) ls	6(4) qz	0	100(68)
79	29(39) mqz	9(12) gn	17(22) ss	6(8) ls	2(2) qz	37(49) b	100(133)
80	50(79) mqz	6(9) gn	17(26) ss,oqz	1(2) ls	6(9) qz,gr	20(32) b,a	100(157)
81	41(52) mqz	5(6) gn	4(5) ss	0	6(7) gr,qz	44(56) b,d,a	100(126)
83	76(73) mqz	13(12) gn	1(1) ss	0	8(8) qz	2(2) r?	100(96)
84	19(30) mqz,hf	2(3) gn	51(83) ss,oqz	9(15) ls	10(16) qz,gr	9(15) d,b	100(162)
86	32(35) mqz	13(14) gn	12(13) oqz,ss	25(27) ls	8(9) gr,qz	9(10) b,d	99(108)
89	8(5) mqz	0	66(41) ss	26(16) ls	0	0	100(62)
90	8(9) mqz	0(0)	9(10) ss,oqz	80(86) ls,ca,ch	2(22) qz	0(0)	99(107)
91	5(6) mqz	0(0)	12(13) ss	72(80) ss	11(12) qz	0(0)	100(111)
93	34(22) mqz	8(5) gn	46(30) ss	9(6) ls	3(2) qz	0	100(65)
94	41(48) mqz	6(7) gn	31(36) ss	16(19) ls	3(4) qz	3(3) d	100(117)
95	46(29) mqz	16(10) gn	17(11) oqz,ss	11(7) ls	5(3) gr	5(3) r?	100(63)
96	25(32) mqz	7(9) gn	26(33) ss,oqz	32(41) ls,ca	6(8) gr,qz	5(6) d	101(129)
97	38(57) mqz	8(12) gn	10(15) ss,oqz	7(10) ls,ch	4(6) qz,gr,do	34(51) b,d	101(151)
98	15(13) mqz	0	69(58) ss,oqz	11(9) ls,ch	1(1) do	4(3) b	100(84)
99	26(24) mqz	9(8) gn,hf	45(42) ss,oqz	5(5) ls,ca	5(5) gr,qz,do	10(9) d,b	100(93)
102	36(51) mqz	3(4) gn	2(3) ss,oqz	14(19) ca,ls	7(10) qz,gr	38(53) b,a,d	100(140)
104	18(26) mqz	2(3) gn	9(13) ss,oqz	11(16) ls,ca,ch	8(11) qz,gr	51(72) b,a,d	99(141)
108	31(44) mqz	19(27) gn	12(17) ss	23(32) ls	12(17) qz,gr	4(5) msc	101(142)
109	45(56) mqz	23(28) gn	5(6) ss	14(17) ls	7(9) qz	6(8) d,b	100(124)
110	49(79) mqz	1(2) gn	17(27) ss	22(36) ls,ch	4(7) gr,qz	6(10) b,d	99(161)
111	49(68) mqz	26(36) gn	6(8) oqz	4(6) ls	9(13) gr	6(9) b,r?	100(140)
112	37(36) mqz	1(1) gn	36(35) ss,oqz,sts	21(20) ls,ch	4(4) qz,gr	1(1) d	100(97)
113	50(45) mqz	6(5) gn	9(8) ss,oqz	16(14) ls	13(12) gr,qz	7(6) d	101(90)
114a	65(45) mqz	10(7) gn,sc	4(3) ss,oqz	0	16(11) qz,gr	4(3) d	99(69)
114b	24(24) mqz	2(2) gn	49(48) ss	12(12) ls	5(5) qz,gr	7(7) d,b	99(98)
117	4(5) mqz	0	31(37) ss,oqz	60(73) ls,ch	2(3) gr,qz	2(3) b,a?	99(121)
118	62(66) mqz	7(7) gn	8(9) oqz,ss	1(1) ch	19(20) qz,gr	4(4) d	101(107)

*Lithologic types are: 1. metamorphics with non-directional structure, 2. metamorphics with directional structure, 3. clastics, 4. non-clastics, 5. plutonics, 6. volcanics. Numbers in parentheses indicate number of samples counted. Letters beneath lithologic percentages indicate predominant rock type in order of abundance. Abbreviations are: a-andesite, b-basalt, ca-caliche, ch-chert, d-dacite, do-diorite, gn-gneiss, gr-granite, hf-hornfels, ls-limestone, mqz-metaquartzite, msc-miscellaneous, oqz-orthoquartzite, qz-quartz, r-rhyolite, sc-schist, ss-sandstone, sts-siltstone, tr-trap.

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