A BASIS FOR PREDICTION OF DENUDATION AND EROSION IN CENTRAL KANSAS

by

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ABSTRACT

A nuclear-waste repository has been proposed for construction within the Hutchinson Salt Member, Wellington Formation (Permian, Guadalupian), at depths of about 1000 feet (300 m) near Lyons, Rice County, central Kansas. One million years hence was defined as the period of concern, during which the nuclear waste would degenerate to a state harmless to life. The objective of the research was to estimate the likelihood that erosion by the Arkansas River and some tributaries would expose the Hutchinson Salt Member at or near the proposed repository site within the period of concern.

Rationale for judgment of erosion was based on comparison of probable effects of stream entrenchment, regional denudation and stream piracy. A maximal-case construct assumed that the present is an interglaciation of the continuing Pleistocene. The interglaciation is presumed to last 100,000 years, to be followed by a glaciation of 500,000 years and an interglaciation and glaciation of 200,000 years each. Probability of occurrence of a present interglaciation shorter than 100,000 years, to be followed by a glaciation longer than 500,000 years is less than 0.01. Present-day climate of parts of the Dakotas, Nebraska and Iowa was judged to be similar to climates of Kansas during glaciations. Available evidence led to the conclusion that regimens of streams of central Kansas were not affected by rise and fall of sea level attendant to interglacial and glacial climatic episodes. Modern denudation

rates of the Arkansas River of central Kansas were extrapolated, adjusted for transition from interglacial to glacial conditions. Probability of as much as 20 feet of denudation of the Arkansas River watershed was judged to be less than 0.003.

Effects of stream entrenchment in the region where the repository is located were estimated on the premise that the Pleistocene history of valley erosion in central Kansas is the best model from which to predict entrenchment. The conclusion was drawn that the Arkansas River will not breach its valley fill during the forthcoming 1 million years. No stream is likely to cut into the Hutchinson Salt Member near enough to the proposed repository to affect the integrity of the salt. The Arkansas River probably will be pirated by the Cimarron River in southwestern Kansas; this event would not markedly alter the regimen of the river in central Kansas. Results of the several lines of inquiry converge on the conclusion that stream erosion will not unroof the Hutchinson Salt Member at or near the repository within the next 1 million years.

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STATEMENT OF THE PROBLEM

A nuclear-waste repository has been proposed for construction within the Hutchinson Salt Member of the Wellington Formation (Permian, Guadalupian) at depths of about 1000 feet (300 m)[1], near Lyons, Kansas (fig. 1). The principal objective of the research described herein is to estimate the likelihood that stream erosion within the next 1 million years would be so deep as to breach the Hutchinson Salt Member at or near the site of the repository.

One million years is defined here as the "period of concern," an interval sufficiently long to ensure decay of radioactive waste to a state that would be harmless to life. By comparison to historical geological standards, one million years is a short time. By comparison with the periods across which events normally are predicted, one million years is an enormous span of time. Consideration of this fact, as it relates to the objective described above, generally raises questions like these:

1. Will conditions as we know them now continue to exist for 1 million years?

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[1] Most values that are conversions from English to metric units have been rounded to show an equal number of significant figures. In some instances, however, additional digits have been retained in the conversion when it seemed that to exclude them would lead to a loss of information. Also, the modifiers that apply to the original number, such as "about," "more than," etc., apply to the metric units as well.

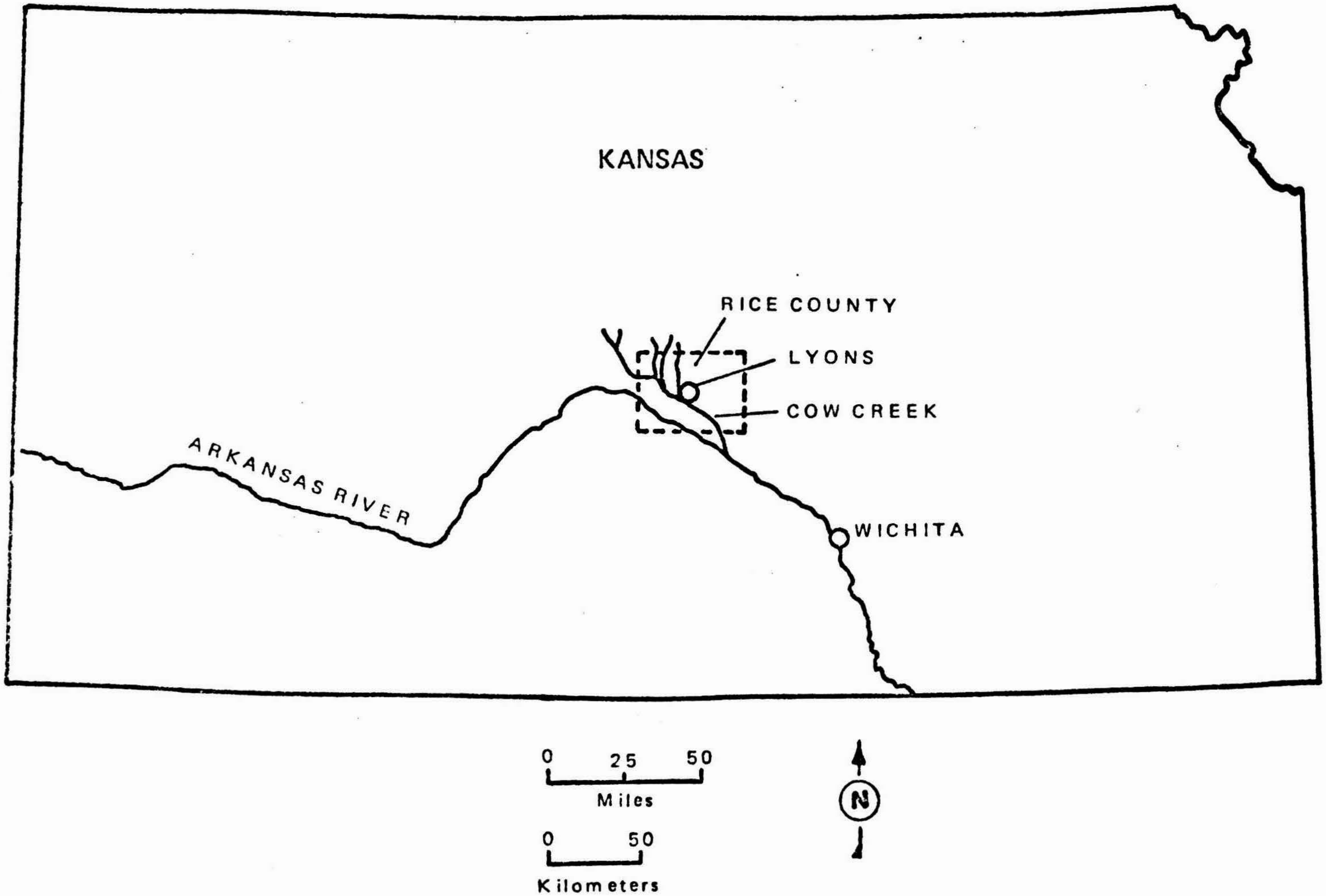

Figure 1.-Location of Lyons, Kansas, with reference to the Arkansas River.

2. If not, can be expect repetition of the glaciations of the Pleistocene?
3. If so, what would be the effects of nearby ice sheets on the regimens of streams in central Kansas?
4. Would the streams be rejuvenated by glacio-eustatic changes in sea level and erode with exceptional speed?
5. What is the likelihood that drainage systems on the Great Plains will be rearranged within the next 1 million years?
6. Will the proposed repository remain within the drainage basin of the Arkansas River (fig. 1)?
7. If not, what effect might such a change have on the depths of erosion within Cow Creek watershed, where the proposed repository is located (fig. 1)?

In order to approach such questions, some unifying framework must exist within which the reasonable (that is, likely, or moderately to highly probable) effects are included and the unreasonable (conceivable, but unlikely) effects are excluded. This implies formulation of a set of general and stable assumptions from which the more likely effects of erosion would be deduced.

After the assumptions are derived and stated, the principal questions to be answered concerning the effects of erosion are: Will the repository be breached directly by a stream cutting through its roof? Will the repository be breached indirectly? (This could happen by lowering of the

Arkansas River drainage basin to a level where the salt of the repository would be penetrated near the repository. Thereafter, circulating ground water could dissolve salt in the repository.)

The pages that follow analyze and describe the major assumptions, i.e., the major premises, from which the results of long-lived erosion will be inferred. Some of the assumptions stated here, such as uniformity, commonly are taken for granted in the normal course of geologic research, whether it be theoretical or applied research. Other assumptions, such as the durations of future glaciations and interglaciations, perhaps never have been required in applied geologic research. However, I consider all of the assumptions to be necessary and fundamentally sufficient for solution of the problem.

UNIFORMITY

The fact is starkly apparent that in the geological past, conditions at the earth's surface have at times been different than conditions now. However, general agreement exists among geologists that the processes in operation have remained the same, although their rates of operation have varied (for discussion, see Simpson, 1963; Kitts, 1963). Within the defined period of concern in this problem, 1 million years, the basic dispositions of some elements in the geological framework are expected to be "constant" and not to change sufficiently to cause major rearrangement of the present hydrologic system. The "constant" elements are considered to include the positions of the continents relative to the poles and relative to each other, positions of mountain ranges, and so on. On the basis of the assumption of uniformity, neither is the character of the processes expected to change, although the rates of stream erosion, for example, would be changed by elements in the geological framework that could be variable within the period of concern - climatic conditions, sea level, and so on.

The assumption of uniformity is not just traditional and convenient - it is necessary for exploration of the problem. Kitts (1963, p. 63) pointed out that there is no logical basis for interpretation of the geological past until the assumption of uniformity is made. Conversely, without some assumption of continuation of processes of the past (especially the recent past, wherein lie the most complete and dependable data) and the present, there is no mechanism and no logical framework suited for prediction of the future - which at best is a treacherous endeavor.

TECTONIC FRAMEWORK OF CENTRAL NORTH AMERICA

Rates of evolution of continental masses, ocean basins, geosynclines, and mountain ranges are slow enough to ensure that within the forthcoming 1 million years no major alteration of the structural make-up of North America will occur.

Assuming that the theory of continental drift is true in general, and that inferred rates of drift of continental plates as based on calculated rates of sea-floor spreading are true in particular, migration of the continental plates on the average is about 1 cm per year, or about 6 miles (10 km)/10^6 years (Dietz and Holden, 1972, p. 103). The maximal rate of migration of continental plates is inferred to have been about 28 miles (45 km)/10^6 years (Dietz and Holden, 1971, p. 104). Clearly, rates of change of at least an order of magnitude greater should be required to bring about enough dislocation of the continent to cause significant change in the present tectonic framework within the next 10^6 years.

In comparision to the period of concern in this research, the major structural elements of central North America are exceedingly old. The Rocky Mountains were elevated during the latter part of the Mesozoic Era; the Ozark Dome was a positive element at least as long ago as during the Permian Period, about 270 m.y. ago (McKee, Oriel and others, 1967, pl. 9; Spencer, 1972, endpaper); the Great Plains has been a continental region since late in the Cretaceous Period; the Mississippi River Embayment also dates from the Cretaceous, more than 70 m.y. ago (Cushing and others, 1964, p. B22-B23; Spencer, 1972, endpaper). If Damon's (1971) theory of the periodicity of orogenesis is correct, the pr probability of orogenesis within the next 1 million years sufficient to alter the tectonic framework of the Midcontinent region is exceedingly low. Although the present topography of the Great Plains and the Central Lowlands provinces is mostly the result of events of the Pleistocene, the

Mississippi River and many of its tributaries occupied basically their present geographical positions during the latter part of the Tertiary Period (evidence to be discussed later). Accordingly, there is no basis in the geological history of the Midcontinent region and its bounding provinces to suggest that the next 1 million years will involve evolution of markedly different structural elements and physiographic provinces than exist now.

AGES OF PLEISTOCENE AND PLIOCENE STRATIGRAPHIC UNITS

The assumption is held that the published identifications and age assignments of stratigraphic units and stream terraces, the identifications and age assignments of fossils, and the paleoecological inferences drawn from them are essentially correct. This information is indispensable to so solution of the problem, of course, and either the correlations and environmental interpretations or the burden of proof for contradictory correlations and interpretations must be accepted. At this time no evidence exists that requires pursuit of the latter alternative. Moreover, to search purposefully for the needed re-examinations or revisions of age assignments and correlations, such as have been proposed by Dort (1966b; 1972), would hopelessly confuse and delay this attempt to predict future courses of events.

RELATION OF THE PLEISTOCENE EPOCH TO THE PRESENT AND NEAR FUTURE

The periods of the Paleozoic and Mesozoic eras are dated as having lasted minimally 25 million years. Each of the epochs of the Tertiary Period lasted for more than 10 million years, with the exception of the Pliocene, the duration of which was 4 million years (all numbers from Spencer, 1972, endpaper).

Although the base of the Pleistocene, as defined traditionally, still is a matter of some debate and is especially subject to refinement outside the type area in Italy and in southern Europe, results of recent research on the age of the lowermost Pleistocene strata seem to converge on some date between 2 and 3 m.y. (Curry, 1966; Glass and others, 1967; Fairbridge, 1968d, p. 916, 918, 923; Tobien, 1970, p. 70; Flint, 1971, p. 412). Climatic "deterioration" and glaciation, at least in Antarctica, however, probably began about 7 million years ago (Denton and others, 1971). The last 1 million years of the Pleistocene probably included the latter part of the Kansan Glaciation, the Yarmouthian Interglaciation, Illinoian Glaciation, Sangamonian Interglaciation and Wisconsinan Glaciation (Glass and others, 1967; Izett and others, 1970; Woolin and others, 1971, p. 212). The inference follows that 1 million years into the future is adequate to include the evolution of a few major episodes of contrasting climatic conditions.

Predictions for the next 1 million years seemingly could proceed only from one of the following assumptions:

1. The climatic conditions of the present, the Recent Epoch, will continue for at least 1 million years.
2. The Pleistocene Epoch of the Quaternary Period, as defined traditionally, was by comparison with preceding epochs of the Paleozoic, Mesozoic and Cenozoic, a discrete, inordinately short epoch; climates of future epochs of the Quaternary will not resemble the Pleistocene.
3. The Pleistocene Epoch has not ended, the Recent is in fact the early part of an interglaciation, and the forthcoming 1 million years will be a continuation of the Pleistocene.

If prediction were to be based on assumption (1) above, much less variation of climatic conditions would be assumed than is justified by the climatic history of the Recent and the last 1 million years of the Pleistocene (Dort, 1970b; Bryson and Wendland, 1967; Porter and Denton, 1967; Bryson and others, 1970; Fairbridge, 1968c, p. 531-535, Wollin and others, 1971). If this assumption were to be used at all, it should be used expediently - that is, only if (a) other alternatives are shown to be less reasonable, or reasonable but intractable, and therefore less promising than the oversimplified assumption (1), or if (b) "worst-case" estimates are considered to be desirable and alternative (1) seems to be best suited for this purpose.

If prediction were to be based on assumption (2) above, then this question would follow: "If the next 1 million years were to be part of an epoch that will not resemble the Pleistocene, what portion of the geological past would this interval resemble?" Obviously, we could not answer this question. Any endeavor based upon this assumption would proceed from almost total lack of data, would be based mostly upon empirically untested and untestable premises, and therefore would bring forth weak inference at best and guesswork at worst.

The proposition of a continuance of the Pleistocene (assumption 3) is not new. Extension of the Pleistocene has been discussed mainly on the grounds that there is no evidence to show that the present is not part of an interglaciation (Kay and Leighton, 1933; Frye and Leonard, 1952, p. 66-67; 1953, p. 2585; Flint, 1947, p. 207-209; 1971, p. 383-384; West, 1968, p. 1, 225; Wollin and others, 1971, p. 199; and others, no doubt). Morrison and others (1957) defended the discreteness of the Recent, but more for utilitarian stratigraphic reasons than its physical or climatic distinction from the Pleistocene. Fairbridge (1968c, p. 526) summarized several lines or stratigraphic evidence that indicate that the Pleistocene-Recent break may be especially significant and, by implication, may be evidence for an epoch that will be distinctly different from the Pleistocene. Elsewhere he has favored strongly the interpretation of the Recent as the early part of an interglaciation (Fairbridge, 1961, p. 542; 1963, p. 439-440).

The positions are not necessarily contradictory, however. Fairbridge's statements in favor of the distinctiveness of the Recent, which seem to be unique, do serve as witness of the paucity of evidence to illustrate the singularity of the Recent.

The proposition of a continuing Pleistocene is supported by these convergent articles of evidence: (a) The climate was warmer than at present during at least one interglaciation (Flint, 1947, p. 207). (b) The enormous ice sheet on Antarctica preceded and seems to have strongly influenced glaciation at midlatitudes (Denton and others, 1971; Fairbridge, 1961). (c) The Antarctic ice sheet is not much smaller than during the glacial maxima (Flint, 1971, p. 80). (d) About 10 percent of the land area of the earth still is overlain by ice sheets (Flint, 1947, p. 207).

In summary, the assumption that contemporary climate will persist for 10^6 years should be rejected. The assumption that the Recent is the early part of an epoch unlike the Pleistocene is almost unsupported by observational evidence. The evidence in favor of the assumption of a continuing Pleistocene is not sufficient to dispel all reasonable doubt, but, by comparison, is formidable. Therefore, the weight of available evidence justifies adoption of the premise of continuing glacial and interglacial episodes similar to those of the Pleistocene.

BASIS FOR THE PROCESS OF EXTRAPOLATION

Prediction of the effects of erosion and denudation necessarily is based on extrapolation. The rationale of extrapolation is to infer future possibilities on the bases of facts (or propositions assumed to be facts) and on the assumption that the facts (or propositions) are parts of unbroken series leading to various possibilities (after Barnhart, 1969, p. 742). Thus, conditions that must precede legitimate extrapolation are: (1) some cyclicity or periodicity and regularity must exist in the data to be used; (2) the "causal" factors must be assumed to remain the same; and (3) the assumption must be held that the "causal" factors will create "effects" like effects that have gone before[2] (Ayers, 1969, p. 35; Cetron and Ralph, 1971, p. 15; Simpson, 1963, p. 38).

Assumption of the continuance of the Pleistocene implies acceptance of a basic kind of cyclicity, a repetition of

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[2] Of course, many qualifications of cause-and-effect exist, including substantial reasons to show that the concept should not be entertained in the strict sense. (see Wilson, 1952, p. 23-24; Walker, 1963, p. 72-74; Bronowski, p. 58-79, esp. p. 76-77.) My objective is not to explore the issue; I am not prepared for such endeavor. Cause-and-effect is a useful construct, moreso because of my (our) conditioning than its own validity, perhaps. Where I speak of causes and effects I do so with qualification, realizing that at the foundation of some things probalilistic systems should prevail. Implicit in discussion of causes and effects therefore is the assumption that correlation rather than causation is the general rule, that one set of events may consistently precede another or be accompanied by another, without the presence of an underlying deterministic relationship.

similar events through time, such as the four major glaciations and three major interglaciations. The probability that the four glaciations are unlinked, unique events is considered to be exceedingly low and is therefore dismissed in favor of some cyclic underlying control (perhaps as described by the Milankovitch theory (see Fairbridge, 1968d, p. 914-915; 1961, p. 569-574)). The quasi-periodic occurrences of these events as part of a major, long-lived cold episode in earth history is accepted here.

A corollary of the assumption of uniformity is that if the combination of a set of conditions, A, is associated with evolution of a condition or set of conditions, B, the repeated combination through time of set A will be associated with the repetition of set B, and not with any other set of "effect" conditions, X. Further, if the occurrence is "periodic", this specifies the state of cyclicity. The assumptions of uniformity, the continuing Pleistocene, and its cyclicity, imply then that future "causes" will be like those that have occurred in the Pleistocene, and that "effects" will be like those that occurred in the Pleistocene.

The foregoing discussion shows that the basic conditions for extrapolation are met in the assumptions of a continuing Pleistocene, the cyclicity of the glaciations, and the constancy of "cause-and-effect."

Serious theoretical and practical limitations are imposed on extrapolations over long periods of time (Simpson, 1963, p. 39) - a general truth that is illustrated with such clarity in the affairs of everyday life that it scarcely needs emphasis here. Extrapolation can be justified on a short-term basis however by (1) the experiential fact that patterns of association among various kinds of "causes" and "effects" are generally accepted as being repetitive and by (2) the pragmatic consideration that in the course of our affairs, events must be predicted and commitments must be made on the bases of the predictions. If the alternative plans of action are to be decided upon by either guesswork or extrapolation based on available data, plans based on extrapolation clearly are to be preferred - not because their success is certain, but because their success is less certain. One million years is hardly "short-term;" nevertheless the point of justification (2) above holds.

CYCLICITY IN THE PLEISTOCENE EPOCH

Problems of the Assumption of Cyclicity

A continuing, cyclical Pleistocene has been stated above as an assumption. Of course, the quality of cyclicity implies similar events repeated with some detectable regularity or near-regularity. To determine cyclicity requires that the beginnings and endings of episodes be defined, and some actual measurement or substantiated inference follows of the time laps between the beginnings and endings. In a general sense, the episodes in the Pleistocene have been defined - namely the four major glaciations and three major interglaciations. But rigorous definition of the temporal and physical boundaries of glaciations and interglaciations within regions and among regions is precluded by the time-transgressive nature of glaciation; the general lack of widespread, isochronous marker units; the different stratigraphic manifestations of cold episodes in glaciated regions as compared to nonglaciated regions; the relatively few absolute ages of key stratigraphic units in the older parts of the Pleistocene; destruction of the stratigraphic record of older climatic episodes by younger glaciations; and the conceptual differences among geologists as to the physical-temporal definitions of glaciations and interglaciations, due partly to conditioning by the geology of the regions within which they have worked (see Frye and Leonard, 1953; Morrison, 1968, p. 10-12, 17-18, 24, 31-33, 64-66, 79; Ray and Karlstrom, 1968). The problem is complicated further by the fact that the lower boundary of the classical Pleistocene is younger by at least 8 million years than the actual onset of the present cold episode in earth history (Flint, 1971, p. 412, 797).

A realistic regard of the Pleistocene would seem to be to consider the classical Nebraskan, Kansan, Illinoian and Wisconsinan glaciations (and by inference, the interglaciations) as cyclical subsets within a continuum extending backward and forward in time for several million years (fig. 2). The four classical glaciations are obviously distinct from their predecessors in the fact of their having advanced to midlatitudes. Seemingly, two hypothetical explanations of the distinction can be proposed:

(1) The four major glaciations could have endured longer, on the average, than their predecessors. Therefore

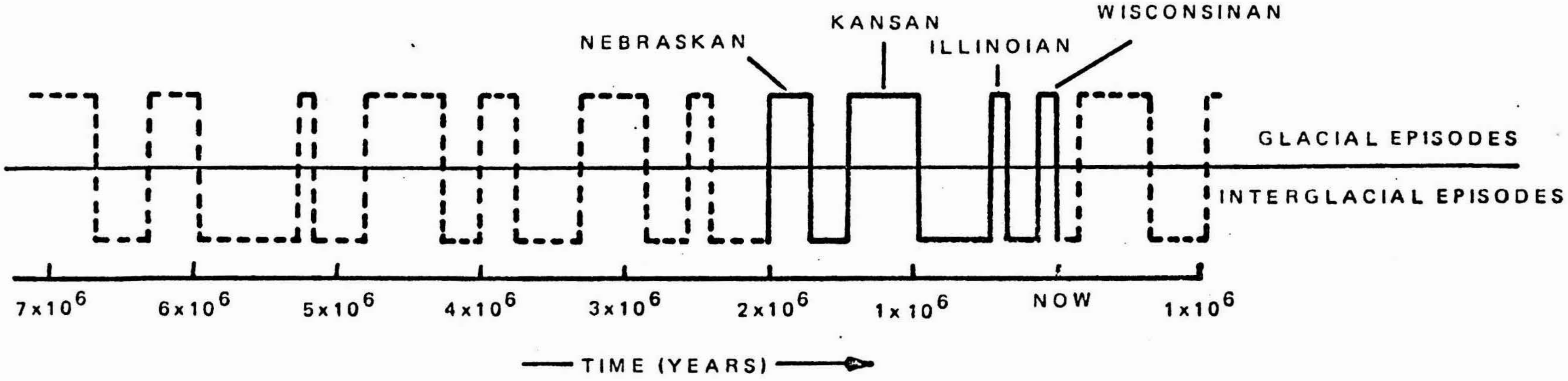

Figure 2.-Diagrammatic representation of a continuum of glaciations and interglaciations extending from longer ago than 7 million years to to some unknown time in the future.

more ice could accumulate during the glaciations. As the central thickness of ice sheets seems to be limited to about 3000 m (10,000 ft) (Fairbridge, 1968a, p. 443), the greater volume of ice led to extension of the sheets to places distant from the region of thickest ice, near Hudson Bay. The southern limits of the ice sheets th therefore would have been functions chiefly of time.

The inference should follow that the four classical glaciations endured enough longer than all cold episodes that came before them that they set the classical glaciciations apart from their predecessors in terms of time and physical extent. Relative to all glacial episodes older than Nebraskan, and on the basis of the property of duration, the classical Pleistocene could be regarded as a separate population of glacial episodes.

(2) The advancement of the ice sheets of the four classical glaciations was a function of the accidental convergence about 2 million years ago of variables not including time (variables maybe mostly unknown, and undefined here, but perhaps including local tectonism, climatic changes, and so on). The inference follows that the Nebraskan, Kansan, Illinoian and Wisconsinan glaciations endured no longer, on the average, than cold episodes that went before them, and that in fact, on the basis of duration, only one population of glacial episodes exists.

These hypotheses have to do with the "causes" of the glaciations and interglaciations of the Pleistocene; the "causes" are unknown. Clearly, the observational evidence necessary to test the hypotheses thoroughly and to choose between them is not available to us. However, a consequence of the first hypothesis would be as follows: The Kansas Glaciation seems to have lasted about four times longer than the Wisconsinan Glaciation (evidence to be discussed later). Therefore, if the spreading of ice sheets were a function of time, with all other factors being about equal, the Kansan ice sheet should have been three to four times as large as the Wisconsinan ice sheet. It was not that much the larger (fig. 3).

General agreement seems to exist that the climatic events of the Pleistocene are somehow correlated with regular, periodic, astronomical fluctuations. At present, the Milankovitch theory (based on changes in distribution of solar heat on the earth's surface, due to periodic variation of the earth's tilt with reference to the plane of the ecliptic, variation of the precession of the earth's axis, and of the earth's eccentric orbit around the sun) or some modification of it is accepted by some geologists as being likely to become part of an eventual integrated theory of the Pleistocene (Fairbridge, 1968b, p. 478; 1968d, p. 915; Jardetsky, 1961; Broecker, 1966). If astronomic fluctuations contribute to the periodicity of the Pleistocene, and especially if they should be so influential as to particially "determine" when glaciations or interglaciations occur, then some regularity is implicit in the history of the pre-Pleistocene and Pleistocene cold cycle, and the large ice sheets of the classical Pleistocene would not necessarily be evidence of a unique set of glaciations and interglaciations.

From a pragmatic standpoint however, the foregoing argument is of secondary importance - for this reason: the four classical glaciations of the Pleistocene are the glaciations whose durations we know best (we know little about the durations of the Permo-Carboniferous or Precambrian glaciations). The Pleistocene record provides the only sample of glaciations and interglaciations whose absolute ages presently are within the limits of our ability to examine - and their absolute durations are not well known at that (see discussion by Flint, 1971, p. 797). Furthermore, if in fact they lasted longer than their predecessors, the next glaciations and interglaciations might well be more like those of the classical Pleistocene than those of the pre-Nebraskan period. By using the only available samples then, the possible inferences are to underestimate future durations, overestimate durations, or to estimate them rather accurately. Of this set, underestimation seems to be the least likely.

Extrapolation requires some estimations of durations of glaciations and interglaciations and of their variability. Two basic questions then are:

(1) What is the statistical meaning of the average durations of Pleistocene glaciations and interglaciations

as based on known radiometric dates, and what are the best ways of applying these ages?

(2) Should the use of such ages be abandoned altogether, and should estimates of durations of glaciations and interglaciations be made on some theoretical astronomic basis, such as the Milankovitch theory?

The Approach to Extrapolation

Although information afforded by the recorded dates of episodes of the Pleistocene is not under close control (see table 1), the information that could be drawn from theoretical models probably would be even less accurate than measured stratigraphic-radiometric dates (Fairbridge, 1968c, p. 914-915; see also Fairbridge's interpretation shown here in table 1 and Flint's discussion (1971, p. 799-800)). The matter to be addressed at this point is to determine whether there is some quality of the recorded absolute dates that suggests the presence of an underlying, hopefully robust, empirical relationship suited for use in extrapolation. Such a relationship should provide a logical basis for estimation of maximal, minimal and average durations of glaciations and interglaciations, without reference to some overriding, reasonable but tenuous theoretical considerations as to the periodicity of changes of climate in the Pleistocene.

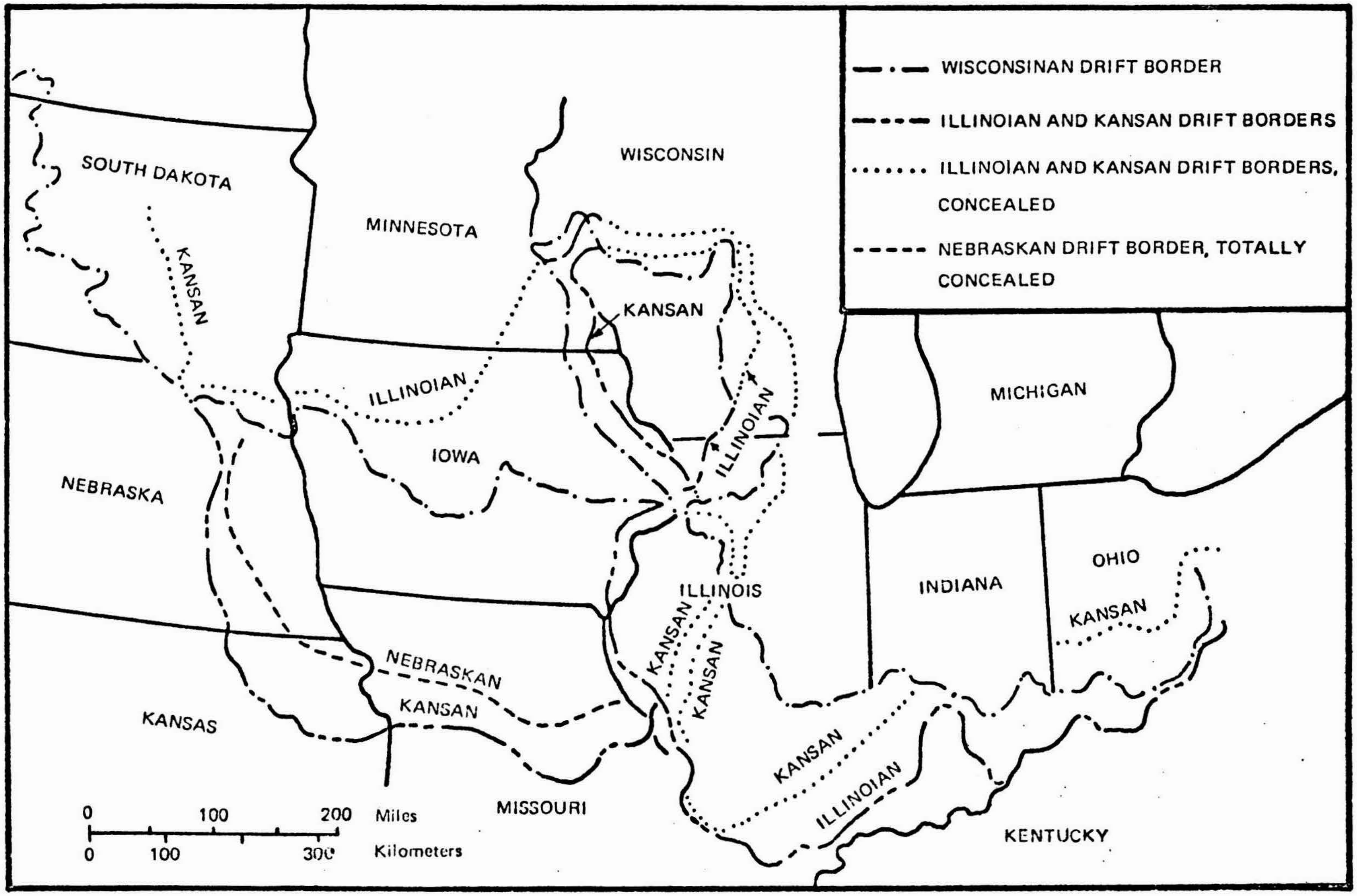

Figure 3.-Drift borders in central United States, showing approximate maximal positions of advancement of Pleistocene ice sheets (modified from Flint, 1957, p. 338).

Choice of a Time Scale for Duration of the Pleistocene

Within the last 25 years the estimated age of the Pleistocene has been extended from about 1 million years to about 2 million years, and in the opinions of some geologists, to more than 3 million years. The matter is unsettled and will remain so until the stratigraphic basis for the lower boundary of the Pleistocene is clearly defined and general agreement upon it is reached (see Flint, 1971, p. 413 for discussion; cf. p. 412).

Table 1 shows a few examples of the range of dates of classical Pleistocene glaciations and interglaciations that have been published recently. Of course, such information raises the question of how to choose a basis for operation from among such divergent evidence. The time scale of Glass and others (1967) (table 2, this paper) seems to be most suited for use in this research, for the following reasons:

(1) Dates of all the major boundaries within the Pleistocene are shown.

(2) It is based on deep sea cores with nearly continuous sequences.

(3) Paleontological evidence correlatable with the type Pliocene-Pleistocene section in Italy is combined with paleomagnetic information.

(4) Some of the younger part of the sequence has been establshed by radiometric dating.

Ages of Bases and Tops of Units of the Classical Pleistocene (years)

	Fairbridge, 1968d, p. 923.	Emiliani, 1961, p. 530.	Glass and others, 1967, p. 442.
Wisconsinan	0 67,000	10,000 70,000	c. 15,000 150,000
Sangamonian	128,000	100,000	380,000
Illinoian	180,000	130,000	470,000
Yarmouthian	230,000	180,000	960,000
Kansan	300,000	200,000	1,470,000
Aftonian	330,000	270,000	1,730,000
Nebraskan	470,000	300,000	2,010,000
Donau (Alps Region)	c. 600,000	(not shown)	(not shown)
Villafranchian	c. 2,000,000	(not shown)	(not shown)

Table 1.- Ages of boundaries of classical Pleistocene units, showing divergence of recently published information.

Episode	Duration (years)
Wisconsinan Glaciation	135,000
Sangamonian Interglaciation	230,000
Illinoian Glaciation	90,000
Yarmouthian Interglaciation	490,000
Kansan Glaciation	510,000
Aftonian Interglaciation	260,000
Nebraskan Glaciation	280,000

Table 2.- Durations of glaciations and interglaciations of the classical Pleistocene as estimated by Glass and others (1967, p. 442).

(5) The date of the base of the Pleistocene is somewhat younger than but generally consistent with dates of the base of the Pleistocene established or estimated independently by the following geologists.

a. Bout (1970, p. 104) at 2.3 m.y. Flint (1971, p. 656) defines the base of the Pleistocene and the Gunz Glaciation, correlative with the Nebraskan, as being above the Perrier-Roccaneyra, and by reference to the information shown by Bout, the age of the base therefore should be about 2.3 m.y.).

b. Tobien (1970, p. 79) at 3 m.y., or, according to the boundary described above, 2.5-2.6 m.y.

c. Funnell (1964, p. 184) at some age between 1.5 and 3.5 m.y.

d. Savage and Curtis (1970, p. 208, 226) at about 2.6 to 3 m.y., or according to the boundary referred to above (Flint, 1971, p. 656), 2.4-2.5 m.y.

(6) Within the older part of the sequence, the dates shown for the Kansan Glaciation (950,000 - 1,460,000 years) are supported generally by the recent, independently determined radiometric ages of ash from the type area of the Kansan Pearlette volcanic ash bed in Nebraska,[3] dated at about 1.2 m.y. (Izett and others, 1971) to about 1.5 m.y. (Boellstorff, 1972). Moreover, ash in southwestern Kansas, probably by early Nebraskan age, has been determined to be 1.9 to 2.7 m.y. old.

Statistical Basis for Application of the Ages of Glaciations and Interglaciations

The main purpose of determining the durations of climatic episodes is to estimate the relative proportions of glaciations and interglaciations presumed to occur within the next 10^6 years. The need for this estimate is based on the premise that episodes of valley cutting and denudation of drainage basins occur mainly during the waxing stages of glaciations

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[3] The Pearlette volcanic ash bed generally has been considered to represent reworked, lenticular fluvial deposits of a single ash fall of Kansan age (see Zeller and others, 1968, p. 60, 63-66; Frye and Leonard, 1952, p. 24, 87-88 for example). Results of recent work suggest that a few Pleistocene ash beds of the Midcontinent are significantly different in ages but are so similar petrographically that they have been identified and used stratigraphically as if they were parts of the Pearlette "marker" ash bed. In fact they may range in age from about 800,000 years to about 2 to 2.5 million years. (See Izett and others, 1970, 1971; Boellstorff, 1972; Stanley and Wayne, 1972, esp. p. 3676-3677.)

and that episodes of valley filling occur mainly during waning glaciations (evidence to be discussed later). If the fractions of the next 10^6 years that should be glacial and interglacial can be estimated, and if rates of valley cutting and filling can be estimated, then some estimate of maximal incision of streams can be made.

More than one method for estimation is available. The assumption could be held that the forthcoming 10^6 years would include glaciations and interglaciations of "average" duration; the average could be determined from records of the classical Pleistocene. But in this study the primary objective is to estimate the amount of incision of streams in the vicinity of Lyons, Kansas, under adverse but reasonable circumstances. Some estimates of the longest glaciations and shortest interglaciations that could be reasonably expected therefore would be valuable information. For these estimates one could choose the Kansan Glaciation (510,000 years) and the Sangamonian Interglaciation (230,000 years), the longest glaciation and shortest interglaciation respectively of the classical Pleistocene. But because the premise is held here that the classical Pleistocene and the glacial events of the next 10^6 years are part of a continuum of numerous glacia-ciations and interglaciations that extends backward into the late Tertiary and forward to some unknown time, the choice of the Kansan and Sangamonian as the maximal and minimal values is open to considerable question. A better method would seem to be to estimate reasonably (to be defined later) the longest glaciations and shortest interglaciations that could be expected to occur within the context of the assumed late Tertiary-Pleistocene-Future glacial continuum.

Definition of Populations

The statistical populations of concern at this point are defined as the durations of glaciations and interglaciations. The hypothetical populations (Griffiths, 1967, p. 14-15) under study are defined as the durations of all glaciations and interglaciations that have occurred since the beginning in the Tertiary of the present cold episode, the latter part of which we call "Pleistocene," and that will occur during the remainder of the cold cycle. Evidence of some past glaciations and interglaciations probably has been obliterated by the processes of younger glaciations. Therefore it seems reasonable to assume that some of the past hypothetical population is totally unavailable for sampling. The existent population (Griffiths, 1967, p. 15) includes the durations of all Tertiary-Pleistocene glaciations and interglaciations of which evidence has been observed. But durations of episodes older than the Donau Glaciation (pre-Gunz; pre-Nebraskan) have neither been determined, nor estimated. Moreover, as stratigraphic research on deposits of this general age progresses, more glacial and interglacial episodes will be recognized, no doubt. (This assertion has some basis in analogy; cf. the recent discoveries of multiple stades in the Kansan of the Midcontinent (Dort, 1966a, 1966b, 1970a, 1970b, Bayne, 1969)). Therefore, probably most of the existent population is not presently accessible for sampling.

The available population (Griffiths, 1967) consists of the estimated durations of the classical Pleistocene episodes - the Nebraskan, Kansan, Illinoian, and Wisconsinan glaciations and the Aftonian, Yarmouthian, and Sangamonian interglaciations. Thus samples of only four and three are available from which to draw inferences about the parameters of the hypothetical, or parent population.

The Hypothesis of Normality and Testing Methods

It is axiomatic that the populations being considered here can be approximated by some kind of frequency distribution. The assumption is stated at this point that the underlying distribution of the hypothetical populations, durations of all glaciations and interglaciations of the late Tertiary-Pleistocene and of the future, if sampled randomly with large ($N > 50$) samples (if indeed N is greater than 50), could be shown to be approximated by one of the continuous theoretical distributions. For the purpose of testing the assumption just stated, the hypothesis is advanced that the distribution of the hypothetical population could be approximated by the normal distribution.

Needless to say, samples of sizes four and three are undesirably small bases for generalizations about populations; but in this instance they are the total available population. Some tests of hypotheses asserting normality of a population consist of the following steps:

(a) Samples are (hopefully) taken randomly in some fashion consistent with the objective and design of the experiment. They are grouped into a set of about 10 to 20 or more classes and depicted as a frequency histogram.

(b) If the underlying distribution is known to be contitinuous, or if some prior knowledge of the contributing variables exists to justify the assumption of continuity (Sokal and Rohlf, 1969, p. 101), a null hypothesis is stated so that no difference is assumed to exist between the frequency distribution of the variable under examination and the normal distribution.

(c) The mean, $\bar{X}$, and the variance, δ^{2}, of the sample are calculated. They are approximations of the true means and variance of the parent population. From the sample mean and variance, frequencies of the normal distribution are computed that would be expected to occur in the classes of the above-mentioned histogram.

(d) The frequency distribution of the samples is tested for consistency with the normal distribution either by the Chi-square goodness of fit test or the Kolmogorov-Smirnov test for goodness of fit.

(e) The frequency distribution is tested for skewness and kurtosis, which tests are directed partly at estimating whether the samples are, in fact, random samples (a question which in the strict sense, is not answerable by analysis of the sample itself, but some judgments can be made (see Griffiths, 1967, p. 262, and his quotation of P.O. Johnson, p. 12). If randomness of sampling can be assumed, tests for skewness and kurtosis also permit inferences to be made about the form of the frequency distribution of the population.

(f) The Chi-square goodness of fit test and Kolmogorov-Smirnov test yield values which, when compared to tables of critical values, show the probability that the sample was in fact drawn from a normal distribution with mean $\mu = \bar{X}$ and variance $\sigma^2 = \delta^2$.

If the Chi-square and Kolmogorov-Smirnov Dmax values exceed the critical values at a level of probability set by the investigator, the null hypothesis is rejected, and an alternate hypothesis is adopted for testing. The alternate hypothesis may assume (a) that the underlying distribution is not approximated by the normal distribution with the given parameters, (b) that the underlying distribution might be approximated by the normal distribution if the variates were transformed, or (c) that the sampling method did not yield a truly random sample. Testing proceeds in this fashion until the results indicate acceptable consistency between the distribution suggested by the sample and some theoretical distribution.

Obviously, with available populations of sizes four and three, the usual effort directed at random sampling is out of the question, and construction of histograms and tests of skewness and kurtosis promise a low yield of information. Therefore, the decision as to the probability that these samples are random samples from normal distributions can be considered to rest entirely on the goodness-of-fit tests. The Chi-square test of goodness of fit is poorly suited for analysis of exceedingly small samples (Sokal and Rohlf, 1969, p. 565; Siegel, 1956, p. 51) and is unsuited for use in the instance at hand. The Kolmogorov-Smirnov test can be applied to exceptionally small samples however, and some tables of critical values allow testing of samples as small as one variate (Siegel, 1956, p. 251; Rohlf and Sokal, 1969, p. 249-251). Because the normal distribution with which the samples of durations of glaciations and interglaciations are to be compared are computed from values of $\bar{X}$ and $\hat{\sigma}^2$ drawn from the samples themselves, standard tables of Kolmogorov-Smirnov critical values are somewhat misleading, inasmuch as they would allow false hypotheses to be accepted too frequently (see Lilliefors, 1967, p. 399; cf. Siegel, 1956, p. 60, or Rohlf and Sokal, 1969, p. 240-251). The appropriate table for use in the present analysis is that of Lilliefors (1967, p. 400).

Tests for Normality of the Populations

The null hypothesis is:

H_o: The durations of the glaciations and interglaciations of the classical Pleistocene, as determined from values shown by Glass and others (1967) (table 2, this paper) are random samples drawn from normally distributed populations.

Alternate hypotheses are:

H_1: The samples of durations were drawn from populations that are not distributed normally.

H_2: The sample of four durations of glacial episodes are non-random samples drawn from populations that are normally distributed. (This hypothesis is stated because the total available populations are included in the samples, no sampling design is practicable, and therefore no *a priori* considerations as to randomness of the samples are included in the context of the experiment.)

If either of the computed values of Dmax of the Kolmogorov-Smirnov test are larger than their corresponding tabled critical values (Lilliefors, 1967, p. 400) the appropriate null hypothesis is rejected. In this instance, one of the alternate hypotheses is true, but the fact that the populations are being dealt with here in totality would preclude further sampling, testing and distinction between the alternate hypotheses.

	Glaciations	Interglaciations
$\bar{X}$	250,000 yrs.	330,000 yrs.
θ	190,000 yrs.	140,000 yrs.
K-S Dmax, computed	0.235	0.347
K-S Dmax, critical value	0.381	0.381

Table 3.- Summary statistics, test for normality of glacial and interglacial episodes. Level of significance, 0.05.

The smallest sample size included in Lilliefor's table is four. Table 4 shows that critical values of Dmax become progressively larger as sample size decreases. Therefore, a transitive relationship can be assumed so that if the computed value of Dmax of a sample of three is smaller than the critical value of Dmax of a sample of four, then it must also be smaller than the critical value of a sample of three.

Sample Size	Critical Values, Dmax
4	0.381
5	0.337
6	0.319
7	0.300
8	0.285
9	0.271
10	0.258

Table 4.- Critical values of Dmax at level of significance α =0.05 (from Lilliefors, 1967, p. 400).

The conclusions follow from the statistics above (table 3) that no reason exists to reject the null hypotheses; durations of glaciations and interglaciations of the classical Pleistocene are presumed to be parts of normal distributions, of which the sample means ($\bar{X}$) and standard deviations ($\hat{\sigma}$) are estimates of the populations' true means (μ) and standard deviations (σ).

Estimation of the Maximal Case

Definition of the Maximal Case

Because the present is assumed to be the early part of an interglaciation, a combination within the next 10^6 years of the shortest reasonable interglaciation followed by the longest reasonable glaciation is considered here to be the Maximal Case, the conditions under which waxing glaciations should endure longest and valley trenching should be deepest. If entrenchment of valleys under these conditions can be shown to be not likely to reach the level of the repository, then all other reasonable combinations of glaciations and interglaciations, being less than the maximal reasonable case, can be dismissed from further consideration, as they necessarily would be of less consequence.

The "Maximal Case" is defined here as the sequential occurrence of an interglaciation short enough and a glaciation long enough that the combination would be exceeded by chance only once in 100 similar events ($P_{max}=0.01$). The assumption is held that the duration of an interglaciation or glaciation is independent of the duration of the episode that preceded it. The occurrence of a "long" interglaciation is assumed to have no effect upon the duration of the following glaciation. Further, this assumption implies that no third, unexplained occurrence affects the durations of interglaciations and glaciations and thereby induces the condition of association between them, such that long interglaciations tend to be followed by long glaciations. This assumption is restated as a first-order null hypothesis and the alternate hypothesis, and tested as follows.

H_o: The duration of a glacial episode is not affected by the duration of the preceding interglacial episode.

H_1: Duration of glacial episodes and durations of their preceding interglacial episodes are "causally" related or directly associated.

Test 1

The level of association between the durations of classical Pleistocene glaciations and interglaciations is tested first by computation of the correlation coefficient (fig. 4).

Durations (yrs. x 10^3)

Interglaciations	Glaciations
Aftonian - 260	Kansan - 510
Yarmouthian - 490	Illinoian - 90
Sangamonian - 230	Wisconsinan - 135

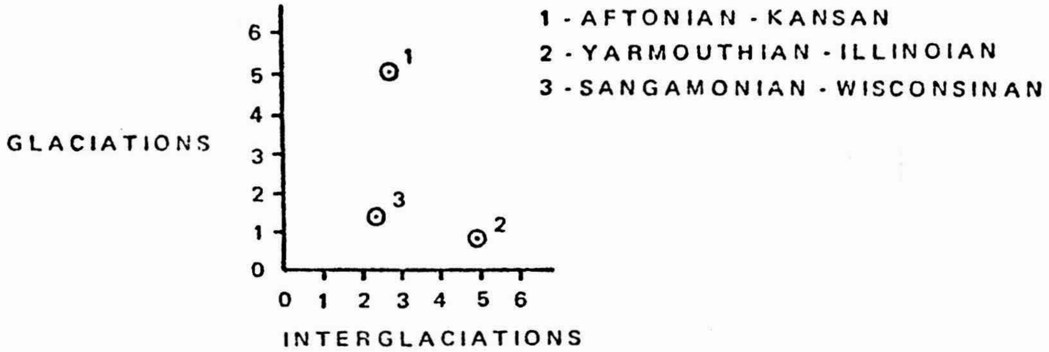

Figure 4. - Relationship among durations of pairs of interglaciations and ensuing glaciations. Computed correlation coefficient $r_{i,g}=-0.49$ (after Sokal and Rohlf, 1969, p. 508-510.)

A second-order null hypothesis and alternate hypothesis are:

H_o: The sample correlation coefficient, $r_{i,g}$ came from a population with a true correlation coefficient of zero, or $\rho=0$.

H_1: ρ is not zero.

Test 2

1. Observed value of correlation coefficient, $r_{i,g}=-0.49$ (sign not considered).
2. Critical value, $\alpha=0.05$, 1 d.f.=0.997 (Rohlf and Sokal, 1969, p. 225).
3. Conclusion: Observed correlation coefficient is not significantly different from zero.

As the correlation coefficient is -0.49, the coefficient of determination, $r^2_{i,g}=0.24$. On the basis of this sample, only 24 percent of the total variation is common to both glaciations and interglaciations; 76 percent of the variation is unexplained. This fact and the nonsignificance of the sample correlation coefficient indicate that no basis exists to reject the null hypothesis. Durations of glacial and interglacial episodes are judged to be neither "causally" related nor directly associated.

Determination of the Maximal Case

The maximal case describes the sequential occurrence of specified conditions. According to results of the hypotheses tested above, a compound event comprising two independent events is defined and the multiplication law applies (see Spiegel, 1961, p. 100, or Moroney, 1951, p. 8-11). The objective of probability of occurrence of the maximal case, $P_{obj}=0.01$, is the combined probability: $P_{obj}=(P_{min,i})(P_{max,g})$ where $P_{min,i}$ and $P_{max,g}$ are the probabilities of the shortest interglaciation and the longest glaciation, respectively. As P_{obj} is specified here as 0.01, $P_{min,i}$ and $P_{max,g}$ can be apportioned equally, and each will be $\sqrt{0.01}$, or 0.1.[4] If we knew the parameters of the populations sampled here, we could specify straightforwardly the durations of interglaciations and glaciations that should be exceeded by chance only 1 time in 10 similar events. As stated previously however, the computed means and standard deviations of glaciations and interglaciations (hereafter shown as $\bar{X}_g$,

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[4] Any combination could be stated whose product is 0.01, but no *a priori* reason exists that requires the factors to be unequal.

$\bar{X}_i$, $\hat{\sigma}_g$, $\hat{\sigma}_i$) are only estimates of the true values (μ_g, μ_i, σ_g, σ_i).

Choice of Methods

Two basic methods of determinig $P_{max,g}=0.1$ and $P_{min,i}=0.1$ were considered to be appropriate for the purpose of this investigation. Two basic assumptions were held. (1) Conservative estimates are to be preferred over liberal ones - that is, if the likelihood exists that conditions either will be overestimated or underestimated, moderate but reasonable overestimation of adverse future climatic conditions is to be preferred. (2) The sample variances, $\hat{\sigma}_g^2$ and $\hat{\sigma}_i^2$, having been computed with Bessel's Correction (Moroney, 1951, p. 225-226; or see discussion by Sokal and Rohlf, 1969, p. 53-55) were accepted as estimates of the population variances σ_g^2 and σ_i^2 that are sufficiently accurate for the objectives of the computations. Consistent with assumption (1) above, the method of estimating the shortest interglaciation and the longest glaciation whose respective probabilities of being exceeded are 0.1, was defined as the method below that yielded the more conservative estimates. (Either method is judged not to differ markedly from the real-world situation.)

Method 1

$\bar{X}_g$ and $\bar{X}_i$ were considered to be accurate estimates of μ_g and μ_i. $\bar{X}_g+1.282\ \hat{\sigma}_g$ includes 90 percent of the durations of the glaciations likely to occur (fig. 5). It follows that the probability of exceeding of the longest glaciation, Gl_{max}, is 0.1. $\bar{X}_i-1.282\ \hat{\sigma}_i$ establishes the duration of the shortest interglaciation, I_{min}; the probability of shorter ones is 0.1.

Method 2

$\bar{X}_g$ is considered probably to be an underestimation of μ_g; $\bar{X}$ is considered probably to be an overestimation of μ_i.[5] Forty-percent confidence limits therefore were established about the means (Sokal and Rohlf, 1969, p. 146; Griffiths, 1967, p. 325; Fisher and Yates, 1963, p. 46). Accordingly, the probability is 0.3 that the confidence interval with the upper limit $L_{u,g}$, does not cover a larger true mean of glaciations, μ_g. Likewise, the probability is 0.3 that the confidence interval with the lower limit $L_{l,i}$, does not cover a smaller true mean of interglaciations, μ_i. If $L_{u,g}$ and $L_{l,i}$ are assumed to be the true values of μ_g and μ_i, it follows that $\mu_g+0.43\ \hat{\sigma}_g$ and $\mu_i-0.43\ \hat{\sigma}_i$ would establish durations of the longest glaciations and shortest interglaciations that should be surpassed with probability of 0.33 (fig. 6). This construct then describes a compound event, as for example the estimation of the longest glaciation Gl_{max}, is determined by (a) the combination of

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[5] It is equally likely that the converse statements are true. But, in keeping with the assumption stated previously that the estimates to be made should be conservative, underestimation and overestimation of μ_g and μ_i are assumed.

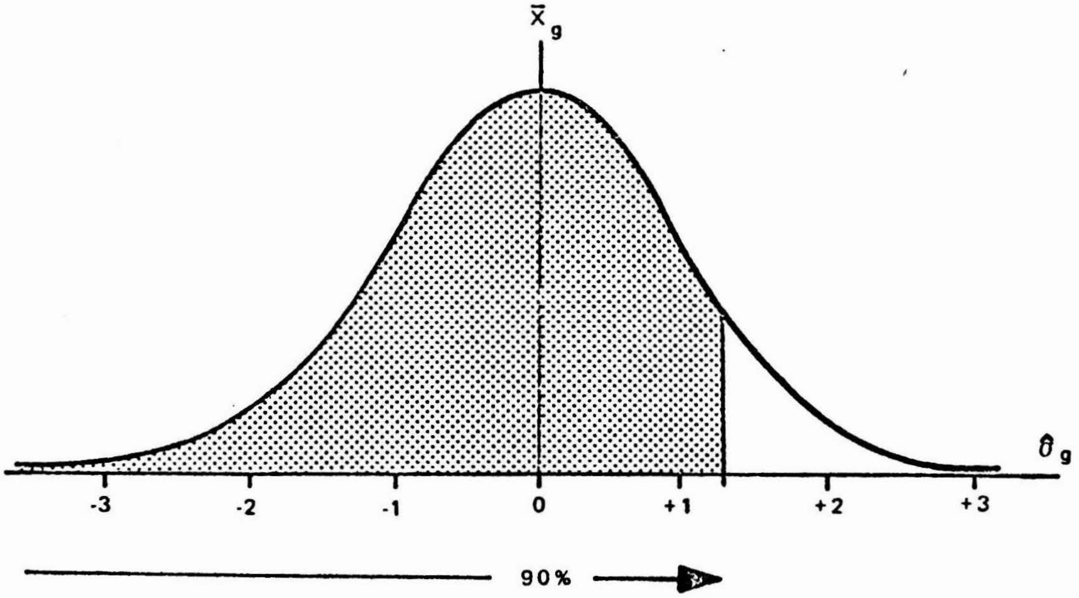

Figure 5.-The normal curve, assuming $\bar{X}_g$ and $\hat{\sigma}_g$ to represent μ_g and σ_g. Ninety percent of all values of durations of glaciations would be included in the shaded area of the curve. The probability of occurrence of a value larger than $\bar{X}_g+1.282\ \hat{\sigma}_g$ is 0.1. (After Spiegel 1961, p. 123, and Rohlf and Sokal 1969, p. 158.)

the probability that $\mu_g > L_{u,g}=0.3$, and (b) the probability of a glaciation occurring that would be longer than $L_{u,g}+0.43$ $\theta_g=0.33$, or (c) (0.3)(0.33), effectively 0.1. Estimation of the shortest interglaciation, I_{min} also follows this argument.

Computed Values

(a) Method 1:

$Gl_{max}=\bar{X}_g+1.1282\ \theta_g=(250{,}000)+(1.282)(180{,}000)=490{,}000$ yrs. (rounded)

$K_{min}=\bar{X}_i-1.282\ \theta_i=(330{,}000)-(1.282)(140{,}000)=150{,}000$ yrs.

(b) Method 2:

Gl_{max}:

(a) $L_{u,g}=\bar{X}_g+t0.6(n-1)\ \frac{\theta_g}{\sqrt{n}}$

$=\bar{X}_{g}+(0.584)(94{,}500)$

$=(250{,}000)+(55{,}000)$

$=(350{,}000$ yrs.)

(b) $L_{u,g}+0.43\ \theta_g=(305{,}000)+(0.43)(189{,}000)$

$=390{,}000$ yrs. (rounded)

(c) $Gl_{max}=390{,}000$ yrs.

I_{min}:

(a) $L_{u,i}$=(similar computation)

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(c) $I_{min}=120{,}000$ yrs.

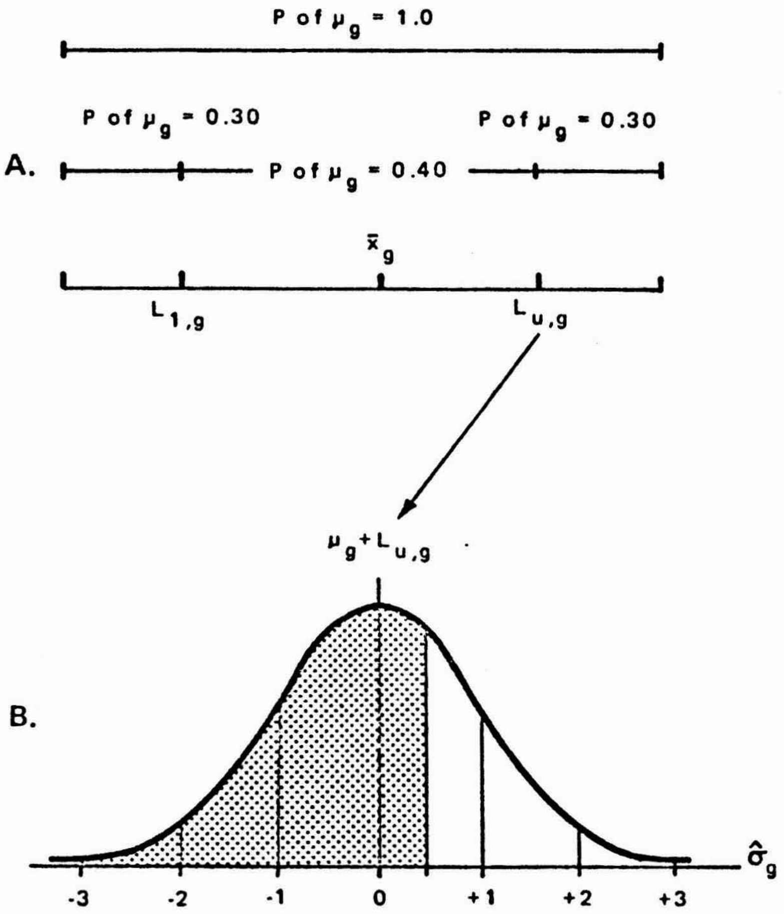

Figure 6.- (a) Forty-percent confidence limits established a around the mean duration of glaciations. Probability that the confidence interval below $L_{u,g}$ does not include μ_g is 0.3.[6]
(b) $L_{u,g}$ assumed to be an accurate estimate of μ_g. Probability of occurrence of a glaciation longer than $L_{u,g}+0.43\hat{\sigma}_g$ is 0.33. Similar computational method was used to determine duration of I_{min}.

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[6] This is not to say that the probability that the true mean is included within this range is 0.7. The confidence derived from this computation rather, is derived from the fact that of every 100 such computations, each with different sample estimates, 70 would include the true mean. Our judgment then is based on the probability of this computation's being included in the set of 70. (For a more complete explanation, see Sokal and Rohlf, (1969, p. 142); Griffiths (1967, p. 266, 325-326); or Moroney (1951, p. 328-241).

Conclusion: Method 1 yields the more conservative estimate
of Gl_{max}, 490,000 yrs.
Method 2 yields the more conservative estimate
of I_{min}, 120,000 yrs.

Statement of the Maximal Case

According to computations shown above the previously stated assumptions, the probability that the present interglaciation will be shorter than 120,000 years is 0.1. The probability that the ensuing glaciation will be longer than 490,000 years is 0.1. The probability of occurrence of a compound event including a shorter interglaciation and (or) a longer glaciation is less than 1 chance in 100. The Maximal Case for the period of concern would include four climatic episodes: (1) an interglaciation continued for about the next 100,000 years, (2) a glaciation of approximately 500,000 years, (3) a second interglaciation, and (4) a second glaciation. Previous calculations lead to the inference that the probability that the second interglaciation would last from 600,000 years hence to 800,000 years hence is at least 0.5. The remaining 200,000 years will be assumed to be a glacial episode.

POTENTIAL EFFECTS OF ICE LOADING IN PROGLACIAL REGIONS

Deductions based on the geophysical properties of the crust and mantle predict that loading of the terrain by a continental glacier should cause downward flexure of the crust, displacement of part of the mantle and, over extended time, establishment of equilibrium by isostatic adjustment (for example, see Brotchie and Silvester, 1969; Farrand, 1968). If the mantle is assumed to be incompressible, the inference follows that beyond the region loaded by an ice sheet, some upward flexure in the crust should be induced by the displaced mantle. This flexure might be "local" as, under the conditions of geophysical theory, a marginal bulge of low amplitude, a "forebulge," should be created around the periphery of an ice sheet (Fairbridge, 1968a, p. 443; Brotchie and Silvester, 1969, p. 5244).

Elevated regions of the geoid that lay in front of or between Pleistocene ice sheets of North America imply strong correlation between ice loading and elevation of periglacial regions (Fischer, 1959a, fig. 4; Fischer, 1959b, p. 56; Farrand, 1968, p. 887, fig. 3). Localized subsidence in formerly rebounding periglacial regions (Fairbridge and Newman, 1968), and the topography and history of some drainage basins in Illinois and Kansas formerly near to the margins of glaciers (Frye, 1963, p. 8-10; Frye and Leonard, 1952, p. 189-194) compose evidence that has been interpreted as indicating that marginal bulges are real. However, the available evidence is not so abundant or conclusive as to permit definition of the dimensions of the forebulges. Predictions of amplitude range from a few meters (Brotchie and Silvester, 1969, p. 5244, table 2) to more than 200 ft (60m) (Frye, 1963, p. 8-9; Frye and Leonard, 1952, p. 190). Inferred widths of the forebulges range from less than 100 mi (160 km) (Frye and Leonard, 1952, p. 190) to about 160 mi (about 250 km) (Brotchie and Silvester, 1969, p. 5244, table 2) to more than 200 mi (300 km) (inferred from Fischer, 1959a, fig. 4). Furthermore, in a part of southwestern Illinois that was formerly occupied by ice sheets, and within which the hypothesis of a marginal bulge was tested by search for direct evidence, a forebulge sufficient to cause detectable deformation of stream terraces or to change the gradients of streams seems not to have existed (Rubey, 1952, p. 83, 120, 146).

In light of this body of evidence, the following set of hypotheses seems to exhaust the reasonable possibilities of the geomorphic effects of forebulges:

a) Forebulges have no basis in geological fact.

b) Forebulges existed around the Pleistocene ice sheets, but their effects on the geomorphology of the periglacial regions were so minor as to cause subtle variation in the terrain that is not manifested as "ordinary" field geologic evidence.

c) In the instances where Pleistocene forebulges can be inferred on the basis of geomorphic evidence, local and fortuitous convergence of circumstances produced landforms that contrast with the normal terrain. Such landforms had low probability of occurrence.

d) Considerably more evidence of forebulges is preserved in the terrain than has been recognized heretofore; deliberate searching for this evidence would lead to delineation of regions formerly situated within forebulges, and to definition of geomorphic effects of forebulges, which mainly should be evident as derangements within stream systems.

Even if the set of hypotheses above are exhaustive and contain a true explanation, evidence presently is not available for testing the hypotheses. Accordingly, by the principle of simplicity, the hypothesis judged to be at once consistent with the observed areal geologic evidence of Pleistocene events in Kansas, not especially complex, and the most likely to be true of future glaciations in Kansas is judged to be (c) above. This hypothesis forms the basis for the following premise: A forebulge that would occur in ice-marginal regions in Kansas should not affect the regimens of streams to such an extent as to cause general derangement of the present major streams or regional reversals of directions of flow. Local parts of the stream network near the ice sheet might be changed markedly, but such events would be random occurrences, mostly dependent upon chance interaction of the streams, the processes of glaciation, and the pre-glacial topography.

CHANGES OF CLIMATE

The Basic Problem

Under the basic premise that the last 10,000 years, approximately, are the early part of an interglaciation in a continuing Pleistocene system, the supporting evidence for assumptions as to climatic conditions in time to come is, of course, the evidence of climates during past glaciations and interglaciations. During the Pleistocene, Kansas was transitional between the glaciated midwestern and the unglaciated southwestern states. Of the four major glaciations of the Pleistocene, only the Nebraskan and Kansan ice sheets entered Kansas (fig. 3). Presumably, ice sheets of the future would also come near Kansas or enter the northern part of the state. Some of the questions to be answered in this regard are: Were the climates of Kansas during glaciations and interglaciations radically different from those of the present? Did Arctic conditions prevail during the cold episodes? What evidence is available to answer these questions?

Basic Assumptions

Information to be used as supporting grounds for inference of paleoclimates of the Pleistocene is abundant in comparison to information available from the older geological epochs. Nevertheless, the information comes from a relatively few intensively studied but widely separated localities, and in general leaves the paleoclimates of the large areas between to be inferred. The assumptions held in the interpretation of paleoenvironments, in a general statement, are that (a) climate is a strong control upon vegetation today (Trewartha, 1968, p. 240-241), and should have been so in the Pleistocene, that (b) climate and vegetation are strong controls on fauna today, and should have been so in the Pleistocene, and (c) therefore genera and species of the Pleistocene fauna and flora lived in environments similar to the environments where these genera and species or their close descendents live today (a major assumption being that in the interim, the species have not changed so that their present habitats are different from their former ones). Accordingly, the assemblages of fossils are correlated with present-day regions in which the ranges of components or their close relatives overlap. The contemporary climate (and by inference vegetation) are assumed to have had Pleistocene counterparts. (For more complete discussion, with qualifications, see Taylor, 1960, p. 3-5; 1965, p. 597-598, 602-603; Kapp, 1965, p. 172-173; Semken, 1966, p. 167; Stephens, 1960, p. 1698-1700.)

Because the Wisconsinan strata are the youngest Pleistocene deposits, and because they are so well exposed in the northern United States where even glacial landforms of Wisconsinan age are preserved in some regions, the complexity of that glaciation with its several stades and interstades has been recognized for many years. Until the last decade or so, however, an oversimplified interpretation of earlier Pleistocene history was commonly held, namely three single episodes of glaciation (Nebraskan, Kansan, Illinoian) separated by two interglaciations (Aftonian, Yarmouthian). Recent lithostratigraphic studies in glaciated and proglacial terrane of northeastern Kansas have yielded evidence that shows that several glacial advances and retreats occurred within the Nebraskan and Kansas glaciations, a discovery more in keeping with the stratigraphic record of the Recent and Wisconsinan than was the former oversimplification (Dort, 1966a, 1966b, 1970a, 1970b; Bayne, 1969). By extension, the fully-known climatic record should show a multitude of fluctuations within glacial and interglacial stades. The climatic record of Kansas is inferred from localities mostly distant from the former ice margins and is not so complete as to allow the description of climates that defined stades and interstades. The conclusions that follow, although based upon the best evidence available, are necessarily generalized. The evidence for the paragraphs below is included in Appendix A; the sources from which it came are shown there.

General Consensus of Pliocene, Pleistocene, and Recent Climates in Kansas

Pliocene Epoch

Climate   Humid, subtropical to tropical throughout most of Kansas. Southwestern Kansas somewhat drier.

	Entire Midcontinent region less continental than now. Climate semiarid, much like present in latter part of Pliocene; endured for long period.
Vegetation	Forests and savannas within stream valleys; grasslands with scattered trees in uplands.
Modern Analogue	None proposed.

Nebraskan Glaciation

Climate	Cooler than present, but temperate. Rainfall greater than Pliocene, greater than present, and more equitably distributed throughout year. No evidence recorded of boreal or tundra climates.
Vegetation	Mostly prairie with some woodland; no extensive forests.
Modern Analogue	None proposed.

Aftonian Interglaciation

Climate	Predominantly semiarid; little different than present except less continental. Rainfall similar to present. Early and late portions of Aftonian seemingly subhumid.

Vegetation	No evidence recorded.
Modern Analogue	None proposed. (Present-day Kansas probably an acceptable approximation.)[7]

Kansan Glaciation

Climate	Cool temperate. Somewhat cooler than present but not radically different. Slightly cooler than Nebraskan. Mean annual temperature probably about same as present. Less continental than present; rainfall probably more equally distributed throughout year. No definite evidence of boreal or tundra climate.
Vegetation	Good floral cover. Prairie, meadow, woodland, but no extensive forests.
Modern Analogue	Central Michigan

Yarmouthian Interglaciation

Climate	Warm, temperate, gradational from subhumid in early Yarmouthian to semiarid in medial Yarmouthian. Frost-free winters. Less continental than present.
Vegetation	No evidence recorded.

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[7] My inference.

Modern Analogue	None proposed. (Present-day Kansas probably an acceptable approximation.)[8]

Illinoian Glaciation

Climate	Slightly cooler than present; less continental. Mean annual temperature probably 40°-45° F (4°-7° C). Average summer and winter temperatures during glacial maxima about 10° F and 20° F (5°-11° C) cooler than present. Summer temperature 65°-70° F (18°-21° C); winters (other than during glacial maxima), similar to central Kansas now (30°-35° F) (-1° to 2° C). Annual precipitation about same as present.
Vegetation	Mostly grassland prairie with pine and spruce woodlands of unknown extent.
Modern Analogues	Southeastern Wyoming; southern New Jersey; southern Wisconsin (summer); northern New Jersey (winter); southeastern North Dakota; no northeastern South Dakota; northwestern Iowa; northeastern Nebraska; central Missouri.

Sangamonian Interglaciation

Climate	Semiarid. Perhaps no freezing in winter; summers cooler than present. Mean annual rainfall

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[8] My inference.

	about same as present. Climate less continental than now. Graded to subhumid in latter part of Sangamonian, with precipitation 40-45 inches (100-115 cm) annually. Mild winters like southeastern Kansas and eastern Oklahoma at present.
Vegetation	Dominantly grassland. Forest border or prairie in northeastern Kansas. Distribution of flora similar to present, but boundaries shifted to east somewhat. Pine and hardwoods along streams in southwestern Kansas. Sagebrush, ragweed, short grasses on uplands.
Modern Analogues	Southeastern Kansas; eastern Oklahoma; southern Arkansas (late Sangamonian). (Present-day Kansas probably an acceptable approximation of average conditions.)[9]

Wisconsinan Glaciation

Climate	Cool temperate; semiarid to subhumid. Less continental than present in early Wisconsinan. Annual precipitation similar to present in general. Gradational into a climate similar to present in medial and late Wisconsinan.

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[9] My inference.

Vegetation	Steppe or savanna in southwestern Kansas. Spruce forest in northeastern Kansas, succeeded by deciduous forest.
Modern Analogues	Eastern South Dakota; southwestern Minnesota.

Recent

Climate	Warm temperate. January average, 32° F (0° C); July average, 79° F (26° C). Eastern, and central Kansas subhumid (20 in. - 44 in. (50-112 cm) average annual precipitation). Western Kansas semiarid. (After Strahler, 1951, p. 345; Field Enterprises Educ. Corp., 1968, p. 192c.)

Conclusions

Although the inferences shown in the paragraphs above were drawn independently (for the most part) by vertebrate and invertebrate paleontologists, palynologists, and geologists, their conclusions are so convergent as to provide a well-founded consensus of the former environments. There is no basis in the stratigraphic record for the assumption that Pleistocene climates in Kansas were markedly different from those that prevail now, even during the glacial episodes. The only information I have discovered that suggests the former presence of frozen ground conditions of tundra climate is the single, questionable occurrence of ice-wedge casts in Kansan outwash in northeastern Kansas (Mudge and Burton, 1959, p. 106). (However, similar features may have been destroyed by weathering and erosion since Kansan time.) Glacial episodes seemingly were accompanied by climatic conditions somewhat cooler, more moist, and more equable than now. Climates of interglaciations probably were more equable than present-day climates, but were similar in other respects. General analogues of the former glacial climates are judged to exist today in the region of the eastern Dakotas, northeastern Nebraska, southwestern Minnesota and northwestern Iowa. The conclusion that tundra conditions were nonexistent (or were very restricted) near the margin of the Kansan ice sheet in Kansas can be tested by comparison of the evidence above with evidence from glacier-marginal regions east of the Mississippi River.

Ice-wedge casts occur locally in Wisconsinan deposits in north-central Illinois (Horberg, 1949; Frye and Willman, 1958) and west-central Indiana (Wayne, 1967, p. 396). Patterned ground in Wisconsinan deposits has been observed at a few places in west-central Indiana (Frye and Willman, 1958; Wayne, 1967, p. 396-398; 399). In no instance, however, have these features been shown to be abundant and widespread. Ice overrode living coniferous forest in southern and southwestern Ohio, where the proglacial zone of low temperatures may have been as narrow as one-half mile (Burns, 1958, p. 223; Goldthwait, 1958).

At the latitude of central Illinois, Wisconsinan ice sheets probably were bordered by a discontinuous, narrow zone of tundra climate, on the average only several miles wide (Frye and Willman, 1958, p. 532-534; Wayne, 1967, p. 403, 409-410; Flint, 1971, p. 498). Wisconsinan deciduous forest in southern Indiana and northern Kentucky, strongly similar to that of the present, suggests that tundra-like conditions did not exist in the ice fronts at the general latitude of the Ohio River (Frye and Willman, 1958, p. 524; Ray, 1965, p. 32-34; 45-46). If frozen ground and tundra climate did extend into Kansas, as suggested by the single occurrence of a possible ice-wedge cast cited above (Mudge and Burton, 1959) and implied by Flint as a generality (1971, p. 507), these conditions very probably were close by the ice front; the low temperatures probably were caused by proximity of the ice itself, rather than by regional cold climates. The assumption that climates in Kansas during glacial episodes were not markedly different from those at the present is therefore upheld by evidence from the Central Lowlands.

GLACIO-EUSTATIC CHANGES OF SEA LEVEL AND INCISION OF STREAMS

The Basic Problem

The primary question to be answered in regard to eustatic fluctuations of sea level is "Would eustatic drop in sea level of 350 to 450 feet (110-140 m) accompanying waxing of ice sheets (about the range estimated by Flint (1971, p. 321) and Russell, (1967, p. 22) for former stands of sea level during glaciations) lead to rejuvenation and downcutting of the Arkansas River and its tributaries in Kansas, or are these streams so remote from the Gulf of Mexico as to function independently from such geologically short-lived changes in sea level?"

Rejuvenation can be attributed to regional epeirogenic uplift, to lowering of local base level or of sea level, to decrease of sediment load of a stream, or to increase in volume of runoff as a result of increased rainfall or stream piracy (Thornbury, 1969, p. 139-140). Streams in the Great Plains and Central Lowlands were entrenched at several times during the Pleistocene. Their valleys were partially filled with alluvium, subsequently dissected to form depositional stream terraces. Valleys of the Arkansas, Missouri, Ohio and other large tributaries are partly filled with alluvium and the modern channel is in some places more than 100 feet (30 m) above the bedrock floor. That changes of climate during the Pleistocene influenced the amounts of erosion and deposition by the streams is generally accepted. The consensus of stated opinions of several geologists who have worked in the Great Plains and Central Lowlands regions is that glacio-eustatic changes in the Gulf of Mexico did not lead to alluviation or entrenchment of valleys of upstream tributaries of the Mississippi (Frye and Leonard, 1952, p. 15-16; Thornbury, 1969, p. 404 (but cf. Thornbury, 1965, p. 61-62); Ray, 1965, p. 24; Frye, 1961, p. 602). Of this group, only Frye and Leonard (1952) stated the basis of their opinion, namely that durations of glaciations and interglaciations were too short to permit migration of knickpoints or decreased gradients as far upstream as Kansas.

Explanatory Hypotheses

In keeping with the opinions of the several geologists cited above, two major hypotheses can be considered:

1) Glacio-eustatic fluctuation of sea level has not affected the regimens of continental-interior streams.
2) Conversely, glacio-eustatic fluctuation of sea level has affected the regimens of continental-interior streams.

If hypothesis (1) is true, other hypotheses follow. Entrenchment of streams during the Pleistocene in the Midcontinent region could be attributed to

(1a) the influence of changes of climate on stream regimens, or, inasmuch as cyclicity of climatic change is a foregone assumption, to
(1b) the interaction of effects of climatic change and rejuvenation by progressive long-term epeirogenic uplift.

If hypothesis (2) were true, the hypotheses that follow are

(2a) past entrenchment might have been a function of the combination of lowered sea level and climatic change, or

(2b) past entrenchment might have been a function of the interaction of lowered sea level, climatic change, and sustained epeirogenic uplift.

Of the four minor hypotheses stated above (1a, 1b, 2a, 2b) two have in common the factor of epeirogenic uplift. It follows that if evidence of epeirogenic uplift during the Pleistocene is substantial, the set of four minor hypotheses can be reduced to a set of two, (1b) and (2b). Fairbridge (1961, p. 547; 1966, p. 480, 484) showed evidence for progressive fall of sea level with each glaciaciation. Because measurement of sea level is referred to "stable" locations on land, perhaps some of the fall of sea level is apparent, being due to epeirogenic uplift of the continents. King (1965) has shown considerable evidence that indicates that epeirogenic upwarping of the continental interior occurred during the Quaternary. In the absence of stronger evidence to the contrary, entrenchment of streams in the Midcontinent seems likely to have been influenced both by climatic change and by long-term epeirogenic uplift. The hypotheses that should account for entrenchment of streams in the tributaries of the Mississippi therefore are:

1. Interaction of the effects of climatic change and rejuvenation by epeirogenic uplift; or

2. Interaction of the effects of glacio-eustatic drop in sea level, climatic change, and rejuvenation by epeirogenic uplift.

Thus, questions to be considered at this juncture are:

1. What kind of test can be devised to eliminate one of the hypotheses above?
2. If a test can be devised, are the means available for carrying it out?
3. If fluctuation of sea level is shown to be a factor in the incision of streams in the continental interior, what is the magnitude of its influence?

Tests of the Hypotheses

Five major delta-plain and fluvial terraces in the Gulf Coast region and in the Mississippi Valley as far north as Cape Gerardeau, Missouri (fig. 7) are composed of alluvium that seems to have been deposited during the three episodes of rising and high-standing sea levels of the classical Nebraskan-Aftonian, Kansas-Yarmouthian, and Illinoian-Sangamonian glaciations and interglaciations, the latter part of the early Wisconsinan glaciation and the "Peorian interglaciation" of the Wisconsinan, and during the Recent Epoch (Fisk and McFarlan, 1955; Bernard and LeBlanc, 1965; Russell, 1967, p. 24-26). Interpretation of the times of deposition of the materials in the terraces was made on logical grounds, but seems to have been independent of detailed

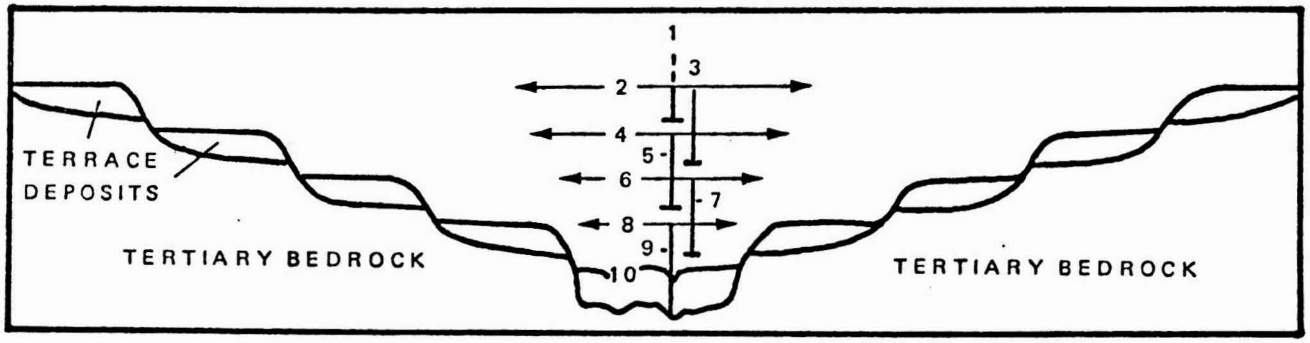

Figure 7.-Diagrammatic relationship of terraces on Gulf Coast and in lower Mississippi River Valley. (1) Nebraskan entrenchment. (2) Aftonian alluviation. (3) Kansan entrenchment. (4) Yarmouthian alluviation. (5) Illinoian entrenchment. (6) Sangamonian alluviation. (7) Early Wisconsinan entrenchment. (8) Peorian alluviation. (9) Late Wisconsinan entrenchment. (10) Recent alluviation. (After Fisk, 1944, and Bernard and LeBlanc, 1965, p. 171.)

correlation of the terraces with unquestioned interglacial deposits in the glaciated regions of the upper Mississippi River watershed. The emergent positions of the terraces at the present time of high sea level suggests that they were deposited during former episodes of rising and high sea level. The age assignments of Fisk and others are generally but tentatively accepted (Flint, 1971, p. 556-558). (Fairbridge (1968e, p. 1132-1133) present a strongly contradictory opinion, however.)

The ages of the delta-plain terraces of the Gulf Coast and fluvial terraces of the lower Mississippi River relative to the ages of fluvial terraces upstream in the Mississippi and its major tributaries is meaningful, because if deposition of the alluvium in the terraces was basically concurrent upstream and downstream, and if the trenching was a function of lowered sea level during glaciation, then the inference follows that downcutting attendant to drop in sea level may have been translated into the upstream tributaries in the Great Plains and Central Lowlands. Conversely, if trenching of valleys in downstream reaches of the Mississippi was accompanied by alluviation in the headwaters and tributaries, the question of glacio-eustatic influence on the regimens of continental-interior streams could be dismissed out of hand.

The postulate of Fisk and others that the sediments now underlying the coastal-plain terraces were deposited during rising and high-standing sea level of interglaciations could be tested of course, by certain correlation of the terraces into the upper Mississippi River Valley. Such correlation has been attempted, but opinions are highly divergent and information needed to resolve the dispute is not available (Flint, 1971, p. 558).[10] Unfortunately, this precludes definite knowledge of whether alluviation took place concurrently up and down the Mississippi River. An alternative approach exists, however, The Red River and the Oauchita River (fig. 8) were tributaries to the Mississippi during the Wisconsinan Glaciation (Fisk, 1944, fig. 78; Saucier and Fleetwood, 1970, p. 880), and probably at other times during the Pleistocene. It seems reasonable to assume that when these streams were alluviated, or entrenched, the Mississippi also should have been alluviated, or entrenched. Therefore, evidence that forms the basis for interpretation of the history of the Red River and Oauchita River valleys also should be applicable to inferences about the history of the lower Mississippi River Valley.

The relation of late Kansan terraces in several of the streams of Kansas to glacial deposits is well established by reference to the Pearlette volcanic ashbed, a marker unit that is found at many localities in stream

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[10] (Flint (1971, p. 556-558) and Thornbury (1965, p. 59-62) described the current state of knowledge. Trowbridge (1954) described some of the major points of disagreement among geologists of the Midwest and the Gulf Coast. Compare also Fisk and McFarlan (1955) and Bernard and LeBlanc (1965) with Fairbridge (1968e, p. 1132-1133).)

terraces and also in outwash deposits incised into Kansan Till (Frye, 1961, p. 601; Frye, Swineford and Leonard, 1948.)[11, 12]

Extension of this relationship into the basin of Red River, and into some other streams of northwestern Texas where the Pearlette ash is found locally, has shown consistently that (a) the valleys were heavily alluviated during the relatively dry retreatal stages of glaciation, that (b) incision occurred during the moist early and medial parts of glaciation, and that (c) interglaciations dominantly were

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[11] In this paper, age of Pearlette ash is shown as Yarmouthian, since revised. Nonetheless, important physical stratigraphic relationships are described.

[12] As discussed previously (p. 21, this paper) results of recent work cast serious doubts on the assumption that the Pearlette ash bed represents one correlative, lenticular unit of reworked deposits of a single late Kansan ash fall. The stratigraphic position of the Pearlette has been a formidable premise in many inferences about the Pleistocene stratigraphy of the Midcontinent; results of work by Izett and others (1970; 1971) and Boellstorf (1972) probably will make all regional correlations that have been based upon the Pearlette marker bed equivocal to some degree. Unquestionably, this recent work is a significant step toward better understanding of the Pleistocene. From an operational standpoint, however, I believe that at present, I have the choice either of accepting the recent conclusions about the Pearlette, or of considering the late Kansan age of the Pearlette, as commonly interpreted, to be accurate enough to be consonant with other general assumptions used in this study. In the present state of knowledge, to attempt to base inferences about regional Pleistocene history upon the work of Izett and others, and Boellstorff, would lead to confounding of the assumptions and evidence, and ultimately to no valid inferences at all. It seems that to base inferences on the classical interpretation of the Pearlette is to admit to oversimplification. However, this course is the only method that will permit a conclusion to be reached that is operationally meaningful.

periods of dynamic equilibrium during which extensive and well developed soils were formed (Frye and Leonard, 1963, esp. p. 31-32; Frye, 1961). This basic relationship also was determined in the Oauchita River Valley (Saucier and Fleetwood, 1970, esp. p. 879). (Fairbridge (1968d, p. 920) briefly stated an opinion contradictory to the statements above, without specific supporting field evidence; it almost certainly is incorrect.) Thus, this general assumption seems to be justified by a convergence of evidence from the lower Mississippi River Valley, some of its tributaries in Texas, and the general relationships of stream terraces in Kansas: the lower Mississippi River Valley and valleys of some of its southern former tributaries, including streams in Kansas, were heavily alluviated during the waning stages of glaciations and during the early parts of interglaciations. The valleys were incised during the early and medial stages of glaciations. Some portions of interglaciations were episodes of equilibrium, when soils were formed.

Two implications of this discussion are that in general, alluviation was accompanied by rising and high-standing sea level, and that incision occurred throughout the watersheds during falling and low-standing sea level. These results may be in conflict with evidence from the upper Mississippi River Valley in the glaciated states of the northern Midwest.[13] If so, the matter is almost irrelevant, for the problem at hand concerns primarily the Arkansas River and its tributaries, which of course do not extend into the upper Mississippi drainage basin.

The assumption of concurrent depositional and erosional episodes in upstream and downstream reaches of the Mississippi River and its southern tributaries, as supported by the foregoing discussion, indicates that in the ideal case, the possibility that effects of sea-level fluctuation might have been translated into the headwaters of the streams cannot be dismissed. The possibility having been admitted requires some estimation of likelihood of the actual occurrence.

Assuming that waxing glaciation and fall of sea level would introduce a reach of steepened gradient ("knickpoint") into the lower Mississippi, this hypothesis is in order:

(1) A reach of steepened gradient could migrate upstream as far as central Kansas and rejuvenate streams in that region.

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[13] I believe that many of the disputed points about this matter and similar problems may have as much to do with semantic inconsistencies that obscure the issues as with actual conflict of geological facts. Frye and Leonard (1953) discussed this matter effectively, but their recommendations seem not to have been generally accepted. Establishment of the "synchroneity" of similar Pleistocene events to the satisfaction of most students of the Pleistocene - at least inter-regionally - probably is not likely to occur unless some definitions of "glacial" and "interglacial" are adopted that are more uniform, more rigorous, and more utilitarian than those currently in use. This may be beyond achievement however. For related discussion see Morrison (1968).

Component hypotheses are:

(1a) A reach of steepened gradient would not be accommodated by the Mississippi or its tributaries before it migrated into Kansas.

(1b) A reach of steepened gradient would migrate upstream, and the rate of migration would be rapid enough that the steepened reach could move to central Kansas before deglaciation, alluviation, and effects of rising sea level could combine to negate its potential conseuqences.

The alternate hypothesis is of course: (2) A reach of steepened gradient could not migrate upstream as far as central Kansas and therefore could not contribute to rejuvenation of streams in that area. These hypotheses can be examined on the following grounds.

<u>Test 1</u>

The average slope of the sea bottom from the shoreline to the 300-foot (90-m) depth on the Mississippi delta complex is 3 to 5 feet per mile (0.6-1 m/km). However, seaward of the mouth of the present birdfoot delta, which is located a short distance from the continental slope, the sea bottom slopes at about 30 feet per mile (6 m/km). (Values calculated from Fisk and McFarlan, 1955, p. 282; see also Bernard and LeBlanc, 1965, p. 137). The Mississippi delta includes several subdeltas of Recent age, built as the river has changed its course and entered the Gulf of Mexico at

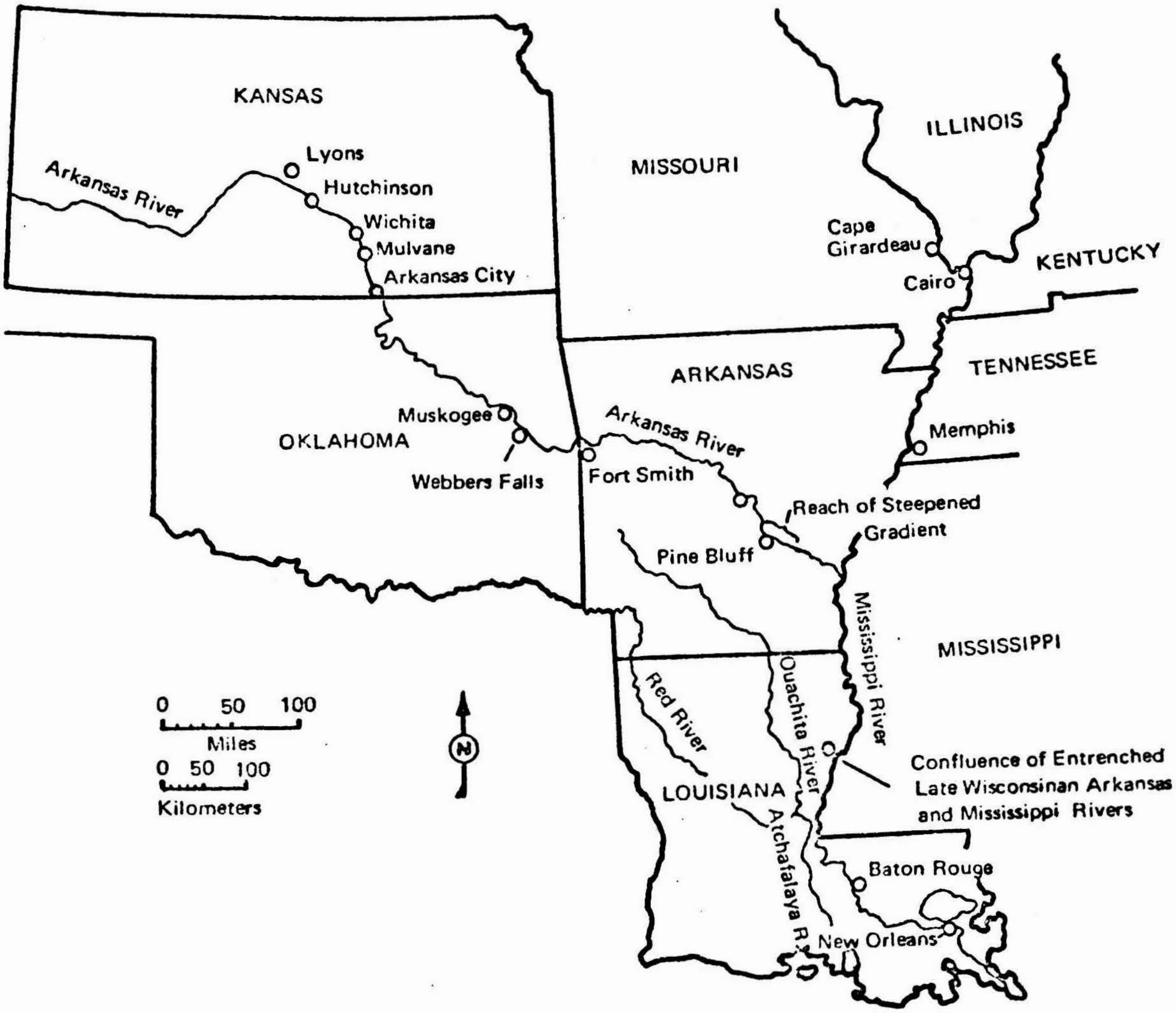

Figure 8.-Locations cited in discussion of effects of glacio-eustatic rise and fall of sea level. State boundaries along Mississippi River are simplified. Reservoirs on rivers not shown. Base after Chamberlin and Grazzini (1968).

several locations (Thornbury, 1965, p. 61-62). The assumption held here is that under normal conditions, the Mississippi progrades a delta and builds the delta plain until the river, being as extended as the modern Mississippi, is diverted into a shorter course with steeper gradient. (If natural conditions prevailed, the lower Mississippi soon would be diverted into the Atchafalaya River (fig. 8) (Thornbury, 1965, p. 62) and would flow into the Gulf of Mexico about 125 miles (200 km) west of the present birdfoot delta.) The building of the main delta complex by increments of subdeltas presumably will continue.

On the basis of these assumptions, two main conditions could exist at the onset of regression of the sea during the early part of a future glaciation: (1) the subdelta could extend to the edge of the continental shelf, as does the present one, or (2) a relatively young subdelta may be located near the shorelines of the delta plain.

During a future glaciation, the average rate of fall of sea level to stabilization at about -100 m (-300 ft) is assumed to be about the same as the rate of rise of sea level during the latter part of the Wisconsinan Glaciation, about 1 meter (3 ft) each 100 to 150 years (Flint, 1971, p. 326; Fairbridge, 1968c, p. 529). If the subdelta extant during a future glaciation extended to near the continental slope, like the present birdfoot delta, and if the slope of the ocean bottom seaward from the delta were similar to that at present (about 30 ft/mi) (6 m/km), then only about 0.1 mile (0.2 km) of the sea floor should be "exposed" each century. On the other hand, if a young subdelta were located near the general coastline, and if slope of the nearshore sea bottom were similar to that of the present (about 3 to 5 ft/mi) (0.6-1 m/km), about 1 to 2 miles (1.5-3 km) of the sea floor should be exposed per century.

Entrenchment of the Mississippi is presumed to have occurred during waxing glaciation and receding sea level, as argued above, and therefore much sediment should have been delivered to the Gulf of Mexico. Assuming that the rate of progradation of the subaerial delta plain would be essentially the same during future receding sea level as in the recent past (3.5 miles per century (5.5 km) (Bernard and LeBlanc, 1965, p. 151)), the delta should prograde at an average rate greater than the rate at which the sea bottom is "uncovered." The inference follows that consistent progradation of the delta at rates equal to or greater than the rate of recession of sea level in some instances might prevent altogether the development of an oversteepened reach in the lower Mississippi.

Test 2

This inference that progradation of the delta might preclude an oversteepened reach can be shown to be false in at least one instance. The Mississippi was entrenched across the continental slope during the Late Wisconsinan

Glaciation (Fisk and McFarlan, 1955, fig. 4). Steepened thalweg gradients and a submarine canyon were developed. Through a distance of about 250 miles (400 km), from the mouth of the submarine canyon to the confluence of the Mississippi and Arkansas River trenches, the thalweg gradient changed from 7 ft/mi (1.3 m/km) where the trench descnded from the continental shelf, to about 4 ft/mi (0.8 m/km) at the general latitude of New Orleans, about 2 ft/mi (0.4 m/km) at the general latitude of Baton Rouge, and about 1.1 ft/mi (0.21 m/km) below the juncture of the Arkansas-Mississippi trenches (fig. 8). (Gradients calculated from Fisk and McFarlan (1955, fig. 4) and Fisk (1944, fig. 78). See also Fisk (1944, pl. 11)).

The aspect of oversteepening of gradients in the lower Mississippi is shown by comparison of these gradients with the thalweg gradient south of Cairo, Illinois, about 0.8 ft/mi (0.15 m/km) (described by Russell (1967, p. 22) as "remarkably uniform" throughout the lower Mississippi; see also Fisk (1944, p. 16 and fig. 78)). Therefore, assuming that on the average, negligible difference exists between the thalweg gradients and water-surface gradients, the Mississippi River seems to have had a water-surface gradient of about 0.8 ft/mi (0.15 m/km) throughout its course south of Cairo, Illinois, to its juncture with the Arkansas River trench (fig. 8) during the Late Wisconsinan Glaciation.

Experiments on the migration of steepened gradients in noncohesive materials indicate that under natural conditions migration should occur only through short distances. The channel should adjust by localized erosion and deposition to make the oversteepened reach so gentle as to be undistinguishable from the average slope of the normal channel (Brush and Wolman, 1960), and thus should halt migration. The observed failure of knickpoints to develop where the gradient of the Mississippi has been steepened artificially by channel straightening supports this inference (Russell, 1967, p. 76). During episodes of entrenchment, the alluvial fill in the valley of the Mississippi was breached (fig. 7). For a considerable part of the time of entrenchment however, the river would have flowed through unconsolidated and noncohesive materials. The convergence of thalweg gradients in the main stem of the entrenched Late Wisconsinan Mississippi valley from about 7 ft/mi (1.3 m/km) on the edge of the continental shelf to a stabilized value of about 0.8 ft/mi (0.15 m/km) throughout a long distance upstream, as discussed above, suggests that channel adjustment in unconsolidated and poorly consolidated materials led to accommodation of steepened gradients, and could have established some limit on the inland translation of steepened gradients.

The gradient of the modern Mississippi south of Cairo, Illinois to Memphis, Tennessee (fig. 8) is about 0.46 ft/mi (0.09 m/km). South of the Arkansas-Louisiana border the gradient is less than 0.32 ft/mi (0.06 m/km) (Russell, 1940, p. 1216). Inasmuch as the gradients of terraces along the Mississippi are about the same as that of the Recent flood plain (Russell, 1967, p. 26), the assumption can be held that the normal gradient of the Mississippi during stages of alluviation (late glaciations-early interglaciations) was less than 0.5 ft/mi (0.1 m/km). On the basis of the discussion of oversteepened gradients above, on the assumption that the entrenchment during the Late Wisconsinan glaciation may be typical of former (and forthcoming) glaciations, and on the assumption that oversteepened gradients generally occur in the Mississippi when sea level declines, the inference follows that moderate steepening of the gradient of the Mississippi during the early-glaciation low stands of sea level may have occurred (and would occur) as far northward as Cairo, Illinois. But the gradient of the entrenched Mississippi above Baton Rouge seems to have steepened from less than 0.5 ft/mi (0.1 m/km) prior to entrenchment, and to have stabilized at only about 1 ft/mi (0.2 m/km). Presumably it would behave in similar fashion during the future.

Thus, at this juncture hypothesis (1) ("A reach of steepened gradient could migrate upstream as far as central Kansas and rejuvenate streams in that region.") has not been shown to be false, but, depending on the truth of the premises used above, an upper limit on steepening of gradient has been established. During episodes of waxing glaciation and falling sea level, no gradient steeper than about 1 ft/mi (0.2 m/km) should migrate from the Mississippi River into its inland tributaries. If the premises used above should be assumed to be false however, the problem can be approached from other standpoints.

Test 3

The potential effect of oversteepened reaches on a stream system is limited by these two principles: (1) During the migration of a knickpoint developed in response to falling sea level, the regimen of the watershed above the knickpoint would be unaffected by fall of sea level; tributaries in the watershed below the steepened reach would begin to adjust to the steepened gradient of the main stream. (2) A knickpoint with a gradient of x ft/mi could migrate upstream only throughout reaches in which the stream's extant gradient would be less than x ft/mi. When the knickpoint would migrate to convergence with an extant reach also of gradient x ft/mi, steepening of the stream and its tributaries in response to falling sea level would no longer occur.

Gradients of selected reaches on the modern Arkansas River are as follows (for locations see fig. 8):

Southeast and northwest of Pine Bluff, Arkansas - 0.8 ft/mi (0.15 m/km)

Fort Smith, Arkansas to Muskogee, Oklahoma - 1.2 ft/mi (0.23 m/km)

Arkansas City, Kansas to Mulvane, Kansas - 2.9 ft/mi (0.55 m/km)

Wichita, Kansas to Hutchinson, Kansas - 5.1 ft/mi (1 m/km)

By principle (2) in the preceding paragraph, the conclusion can be drawn from the gradients shown above that if rejuvenation and entrenchment of the Mississippi River by falling sea level should occur, and if during the early stages of entrenchment the valley were to acquire a thalweg profile similar to that of maximal entrenchment in the Late Wisconsinan, the resultant oversteepened gradients of about 1 ft/mi (0.2 m/km) in the lower Mississippi could migrate through the alluviated Arkansas River Valley only into central Arkansas. The drainage basin of the Arkansas River upstream from about Fort Smith, Arkansas should be unaffected.

Indeed, steepening of the gradient of the Arkansas River of central Kansas in response to lowered sea level would require the translation upstream of gradients steeper than 5 ft/mi (1 m/km). Two possibilities of such an occurrence seem to exist. (1) The translation headward of a steep gradient that might develop where the Mississippi would flow across the edge of the continental shelf could occur. But there is no evidence that justifies acceptance of this proposition, as the foregoing discussion shows that gentler gradients apparently evolved to stability upstream from the continental shelf during the Late Wisconsinan entrenchment. (2) Where the entrenched Arkansas River flowed from terrain of resistant Paleozoic rocks onto relatively weak Cretaceous and Tertiary rocks near Little Rock, Arkansas (fig. 8), a "fall line" developed (Fisk, 1944, pl.

11) wherein the gradient was about 10 ft/mi (2 m/km). If the Arkansas were re-entrenched to bedrock, this reach of steep gradient could migrate upstream. I the ideal case, if this reach could migrate rapidly enough and maintain its steepness, the Arkansas River of central Kansas and its tributaries in that region could be rejuvenated by steepening of gradient.

As stated above, during each episode of entrenchment the Mississippi River cut through its alluvial fill. With the general exception of entrenchment during the Illinoian Glaciation, alluvium in valleys of many streams in the Great Plains also was cut through during each glaciation (Frye and Leonard, 1957b, p. 38). If, for the sake of discussion, the assumption is held that the implications of Test 1 above are incorrect, and that a steepened gradient of more than 5 ft/mi (1 m/km) (sufficient to alter the regimen of the Arkansas River near Hutchinson, Kansas) could migrate upstream from the submarine canyon in the receded Gulf of Mexico, the reach would be translated through alluvium and locally, through bedrock for about 1150 miles (1850 km).[14] On the other hand, if the alluvium of the Mississippi and Arkansas Valleys were cut through as during the Pleistocene, the steep gradient at the fall line near Little Rock, Arkansas, could migrate headward. To reach central Kansas,

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[14] Bedrock crops out in the Arkansas river at Webbers Falls, Oklahoma, for example (fig. 8) (Wilson and Newell, 1937, pl. 1).

this steep gradient would be translated through about 550 miles (880 km).

Assuming that about one-half of the interglaciations were periods of near equilibrium of sea level, fall of sea level should have occurred during about the latter one-fourth of interglaciations and the earlier one-half of glaciations. If the glaciations and the interglaciations of the classical Pleistocene are assumed to be a random sample from a normal distribution (as discussed previously) the true mean duration, with 95 percent probability, of future "Pleistocene" interglaciations would lie between 170 x 10^3 years and 490 x 10^3 years, and of future "Pleistocene" glaciations between 60 x 10^3 years and 440 x 10^3 years. Therefore, if the beginning of migration of the oversteepened gradient were assumed to be coincident with the onset of regression during an average late interglaciation-early glaciation cycle of downcutting, the time range, with 95 percent probability, within which an oversteepened gradient could migrate to central Kansas would be 75,000 to 345,000 years, as calculated below.

Average interglaciations:
Minimal duration/4 = 170,000/4 = 45,000 yrs.
Maximal duration/4 = 490,000/4 = 120,000 yrs (rounded)

Average glaciations:
Minimal duration/2 = 60,000/2 = 30,000 yrs
Maximal duration/2 = 440,000/2 = 220,000 yrs

Combined:
Minimal interglaciation + minimal glaciation - 75,000 yrs
Maximal interglaciation + maximal glaciation = 340,000 yrs

Thus, under average conditions, a reach of oversteepened gradient would necessarily move headward from the mouth of the Mississippi, through alluvium and through bedrock, at some rate between about 0.003 mi/yr (0.005 km/yr) to about 0.015 mi/yr (0.024 km/yr), or about 16 to 80 ft/yr (5-24 m/yr). Under conditions of the Maximal Case (discussed on p. 45) an oversteepened reach translated from the mouth of the Mississippi necessarily would migrate headward at a rate greater than about 20 ft/yr (6 m/yr). Such rates might be attained in alluvium, but at places where the oversteepened reach would flow across bedrock, migration should occur at rates at least one order or magnitude slower.

To cut through the more than 200 feet (60 m) of alluvium of the lower Arkansas and Mississippi valleys and to re-expose the fall line in central Arkansas should require a considerable part of an episode of entrenchment. If only about one-fourth of the episode were required to breach the alluvium, the steep gradient at the fall line would necessarily migrate headward to central Kansas through resistant Paleozoic rocks at some rate between 10 and 50 ft/yr (3-15 m/yr). Under conditions of the Maximal Case, the rate of migration would be about 14 ft/yr (4.3 m/yr). Clearly, such rates would not occur.

Conclusions

On the basis of the evidence used here, the hypotheses stating that (a) the Mississippi system would not accommodate a reach of oversteepened gradient before it reached Kansas, and (b) that a reach of oversteepened gradient could migrate to Kansas within the reasonable probable limits of time are shown to be almost certainly false; by extension, the main hypothesis, stating that streams in central Kansas could be rejuvenated by headward migration of steepened gradients, is shown to be almost certainly false. The surviving hypothesis ((2), p. 70) asserts that a reach of oversteepened gradient that accompanied falling sea level would not migrate upstream as far as central Kansas. By similar argument, neither should rising sea level have affects in central Kansas.

In conclusion of this general topic, the single remaining major hypothesis from the array above leads to the premise accepted here that entrenchment of streams in the continental interior has been, and should be, the effect of only two factors, climatic change and epeirogenic uplift. Entrenchment of the Mississippi and its tributaries most probably is due to the greater competence and capacity of each stream during the early parts of glaciations than during the latter parts of glaciations and interglaciations. Increased precipitation and increased vegetation can be inferred to have generally accompanied the onset of glaciation; hence decreased sediment load can be inferred (in keeping with the theory of Langbein and Schumm (1958)). The main streams could therefore erode the alluvial fill of the preceding episode of waning glaciation and interglaciation.

Fall of sea level, rejuvenation of the Mississippi and its tributaries and entrenchment of valleys seem to be concurrent. But outside the Mississippi River itself these events seem only to be correlated, and to be independent of a direct "causal" relationship.[15]

METHODS OF INFERRING THE EFFECTS OF EROSION AND DENUDATION

Three specific questions to be answered regarding the safety of the proposed repository are: (1) Would the repository be breached by lowering of the Arkansas River drainage basin to such a level that the Hutchinson Salt Member would be penetrated at or near the repository? (2) Would the repository be breached directly, by a stream cutting through its roof? (3) How might the effects of potential stream piracy be related to events described in questions (1) and (2) above?

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[15] The fall line in the entrenched Arkansas River at Little Rock might be considered as evidence that steep gradients in fact migrated long distances up the Mississippi. However, construction of the knickpoint could have occurred as a result of the river flowing from terrain of resistant Paleozoic rocks onto terrain of easily eroded Cretaceous and Tertiary rocks.

Denudation

Denudation rates are measurements of the lowering of the land surface within a drainage basin. They are computed from amounts of material removed from drainage basins as suspeneded load, dissolved load, and bed load. Rates of denudation cannot be interpreted so as to yield measurements of differential lowering of the land surface within a drainage basin. They yield information only about the rates of uniform lowering of the surface, and in this regard they are somewhat artificial. Nevertheless, denudation rates are valuable information for inferences of the past and future average vertical positions of drainage basins within the landscape.

Valley Erosion

Valley erosion is defined here as the entrenchment and lateral migration of a stream channel within bedrock. The term "stream entrenchment" refers to vertical incision of a stream into bedrock or into alluvium filling its valley. The variables of which valley erosion has been a function are not well known. Cyclicity of valley erosion has been a function are well known. Cyclicity of valley erosion and valley filling is well recognized from the Pleistocene history of the Mississippi River and of some other streams of the Midcontinent. The observation that most streams of the

Midcontinent have entrenched their valleys deeper into bedrock during each glaciation except the Illinoian (Frye and Leonard, 1957b, p. 37-38) is true in most instances, but exceptions to the general rule seem to be numerous enough to require that the generality should be applied cautiously. (This matter will be discussed in a following section.)

Constraints of the Information Base

In a foregoing part of this report, major variables that affect the long-term performance of streams were defined as epeirogenetic movements, glaciations and interglaciations, and the relative durations of climatic episodes. Epeirogeny presumably has been continuous, although not constant, throughout the Pleistocene; it is assumed to occur now and to continue throughout the next one million years. Because the rate of epeirogeny in the Midcontinent cannot be measured directly, and to my knowledge has not been estimated, it follows that no approximations of its variation are obtainable. The condition enforced thereby is that the rate of epeirogeny, whatever that rate may be, for practical purposes can be considered to be constant. This premise defines glaciations and interglaciations, and other climatic variations, and their durations as the remaining "uncontrolled" variables.

Because durations of future climatic episodes have been estimated under the Maximal-Case construct (p. 45) thereby "fixing" this variable, the variations of climatic conditions among glaciations and interglaciations stand as the unregulated major variables. As discussed previously however (p. 57-59), the information about past climates that is available to be evaluated now is a kind that permits only qualitative estimation of climatic conditions that existed during glaciations and interglaciations of the classical Pleistocene. The information is not useful for estimation of the variations among glaciations and among interglaciations. Therefore, only qualitative estimations can be made of climatic conditions that should occur during glaciations and interglaciations of the future.

In brief, of the three major variables determinant in stream erosion and denudation, only the durations of near-past and near-future climatic episodes can be quantified (and that quantification is general). By adherence to the principle of simplicity, the working assumptions having to do with rates of epeirogeny or changes of climate should be the simplest assumptions that will explain the available facts about epeirogeny and changes of climate. On this premise therefore, there seems to be no factual justification for any assumptions other than that the rate of epeirogeny is effectively constant, and that the climatic conditions of glaciations and interglaciations in central Kansas are represented typically by areas of sympatry (in the instance of glaciations) and by conditions of the present (in the instance of interglaciations).

If these assumptions are held, modern rates of denudation for selected watersheds can be used to approximate long-term conditions by extrapolation across the durations of future glaciations and interglaciations. Present rates of denudation in a specified drainage basin can be transformed to rates presumed to be representative of glaciations by appropriate scaling. The scaling can be done with reference to parameters computed from drainage basins that are in areas of sympatry, and that are similar in major attributes to specified drainage basins in Kansas.

Because no methods seem to have been derived whereby to establish the relationships between rates of denudation and valley erosion within modern valleys, the modern records of stream discharge, suspended sediment, and dissolved solids that are used to compute denudation cannot be used to compute rates of valley erosion. Because effective constancy of the rate of epeirogeny and uniformity of climatic conditions among glaciations and among interglaciations are enforced assumptions, and because of the variations among drainage basins in amounts of erosion and in history of erosion, the conclusion is forced that insofar as is practicable, estimates of past rates of valley erosion (and by implication, estimates of future rates of valley erosion) of any stream should be made on the basis of evidence contained in the drainage basin of the stream. Accordingly, this premise is defined: the Pleistocene history of entrenchment of a stream serves as the best model of the future entrenchment of the stream.

Rationale for Inferring Effects of Erosion and Denudation

Inferences about the potential effects of erosion and denudation will be made on the basis of the Maximal-Case construct wherein the probability of occurrence of previously specified climatic episodes is 0.01. The simplified primary working hypothesis is stated here as: (1) under the Maximal-Case concept, the proposed repository would be breached by erosion of the bedrock overlying the Hutchinson Salt Member. The alternate hypothesis, of course, is (2) under the Maximal-Case concept, the proposed repository would not be breached by erosion of the bedrock overlying the Hutchinson Salt Member.

Because, to my knowledge, there is no means by which to extrapolate from modern measurements of stream discharge, suspended sediment load, bed load, and dissolved load to prediction of the variable erosion within watersheds, the primary hypothesis will be tested by independent statement and testing of subordinate hypotheses regarding the predicted effects of denudation and of valley erosion.

PHYSIOGRAPHIC AND GEOLOGIC SETTING OF CENTRAL KANSAS

Kansas comprises several physiographic regions (fig. 9) each of which is delineated on the basis of its bedrock geology and topography.

The High Plains of western Kansas are underlain by the Pliocene Ogallala Formation, a thick sequence composed mostly of silt, sand, and gravel deposited by streams that flowed eastward from the Rocky Mountains. The Smoky Hills, Red Hills and Wellington Area provinces are underlain by Cretaceous and Permian bedrock respectively, and are dissected by streams that flow eastward from the Ogallala Formation. Great Bend Province is an extensive alluvial plain underlain by Nebraskan, Kansan, and Illinoian fluviatile deposits. The Flint Hills Upland is composed of a series of cuestas developed upon westward-dipping, chert-bearing, resistant Permian limestone strata. Permian and Pennsylvanian strata that dip gently westward underlie the Osage Cuesta Plains and the Cherokee Plain, and extend beneath the Pleistocene deposits of the Dissected Till Plains.

Evolution of Stream Systems in Western and Central Kansas

The Pennsylvanian System of Kansas was overlapped by the Permian Wolfcampain and Leonardian series which extended across Kansas and some distance into Missouri (McKee, Oriel, and others, 1967, pl. 9). Triassic rocks are not present in Kansas, and Jurassic rocks are present only in the subsurface in the western part of the state (Zeller and others, 1968, p. 53-54). Eastern Kansas was emergent during the latter part of the Permian (McKee, Oriel, and others, 1967, pl. 9), and

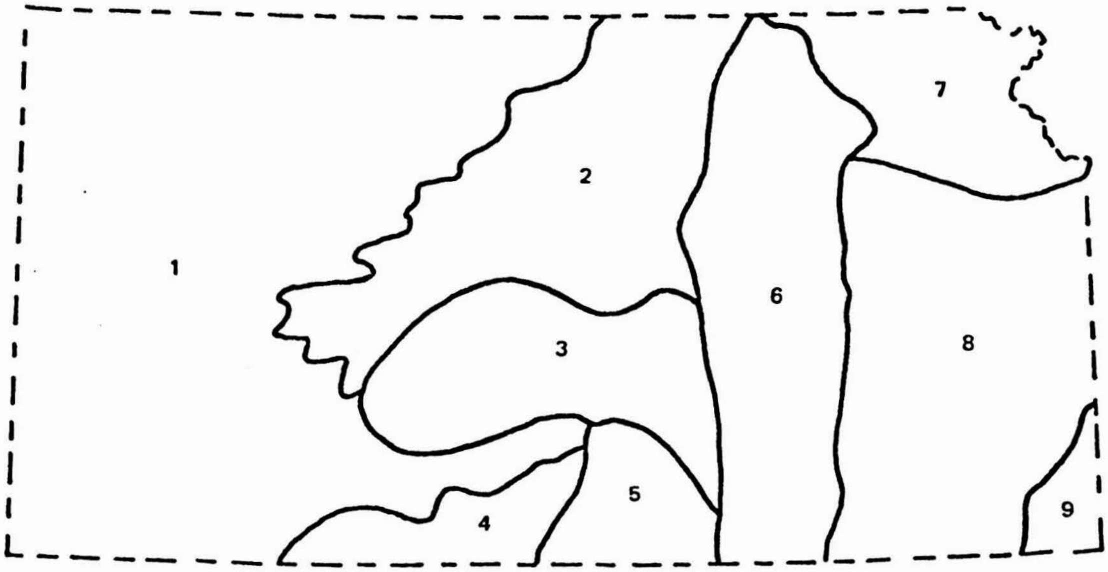
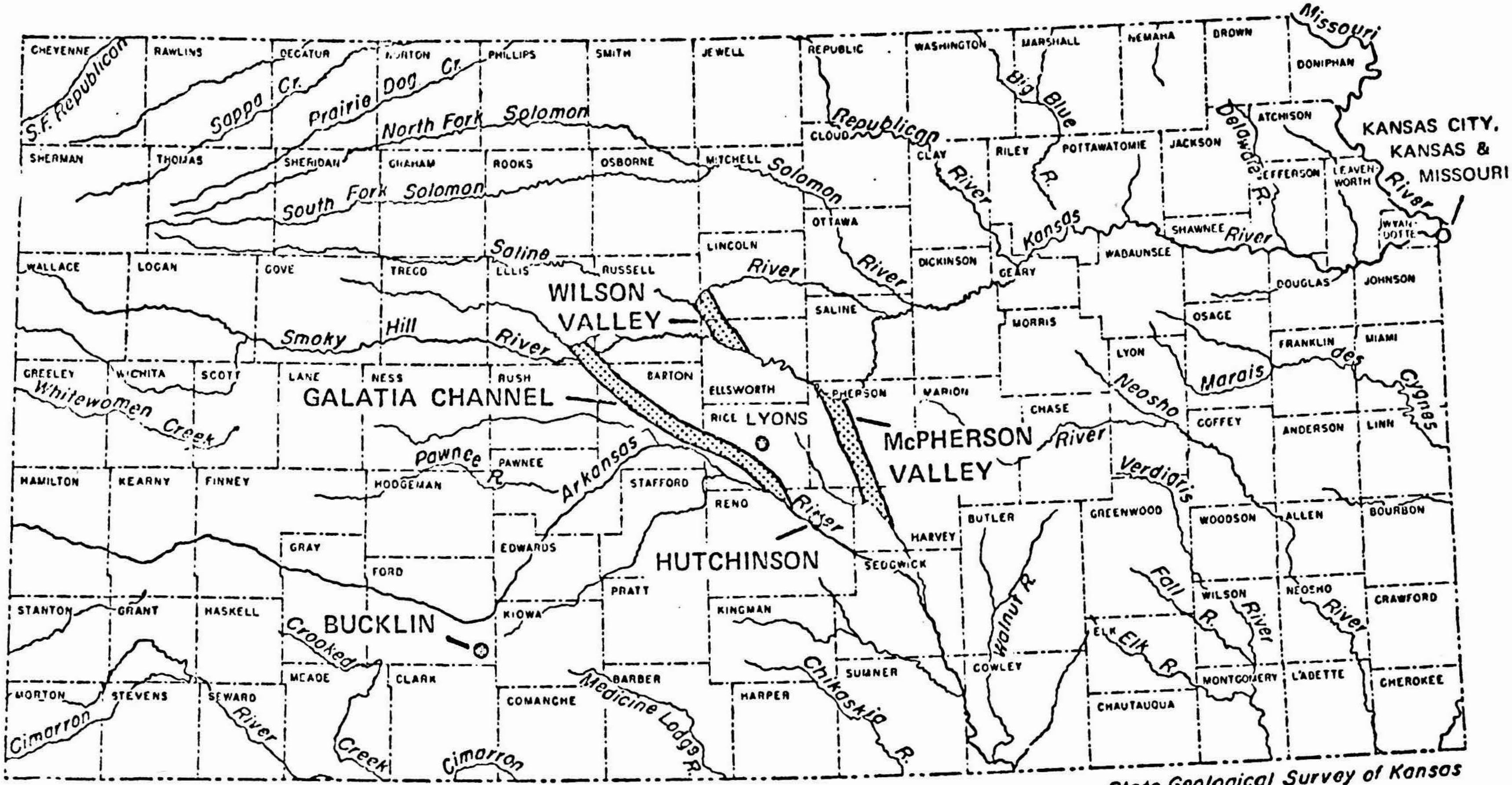


Figure 9.-Physiographic provinces of Kansas. 1- High Plains. 2- Smoky Hills. 3- Great Bend. 4- Red Hills. 5- Wellington Area. 6- Flint Hills. 7- Dissected Till Plains. 8- Osage Cuesta Plains. 9- Cherokee Plain. (After Frye and Leonard, 1952, p. 202.)

all of Kansas was emergent during the Triassic Period. Easastern and central Kansas were emergent during Jurassic time. Pennsylvanian and Permian beds were beveled by erosion during the latter part of the Permian Period, the early part of the Mesozoic Era, and, as shown by Frye and Leonard (1952, p. 180-181), during the early part of the Cretaceous Period when seas advanced eastward, overstepping the dissected pre-Cretaceous topography. The farthest eastward extent of Cretaceous beds is not known, but the Pennsylvanian and Permian terrain probably was overstepped - at least locally - as far eastward as Johnson County, Kansas (O'Connor, 1971, p. 27-28) (see Figure 10, this paper, for location of Johnson County).

Continental erosion during the Paleocene, Eocene, Oligocene, and Miocene epochs of the Tertiary Period removed Cretaceous rocks from Kansas east of the Flint Hills. Peneplain-like topography seemingly was developed upon the Pennsylvania and Permian bedrock in eastern Kansas. Some of the Cretaceous rocks of central Kansas were eroded from above the underlying Permian rocks locally during these epochs of the Tertiary. By early in Pliocene time, the Flint Hills were a terrain of moderately high-standing, eastward-facing cuestas that separated regions of very low relief on the east and west.

During the Pliocene, the truncated Cretaceous and Permian rocks that lay to the west of the Flint Hills may have been covered entirely by the dominantly fluvial deposits of the Ogallala Formation, for large outliers of the Ogallala



State Geological Survey of Kansas

Figure 10.- Counties, major rivers, and selected cities of Kansas. Galatia channel, Wilson Valley and McPherson Valley, abandoned Pleistocene river valleys also are shown. (After Bayne, Franks, and Ives, 1971, fig. 16, 19, pl. 2; and Jewett, 1964.)

System	Series	North American Stages, Geologic-Climate Units, and Special Lithostratigraphic Units			Stratigraphic Equivalents of the Mediterranean Region
Quaternary	Pleistocene	Kansan Glaciation			
		Aftonian Interglaciation		Fullerton Fm.	Upper Villafranchian Stage
		Nebraskan Glaciation		Holdrege Fm.	Middle Villafranchian Stage
Tertiary	Pliocene	Asian Stage	Ogallala Formation	"algal limestone" Kimball Member	Astian Stage-- Lower Villafranchian Stage
				Ash Hollow Member	
				Valentine Member	

Figure 11.- Standard time scale of the Pliocene and the earlier part of the Pleistocene, showing correlative units of North America and Europe (after Moore, 1949, and Tobien, 1970). Although the Holdrege and Fullerton formations are Nebraskan, their positions in the illustration above are intended to show informally that inasmuch as the uppermost Fullerton shows evidence of development of Aftonian soil, these lithostratigraphic units are records of Nebraskan and Aftonian time (see Zeller, 1968, p. 66; Fent, 1950, p. 64; Frye and Leonard, 1952, p. 61, 68-69; and Bayne, 1956, p. 71).

are present as far eastward as McPherson and western Marion counties (fig. 10), near the western flank of the Flint Hills (see Jewett, 1964). Several remnants of the so-called "algal limestone," the uppermost beds of the Ogallala (fig. 11), are present on the crest of the divide between the Saline and Smoky Hill rivers in Russell and Lincoln counties (fig. 10), there are many exposures in Ellsworth County (Bayne, Franks and Ives, 1971), and isolated exposures also have been found in Barton and Rice counties (fig. 10) (Frye, 1945; Fent, 1950; Merriam, 1963, and authors cited therein, Appendix A).

The "algal limestone" probably is an almost synchronously deposited relict caliche, formed during latest Pliocene and perhaps early Pleistocene time on the irregular, but generally low-relief, eastward-sloping surface of the Ogallala Formation and Cretaceous rocks (Swineford and others, 1958; Bayne, Franks and Ives, 1971, p. 27-29). The prevailing climate probably was long-lived and comprised alternating arid and moderately wet periods (Swineford and others, 1958, p. 114-115; Reeves, 1970, p. 359.) Assuming former continuity of the so-called algal limestone, which seems to be a reliable premise, the exposures in Russell, Ellsworth, Lincoln, Barton, and Rice counties provide a basis for inference of the early history of the stream system of central Kansas, in the context of the following points:

a) The Ogallala Formation is demonstrably of Pliocene age and is predominantly a fluvial deposit.

b) The "algal limestone" is the topmost unit of the Ogallala Formation and probably is the youngest Pliocene unit in Kansas.

c) The "algal limestone" is a caliche, not a fluvial deposit.

d) The "algal limestone" suggests therefore that during its accumulation rainfall was low, that fluvial processes were markedly reduced, were about in equilibrium with deposition, and perhaps were even non-effectual in large areas of western Kansas (see also Swineford and others, 1958, p. 114-115).

e) Remnants of the "algal limestone" overlie Cretaceous rocks on the highest parts of the Saline River-Smoky Hill River drainage divide at several places in central Kansas (references shown above).

f) The streams that have dissected the "algal limestone" and Cretaceous rocks in central Kansas also dissect the Ogallala Formation and the "algal L limestone" in their headwaters in western Kansas.

g) Therefore, the streams that now flow through western and central Kansas did not deposit the "algal limestone", but almost surely were established contemporaneously with deposition of the limestone, or evolved on its upper surface (see also discussion by Bayne, Franks, and Ives, 1971, p. 27).

h) Therefore, these streams probably are as young as or are younger than the latest Pliocene rocks of central Kansas. As the Ogallala Formation probably overstepped Cretaceous and maybe Permian rocks as far eastward as the western flank of the Flint Hills, the streams that cross central Kansas today probably have been superimposed throughout most of their courses - if not all of their courses - from the top of the Ogallala Formation into Cretaceous and Permian bedrock.

Thus the erosion and denudation of valleys and watersheds of central and western Kansas seem to be dated reliably as having begun no longer ago than late in the Pliocene Epoch or early in the Pleistocene (Swineford and others, 1958, p. 114), the precise demarcation of which cannot be made on the basis of areal geologic evidence. (This approximate date is consistent with conclusions of Soister (1967) as to the age of establishment of the Arkansas River of eastern Colorado.)

RATE OF DENUDATION, ARKANSAS RIVER DRAINAGE BASIN, CENTRAL KANSAS

Rates of denudation are defined as measurements of uniform lowering of the land surfaces within drainage basins. The earliest research on this subject in the United States was the general survey of denudation rates by Dole and Stabler (1909). Recent descriptions of denudation rates in the United States are included in papers by Judson and Ritter

(1964) and Ritter (1967; 1968). Denudation rates in various climatic regions of the world were discussed by Corbel (1959). Many other papers deal with rates of denudation of local drainage basins as determined from suspended and bed loads or dissolved loads, or both, or from areal geologic information.

Method of Computation of Denudation Rates

The basic method of computing the denudation rates of a drainage basin was stated by Dole and Stabler (1909, p. 80-81) as:

a) Annual denudation, as tons of suspended and dissolved sediment per square mile = (solids (ppm)) x (discharge (cu ft/sec/sq mi) x (0.985).[16]

b) Annual denudation, as 10^{-6} in/sq mi = (tons/sq mi) x (0.1917).[16]

Specific gravity of sediment was assumed to be 2.64, corresponding to an average density of 165 lbs/cu ft (2.64 g/cu cm) of solid rock of the upper part of the crust. The basic method of Dole and Stabler has been used with only minor modification, and some recent computations of denudation rates are based on the simple formula: denudation (in/10^3 yr) = (tons/sq mi/yr) x (5.2×10^{-3})[16] (Judson and Ritter,

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[16] Derivations of the constants are not shown by Dole and Stabler (1909) but they are included herein in Appendix B. Derivation of the constant 5.2×10^{-3} is not shown by Judson and Ritter (1964) but it is a rearrangement of the formula of Dole and Stabler (1909) and is included in Appendix B, this paper.

1964, p. 3395-3396). Measurements of suspended and dissolved loads used in the computations mostly are those reported by the U. S. Geological Survey in water-supply reports. Amounts of bed load commonly are estimated as a fraction of the suspended load.

General Variables and Sources of Error

Natural variables that influence the sediment yields of drainage basins, hence the denudation rates, are numerous indeed, the more obvious of which include climate, vegetation (Langbein and Schumm, 1958), drainage area and drainage-basin relief (Schumm, 1963), and properties of bedrock and soils. (For more complete discussion of natural variables see Anderson, 1954; Cleaves and others, 1970; Douglas, 1964; Gibbs, 1967; Glymph, 1954; Janda, 1971; and Judson, 1968. Many other papers deal with this general subject, of course, but these survey the topic.)

Artificial variables chiefly are the many activities of man which almost without exception tend to accelerate rates of denudation. Activities that increase yields of suspended sediment include mainly deforestation and cultivation, urban construction activities, and mining (for general discussion see Brune, 1952; Judson, 1968; Leopold, 1956; and especially Meade, 1969). Activities that markedly increase the dissolved loads of some streams are mining, production of petroleum and natural gas, use of fertilizers and pesticides, air pollution, and various other forms of industrial and domestic pollution, most of which contribute dissolved solids directly, and some of which lead to comparatively rapid rates of solution of some kinds of bedrock (see Meade, 1969; Winkler, 1970).

Consequently, accurate and precise determination of rates of denudation of regions of the United States, as the rates might have been when the terrain was in its pristine state, seem to be beyond achievement. Rough estimates of the net acceleration of denudation rates by man's occupancy of the land generally range from about a factor of 10 to a factor of 100, and for small areas, 1000 (Meade, 1969, p. 1267; Brune, 1952, p. 37-38; Judson, 1968, p. 365-366).

Other sources of error that enter measurements of denudation rates are the portion of the dissolved load that enters the fluvial system from the atmosphere, orginating naturally as salts from the oceans and as soil dust, and artificially, as various forms of air pollution, including soil dust. The atmospheric contribution to total dissolved load locally is as much as 50 percent in some regions, even in the interior of the continent (Meade, 1969, p. 1271-1272; Janda, 1971). Other dissolved constituents occur in stream water owing to breakdown of organic materials in the soil (Janda, 1971, p. 69).

Even if all the effects of artificial variables due to man's activities and of natural variables due to atmospheric salts could be subtracted during computations of denudation rates, the remaining values would not necessarily be accurate estimates of denudation, in the strict sense of the term. In instances where part of the dissolved load in the surface-water system actually enters the system as ions in connate water that migrates from marine sedimentary rocks, the computed denudation rates are proportionately erroneous, as these ions have not been removed strictly from the bedrock. Even is the amounts of solid bedrock dissolved in surface water could be determined accurately, the transformation of these amounts into rates of denudation would be somewhat misleading of course, inasmuch as ample areal geologic evidence exists to show that considerable dissolution of subsurface rock can occur without concommitant lowering of the land surface. So, in some respects, measurements of denudation rates from dissolved loads unavoidably tend to be overestimated. On the other hand, measurements of denudation owing to solution of bedrock that are contained in the literature seem to be based exclusively on surface-water records; they therefore do not take into account the amounts of dissolved solids removed from drainage basins within downstream ground-water flow in alluviated valleys.[17]

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[17] If measurements of denudation owing to this process have been made and published, I have not discovered them in the course of a reasonably extensive search. I conclude therefore that this aspect of the matter is largely unevaluated.

Basic Assumptions and Purpose of the Experiment

The foregoing discussion and the published evidence referred to above should be sufficient to show that measurement of denudation rates in the explicit connotation of the term is unachievable, and that close approximations of denudation rates are the best results that can reasonably be expected. As stated previously, the main purpose of this part of the problem is to determine the likelihood that the proposed repository would be unroofed by denudation in the Owl Creek drainage basin (fig. 12). In consideration of this practical aspect, and in consideration of the impracticality of accurate measurement of natural denudation rates, the _ad hoc_ assumption is stated that contemporary circumstances of flow and sediment yield are typical of those that will occur under the interglacial regimen of the Arkansas River drainage basin of central Kansas. This assumption accepts as natural factors all the influences of human activities on the regimen of the Arkansas River. The operational value of the bias introduced by this assumption is to reduce the risk of underestimating the long-term effects of denudation in central Kansas.

Denudation Rates of the Arkansas River Near Hutchinson, Kansas

Denudation rates of the Arkansas River near Hutchinson were computed following the basic formulae of Dole and

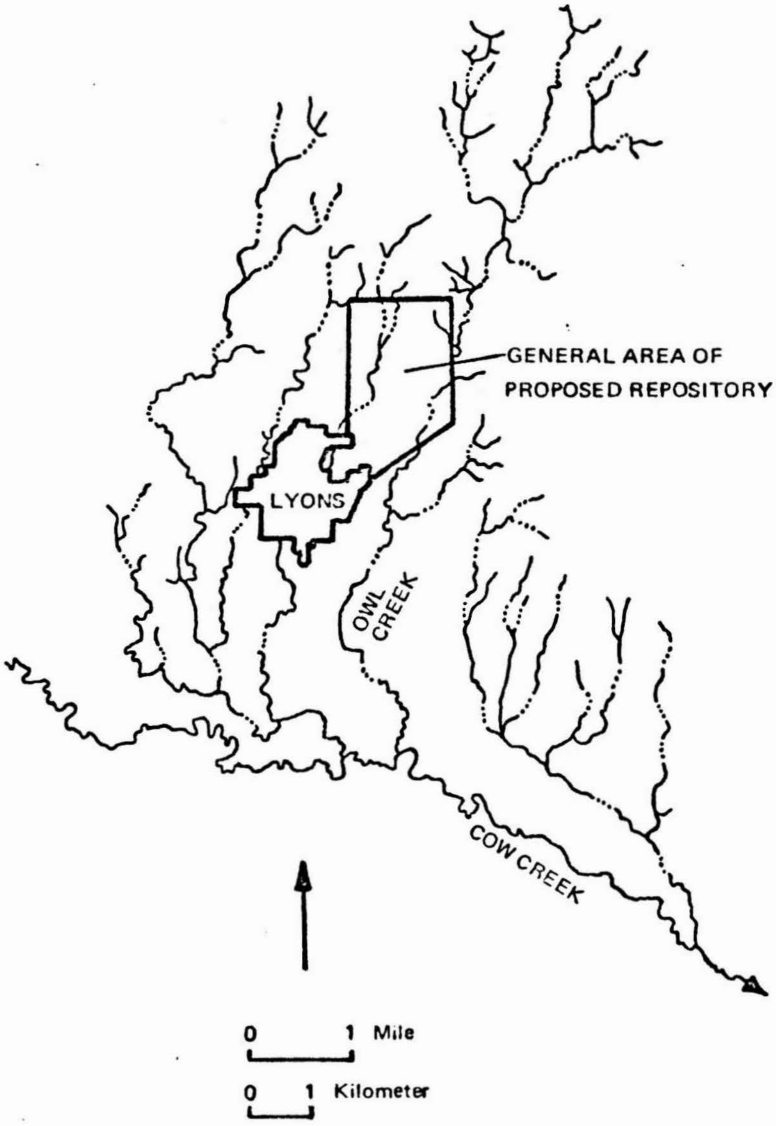

Figure 12.- Location of the proposed repository with respect to Lyons, Owl Creek and Cow Creek. Cow Creek flows into Arkansas River near Hutchinson, about 25 miles (40 km) southeastward from Lyons (fig. 10). (After Fent, 1950, pl. 2; Bayne, Ward, and O'Connor, 1971, fig. 11; and Goebel, 1971, p. 40.)

Stabler (1909) as stated by Judson and Ritter (1964), and as shown in Appendix B. Sources of values of discharge and suspended and dissolved loads are water-supply papers published by the U. S. Geological Survey and the State of Kansas. These sources are shown in Appendix C. The water-supply reports show values of annual discharge either as acre-feet or as values that can be converted to acre-feet. They show values of annual suspended load in tons. Some records of the Arkansas River at Hutchinson show only sets of about 10 to 20 daily measurements per year of dissolved load in parts per million. Other records show sets of about 10 to 20 daily values of dissolved load in tons. Both kinds of values were used to compute single-value estimates of annual dissolved load and denudation due to solution of bedrock. These values are assumed to be accurate estimates of annual denudation due to solution of bedrock. Accordingly, in addition to the effects of natural and artificial variables as discussed above, denudation rates of the Arkansas River discussed here contain some variation due to small-sample estimates of dissolved loads.

Statement of the Problem

Owl Creek and a smaller, unnamed creek flow across the site of the proposed repository. They are tributary to Cow Creek (fig. 12); Cow Creek is tributary to the Arkansas River. It follows that denudation rates of the Arkansas River or of Cow Creek establish an upper limit upon denudation rates of streams that cross the repository site. The basic problem at this juncture therefore, is to develop a method whereby modern denudation rates of this system, rates assumed to be characteristic of interglacial episodes, can be extrapolated across time as specified in the Maximal-Case construct so as ultimately to determine the likelihood that the proposed repository would be unroofed by denudation.[18]

An intuitive response to survey of the problem is the simple inference that inasmuch as the term "denudation" is defined to mean removal of sediment from a drainage basin by the stream itself, some direct relationship should exist between discharges of streams and their denudation rates from which a predictive method could be derived. Accordingly, the basic working hypothesis is stated that (a) a direct relationship in the Owl Creek-Cow Creek-Arkansas River system exists between discharge per unit of time and denudation per unit of time, and (b) this relationship can be used to extrapolate across the time specified in the Maximal-Case construct.

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[18] Several methods of predicting denudation rates were explored during the course of this study. All methods yielded information of value, of course, but most methods produced answers that were somewhat imprecise and inaccurate (for example, see Stewart, 1971, p. 2-3). Several cycles of hypotheses and tests that led to insufficient answers have preceded the results reported here. The following passages summarize only the last generation of hypotheses and the tests to which they were subjected.

Constraints of the Information

In the ideal case, measurements of discharge, and suspended and dissolved sediment load and bed load of Owl Creek would have been measured throughout a long period of time. In the actual case, discharge, and suspended and dissolved sediment loads only of Cow Creek and the Arkansas River have been measured throughout a short period of time, and seemingly bed load cannot be measured accurately in any case (Leopold, 1956, p. 640). Available records pertaining to Cow Creek and measured at Lyons, Kansas, are not as complete as records pertaining to the Arkansas River near Hutchinson, Kansas. Cow Creek is close to the repository site, of course, and therefore analysis of these records is desirable. However, records of the Arkansas River near Hutchinson were taken only about 4 miles (6.5 km) downstream from the confluence of Cow Creek and the Arkansas, and inasmuch as the denudation rates of the Arkansas establish limits on those of Cow Creek, the superior quality of records from near Hutchinson is a matter of overriding importance. The analyses that follow are based on records of the Arkansas River near Hutchinson, except where specified otherwise. In computations of denudation rates, bed load is estimated to be 10 percent of suspended load.

Water Year	Total Discharge (acre-feet)	Denudation Rate ($ft/10^6$ yr)
1962	515,756	20.0
1963	284,945	9.9
1964	145,860	5.6
1965	716,864	35.2
1966	428,784	16.2
1967	430,816	16.8
1968	171,153	7.1
1969	466,850	18.5
1970	332,000	12.6
1971	242,900	11.8

Table 5.- Annual (water-year) discharges and denudation rates of the Arkansas River near Hutchinson, Kansas, water years 1962 through 1969. Sources of data shown in Appendix C. For conversion of numbers to metric system: (a) discharge (acre-feet) x 1233 = discharge (cu m); (b) denudation rate ($ft/10^6$ yr) x 0.3048 = denudation rate ($m/10^6$ yr).

The statistical populations of concern at this point are defined as annual discharges and annual denudation rates of the Arkansas River near Hutchinson. The values shown above are regrettably small samples from which to draw inferences about the entire populations. Nevertheless, they compose the entire available populations, and as such, represent the maximal amount of information.

The hypothesis is stated at this point that inasmuch as annual (water-year) discharges and denudation rates are continuous variables, the hypothetical populations comprising all annual discharges and all annual denudation rates of the Arkansas River can be approximated by the normal distribution. The assumption is held that the values shown in Table 5 above are random samples. Because these few samples make up the total available populations, a deliberate random-sampling design is not practicable. The assumption of randomness implies that for the purpose of this experiment, the manner of tabulation of the raw data included no procedures, premeditated or otherwise, that would bias the samples. (See p. 31-47 for a more complete statement of the background of testing procedures.)

Tests for Normality of the Populations

The null hypothesis is:

H_o: Annual (water-year) discharges and denudation rates of the Arkansas River near Hutchinson, Kansas, shown in Table 5, are random samples drawn from normally distributed populations.

Alternate hypotheses are:

H_1: The samples of discharges and denudation rates are random samples drawn from populations that are not normally distributed.

H_2: The samples of discharges and denudation rates are non-random samples drawn from populations that are normally distributed.

H_3: The samples of discharges and denudation rates are nonrandom samples drawn from populations that are not normally distributed.[19]

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[19] Alternate hypotheses H_2 and H_3 are stated only for completeness. If the null hypothesis is rejected, one of the alternate hypotheses is true; but because all of the available population is included in the sample, there is no option to take samples under another sampling plan and no option to make randomness more nearly certain by changing sampling procedures. Accordingly, there is no method based on *a priori* evidence to allow judgment between randomness and nonrandomness of samples, and to choose among the alternate hypotheses. So, if the null hypothesis were to be tested and rejected here, the samples would still be assumed to be random, and the set of hypotheses would be restructured on the basis of the assumption that the variables are not normally distributed on the linear scale, but are so on a logarithmic scale, or some other scale, such as square roots, etc.

The above argument that proposes no alternate sampling plans can be challenged, of course. Values used in computations, such as discharges of streams or denudation rates, need not be water-year values; they could be daily, weekly, or monthly values, and so forth. However, results of experiments, not reported here, using records of discharge of the Mississippi River indicate that as the lengths of periods over which units of measurements (average discharge in cfs, for example) increase from say, weekly values to yearly values, the variables tend to converge from a markedly skewed-right distribution to a normal distribution (linear-scale or logarithmic). Because numbers showing annual values are means of sets of means, the apparent normality of yearly values seems to conform with the predictions of the central-limit theorem (Griffiths, 1967, p. 27; Sokal and Rohlf, 1969, p. 130). It seems therefore, that annual values of discharges and denudation rates may be the best compromise, on the one hand restricting the samples to only a few variates, but on the other, allowing the use of the powerful inferential methods of the normal distribution. This observation is the starting-point for the current experiment having to do with water-year discharges and denudation rates of the Arkansas River near Hutchinson.

From the statistics in Table 6 the conclusions follow that no compelling evidence exists to reject the null hypothesis, whether the variates are measured on the linear or common-logarithmic scales. Annual discharges and denudation rates of the Arkansas River near Hutchinson are presumed to be random samples of normal distributions, of which the sample means ($\bar{X}$) and standard deviations ($\hat{\sigma}$) are estimates of the populations' true means (μ) and standard deviations (σ).

	Annual Discharge (acre-feet)		Annual Denudation Rates ft/10^6 yr)	
	Linear	Log_{10}	Linear	Log_{10}
$\bar{X}$	373,595.7	5.52622	15.37	1.13169
$\hat{\sigma}$	174,032.0	0.21817	8.44	0.23160
K-S Dmax, computed	0.107	0.110	0.192	0.132
K-S Dmax, critical value ($n=10$; $\alpha=0.05$)	0.285	0.285	0.285	0.285
P of K-S Dmax, computed	$P > 0.2$	$P > 0.2$	$P > 0.2$	$P > 0.2$

Table 6.- Summary statistics, tests for normality of annual discharges and denudation rates, Arkansas River near Hutchinson, Kansas. Linear-scale values rounded. Critical values from Lilliefors (1967, p. 400). Basic data shown in Table 1. For conversion of numbers to metric system: (a) discharge (acre-feet), linear value or antilogarithm x 1233 = discharge (cu m); (b) denudation rate (ft/10^6 yr), linear value or antilogarithm x 0.3048 = denudation rate (m/10^6 yr).

Results of experiments referred to in footnote 18 suggest however that in general, lognormality of discharges may be prevalent over normality of measurements on the linear scale. This conclusion is supported by results of a test of the hypothesis of normality of annual discharges of the Arkansas River downstream from Hutchinson at Arkansas City, Kansas, wherein the null hypothesis and the set of alternate hypotheses (H_1-H_3) are expressed as those above, all the qualifications of footnote 18 apply and the sample size (54) is reasonably large.

The statistics in Table 7 lead to the conclusion that if the sample of 54 variates is a random sample from a normal population (linear scale), the probability of occurrence of a value of K-S Dmax as large as 0.1268 is between 1 and 5 times in every 100 such samples. Therefore on the basis of this evidence, either the hypothesis of normality of yearly discharges, linear scale, must be rejected, or the hypothesis of randomness of the samples must be rejected. The complications of the latter alternative have been discussed above, and accordingly, the set of hypotheses is restructured so that lognormality and random samples are specified. Inspection of the statistics of Table 7 and similar argument shows that no evidence exists to require rejection of the second null hypothesis. Annual discharge of the Arkansas River at Arkansas City is assumed to be lognormally distributed. Therefore, in consideration of the results of this test and the statements made in footnote 18, and because the scale of measurement is arbitrary as long as assumptions of all subsequent tests are met (Sokal and Rohlf, 1969, p. 381), for convenience of computation the common-logarithmic scale is used in the majority of tests that follow.

	Annual Discharge (acre-feet)	
	Linear Scale	Log_{10} Scale
$\bar{X}$	1,258,000	6.00787
$\hat{\sigma}$	815,370	3.29461
K-S Dmax, computed	0.1268	0.0637
K-S Dmax, critical value (n-54; $\alpha = 0.05$)	0.1206	0.1206
P of K-S Dmax, computed	$0.01 < P < 0.05$	$P > 0.02$

Table 7.- Summary statistics, test for normality of annual discharges, Arkansas River at Arkansas City, Kansas. Period of record is 54 years (1903-1906 and 1922-1971), the longest record of discharges of the Arkansas River in Kansas. Linear-scale values rounded. Critical values computed from Lilliefors (1967, p. 400). Sources of data shown in Appendix C. For conversion of numbers to metric system: discharge (acre-feet), linear value or antilogarithm x 1233 = discharge (cu m).

Measurement of Association Between Discharge and Denudation Rates

At the outset of the endeavor to determine the long-term effect of denudation in the Arkansas River drainage basin, I proposed to calculate expected values of denudation rates by referring to modern rates of denudation in the areas of sympatry. As shown above, however, denudation is a function of many variables, and I have found that to account for or even estimate the bias introduced into denudation rates by differences between regions in natural variables alone is impracticable, and that to assume identity of the natural variables leads to imprecise and inaccurate estimates of denudation (see Stewart, 1971, p. 2-3). Therefore, the purpose of an effort to measure the association between discharge and denudation rate is based on the following rationale.

As shown previously, inferences of the climates of glaciations in Kansas were made chiefly on the basis of the assumption that the climate of Kansas during glacial episodes was a strong control upon the flora, that the flora was a strong control upon the fauna, and that these relationships among climate, flora, and fauna hold today. It follows that the climates of Kansas during glacial episodes can be inferred by reference to regions where the modern flora and fauna are similar to those that can be shown to have inhabited Kansas during glacial episodes. Thus, an area of sympatry is defined to include eastern North Dakota, eastern South Dakota, northeastern Nebraska, southwestern Minnesota, and northwestern Iowa. Although stream discharge, in general, is a function of precipitation, temperature, vegetation, soil types, bedrock, ground-water regimen, land use, and other factors, it probably is less "determined" by conditions of the terrain and therefore more "determined" by climatic conditions than any other measurable property that Kansas and the area of sympatry have in common.

The working assumption is stated here that the soils, topography, and other qualities of the terrain in south-central Kansas and the area of sympatry are similar enough that their effects on discharge are about equal in magnitude and direction. Therefore, the property of stream discharge can be assumed to be independent of the terrains of the regions and dependent upon climatic conditions. Thus, if this working assumption is held, and if a definite relationship between stream discharge and denudation rates of the Arkansas River at Hutchinson can be determined, then a predictive method can be derived whereby, on the basis of comparison of stream discharges of Kansas with those of the area of sympatry, denudation rates of the Arkansas River can be extrapolated across the periods of time stipulated in the Maximal-Case construct.

Because annual discharge and denudation rate of the Arkansas River are variables that cannot be measured without components of random error, the appropriate method for testing the level of their association is correlation analysis (Griffiths, 1967, p. 455; Sokal and Rohlf, 1969, p. 495-497). This model leads to estimation of the degree to which variables covary; no functional relationship and no assumption of cause-and-effect are implicit in the test, although the variables may be related in such fashion. Thus the inference follows that if stream discharge and denudation are closely related, values of the one variable can be predicted if values of the other variable are given. Inasmuch as both variables include random error, all estimates based on one variable or the other can be assumed to be correct only within specific limits.

If the objective of the analysis is to estimate the degree of covariance between the populations from which the samples are drawn, the assumption that the frequency distribution of the variables is approximated by the bivariate normal distribution must be met (Sokal and Rohlf, 1969, p. 499). The assumptions of lognormality of annual discharges of the Arkansas River and of its annual denudation rates have been discussed above. Although the tests of the hypotheses of normality of the variables led to no rejection of the hypotheses, the condition of bivariate normality was not specifically evaluated. The general case seems to be, however, that if samples of two variables meet the assumption of normality, bivariate normality is subsumed (for example, see Griffiths and Ondrick, 1968, p. 21). In the instance at hand, samples of annual discharge and denudation rates of the Arkansas River are assumed to be drawn randomly from populations that compose a bivariate (log) normal distribution.

Figure 13 shows that a straight-line relationship approximates the association of the variables. The sample correlation coefficient, r, is 0.979. The test below evaluates the hypothesis that this sample is in fact a random sample from a population in which ρ, the parametric value of the correlation coefficient is 0.

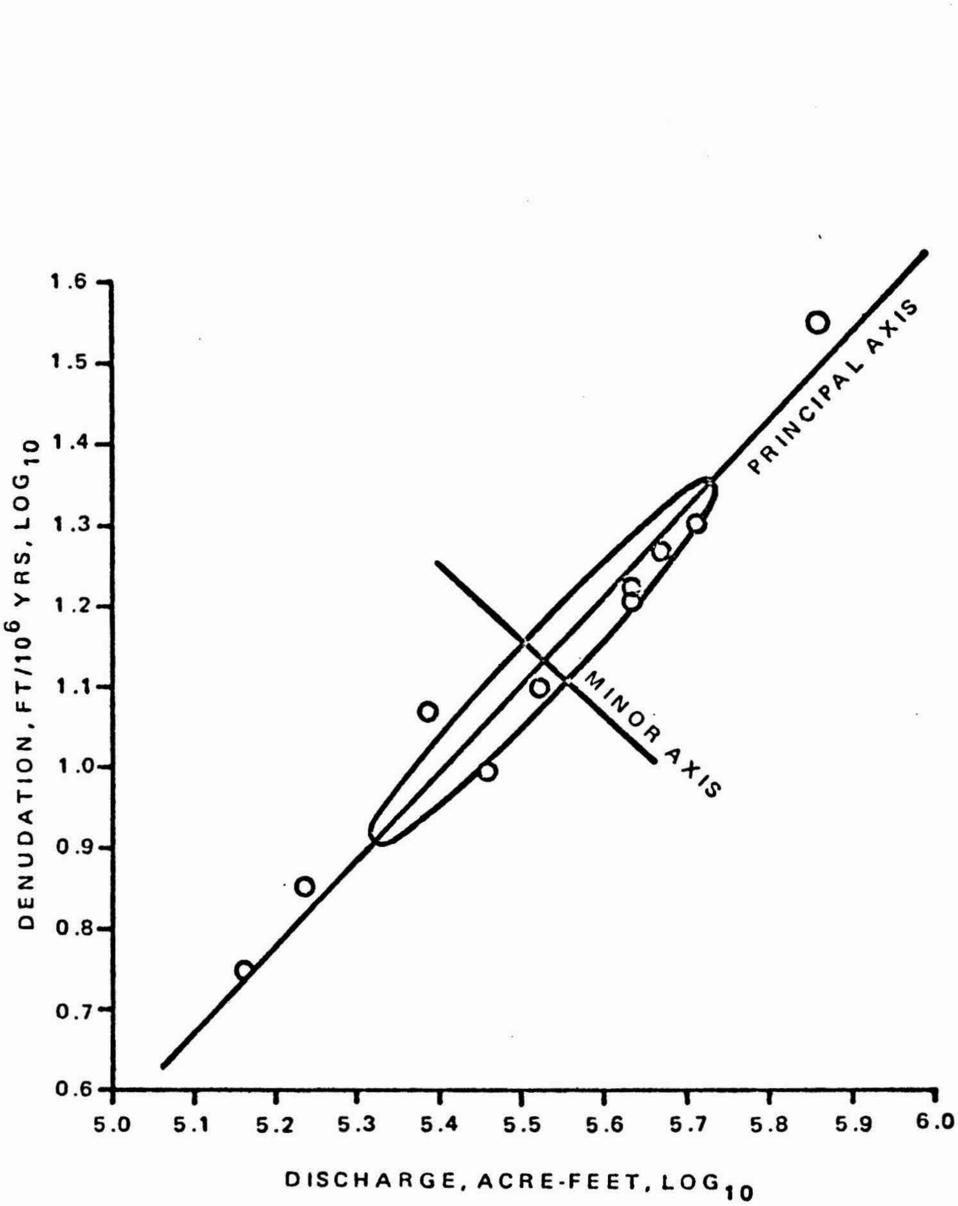

Figure 13.- Relationship between annual discharge and annual denudation rate, Arkansas River near Hutchinson, Kansas, showing principal axes and the elliptical 95-percent confidence region of the bivariate mean. Data are shown in Table 5. The principal axis represents the trend of the data. (See Sokal and Rohlf, 1969, p. 526-532; construction of confidence region follows Sokal and Rohlf, 1969, p. 528-531.) For conversion of numbers to metric system: (a) discharge (acre-feet), antilogarithm x 1233 = discharge (cu m); (b) denudation rate (ft/10^6 yr), antilogarithm x 0.3048 = denudation rate (m/10^6 yr).

$r = 0.979$

$H_o: \rho = 0 \quad H_1: \rho \neq 0$

Maximal value, $r(0.01,8) = 0.765$

(Arkin and Colton, 1963, p. 155)

The conclusion drawn from these statistics is that if in fact the parametric value of the correlation coefficient is 0, the probability of occurrence of a sample value of $r = 0.979$ is considerably less than once in 100 similar trials. On this basis the null hypothesis is rejected and the variables are assumed to be highly correlated.[20]

The coefficient of determination, $r^2 = 0.958$, shows that almost 96 percent of the variation is common to both variables; only slightly more than 4 percent of the variation is unaccounted for in the association. The inference is drawn therefore that about 96 percent of the variation in denudation rates of the Arkansas River at Hutchinson is "determined" by variation in discharge.

Because denudation rates of the Arkansas are scaled to 1-million-year equivalent amounts (fig. 13), it follows that if the true average annual discharge of the Arkansas were predicted, the amount of denudation that would be "produced" by that average discharge throughout a given time span could be predicted. The sample value of the mean annual discharge of the Arkansas River, $\bar{X}_{ds}$, is an estimator of the parametric

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[20] Calculation of confidence limits to the correlation coefficient would be a helpful statistic. Due to the small sample size however, this seems not to be advisable (see Sokal and Rohlf, 1969, p. 517-518).

value, μ_{ds}; its corresponding value of average denudation rate $\bar{X}_{dr}$ estimates the parametric value M_{dr}. Because both variables as measured include random error, the sample means also are subject to error as estimators of μ. In order to reach a high level of reliability in inferences based on the joint mean values, it is desirable to refer to the elliptical confidence region about the principal axes of the scattergram in Figure 13. Inasmuch as these data are highly correlated, the ellipse is quite narrow. On the basis of all the assumptions stated previously about randomness of samples and bivariate lognormality of the variables, it can be expected that 95 percent of all ellipses constructed from similar sets of samples would include the true mean value of (μ_{ds}, μ_{dr}). Therefore the probability that the ellipse shown in Figure 5 does not include (μ_{ds}, μ_{dr}) is 0.05. Thus, considering all prior assumptions and evaluations, and with reference to Figure 13, the statement can be made that the probability is 5 or less chances in 100 that the true mean discharge of the Arkansas River at Hutchinson, under present interglacial conditions would exceed 5.738944 ($\log_{10}$) or about 548,000 acre-feet (676×10^6 cu m) and that the true mean denudation rate would exceed 1.357790 ($\log_{10}$), or about 23 feet (7 m)/10^6 years.

Extrapolation of Denudation Rates to the Maximal-Case Construct

Repeated here for clarity, the Maximal-Case construct of the period of concern includes four climatic episodes: (1) an interglaciation continued for about the next 100,000 years,

(2) a glaciation of approximately 500,000 years, (3) a second interglaciation of 200,000 years, and (4) a second glaciation of 200,000 years. The problem to be dealt with is how to adjust the inferred maximal average interglacial denudation rates so that they can be extrapolated across the time postulated above to be the durations of glacial episodes.

The assumption was stated previously that of all the properties usable for prediction that Kansas and the area of sympatry hold in common, stream discharges are probably the least dependent upon the terrain and the most dependent upon climatic conditions. The most desirable immediate objective therefore in using stream discharges of Kansas and the area of sympatry is to find a basis for scaling the discharge of the Arkansas River for glacial conditions. Heretofore in this paper, Kansas as a whole has been referred to in comparison with the area of sympatry. Because the performance of the Arkansas River is the chief matter to be predicted, and because the Arkansas River above Hutchinson derives most of its water from the central Kansas watershed, the region of interest is redefined to be that part of the Arkansas River watershed that is located in south-central Kansas. This region and the area of sympatry are shown in Figure 14.

The primary null hypothesis for the experiment that follows asserts that on the average, mean annual discharge/sq mi of the area of sympatry is no different from that of south-central Kansas. Data that are the basis of testing this hypothesis against its alternate (Table 8) are values of discharge/sq mi

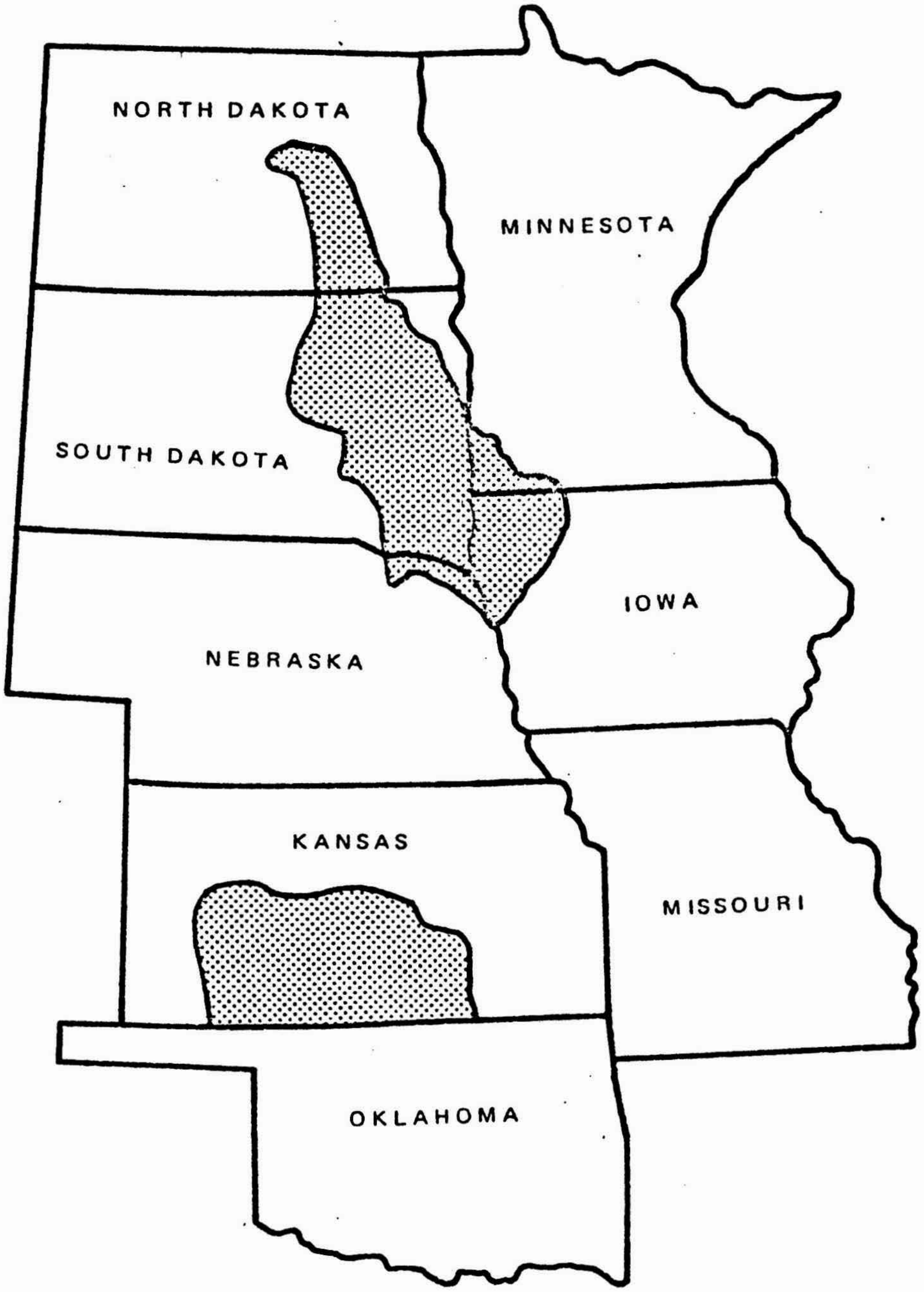

Figure 14.- Shaded area in Kansas shows the location of the watershed from which most of the discharge of the Arkansas River at Hutchinson is derived. Shaded area extending from Iowa to North Dakota shows the area of sympatry, within which the modern climate is believed to be generally similar to that of Kansas during Pleistocene glacial episodes. (Map after U. S. Geol. Survey, 1970c, p. 13.)

as measured at only one gauging station on each of the streams in south-central Kansas and each of the streams in the area of sympatry for which values of annual discharges are recorded in water-supply papers (sources of data shown in Appendix C). (There are no replicate measurements within drainage basins; in instances where drainage basins contain more than one gauging station, one station was selected at random. This procedure is based on the assumption that the regimen of a stream is unique and therefore that only one variate per drainage basin should be included in the sample.)

Because gauging stations are constructed for a variety of definite purposes, nonrandomness of their placement is (at least) suggested. By a general inspection of the records involved here, one can be led to the hypothesis that sites of gauging stations are biased toward the larger drainage basins. A consequent of this hypothesis (H-1) is the secondary hypothesis (H-2) that areas of drainage basins and values of discharge/sq mi are correlated. If both hypotheses are true, a consequent of them is the tertiary hypothesis (H-3) that a computed mean value of discharge/sq mi, either of south-central Kansas or the area of sympatry, is not the desired independent measurement of this propoerty of the regions but rather is a measurement of the interaction of drainage-basin areas and discharges. If testing of this tertiary hypothesis against its alternate leads to rejection of H-3, then H-2 and H-1 are necessarily rejected also. The alternate hypothesis of H-3 is stated as H-4: Measurement of discharges/sq mi are independent of interaction with drainage-basin areas.

A suitable test for interaction is correlation analysis, to measure the intensity of association of the variables. As discussed in passages above, the main assumptions of correlation analysis are that the samples analyzed are random samples from a bivariate normal distribution. Tests below follow the general plan used previously in correlation analysis of discharges and denudation rates of the Arkansas River at Hutchinson, Kansas. Samples included below compose the total available populations; therefore all the constraints of sampling discussed in reference to discharges and denudation rates of the Arkansas River apply. The array of hypotheses to be tested is structed in the same fashion as the sequence $H_0 - H_3$ used in testing for normality of samples of discharges and denudation rates of the Arkansas River at Hutchinson. For the sake of brevity, this sequence is reduced below to a comprehensive null hypothesis and one alternate hypothesis.

H_0: Areas of drainage basins and values of discharge/sq mi of south-central Kansas and the area of sympatry are random samples drawn from populations that are normally distributed.

H_1: They are not.

South-Central Kansas		Area of Sympatry	
Area of Drainage Basins, Sq Mi	Mean Annual Discharge/ Sq Mi	Area of Drainage Basins, Sq Mi	Mean Annual Discharge/ Sq Mi
33,157	23.1	460	9.4
728	67.4	56	17.2
21	29.0	42	15.7
1250	143.6	1090	5.1
2010	29.6	265	12.5
1306	45.2	240	32.9
63	159.9	65	179.4
30	359.7	440	164.5
1872	29.1	170	145.6
903	110.6	2450	40.2
426	327.9	1540	10.9
356	61.0	480	22.3
61	75.9	210	16.4
		2738	208.1
		540	41.8
		1600	136.2
		1680	53.4
		298	36.2
		1680	18.3
		225	8.4
		520	75.2
		48	119.4
		265	97.0
		39	310.0
		279,500	63.0

Table 8.- Areas of drainage basins and discharges/sq mi, south-central Kansas and area of sympatry. Only contributing drainage area shown. Sources of data shown in Appendix C. For conversion of numbers to metric system: (a) area of drainage basins (sq mi) x 2.59 = area (sq km); (b) mean annual discharge/ sq mi (acre-feet) x 1233 = discharge (cu m).

	A				B			
	Kansas		Area Sympatry		Kansas		Area Sympatry	
	Linear	Log_{10}	Linear	Log_{10}	Linear	Log_{10}	Linear	Log_{10}
n	13	13	25	25	13	13	25	25
$\bar{X}$	3244.8	2.66858	11865.6	2.66603	132.6	1.95287	73.6	1.61368
$\hat{\sigma}$	9013.8	0.88900	55762.6	0.65028	118.95	0.40948	78.299	0.50299
K-S Dmax (computed)	0.478	0.161	0.525	0.147	0.222	0.111	0.218	0.118
K-S Dmax (critical) ($n,\alpha=.05$)	0.234	0.234	0.180	0.180	0.234	0.234	0.180	0.180
P of K-S Dmax, computed	$P<0.01$	$P>0.20$	$P<0.01$	$P>0.20$	$0.05<P<0.10$	$P>0.20$	$P<0.01$	$P>0.20$

Table 9.- Summary statistics, tests for normality of (a) areas of drainage basins and (b) values of mean annual discharge/sq mi, south-central Kansas and the area of sympatry. Critical values from Lilliefors (1967, p. 400). For conversion of numbers to metric system: (a) areas of drainage basins (sq mi), linear value or antilogarithm x 2.59 = area (sq km); (b) mean annual discharge/sq mi (acre-feet), linear value or antilogarithm x 1233 = discharge (cu m).

The statistics above lead to the rejection of the null hypothesis specifying that the samples of drainage-basin areas and mean annual discharges, as measured on the linear scale, are random samples from normal distributions. On the other hand, when variates are transformed to the common-logarithmic scale, computed values of the K-S Dmax statistic and associated probabilities provide no evidence requiring rejection of the null hypothesis specifying that the samples are random samples from lognormal populations. In consideration of these results the assumption of lognormality of the variables is adopted and bivariate normality is subsumed.

Inspection of the scattergrams in Figures 15 and 16 suggests an almost "random" distribution of sample values and a low level of association between the variables of each pair, both in Kansas and in the area of sympatry. Tests shown below of the hypotheses that these samples are random samples from normal populations in which the true correlation coefficient is zero show no evidence to reject this hypothesis.

South-Central Kansas	Area of Sympatry
$r = -0.308$	$r = -0.043$
H_0: $\rho=0$	H_0: $\rho=0$
H_1: $\rho\neq0$	H_1: $\rho\neq0$
Maximal value, $r(0.01,11) = 0.684$	Maximal value, $r(0.01,23) = 0.505$
(Arkin and Colton, 1963, p. 155.)	(Arkin and Colton, 1963, p. 155.)

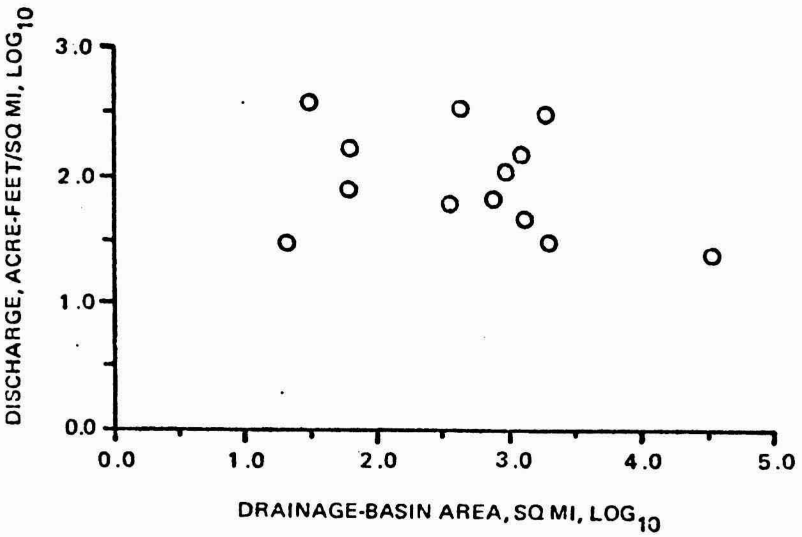

Figure 15.- Relationship between drainage-basin areas and mean annual discharges/sq mi, Arkansas River drainage basin of south-central Kansas. Correlation coefficient, r = -0.308; coefficient of determination, r^2 = 0.095; coefficient of nondetermination, $1-r^2$ = 0.905. For conversion of numbers to metric system: (a) areas of drainage basins (sq mi), antilogarithm x 2.59 = area (sq km); (b) mean annual discharge (acre-ft/sq mi), antilogarithm x 1233 = discharge (cu m).

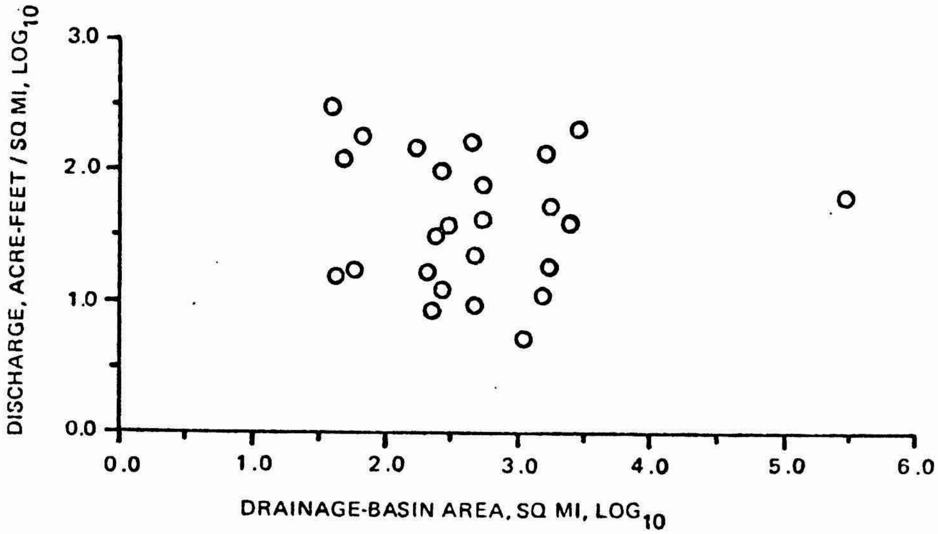

Figure 16.- Relationship between drainage-basin areas and mean annual discharges/sq mi, area of sympatry. Correlation coefficient, r = -0.043. Coefficient of determination, r^2 = 0.002. Coefficient of nondetermination, $1-r^2$ = 0.998. For conversion of numbers to metric system: (a) areas of drainage basins (sq mi), antilogarithm x 2.59 = area (sq km); (b) mean annual discharge (acre-ft/sq mi), antilogarithm x 1233 = discharge (cu m).

The coefficients of determination and nondetermination show that in the cases of south-central Kansas and the area of sympatry, respectively, only about 1 percent and essentially none of the variation in mean annual discharge/sq mi is explained by basin area. In conclusion of these tests therefore, the judgment is made that measurements of mean annual discharge/sq mi in south-central Kansas and in the area of sympatry are independent from the effect of basin area. No significant interaction is present. Therefore, comparison of mean annual discharge/sq mi between these two regions should be an actual comparison, and should be a general index from which to estimate the discharge of the Arkansas River during glacial episodes.

The grand average values of mean annual discharge/sq mi in each region, hereafter shown as $\bar{X}_k$ and $\bar{X}_{as}$, only estimate the true means, μ_k and μ_{as}. Although the apparent ratio of $\bar{X}_{as}$ to $\bar{X}_k$ is about 0.5 (25.5/50.7), the question arises as to whether this difference is real, or whether it is an accident of sampling. This question is equivalent to asking whether the samples were drawn from one population or two. Inasmuch as lognormality of the variables is assumed, the populations under examination can be characterized by two qualities, their variances and means. The question of chief importance here is whether the mean values are significantly different. This question is evaluated below by Student's t-test.

1. $H_0: \mu_k = \mu_{as}$

   $H_1: \mu_k > \mu_{as}$

2. Data$_{(\log 10)}$: $\bar{X}_k = 1.95287$ $\bar{X}_{as} = 1.61368$

   $\theta_k = 0.16767$ $\theta_{as} = 0.25299$

   $n = 13$ $n = 25$

3. Assumptions: 1) Random samples drawn from lognormal distributions (tested previously).

   $\sigma_k^2 = \sigma_{as}^2$

4. Test of equality of variances:

   a. $H_0: \theta_k^2 = \theta_{as}^2$

   b. $H_1: \theta_k^2 \neq \theta_{as}^2$

   c. F-ratio of variances = $\frac{0.25299}{0.16767}$ = 1.51

   d. $0.2<P<0.5$

   e. Conclusion: This evidence does not require rejection of H_0. H_1 rejected.

5. a. $$t = \frac{\bar{X}_k - \bar{X}_{as}}{\sqrt{\frac{\theta_k^2}{n_k} - \frac{\theta_{as}^2}{n_{as}}}} =\ldots \frac{(0.339190)}{(0.151710)} = 2.24$$

   b. degrees freedom = 36

   c. $t_{0.025(36)} = 2.03$ (one-tailed)

      $t_{0.01(36)} = 2.44$

   d. $0.01<P<0.025$

6. Conclusion: If $\bar{X}_k$ and $\bar{X}_{as}$ are in fact random samples from the same population, the probability of occurrence of a t-statistic as large as 2.44 is less than 5 in 200 similar trials. H_0 rejected. $\bar{X}_k$ accepted as being significantly greater than $\bar{X}_{as}$. Critical values of F-distribution from Rohlf and Sokal (1969, p. 180). Critical values of t from Arkin and Colton (1963, p. 121).

From the evidence shown above, the inference is drawn that the average annual discharge/sq mi in south-central Kansas is significantly greater than average annual discharge/sq mi in the area of sympatry; in other words, on the basis of the probability statement above, the ratio of discharge/sq mi, area of sympatry, to discharge/sq mi, south-central Kansas, is taken to be less than 1. The true ratio is assumed to be some value about the same as the ratio of sample means, i.e., about 1/2.[21]

Thus it seems that the assumption can be held safely that the onset of a glacial episode would lead to a reduction of discharge of the Arkansas River at Hutchinson to about one-half its present (interglacial) volume. This matter can be

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[21] This statistic may seem strange in view of the facts that although annual precipitation in the area of sympatry is about the same as in south-central Kansas, temperature and solar radiation in the area of sympatry are somewhat lower (Gerlach, 1970, p. 93, 97, 102-103). Hence, one might expect a lower level of evaporation and a similar or even larger amount of runoff in the area of sympatry. The apparently much-reduced runoff could be due partly to differences in land use, but the general relationship could be mostly free of man's influence and be due to natural differences in vegetation.

taken somewhat farther however, inasmuch as 95-percent confidence limits about the sample means show that at a probability level of 0.025, the $\bar{X}_k$ could be as small as 1.70529, and $\bar{X}_{as}$ could be as large as 1.82091. A construct in which the means are equal can be derived wherein the difference between the upper limits above is halved, and both means are assumed to be 1.76310. The probability of such an instance can be shown to be approximately 0.004; this is the probability that discharge per unit area is the same under both glacial and interglacial conditions.

The worth of this statistic is that it permits the evaluation of all the alternative relationships between discharge and denudation rates that can exist under the construction of this problem. These alternatives are shown below.

Case 1. The Maximal-Case construct, assuming ratio of discharges of the Arkansas River, glacial/interglacial episodes to be 1/2.

Sequence: Interglaciation - 100,000 yrs
Glaciation - 500,000 yrs
Interglaciation - 200,000 yrs
Glaciation - 200,000 yrs

Denudation: Rates (upper limit, 95-percent confidence level; probability of exceedence 0.025):

Interglaciations: 25 ft (7.6 m)/10^6 yrs (rounded)

Glaciations: 12 ft (3.7 m)/10^6 yrs (rounded)

Total denudation: ((25ft)(0.1)) plus ((12 ft)(0.5)) plus ((25 ft)(0.2)) plus ((12 ft)(0.2)) =. . . 16 ft(4.9 m).

Because probability of occurrence of the Maximal Case is 0.01, and probability of exceedence of the interglacial denudation rate cited here has been shown previously to be 0.025, the probability of more than say, 15 to 20 (4.6-6 m) feet of denudation in the Arkansas River drainage basin above Hutchinson is (0.01)(0.025) = 0.00025, or about 3 chances in 1000.

Case 2. The Maximal-Case construct, assuming ratio of discharges of the Arkansas River, glacial/interglacial episodes to be 1, is of course, the case in which the maximal denudation rate of interglaciations would be sustained for 10^6 years. Denudation therefore would be approximately 25 (7.6 m) ft. Inasmuch as probability of occurrence of a 1:1 ratio of glacial and interglacial denudation rates alone is 0.004, or 4 chances in 1000, it can easily be seen that the overall probability of denudation in the Arkansas River above Hutchinson exceeding 25 ft (7.6 m)/10^6 yrs is for all practical purposes, zero.

From the argument above the conclusion is drawn that from an operational standpoint, the upper limit of expectable denudation of the Arkansas River drainage basin above Hutchinson within the next 1 million years is less than about 25 feet (7.6 m).[22]

The Pleistocene history of the Arkansas River is so singularly different from that of most other streams in the unglaciated Midcontinent that interpretation of these results to explain the areal geology of other drainage basins should not be extended too far. Moreover, the effect of our culture on these computed denudation rates removes the opportunity for strong inferences about their meaning as far as Pleistocene events are concerned. Nevertheless, it seems that the general relationship between discharge during glaciations and interglaciations might hold, and that on the average, their ratio might be about 1/2. Figures 17 and 18 indicate that on the basis of the scales used in the scatter diagrams, the relation between discharge and denudation owing to removal of material by suspended and bed load is more "direct" (closer to 1:1) than discharge and denudation owing to removal of material by dissolved load. This relationship seems reasonable, in that

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[22] The reader should bear in mind that even these low values are subject to all the artificial variables discussed previously, the net effect of which is to lead to overestimation of denudation rates. Also worthy of mention at this point is the fact that the rate of denudation of the drainage basin of Cow Creek is about 75 ft (23 m)/10^6 yrs. Assuming that the ratio of suspended and bed load, combined, to dissolved load is about constant, the inference can be drawn that the tributaries of the Arkansas River seem to deliver about 2 or 3 times more sediment to the Arkansas River than it removes, and that the Arkansas continues to store sediment and alluviate its valley - as it seems to have done throughout the Pleistocene.

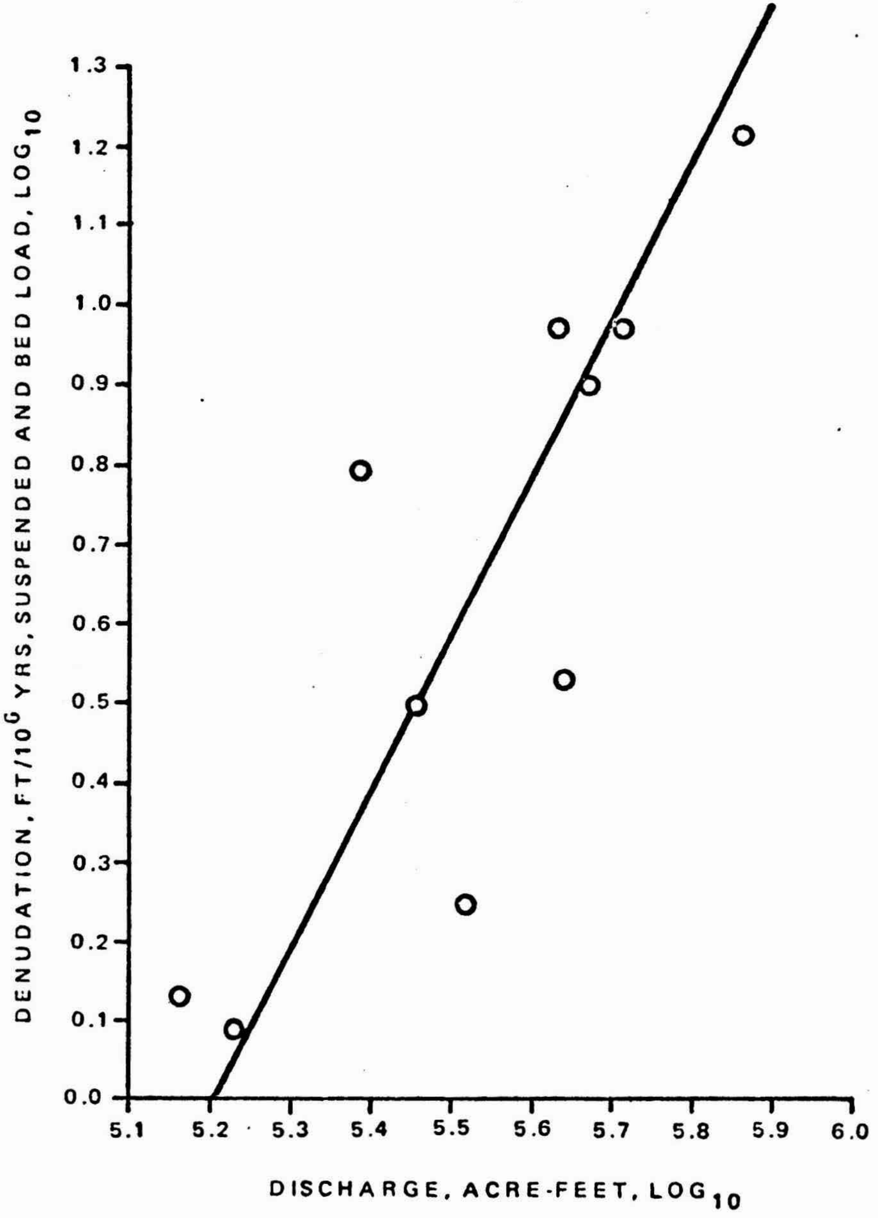

Figure 17.- Relationship between annual discharge and annual denudation rate due to suspended and bed load, Arkansas River near Hutchinson, Kansas. The principal axis represents the trend of the data. Correlation coefficient, $r = 0.841$. For conversion of numbers to metric system: (a) annual discharge (acre-feet), antilogarithm x 1233 = discharge (cu m); (b) denudation rate (ft/10^6 yr), antilogarithm x 0.3048 = denudation rate (m/10^6 yr).

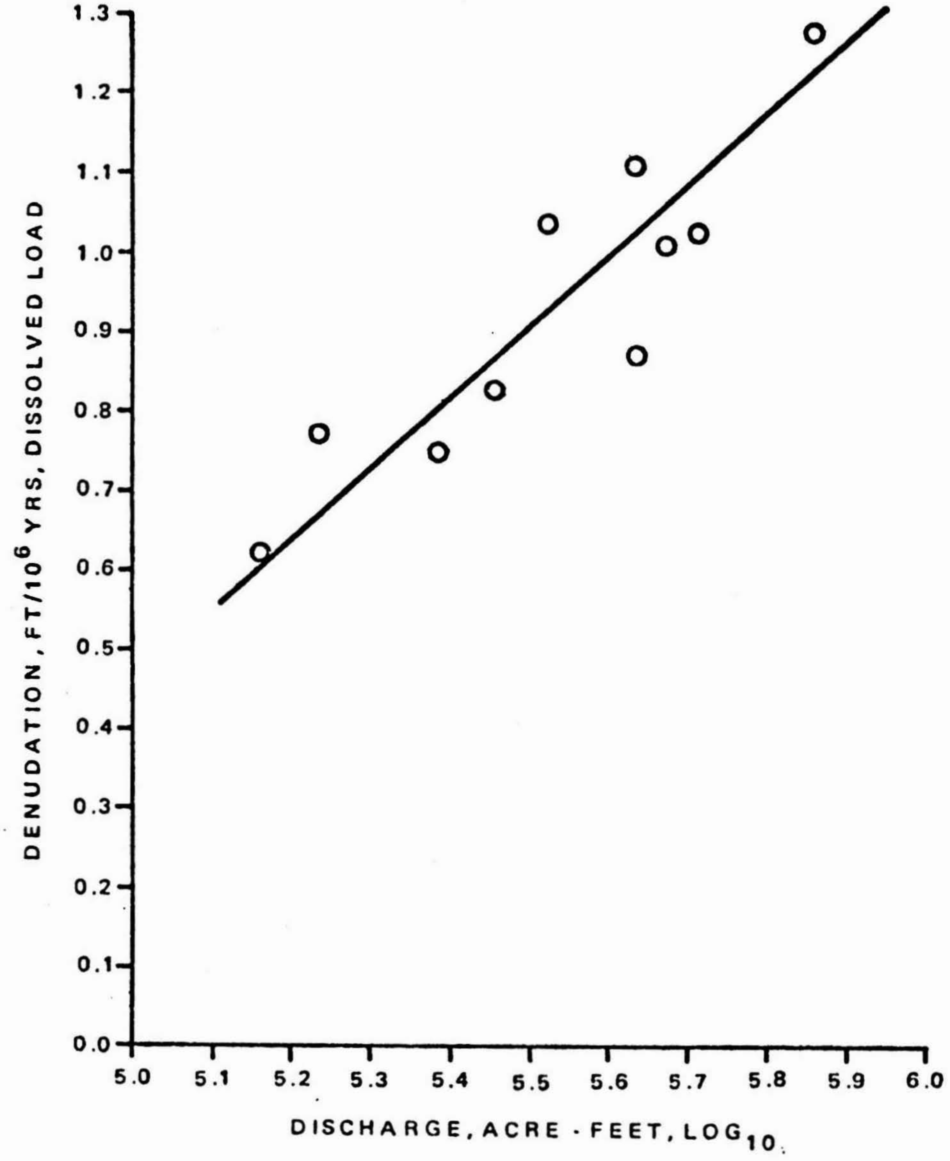

Figure 18.- Relationship between annual discharge and annual denudation rate due to dissolved load, Arkansas River near Hutchinson, Kansas. The principal axis represents the trend of the data. Correlation coefficient, r = 0.901. For conversion of numbers to metric system: (a) annual discharge (acre-feet), antilogarithm x 1233 = discharge (cu m); (b) denudation rate (ft/10^6 yr), antilogarithm x 0.3048 = denudation rate (m/10^6 yr).

available energy and movement of suspended and bed load are directly associated; dissolved solids should enter the surface water from ground water even during periods of low flow. Figure 18 seems to support this explanation, as dissolved load of the Arkansas River decreases less per unit of decrease in discharge.

Elsewhere in this paper the entrenchment of streams in the Midcontinent has been explained on the basis of areal geologic evidence as the result of greater competence and capacity of streams during the early parts of glaciations than during the later parts of glaciations and during interglaciations (p. 82). The proposed ratio of glacial: interglacial discharges of 1:2 would seem to contradict this explanation, and therefore to require the rejection either of the supposed ratio of discharges or the supposed times of entrenchment of valleys. However, both lines of evidence can be included in the following explanation: In the general case of streams in the unglaciated Midcontinent, discharge of streams could be assumed to decline during glacial episodes in spite of greater precipitation and lower temperature. This decline might be due to a markedly increased cover of vegetation. If so, then sediment yields from tributaries might decline remarkably, and introduce into the trunk streams a state of relatively higher capacity in spite of a decrease in total discharge. If all these assumptions were true, during early parts of glaciations an underloaded stream could be inferred to begin to erode its own alluvium, eventually the bedrock, and as a final result, to be nested in a valley containing paired depositional terraces.

EROSION OF VALLEYS IN CENTRAL KANSAS

The post-"algal-limestone" history of the stream systems of central Kansas is complex and is not understood completely. The matter of chief concern at this point is (a) to establish the maximal amount of entrenchment that occurred during post-"algal-limestone" time, and (b) to estimate the amount of time required for this downcutting, so as (c) to estimate a maximal rate of entrenchment during the recent past that is based on areal geologic evidence and that can be used for, or compared to, predictions made in other parts of this study.

In central Kansas, from Russell and Barton counties on the west to Saline and McPherson counties on the east, the Saline River (fig. 10) is the most deeply entrenched stream (Frye and Leonard, 1952, p. 2, cross-sections B-B' and C-C').[23] In eastern Russell County, the Saline River lies about 300 feet (90 m) below the general level of the "algal limestone" (as recorded by Frye, 1945, p. 89), and about 450 feet (140 m) below the crest of the highest nearby drainage divide, the

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[23] From this point forward the assumption is held that in the many instances when the reader encounters names of counties, he will refer to Figure 10 for their locations if he so pleases.

divide between the Smoky Hill and Arkansas rivers in northern Barton County (Frye and Leonard, 1952, cross-section B-B'). Pleistocene deposits at lowest elevations in the valley of Saline River are Wisconsinan (Frye and Leonard, 1952, as shown above) and locally the valley also contains Illinoian, Kansan, and Nebraskan terrace deposits (Bayne and Fent, 1963; Frye and Leonard, 1952, p. 193-196). These deposits show that the 300 feet (90 m) of entrenchment of the Saline River below the "algal limestone" was an intermittent process that lasted at least from early in the Nebraskan Glaciation into the Wisconsinan Glaciation.

In Rice County, however, lowermost strata in Chase Channel, a part of Galatia channel, an early Pleistocene stream valley (fig. 10, 19, 20), lie upon Permian bedrock almost 250 feet (75 m) below the position of the "algal limestone" on uplands only a few miles distant (Fent, 1950, p. 20, 21, pl. 3). The lowermost deposits of the former stream channel are among the oldest Pleistocene deposits in central Kansas, and are designated as the Nebraskan Holdrege and Fullerton formations (fig. 11) (formerly members of the Chase Channel Formation (Fent, 1950) and of the Blanco Formation (Bayne, 1956)). Caliche nodules near the top of the Fullerton may have been deposited during formation of soil during the Aftonian Interglaciation (implied by Fent, 1950, p. 64, and Frye and Leonard, 1952, p. 61, 68-69; see also Bayne, 1956, p. 71).

The Holdrege and Fullerton formations also are present in the lowermost parts of two large, buried stream channels

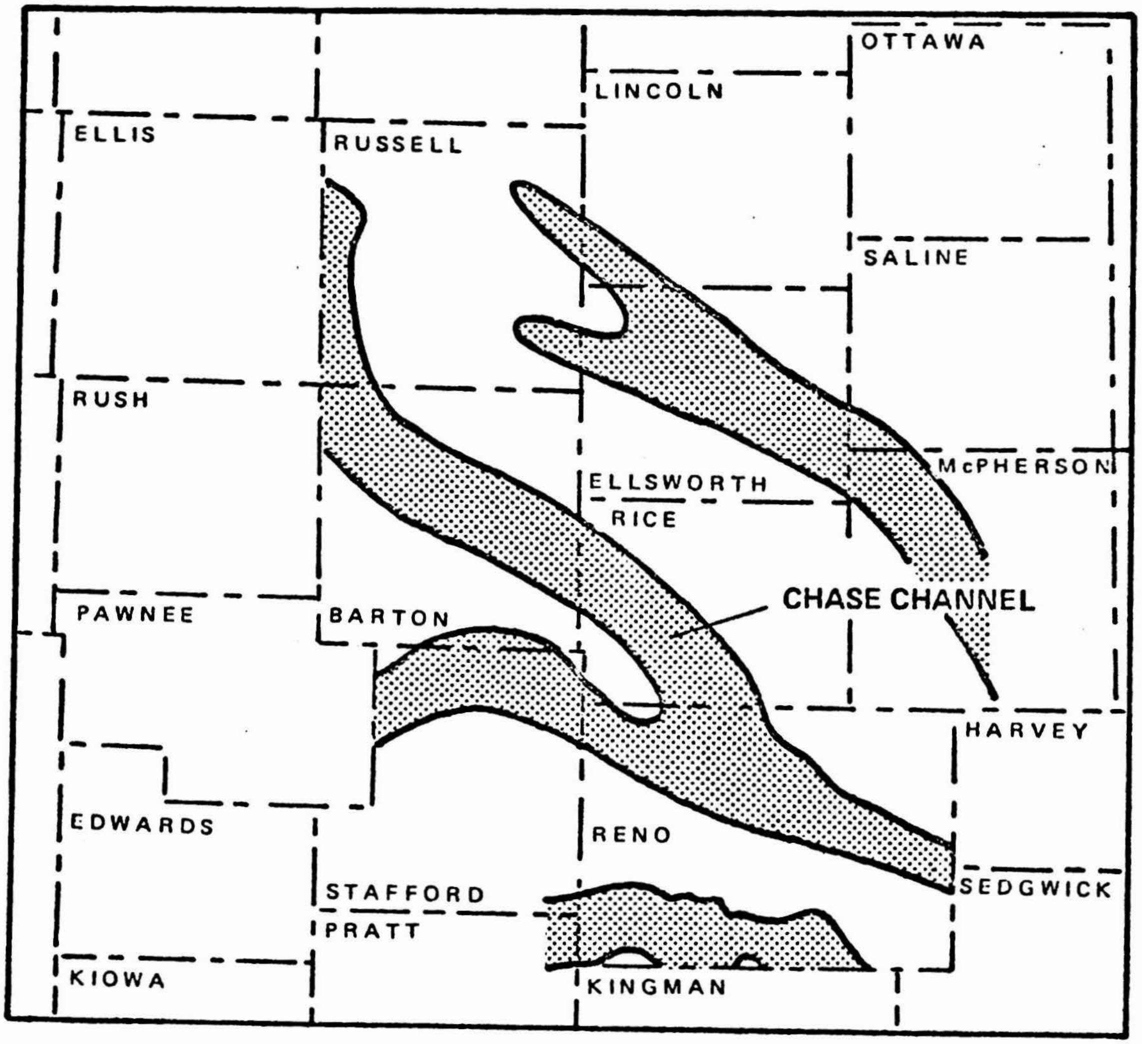

Figure 19.- Shaded patterns show general locations of buried early Pleistocene stream channels (after Bayne, 1956, p. 23; Fent, 1950, fig. 5; Frye and Leonard, 1952, p. 194).

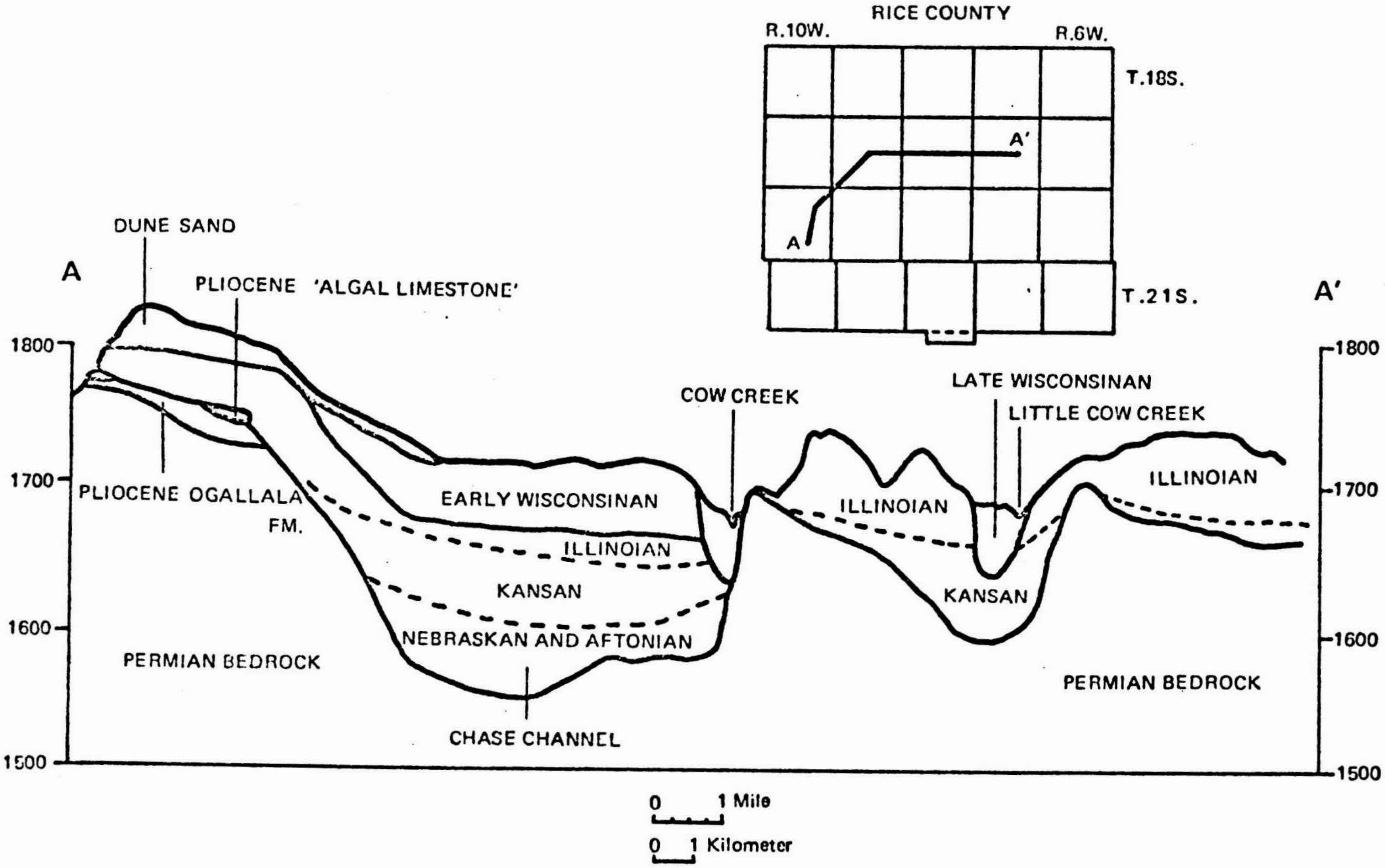

Figure 20.- Cross section of western central Rice County, showing depth of Chase Channel and position of Cow Creek Valley in thick alluvium deposited by ancestral Smoky Hill River (Nebraskan-Aftonian, Kansas) and by Arkansas River (early Wisconsinan). (From Fent, 1950, pl. 3, cross-sections D-E, E-F; p. 21-22; Frye and Leonard, 1952, p. 52; Bayne, Franks, and Ives, 1971, p. 29-30). For conversion of elevations shown on margins of cross-section from feet to meters, multiply numbers by 0.3048.

in Reno County that are downstream extensions of buried early Pleistocene channels in Stafford and Pratt counties to the west and of the Chase Channel in Rice County to the north (fig. 19) (Bayne, 1956). The base of the Holdrege Formation lies as much as 300 feet (90 m) below Permian rocks on crests of nearby uplands. Inasmuch as the "algal limestone" is not present in Reno County, no exact measurement of entrenchment below the "algal limestone" can be calculated. Because there is considerable evidence on which to base the premise that the "algal limestone" formerly extended throughout central Kansas (as discussed above) and because the "algal limestone" is in place on slopes below drainage divides at many places in Ellsworth County (Bayne, Franks and Ives, 1971, pl. 1), the assumption can be held that the "algal limestone" formerly existed in Reno County on slopes lower than the present crests of uplands. Accordingly, the inference follows that entrenchment of the pre-Holdrege channels below the former level of the "algal limestone" in Reno County was less than 300 feet (90 m).

Nebraskan deposits also overlie eroded bedrock in Barton, Stafford, Pratt, and Ellsworth counties (Frye and Leonard, 1952, pl. 2; Bayne, Franks and Ives, 1971). The two deep abandoned valleys in northern Stafford and southern Barton counties contain Nebraskan strata whose bases lie about 330 feet (100 m) below the drainage divide between the Smoky Hill and Arkansas rivers, in northern Barton County (Frye and

Leonard, 1952, pl. 2, cross-section B-B', cf. Latta, 1950, pl. 3, cross-section G-G').

At many other places in Kansas, and reasonably near to Rice County in Barton, Russell, Reno and Sedgwick counties, Nebraskan deposits are on stream divides high in the uplands and are among the highest terraces in valleys of some of the major streams (Latta, 1950, p. 68, pl. 1; Frye and Leonard, 1952, p. 63-64; Bayne and Fent, 1963, p. 365-366; Bayne, 1956; Lane and Miller, 1965). This evidence leads to the inference that much of the relief between bottoms of deep, buried channels and crests of flanking uplands is the result of an episode of predominant downcutting that began after formation of the "algal limestone" late in Pliocene time and lasted only until some time during the Nebraskan, when deposition of the Holdrege Formation began. (See also Soister's (1967, p. D45) discussion of similar history of Arkansas River, eastern Colorado, and Fairbridge's (1968e, p. 1136) discussion of late Tertiary-early Pleistocene erosion in the southwestern U. S.)

As stated previously, the Saline River is the most deeply entrenched stream in central Kansas. However, downcutting of the Saline River took place intermittently between episodes of alluviation during the interval between the late Pliocene and some part of the Wisconsinan Glaciation - throughout almost the entire Pleistocene. As entrenchment of the Saline River in Russell County generally is only about 50 to 150 feet (15-45 m) more than entrenchment of Chase Channel and other pre-Aftonian channels in Rice, Reno, Stafford and Barton counties, entrenchment of streams during the post-"algal limestone," pre-Aftonian part of the Pleistocene seems to have occurred more rapidly than entrenchment during the post-Aftonian Pleistocene. The post-Ogallala, pre-Aftonian time interval probably was an episode of singularly long-lived and deep erosion: the amounts of entrenchment during this interval should therefore provide an estimate of the most rapid rates of entrenchment that have taken place in central Kansas from the onset of the classical Pleistocene Epoch to the present.

Estimation of the Rates of Incision of Streams in Central Kansas

Measurement of any rate of entrenchment of stream valleys presupposes that time and amounts of entrenchment can be determined with reasonable accuracy. For the purpose at hand, information is needed that will define in time the beginning and ending of entrenchment that occurred after deposition of the "algal limestone" and before deposition of the Holdrege and Fullerton formations.

As pointed out above, the Holdrege and Fullerton formations formerly were classified as members of the Chase Channel Formation (Fent, 1950) and the Blanco Formation (Bayne, 1956). They are considered to be stratigraphically equivalent to Blancan strata in Texas and Nebraska, and thereby equivalent to the terrestrial Villafranchian strata of the Mediterranean region (fig. 11) (Moore, 1949, especially p. 1278; Frye and Leonard, 1952, p. 66-68). The Kimball Member of the Ogallala Formation, of which the "algal limestone" is the uppermost part, is correlative with the Astian strata of the Mediterranean area (fig. 11) (Moore, 1949, p. 1277). On the basis of recent information (see Tobien, 1970, p. 79, 85-88), this correlation implies that the Holdrege and Fullerton formations are in fact correlative only with the Middle and Upper Villafranchian. By comparison with evidence from radiometric dating of the Astian and Villafranchian then, the age of the "algal limestone" can be taken as being about 3.0 million years (the approximate age of the uppermost Astian beds), and the age of the uppermost Fullerton as being about 1.8 m.y. (Tobien, 1970, p. 79). The conclusion follows that the duration of the interval following deposition of the "algal limestone" and concluding with deposition of the Fullerton Formation was about 1.2 m.y.

The qualification should be made here, however, that correlation of the Blancan and Villafranchian strata has been a matter of occasional dispute. Funnell (1964, p. 183-184) and others have considered the Blancan to be Pliocene-Pleistocene, and according to Funnell (1964, p. 184), the Blancan includes strata ranging in age from 4.1 m.y. to 2.05 or 2.25 m.y. The span of time represented by Blancan deposits (or the Holdrege and Fullerton formations under this classification) would range from 1.85 m.y. to 2.05 m.y., considerably longer than the 1.2 m.y. under consideration on the basis of Tobien's work.

The Holdrege and Fullerton formations represent an episode of considerable deposition as well as erosion, of course. This deposition presumably occurred during the latter part of the Nebraskan Glaciation, as the Holdrege and Fullerton of the type region were laid down during the time of retreat of the Nebraskan continental glacier and perhaps during part of the ensuing Aftonian Interglaciation (Frye and Leonard, 1965, p. 208). At present, the information is not available to determine how much of the approximately 1.2 (Tobien, 1970) or 2.05 (Funnell, 1964) m.y. was consumed solely by the process of erosion. Therefore, only the minimal rates of erosion during the post-"algal limestone," pre-late Nebraskan interval are estimable. Nonetheless, these rates are useful in the context of this study, for the following reasons.

1) The rates should be the highest among those calculable for all stages of the Pleistocene, as total incision of the Saline River, for example, during the interval lasting from the time of breaching of the "algal limestone" to the Wisconsinan was only slightly more than incision that occurred during the interval lasting from time of incision of Chase Channel through the "algal limestone" to the Aftonian (300 ft cf. 250 ft) (90 m cf. 75 m).
2) On the assumption that major episodes of climatic change similar to episodes of the Pleistocene will

occur during the next 1 million years (a premise argued previously), these episodes are presumed to include minor episodes of deposition as well as erosion, and therefore,

3) the rates of erosion that occurred during the interval from the late Pliocene to the late Nebraskan should be valid estimations of the maximal rates of stream incision that are likely to prevail during climatic episodes of the next 1 million years.

In summary, the Holdrege and Fullerton lie upon eroded bedrock about 250 feet (75 m) below the "algal limestone" and as much as 330 feet (100 m) below the Arkansas River-Smoky Hill River divide. This erosion could have occurred during a span of time that may have been as short as 1.2 m.y. or as long as 2.05 m.y. Accordingly, rates of maximal, historical entrenchment of the main channels of the major early Pleistocene streams of central Kansas aretimated to have ranged from a minimum of about 120 feet (37 m)/ 1 million years to a maximum of 275 feet (84 m)/ 1 million years.

EXTRAPOLATION FROM SPECIFIC PLEISTOCENE HISTORY, ARKANSAS AND SMOKY HILL RIVERS

The primary objective of this research, as stated preusly, effectively is to determine how much the drainage basin of Owl Creek (or Cow Creek, or the Arkansas River) will be lowered into the bedrock. The secondary objective of this endeavor is to estimate the likelihood that damage to the repository might result from entrenchment of nearby rivers. The Smoky Hill River o Ellsworth County is the only stream judged to be near enough to the repository site to merit investigation.

Assumptions held in this approa the problem are repeated here for clarity.

a) The Pleistocene history of a stream serves as the best model for deduction of events likely to occur within the stream's watershed.

b) The next 1 million years will comprise an interglaciation of about 100,000 years, a glaciation of 500,000 years, and interglaciation of 200,000 years, and a glaciation of 200,000 years.

c) Valley erosion would occur during waxing glaciation, and valley alluviation would occur during waning glaciation. Interglaciations are episodes of effective erosional-depositional equilibrium.

d) The drainage network of centr Kansas has been superimposed into bedrock and has created the modern topography.

e) The location of Cow Creek relative to nearby streams suggests that Cow Creek will not be pirated from the Arkansas River drainage basin within the next 1 million years. Accordingly, the assumption is stated that Cow Creek will be within the Arkansas River's drainage basin for the next 1 million years.

Figure 20 shows that Cow Creek flows within a thick valley fill, in which deposits of all glaciations are recognized. Lowermost deposits in the valley fill are the Nebraskan Holdrege and Fullerton formations. The channel that the Holdrege and Fullerton occupy was cut by a stream that flowed through Galatia channel from the headwaters of the ancestral Smoky Hill River southeastward to the Arkansas River (fig. 10). During the early part of the Wisconsinan, the Arkansas River flowed through the valley now occupied by the lower reaches of Cow Creek (Fent, 1950, p. 22). Cow Creek has occupied its present position only since sometime during the Wisconsinan. Thus the information necessary to deduce the long-term rates of entrenchment and alluviation of the valley of Cow Creek is not available from known stratigraphic record of the stream. Therefore, an alternative basis for inferences about the future entrenchment and filling of Cow Creek is required.

Because Cow Creek is tributary to the Arkansas River, entrenchment and filling of the Arkansas River Valley necessarily would establish limits upon events that could occur within the Cow Creek and Owl Creek watersheds. Therefore, consistent with the assumptions stated above, a Maximal-Case construct of valley erosion might be inferred from the Pleistocene history of the Arkansas River in central Kansas.

The record of the Arkansas River is straightforward for the purpose of deductive inference. The valley of the Arkansas River in central Kansas was heavily alluviated during each episode of the Pleistocene. Successive valley erosion during the Kansas, Illinoian, and Wisconsinan glaciations was not sufficient to breach the valley fill of the preceding interglaciations (Frye and Leonard, 1952, p. 198, 206, 209). Consequently, the Arkansas River alluvial plain is topographically high in comparison to the valleys of the rivers that lie to the north and south (fig. 21). Therefore, because the assumption is held that the Pleistocene history of a stream serves as the best model for deduction of events likely to occur within the watershed of that stream, and because the Pleistocene history of the Arkansas River shows progressive aggradation of its valley, the inference is drawn that the Arkansas River will not breach its Pleistocene valley fill during the glaciation presumed to occur under the Maximal-Case construct. In fact, the only nearby stream judged to be likely to entrench its valley to near the Hutchinson Salt Member is the Smoky Hill River in Ellsworth County. This matter does not merit serious consideration however, because (1) the probability of such an event is less than 0.01; (2) if the Smoky Hill River were to cut into the Hutchinson Salt Member, the event should not occur until about 300,000 to 350,000 years from now; and (3) even if the Hutchinson Member were breached by the Smoky Hill River in Ellsworth County, and near-surface dissolution of the salt were to begin, central Ellsworth County is farther from Lyons, Kansas, than the eastern margin of the salt is judged to have retreated during the past 1 million years (U. S. Atomic Energy Commission, 1971, p. 43). (Points 1 and 2 above are argued in Appendix C.)

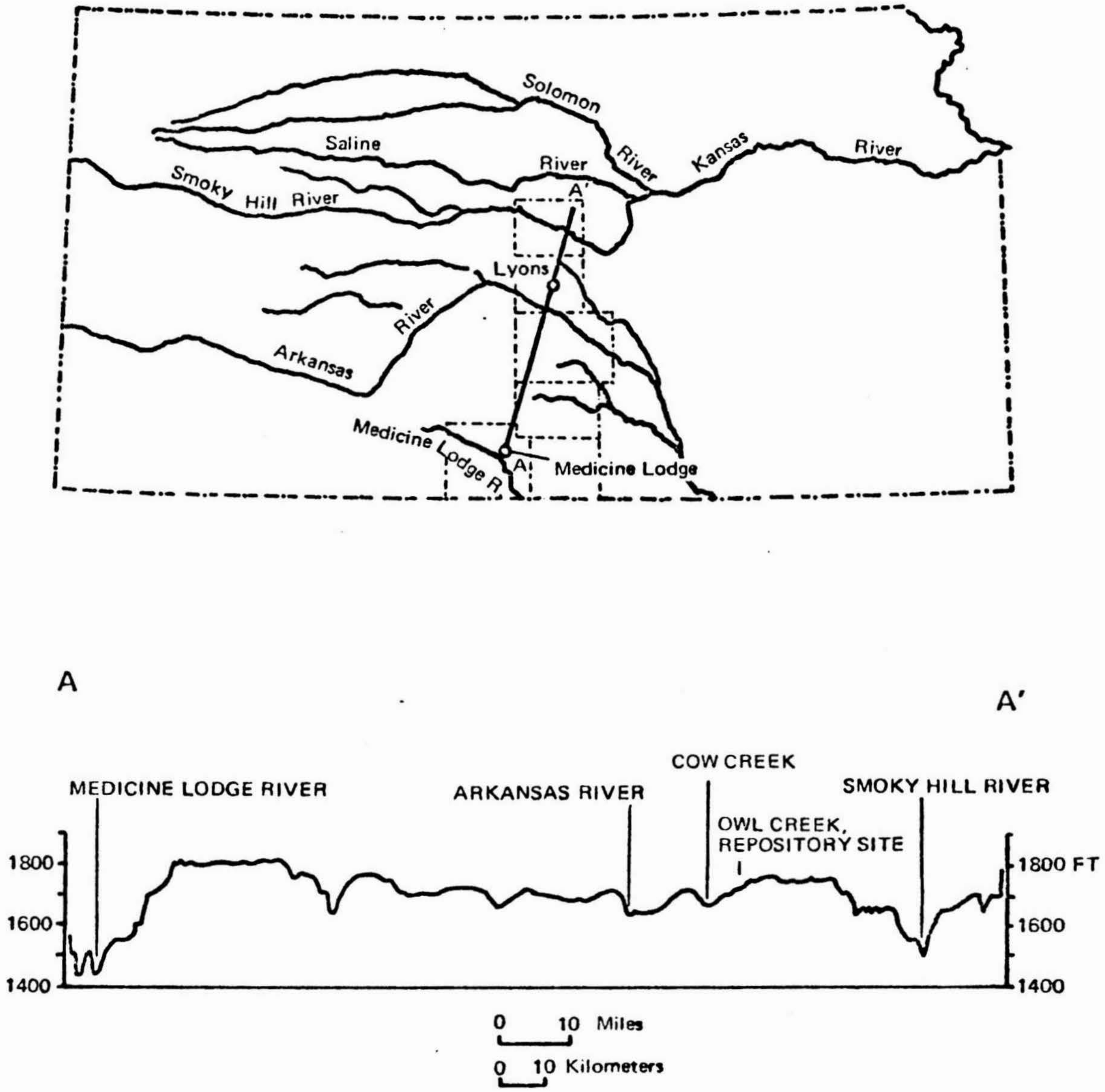

Figure 21.- Simplified topographic profile showing elevation of Arkansas River relative to Smoky Hill and Medicine Lodge rivers. Vertical exaggeration, 66X. Location of profile shown on map above. (Profile based on U. S. Army Map Service, 1955, 1959.) For conversion of elevations shown on margins of cross-section from feet to meters, multiply numbers by 0.3048.

POTENTIAL EFFECTS OF STREAM PIRACY

On the whole, the landscape of Kansas can be described as mature. The drainage system is well integrated and stream divides are narrow. In comparison to valleys of other major streams of central Kansas, the valley of the Arkansas River is topographically high (fig. 21, this paper; see also Frye and Leonard, 1952, pl. 2, cross-sections A-A', B-B', C-C'). Because of the high position of this river, piracy seemingly could occur at places in western and central Kansas where other rivers are near to the Arkansas and where their tributaries are eroding toward its channel. Localities that are especially suggestive of potential piracy are in the headwaters of Sand Creek and Bluff Creek in southeastern Ford County (fig. 10, 22) and in the headwaters of the Cimarron River in Grant and Kearny counties (fig. 10).

The divide between Sand Creek and Rattlesnake Creek, a tributary of the Arkansas River, has almost been cut through in T. 29 S., R. 21 W., about 5 miles (8 km) south of Bucklin, Kansas (fig. 22). Likewise, the divide between Bluff Creek and Mulberry Creek, also a tributary of the Arkansas River, has almost been cut through in T. 29 S., R. 23 W., about 12 miles (19 km) southwest of Bucklin. Gradients of Sand and Bluff creeks are about 17 ft/mi (3.2 m/km) in this region, whereas gradients of Rattlesnake Creek, Mulberry Creek, and the Arkansas River are about 7 ft/mi (1.3 m/km). Headwater reaches of all these streams flow across terrain that can be

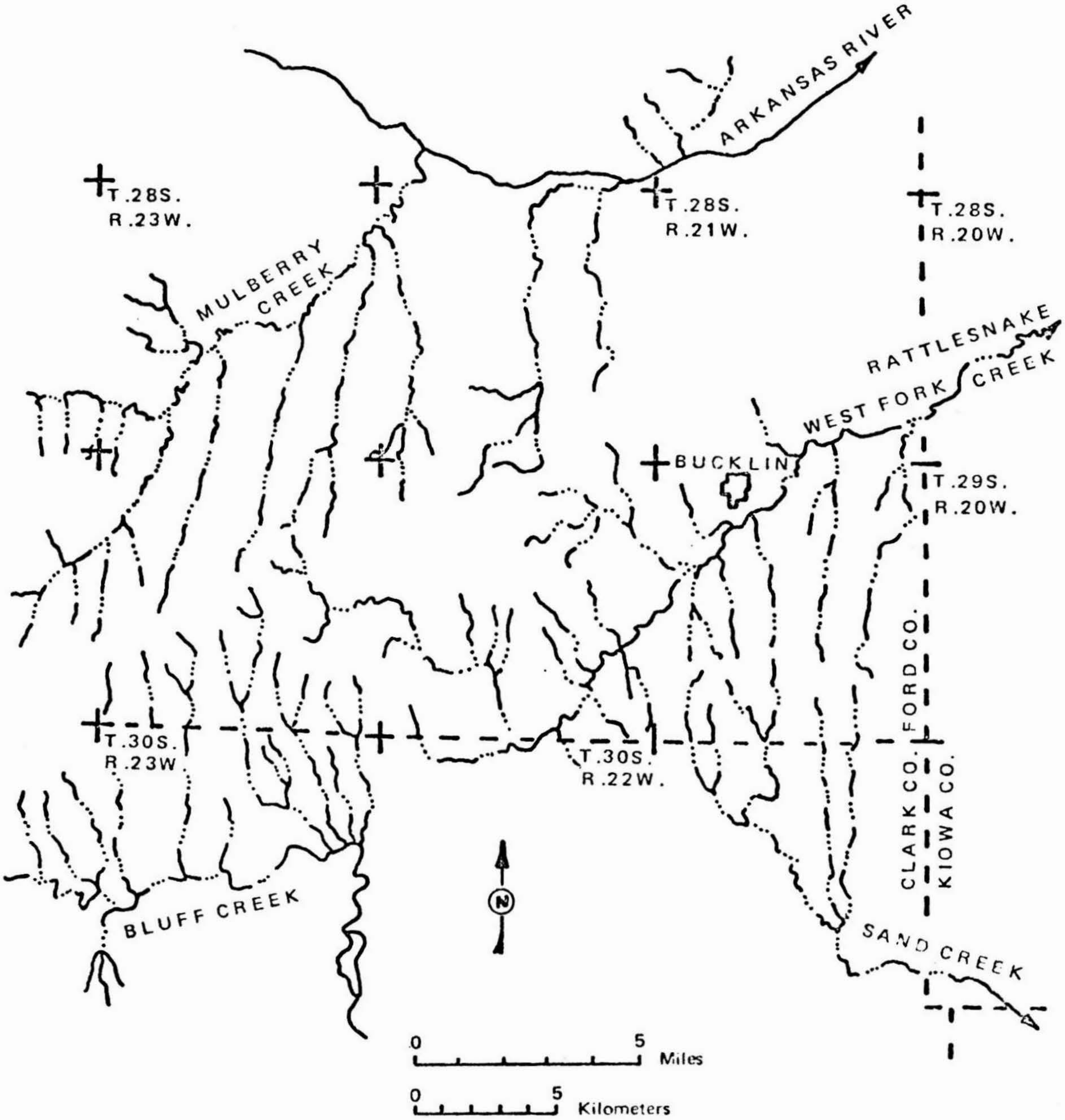

Figure 22.- Headwater areas of Mulberry Creek, West Fork of Rattlesnake Creek, Bluff Creek, and Sand Creek, Ford, Clark and Kiowa counties, Kansas. Sand Creek and Bluff Creek may capture West Fork of Rattlesnake Creek and Mulberry Creek respectively, and may thereby eventually divert the Arkansas River southward into the Cimarron River (fig. 10). (Map based on U. S. Army Map Service, 1968.)

assumed to be generally of the same resistance to erosion throughout. Also, discharges of the headwater tributaries seem to be not markedly different. Therefore, the inference can be made that Sand Creek should capture the drainage of Rattlesnake Creek southeast of Bucklin and Bluff Creek should capture the drainage of Mulberry Creek west of Bucklin (fig. 22). By extension of the headwaters that now are in Rattlesnake Creek drainage basin or by continued piracy of Mulberry Creek, Sand Creek or Bluff Creek could capture the Arkansas River northwest of Bucklin and divert it southward to the Cimarron River, thence to Oklahoma.

The drainage system is complex in some places on the extensive terrain of sand dunes in northern Grant and southern Kearny counties, and it is not clear as to whether the rate of erosion of the Arkansas or of the Cimarron is the greater. The gradient of the Cimarron seems to be slightly the larger, its headwaters region extends near to the main channel of the Arkansas and it seems to be actively eroding. The Cimarron may cut through the narrow divide in southwestern Kearny County and divert the Arkansas southward into Oklahoma (fig. 10).

If the events described above were to occur, their effects on the drainage basin of the Arkansas River eastward to the vicinity of Lyons, Kansas, would be to reduce the discharge of the Arkansas River about 25 percent, but, of course, also to reduce the load of sediment that would pass through the drainage basin. As discussed previously, sediment yields of streams generally are moderately to strongly correlated with stream discharges. Inasmuch as no evidence exists to show that piracy of the Arkansas near Bucklin or in Kearny County should reduce the sediment load in downstream reaches by amounts greater than about 25 percent,[24] the following conclusion can be drawn: Stream piracy that is considered to be most likely to occur during the period of concern should not drastically change the regimen of the Arkansas River near Lyons; piracy should not cause the Arkansas to entrench its channel.

CONCLUSIONS

The available evidence lends support to the assumption that glacial and interglacial episodes similar to those of the Pleistocene will continue throughout the next 1 million years. Estimated durations of glaciations and interglaciations of the classical Pleistocene that are judged to be the most nearly reliable are the basis of a Maximal-Case construct. This construct specifies the following sequence of events, of which the probability of exceedence is 0.01: an interglaciation of about 100,000 years and a glaciation of about

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[24] On the contrary, Collins (1965, pl. 1) showed that sediment yields in the Arkansas River watershed upstream from Bucklin to the Kansas-Colorado border, and downstream from Bucklin, past Lyons, to about Hutchinson, are almost the same (less than 50 tons/sq mi)(17.5 metric tons/sq km).

500,000 years, followed by an interglaciation and glaciation, each of about 200,000 years.

Climatic changes that would accompany glaciations are approximated by present conditions in eastern North and South Dakota, northeastern Nebraska, northwestern Iowa, and southwestern Minnesota. Present climatic conditions in Kansas are considered to be representative of interglaciations. If continental glaciers were to advance into central Kansas, and a forebulge were to develop in the ice-marginal regions, regimens of streams within the region of the forebulge should not be affected to an extent that would cause derangements of present major stream systems or reversals of directions of flow. Fall and rise of sea level attendant to glaciations and interglaciations would not affect entrenchment of streams and alluviation of valleys in the Midcontinent. Entrenchment of streams in this region seems to have occurred during waxing glaciations; alluviation of valleys seems to have occurred during waning glaciations and the early parts of interglaciations. These events seem to be due only to changes of climate and epeirogenic uplift, and seem to be correlated with, but not be "caused" by glacial fluctuations of sea level.

The streams of central Kansas are judged to have been superimposed into the Cretaceous and Permian bedrock from a terrain developed on the Pliocene Ogallala Formation. Rates of entrenchment of the channels of major early Pleistocene streams of central Kansas are considered to have been uncommonly rapid; therefore they can be considered to be maximal estimates of entrenchment to occur within the next 1 million years. These early Pleistocene rates probably ranged from about 120 ft (37 m)/10^6 yrs to about 275 ft (84)/10^6 yrs.

Denudation of the Arkansas River drainage basin above the confluence of Cow Creek and the Arkansas River will establish an upper limit on denudation of the tributary drainage basins in which the proposed repository site is located. The probability that denudation will exceed 15 to 20 feet (4.5-6 m) is judged to be about 0.003; for all practical purposes, the probability that denudation will exceed 25 feet (7.6 m) is considered to be zero.

The conclusion is drawn that the Arkansas River will not breach its valley fill during the forthcoming 1 million years. The only nearby stream considered to be likely to entrench its valley to depths near the Hutchinson Salt Member is the reach of the Smoky Hill River in Ellsworth County, about 25 miles (40 km) north of the proposed repository site. However, the probability of this amount of entrenchment is less than 0.01. Even if such entrenchment of the Smoky Hill River were to occur, the Hutchinson Salt Member would not be incised until about 350,000 years from now. Furthermore, the incision would occur farther from the proposed repository site than the eastern margins of the salt strata are judged to have been eroded during the past 1 million years.

The Arkansas River is likely to be pirated by the headwaters of the Cimarron River near Bucklin, Ford County. If this piracy were to occur, the regimen of the Arkansas River would not be changed drastically; the river should not be caused to entrench its channel.

From an operational standpoint, the evidence summarized above converges on this conclusion: the probability that stream erosion will unroof the Hutchinson Salt Member at or near the proposed repository site is judged to be so small that this matter merits no further consideration.

APPENDIX A

Data used for interpretation of paleoclimates. Summarized in Table 1.

Selected Key to References

References shown below in abbreviated form are listed completely under "References Cited." Numbers shown after summary statements in following parts of this appendix, as (1-154) for example, signify reference number 1 (Frye and Leonard, 1952), page 154. These references were selected because they are synthetical and have to do with paleoclimates. Many other sources of information that concern descriptions of stratigraphy and local faunas are available.

1) Frye and Leonard, 1952
2) Ruhe, 1970
3) Kapp, 1970
4) Wright, 1970
5) Hoffman and Jones, 1970
6) Hibbard, 1970
7) Kapp, 1965
8) Semken, 1966
9) Taylor, 1960 (Table 2, p. 15, interpreted by me.)
10) Leonard, 1950
11) Leonard, 1952
12) Taylor, 1965

13) McGregor, 1968
14) Wilson, 1968
15) Schultz, 1967
16) Miller, 1970
17) Berry and Miller, 1967
18) Caspall and Dort, 1970
19) Frye and Leonard, 1967

Kansas, General

Pliocene Epoch

1. Semi-desert; semiarid; rainfall probably 15 to 25 inches (38-64 cm) and mean annual temperature 50°-55° F (10°-13° C). (19-435, 438)

Nebraskan Glaciation

1. Cool temperate; no indication of boreal climate. (1-154)
2. No faunal evidence for cold climate. (6-395)
3. Cool, humid. (19-435)

Kansas Glaciation, General

1. Slightly cooler than Nebraskan. (6-400)
2. Slightly cooler. No boreal climate. Good floral cover, including prairie, meadow, woodland, but no extensive forests. More abundant or better distributed rainfall than present. Lower mean temperatures; no "extreme"

temperatures. Similar to Nebraskan. (1-160 to 162)

Late Kansas

1. Average temperature lower than Illinoian and lower than present. (1-165)
2. Western Kansas - environment similar to central Michigan today. (11-10)
3. Annual mean temperatures perhaps somewhat lower than present. More equable without much lowering of annual mean temperatures, compared to present. Lacked extremes of high summer temperature and severe drought. In general, climate seems to have been "not unlike that of the present" but plains "better watered." No evidence of widespread forests on Plains Border and Plains provinces. Fauna does not suggest timbered area. (10-44)[1]

Illinoian Glaciation, General

1. Prairies, meadows, woodland border. Climate like present, but slightly greater rainfall. (1-165 and 166)

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[1] Evidence referred to in this reference described as having been collected from deposits classified as Yarmouthian. These deposits are now classified as Kansan (Frye, 1961, p. 601; Zeller, 1968).

Late Illinoian

1. Environmental conditions "not remarkably different from... today," but more moist and perhaps slightly cooler. (11-10)

Sangamonian Interglaciation

1. Dominantly grassland. Forest border and prairie in northeastern Kansas. Distribution of climatic and floral zones in Kansas similar to present, but boundary lines perhaps shifted to east. (1-120 and 123)

Wisconsinan Glaciation, General

1. Steppe or pine savanna. (5-360)

Early Wisconsinan

1. A "reasonable amount of rainfall" and vegetation at least as dense as at present. Temperatures slightly lower. (11-14)

Medial Wisconsinan

1. Similar to present. (1-135)

Late Wisconsinan

1. Similar to present. Vegetation reduced from medial Wisconsinan time. Arid hot summers; cold, dry winters. (1-180)

2. Extreme winter temperatures like present developed in Late Wisconsian. Continental climate characteristic of Great Plains and zonation of climate late Wisconsinan. (6-407)
3. Environment "...very like present conditions in the Great Plains." (11-16)

Northeastern Kansas

Nebraskan Glaciation

1. Rainfall higher, more equitably distributed. Cool, temperate. Not boreal. (1-151 and 154)

Kansan Glaciation

1. Cooler than present. (1-160)

Sangamonian Interglaciation

1. Forest. More moist than present. (2-49)
2. Forest border and prairie. (1-123)

Wisconsinan Glaciation

1. Woodland. (3-153)
2. Boreal forest. (13-86)
3. Boreal forest succeeded by deciduous forest or prairie. (18-380 and 381)

Central Kansas

Evidence from general area of Lincoln, McPherson and Kingman counties, Kansas.

Pliocene

1. Rexroad Formation.- Frost-free winters; moist tropical climate like northern South America. Braided streams, gallery forests, savanna valleys, scattered groves of trees. (6-398)
2. Ogallala Formation.- Gallery forest, savanna, grassland. Humid subtropical. (14-75 and 124)

Nebraskan Glaciation

1. Woodlands, no forests. (1-153)

Illinoian Glaciation, General

1. 'Ecological conditions compare well with modern conditions in same latitudes but further eastward toward humid Missouri-Mississippi valley (central Missouri).' (11-10)

Early Wisconsinan Glaciation

1. More rainfall than present. Denser flora. Somewhat cooler. (1-177)

Late Wisconsinan

1. Similar to present. (1-180)

Southwestern Kansas

Evidence from general area of Meade County, Kansas, and Beaver and Harper counties, Oklahoma.

Pliocene

1.	Bender Local Fauna.-	"Semiarid-dry subhumid. Mean annual precipitation little different. Summers slightly cooler. Winters little if at all cooler. Continentality reduced." (12-604)
2.	Rexroad Local Fauna.-	"Dry subhumid. Mean annual precipitation slightly greater. Freezing temperatures rare or absent. Summers slightly cooler. Continentality much reduced." (12-604)
3.	Rexroad Formation.-	Mostly mesothermal, subhumid, but partly semiarid. (9-15)
4.	Ogallala Formation.-	Subhumid. (9-15)

Consensus: Temperate, warm, more equable, less continental. Subhumid.

Nebraskan Glaciation

1. Rainfall considerably higher than now, more equitably distributed; cool, temperate. Open prairie to woodland; no extensive forest. (1-153, 154 and 155)
2. Microthermal. (9-15)

Consensus: Cool temperate. Rainfall higher than present, more evenly distributed throughout year. Prairie with woodland.

Aftonian Interglaciation, General

1. Probably semiarid. Summers cooler than present, winters warmer. Average annual precipitation similar to present. (17-301)

Consensus: Semiarid grading into subhumid in latter part of Aftonian; less continental. Precipitation similar to present; perhaps somewhat less during early part of Aftonian. Climate less continental.

Early Aftonian

1. Mesothermal. (9-15)

Medial Aftonian

1. Semiarid; rainfall about 15 to 18 inches (38-46 cm/yr) per year. (6-400)
2. Semiarid. (9-15)

Late Aftonian

1. Subhumid, maritime. (6-400)
2. Mesothermal, subhumid. (9-15)
3. Subhumid. Mean annual precipitation greater, but perhaps only slightly. Summers cooler. Winters no cooler. Continentality reduced. (12-604)

Kansas Glaciation, General

1. Microthermal, subhumid. (9-15)
2. "Dry subhumid. Mean annual precipitation little different. Summers much cooler. Continentality reduced." (12-604)

Consensus: Cool temperate, subhumid. Rainfall similar to present climate. Less continental.

Yarmouthian Interglaciation, General

Consensus: Warm temperate, subhumid to semiarid, continentality much reduced.

Early Yarmouthian

1. Maritime. Frost-free winters. (6-403)
2. Mesothermal. (9-15)
3. "Dry subhumid. Freezing temperatures rare or absent. Mean annual precipitation slightly greater or summers slightly cooler. Continentality much reduced." (12-604)

Medial Yarmouthian

1. Semiarid, caliche-forming. (6-403)
2. Semiarid. (9-15)

Illinoian Glaciation, General

1. Area of geographic overlap of living forms of vertebrates with fossil fauna is southeastern North Dakota and northeastern South Dakota. (7-190)

2. Vegetation may have resembled pine savannas of lower Rocky Mountain slopes. (7-233)
3. Mean annual temperature probably 40-45° F (4°-7° C) (presently 55° F (13° C)). Average winter temperatures about 20° F (11° C) cooler and summer temperatures about 10° F (5° C) cooler than present during glacial maximum. (7-234)
4. Annual precipitation may be not much different from present 20-25 inches (50-64 cm). (7-234)
5. Present area of sympatry of fauna southeastern Wyoming, north-central Colorado. Fauna represents present climatic conditions of southeastern plains of Wyoming. Representative of cooler, probably glacial times. (8-169)
6. Other Illinoian fauna considered representative of present eastern Dakotas, Nebraska, Iowa or more eastern points (several authors referred to by author shown here). (8-170)
7. Microthermal, subhumid. (9-15)
8. Cooler summers than present. (15-325)
9. Cool summers, similar to southeastern South Dakota, northeastern Nebraska, northwestern Iowa (65°-70° F) (18°-21° C). Winters no more severe than east-central Kansas (30°-35° F) (-1° to 2° C). Precipitation perhaps no greater than at present. (16-45)
10. "Dry subhumid. Mean annual precipitation little different. Summers much cooler, winters perhaps like those today. Continentality reduced." (12-604)

Consensus: Cool temperate, less continental. Annual precipitation about the same. Climate probably similar to the approximate area of South Dakota and southeastern North Dakota. Mostly grassland and prairie, with woodlands of pine and spruce of undetermined extent.

Early Illinoian

1. More moist than present. Winters no colder than present. No summer extremes. (6-404)

Medial Illinoian

1. Winters no colder than present. No summer extremes. (6-404)
2. Climate similar to eastern Dakotas. Summer temperature about 10° F (5° C) lower than present. (7-168)
3. "Summers cooler and more moist than present. Climate less continental." Pine savanna in uplands. (7-232)

Late Illinoian

1. Spruce, pine, scarp woodlands. (3-151 and 152)
2. Winter temperatures like present in southern New Jersey; summer temperatues like northern New Jersey and southern Wisconsin. (6-405)
3. Spruce absent or scattered. Higher summer temperatures. Drier. (7-243)

4. "Moist subhumid. Mean annual precipitation slightly greater (20-25 inches (50-64 cm). Summers much cooler, winters slightly warmer. Continentality reduced." (12-604)
5. Greater or more effective rainfall. Markedly cooler summers. Winter no more severe than Nebraska at present. (15-330)
6. Higher average temperature than Illinoian maximum; more extremes. Less effective moisture than Illinoian maximum. Pine and spruce decreased. Dry uplands. (7-232)

<u>Sangamonian</u> <u>Interglaciation</u>, <u>General</u>

1. Trees fewer. Warmer than Illinoian. Prairie vegetation. (3-153- and 154)
2. Much less continental. Above freezing in winter. Summers cooler. Mean rainfall about same. (6-405)
3. Mild winters with temperature seldom freezing. Rainfall may not have been much different than present, but perhaps more equally distributed throughout year. (7-216)
4. Mesothermal, humid. (9-15)

Consensus: Chiefly warm, semiarid, less continental. Expecially semiarid in medial Sangamonian. Warm, humid in Late Sangamonian. Annual precipitation about the same as present during most of interval. Winters above freezing. Summers cooler than now. Prairie vegetation with gallery forests.

Early Sangmonian

1. Climate semiarid, not as continental as present. Winter temperatures warmer than present, perhaps with no freezing. Summers not as hot as today. Mean annual rainfall perhaps same as today. (7-237)
2. Pine and deciduous trees in moist habitats around streams. (7-244)
3. "Semiarid. Mean annual precipitation little different. Freezing temperatures rare or absent. Summers slightly cooler. Continentality much reduced." (12-604)
4. "Warm and dry, perhaps not as continental as today." Pine and hardwoods along streams. Sagebrush, ragweed, short grasses in dry uplands. (7-232)

Medial Sangamonian

1. Believed to have been time of caliche formation. Rainfall perhaps scanty and sporadic. Climate probably as continental as today. (7-232 and 238)
2. Caliche-forming, low precipitation. Semiarid and warm. (7-232)

Late Sangamonian

1. Warm, moist, temperate, equable. Rainfall 40-45 inches (100-155 cm) per year. Climate similar to southeastern Arkansas. Summers cooler, more moist. (6-406)

2. Mild winters without extremely low temperatures. Conditions like southeastern Kansas and eastern Oklahoma today. Normal annual average temperature at least 5° F (3° C) warmer than today; minimal winter temperatures 20° F (11° C) warmer than present. Rainfall about 40 inches (100 cm) per year (presently 20 inches (50 cm) per year). (7-238)
3. "Humid, no seasonal moisture deficiency. Mean annual precipitation 40-45 inches (100-115 cm). Winters much milder. Summers much wetter, slightly cooler. Continentality much reduced." (12-604)
4. More precipitation than present. Cooler summers, warmer winters. Less continental climate. Pine savanna in uplands with abundant grasses. (7-232)

Wisconsinan Glaciation, General

1. Steppe or savanna. (5-362)
2. Microthermal, subhumid. (9-15)

Consensus: Cool temperate. Less continental. Annual precipitation similar to present. Climate perhaps similar to eastern South Dakota.

Early Wisconsinan

1. More rainfall than present. Denser flora. Somewhat cooler. (1-177)

2. "Semiarid to dry subhumid. Mean annual precipitation no greater, perhaps less. Summers much cooler. Continentality reduced." (12-604)

Medial Wisconsinan

1. Climate similar to present. (1-135)

Late Wisconsinan

1. Similar to present. (1-180)
2. Climate comparable to extreme northeastern South Dakota and adjacent Minnesota. Mean annual temperature in this area 42° F (5.6° C), precipitation 22 inches (56 cm) per year. (15-333)

APPENDIX B

Derivation of Constants Used by Dole and Stabler (1909) and by Judson and Ritter (1964), and Ritter (1967; 1968).

The basic method of computing denudation rates of streams, as originally stated by Dole and Stabler (1909, p. 80-81) is: Annual denudation, as tons of suspended and dissolved sediment per square mile = (solids (ppm)) x (discharge (cu ft/sec/sq mi)) x (0.985). Annual denudation as 10^{-6} in/sq mi = (tons sediment/sq mi) x (0.1917). Derivation of the constants 0.985 and 0.1917 was not stated. These constants are derived in sections A and B below. Computations of denudation rates reported by Judson and Ritter (1964, p. 3396) and Ritter (1967; 1968) employ the formula: Denudation (in/10^3 yrs) = (tons/sq mi/yr) x (5.2×10^{-3}). The constant 5.2×10^{-3} is a modification of the basic formula of Dole and Stabler (1909, p. 80-81) and is derived in section C below.

A. Deriviation of the constant 0.985, as used by Dole and Stabler (1909) to compute tons of rock eroded per square mile per year in a drainage basin.

   1. Dissolved solids in water, sediment concentration, and runoff, shown by the United States Geological Survey in _Water-Supply Papers_, are expressed as parts per million, and cubic feet per second (runoff).

2. Areas of drainage basins are published in <u>Water-Supply Papers</u>, expressed as square miles.
3. Tons of bedrock removed from the drainage basin annually are expressed with one square mile considered as the fundamental unit area.
4. a. Mean annual discharge per square mile in a drainage basin = Mean annual discharge from the drainage basin (cu ft/sec) ÷ area of drainage basin (sq mi) = mean annual discharge expressed as (cu ft/sec)/(sq mi) = (S cu ft/sec)
   b. One year = 31.5669×10^6 seconds (Weast, 1969, p. F96)
   c. Total annual discharge per square mile = (S cu ft/sec) x (sec/yr) = (T cu ft/yr)
   d. Density of water = 62.43 lbs/cu ft
   e. Pounds of discharge per square mile per year = (T cu ft/yr of discharge) x (density of water) = (T cu ft/yr) x (62.43 lbs/cu ft) = (U lbs discharge/yr)
   f. (U lbs discharge/yr)/10^6) = (V million lbs discharge/yr)
   g. (V million lbs discharge/yr) x (W ppm dissolved (or suspended) solids) = (X lbs dissolved (or suspended) solids/yr)
   h. (X lbs dissolved (or suspended) solids/yr)/1 ton/2000 lbs) = (Y tons dissolved (or suspended) solids/yr)

5. In abbreviated form:

   a. Millions of pounds of discharge per square mile per year:

$$\frac{(S \text{ cu ft})}{(1 \text{ sec})} \times \frac{(31.5569 \times 10^6 \text{ sec})}{(\text{yr})} \times \frac{(62.43 \text{ lbs})}{(1 \text{ cu ft})} =$$

$$\frac{(S)(31.5569)(62.43)(10^6)\text{ lbs}}{\text{yr}} = \frac{V \times 10^6 \text{ lbs}}{\text{yr}}$$

   b. Tons per square mile per year of rock:

$$\frac{(V \times 10^6 \text{ lbs discharge})}{(\text{yr})} \times \frac{(W \text{ parts})}{(10^6 \text{ parts})} \times \frac{1 \text{ ton}}{(2000 \text{ lbs})} = Y \text{ tons/yr}$$

   c. And, of course, by the associative principle of multiplication, the first factor in the left side of the equation above can be replaced by the left side of the equation shown under 5a. above, the whole of which reduces to $\frac{(S)(W)(31.5569)(62.43)}{(1 \text{ yr})(2000)}$. Because the numbers 31.5569, 62.43, and 2000 are constants and become dimensionless in the computations above, a dimensionless constant can be defined from them, as: (31.5569)(62.43)/(2000) = 0.9850486, rounded to 0.985.

B. Derivation of the constant, 0.917, used by Dole and Stabler (1909, p. 81) to compute depth of denudation as 10^{-6} inches/yr, as: (tons/sq mi)/(0.1917) = denudation, 10^{-6} in/yr.

   a. 1 sq mi = (27,878,400 sq ft) (144 sq in/sq ft) = 4,014,489,600 sq in

b. Therefore, 10^{-6} in. of rock removed from 1 sq mi/yr = 4,014.4896 cu in.

c. 1 cu ft rock - 165 lbs rock (assumed above)

1 cu in rock = (165 lbs/cu ft)/(1728 cu in/cu ft) = 0.095486 lbs/cu in

d. Therefore, 10^{-6} inches of rock removed from 1 sq mi = (4,014.4896 cu in) x (0.095486 lbs/cu in) = 383.275539 lbs rock

e. 383.275539 lbs = 0.191663 tons = 0.1917 tons

f. Therefore, for each 0.1917 tons of rock removed per square mile, the terrain is lowered by 10^{-6} inches, as, (Y tons/sq mi/yr)/(0.1917) = (Z in x 10^{-6}/sq mi/yr) denudation.

g. And, (Y tons/sq mi/yr)/ (0.1917) = (Y tons/sq mi/yr) x (1/0.1917) = (Y tons/sq mi/yr)(5.216484) = (Z in x 10^{-6}/sq mi/yr) denudation.

h. And, because 1 sq mi can be considered to be a fundamental unit area, (Z in x 10^{-6})/yr = Z in/10^{6} yr denudation of the entire drainage basin.

C. The basic equation of Dole and Stabler (1909), shown in section A above, was rearranged by Judson and (Ritter (1964, p. 3395-3396) to compute denudation in inches/10^{3} years by multiplying annual sediment produced per unit area by the constant 5.2 x 10^{-3}. The formula is stated as D =(5.2 x 10^{-3})(tons/mi^{2} year) (Judson and Ritter (1964, p. 3396).

a. "D" signifies denudation as in /10^3 yrs

b. D =(5.2×10^{-3})(tons/sq mi/yr)

c. As shown in B(g) above, (Y tons/sq mi/yr) x (5.216484)... = Z in/10^6 yr

d. As (Z in/10^6 yr) ÷ (10^3) = (Z in/10^3 yr), then (Y tons/sq mi/yr) x (5.216484) x ($1/10^3$), or (Y tons/sq mi/yr) x (.005216484) = Z in/10^3 yr

APPENDIX C

SOURCES OF DATA FOR COMPUTATIONS CONCERNING STREAM DISCHARGES AND DENUDATION RATES

1. Sources of data used to compute denudation rates, dissolved and suspended and bed loads, Arkansas River at Hutchinson, Kansas. Complete titles are shown in section of the report entitled "Selected References."

   a. U. S. Geol. Survey, 1964, Quality of surface waters of the United States, 1962; pts. 7 and 8, lower Mississippi River basin and western Gulf of Mexico basins: U. S. Geol. Survey Water-Supply Paper 1944, p. 65, 67-68.

   b. __________, 1966b, Quality of surface waters of the United States, 1963; pts. 7 and 8, lower Mississippi River basin and western Gulf of Mexico basins: U. S. Geol. Survey Water-Supply Paper 1950, p. 68, 70-71.

   c. Reports on water resources data for Kansas are shown with full title in the section of the report entitled "Selected References."

U. S. Geol. Survey Publication Dated:	Page Number
1965	113, 115-116
1966a	132, 134-135
1967b	130, 132-133
1968b	104, 107
1969b	124-125, 127

U. S. Geol. Survey Publication Dated:	Page Number
1970b	122-123, 125
1971a	139
1971b	92, 94-95
1972a	132
1972b	85, 87

2. Sources of data used to compute discharge/sq mi, Arkansas River drainage basin, south-central Kansas, and the Area of Sympatry. Complete titles are shown in the section of the report entitled "Selected References."

   a. Kansas:

   U. S. Geol. Survey, 1968, Water resources data for Kansas, 1967; pt. 1, surface water records: U. S. Geol. Survey, Lawrence, Kans., p. 121, 123, 124, 127, 128, 132, 133, 137, 141, 142, 143, 144, 145.

   b. Area of Sympatry:

   U. S. Geol. Survey, 1969, Surface-water supply of the United States, 1961-1965; pt. 6, Missouri River basin, v. 2, Missouri River basin from Williston, North Dakota, to Sioux City, Iowa: U. S. Geol. Survey, Water-Supply Paper 1917, p. 421-423; 425-433; 439-441; 451-456; 460-462; 466-468; 472-480; 484-485; 489-491; 495-497; 501-506; 510-512; 516-518; 525-530.

   U. S. Geological Survey, 1969, Surface-water supply of the United States, 1961-65; pt. 5, Missouri River basin, v. 3, Missouri River basin from Sioux City, Iowa to Nebraska City, Nebraska: U. S. Geol. Survey, Water-Supply Paper 1918, p. 14-19; 26-28; 50-55.

3. Sources of data used to compute annual discharge, Arkansas River at Arkansas City, Kansas.

   a. U. S. Geological Survey water-supply papers listed below are shown with full titles in the section of the report entitled "Selected References."

U. S. Geol. Survey Publication Dated:	Page Number
1954	161
1955a	165
1955b	257
1956	161
1957	155
1958a	154
1958b	153
1959	156
1960a	159
1960b	154
1962	153
1969e	191-193

   b. Reports on water-resources data for Kansas referred to below are shown with full titles in the list of selected references.

U. S. Geol. Survey Publication Dated:	Page Number
1967a	139
1968a	140
1969a	145
1970a	147
1971a	152
1972a	144

APPENDIX D

Valley Erosion of the Smoky Hill River in Ellsworth County, Kansas

The Smoky Hill River is assumed to have been superimposed into Cretaceous bedrock from the Pliocene Ogallala Formation and the "algal limestone." For computation of entrenchment during Nebraskan time, the assumption is held that before Nebraskan entrenchment began, the course of the Smoky Hill in Ellsworth County was near its present geographic position (Bayne, Franks, and Ives, 1971, p. 29), and that the stream flowed across a terrain of low relief underlain by the "algal limestone." The approximate elevation of the "algal limestone," and presumably of the ancestral Smoky Hill River, is assumed to have been about 1770 feet (540 m) (see Bayne, Franks, and Ives, 1971, p. 28, fig 16). As discussed in the main text of this report, considerable evidence shows that entrenchment of streams of the Midcontinent occurred during the earlier parts of glaciations. Entrenchment of the Smoky Hill from about the elevation 1770 feet (540 m) presumably began during the earlier one-half of the Nebraskan Glaciation.

During the Nebraskan Glaciation and the Aftonian Interglaciation, the headwaters of the modern Smoky Hill River were drained southward through Galatia channel to the Arkansas River (fig. D-1). The modern Smoky Hill River of Ellsworth County drained the headwaters of the Saline River

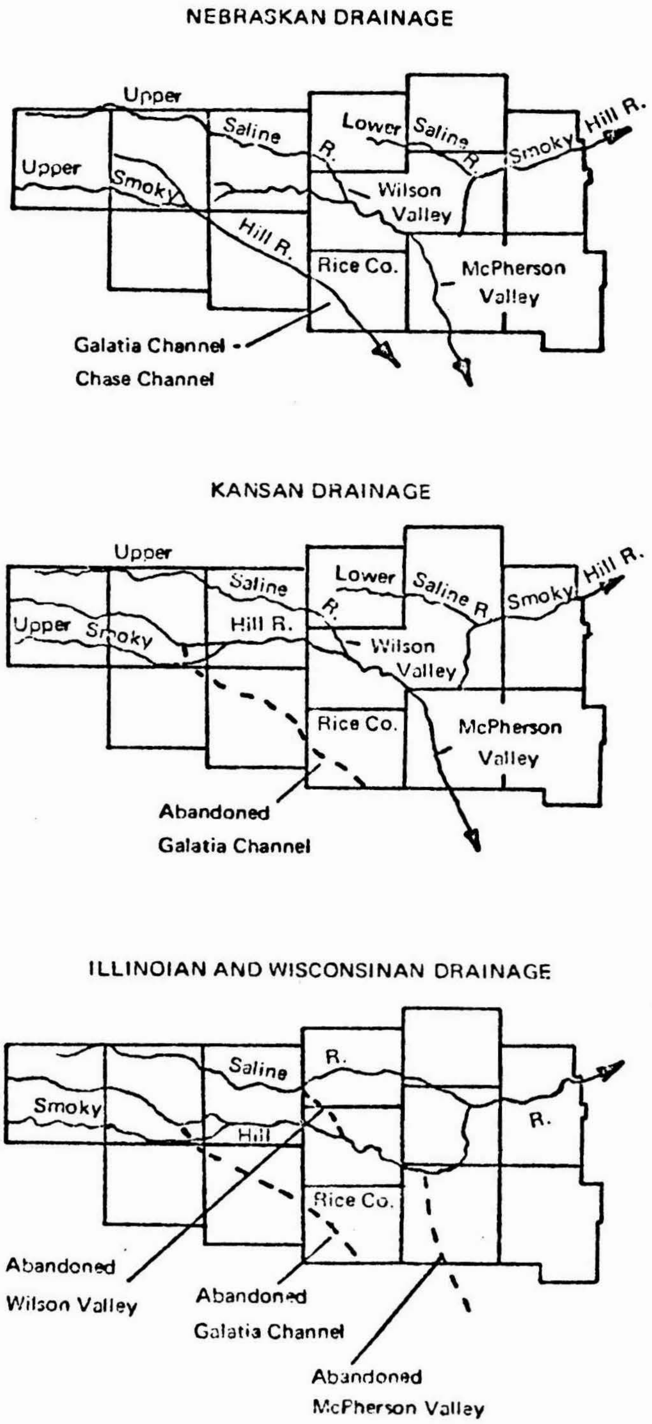

Figure D-1.- Changes in drainage system of central Kansas throughout Pleistocene time. Ellsworth County is next county north of Rice County. (After Bayne and Fent, 1963, fig. 1, 3, 6).

through Wilson Valley (fig. D-1). During early Kansan time, Galatia channel was abandoned; the Smoky Hill acquired its modern headwaters and still drained the headwaters of the modern Saline River through Wilson Valley. During late Yarmouthian and early Illinoian time, the headwaters of Saline River were pirated from Smoky Hill River and the modern drainage systems were established. (All the paragraphy above based on Bayne, Franks, and Ives, 1971, p. 29-32.)

A cross section considered to be typical of the Smoky Hill River Valley in Ellsworth County is shown in Figure D-2. This cross section provides basic data for inferences that follow. Terrain shown in Figure D-2 seemingly is a short distance downstream from the former confluence of the Smoky Hill River and Wilson Valley. Pre-Kansan and post-Yarmouthian discharges of Smoky Hill River are assumed to have been about equal. Its presumed large discharge during Kansan time, when it possessed both its modern headwaters and the headwaters of Saline River, is assumed not to be a condition so extraordinary as to invalidate the assumption that the Pleistocene history of the Smoky Hill is the best model from which to predict its future performance.

The Smoky Hill River Valley shows evidence of cyclic valley erosion and alluviation. During the waxing Kansan, Illinoian, and Wisconsinan glaciations, alluvial fill deposited during the waning stages of the preceding glaciation was breached and bedrock below was incised (fig. D-2).

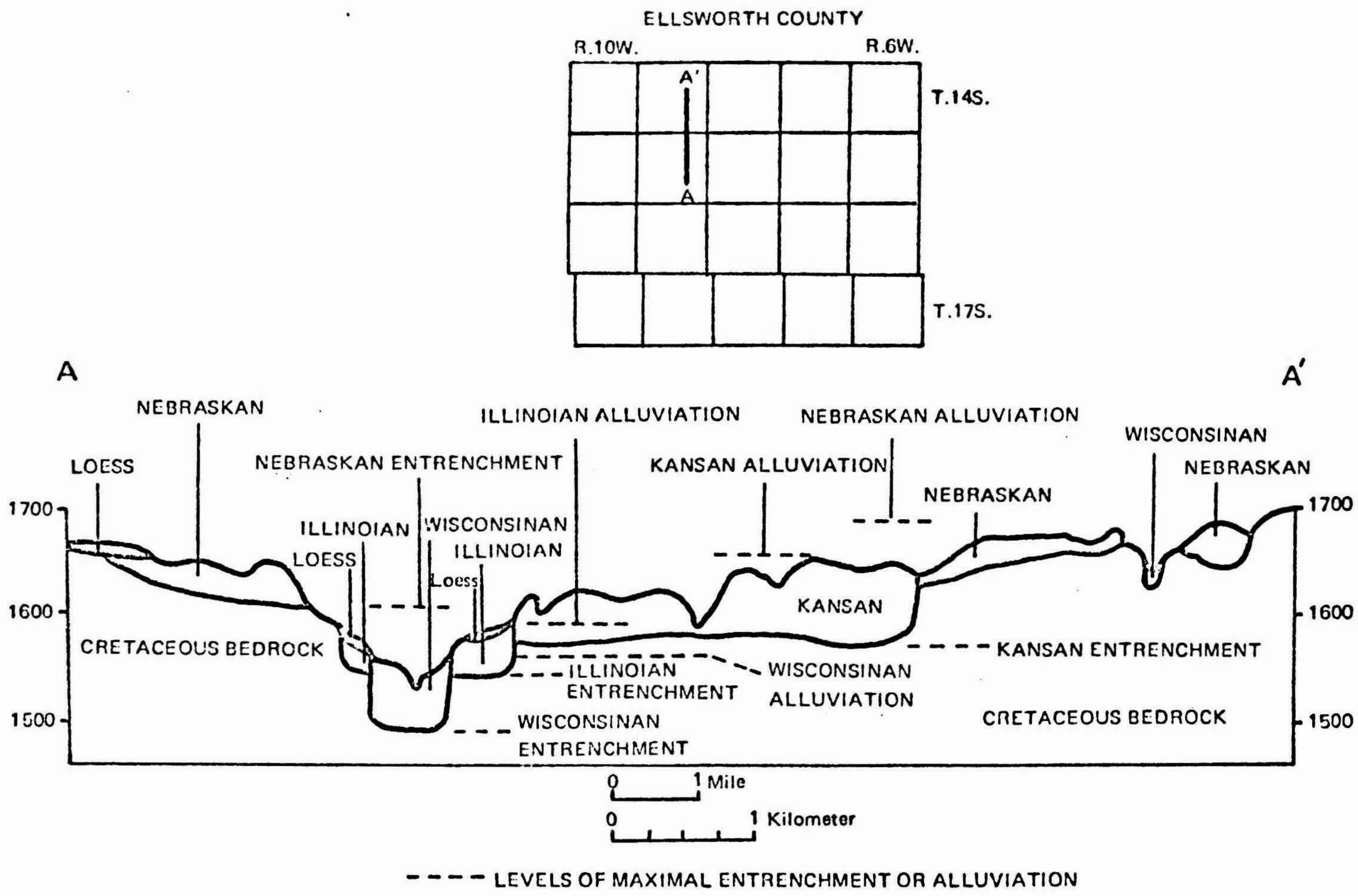

Figure D-2.- Cross-section of Smoky Hill River Valley, northwestern Ellsworth County, showing topographic positions of Pleistocene deposits (after Bayne, Franks, and Ives, 1971, pl. 2, cross-section D-D'). For conversion of elevations shown on margins of cross-section from feet to meters, multiply numbers by 0.3048.

Consequently, the modern Smoky Hill River is flanked throughout most of Ellsworth County by paired depositional terraces.

Because the valleys of the Smoky Hill were narrower with successive episodes of entrenchment (and consistent with the previously stated assumption that the Pleistocene history of a drainage basin is the best model of the future behavior of that basin) the inference is stated that the next episode of entrenchment should produce a valley that is narrower than the Wisconsinan valley. Inasmuch as the duration of the next glaciation has been estimated under the Maximal-Case construct, if the width of the next valley can be estimated and if the average rate of valley erosion can be estimated, then an approximation of valley entrenchment can be made that would be exceeded with probability of only 0.01. Because of the "nesting" of valleys, this approximation would better be computed in terms of the approximate cross-sectional area of the valley eroded per unit of time than in terms of vertical distance eroded per unit of time.

Ratios of valley widths are: Illinoian/Kansan 0.53; Wisconsinan/Illinoian 0.62. The true ratio is assumed to be about 0.5. Average width of the Wisconsinan valley is assumed to be about 2600 ft (800 m). (Measurements taken from Bayne, Franks, and Ives, 1971, pl. 2, cross-section I-I'). The width of the next valley is estimated to be about 1300 ft (400 m).

Rates of cross-sectional areas eroded are: Kansan, 2.8 sq ft/yr (0.26 sq m/yr); Illinoian, 9.3 sq ft/yr (0.86

sq m/yr); Wisconsian, 3.0 sq ft/yr (0.28 sq m/yr). The true mean rate of erosion of cross-sectional area is assumed to be about 5 sq ft/yr (0.46 sq m/yr). (These rates were computed as (valley width x valley depth)/(duration of earlier one-half of appropriate glaciation).) (Measurements taken from Bayne, Franks, and Ives, 1971, pl. 2, cross-section I-I'.)

By extrapolation of the data and assumptions set out above, hypothetical consequences of the Maximal-Case construct would be: (5 sq ft valley cross-section eroded/yr) (0.46 sq m/yr) x (250,000 yrs) = 1.25 x 10^6 sq ft (1.16 x 10^6 sq m) cross-sectional area eroded. Therefore, depth of the valley would be 1.25 x 10^6 sq ft) (1.16 x 10^6 sq m)/ (13 x 10^2 ft) (400 m) = 950 ft (290 m) (rounded). If the Smoky Hill River were to be entrenched by 950 ft (290 m), the Hutchinson Salt Member of the Wellington Formation would be breached.

On the basis of the premise that the Pleistocene history of a drainage basin is the best model from which to infer future events, the inference follows that the 950 ft (290 m) of entrenchment deduced above should be in keeping with the model itself, i.e., should be consistent with aspects of the model heretofore not included in the deductions. Accordingly, the hypothesis is stated that the consequences of the inferred 950 feet (290 m) of entrenchment would be consonant with other aspects of the Pleistocene history of the Smoky Hill River valley in Ellsworth County.

The hypothesis can be tested on the following basis. The elevation of the Smoky Hill valley near the location of Figure C-2 is about 1500 ft (460 m). The elevation of the Kansas River (to which the Smoky Hill is a tributary) at Kansas City, Mo. is about 750 ft (230 m). If the Smoky Hill were to be entrenched, intact, during the presumed forthcoming glaciation with all other factors being stable, its elevation at Kansas City would be 200 ft (60 m) below present mean sea level. Clearly, this consequence is so inconsistent with the general Pleistocene history of the central United States as to be untenable. The conclusion is drawn therefore, that if the Smoky Hill River were to be entrenched 950 ft (290 m), either its gradient must become markedly less steep, or epeirogenic uplift must be of such rate as to compensate for the entrenchment, maintain the stream's gradient, and maintain or increase the elevation of the continent.

Gradients of the Smoky Hill in Ellsworth County as shown by Bayne and Fent (1963, p. 370) are: Kansan, about 4.5 ft/mi (0.85 m/km); Illinoian, about 3.5 ft/mi (0.66 m/km); Wisconsinan, about 3.8 ft/mi (0.72 m/km). The present gradient of the Smoky Hill River across Ellsworth County is about 3.7 ft/mi (0.7 m/km). The gradient of the Smoky Hill River of central Kansas is inferred to have differed so little as to have been effectively constant throughout the Pleistocene. Consequences of the assumptions of "constant" gradient and of the amounts of entrenchment deduced above are that stream gradients of the Smoky Hill could be maintained, and 950 ft

(290 m) of entrenchment could occur, only if 950 ft (290 m) of epeirogenic uplift were to occur concurrently, and within about 250,000 years. Although the rate of epeirogenic uplift that would produce such effect, about 4 ft (1/2 m)/1000 years, is approximately the same rate as epeirogenic uplift now occurring on some coastlines (Schumm, 1963, p. H7), there is no evidence in the Pleistocene history of the unglaciated Midcontinent to suggest that epeirogenic uplift approaching 4 ft (1.2 m)/1000 yrs occurred. Therefore, 950 feet (290 m) of epeirogenic uplift is regarded here as being inconsistent with the Pleistocene model, and therefore an untenable assumption.

Thus, nesting of the next stream valley, maintenance of the ratios of widths of valleys to next older valleys, maintenance of rate of erosion of cross-sectional area, and maintenance of stream gradient cannot occur simultaneously under the assumptions held in this problem. The conclusion is forced that if entrenchment of the valley of the Smoky Hill River by about 950 feet (290 m) were to occur, the gradient of the Smoky Hill in central Kansas necessarily would become significantly less than the modern 3.7 ft/mi (0.7 m/km).

Consequences of this conclusion, the previously stated assumptions, and other assumptions (stated below) that are judged to be stable are as follows.

1) Under the assumption that the first one-half of the next glacial episode <u>will</u> be an episode of erosion

of the Smoky Hill River Valley, the conclusion follows that the sediment delivered to the Smoky Hill River upstream from Ellsworth County shall be moved downstream. Of course, a corollary to this statement is that the power of the Smoky Hill will be sufficient to transport its load.

2) The assumption is held that the Smoky Hill River will not extend its headwaters into any terrain that would introduce into the system types or sizes of sediments that would be significantly different from those eroded during the classical Pleistocene.

3) The assumption is held that the average discharge of the Smoky Hill during the next glaciation would not be markedly different from the average discharge in glacial episodes of the classical Pleistocene.

4) Therefore, as suspended sediment load, the major part of the load of this stream, is closely correlated with stream discharge, suspended sediment load during the next glaciation should be about the same as during the glaciations of the Pleistocene.

5) The assumption of basic identity of rates of valley erosion during glaciations implies the assumption of basic identity of power.

6) Power of a stream is defined as $\rho gAvs$, where ρ = mass density of water, g = acceleration of gravity, A = cross-sectional area (of the stream itself), v = mean flow velocity of the water, and s = slope of

energy grade line (Leopold, Wolman and Miller, 1964, p. 171, 173, 177). Av can be expressed as Q, the discharge. Thus the available power of a stream can be defined as ρgQs. Rho and g can be considered to be physical constants. Q of the next glaciation is assumed to be "constant," i.e., not significantly different from discharges during glaciations of the classical Pleistocene.

7) Therefore, as ρ and g are constants and Q is assumed to be constant, if power of the Smoky Hill River during glaciations is to remain constant, the gradient of the stream must remain constant. Inasmuch as the point has been made that constancy of gradient and entrenchment of 950 ft (290 m) would require an inordinately large rate and amount of uplift, and inasmuch as that rate and amount of uplift have been rejected as untenable assumptions, the conclusion is forced that the gradient of the Smoky Hill River cannot hold. Therefore, under the construction of this argument power of the Smoky Hill River cannot be maintained throughout the next glaciation.

8) Thus, it can be shown that the assumption of another nested valley and constancy of rate of erosion are mutually exclusive under the Maximal-Case construct. Either (a) the assumption of another nested valley must be rejected, or (b) the assumption of constancy

> of rate of valley erosion must be rejected, or (c) both assumptions must be rejected. If the assumption of constancy of rate of valley erosion were rejected, 950 feet (290 m) of entrenchment would not occur. If the assumption of another nested valley were rejected, the rate of valley erosion could be maintained only by widening of the valley, in which case 950 ft (290 m) of entrenchment would not occur. Rejection of both assumptions would amount to rejection of the assumption that the Pleistocene history of a stream is the best model of the future behavior of that stream; and, with rejection of this basic premise any possibility at all could be considered a reasonable prospective event.

In summary, the amount of entrenchment of the Smoky Hill River expected to occur under the Maximal-Case construct is less than 950 feet (290 m). A more exact conclusion is not determinable with the information at hand. Even under the original construct rejected above however, entrenchment to 800 ft (244 m) (presumed to be about the depth of the Hutchinson Salt Member) would have required about 300,000 to 350,000 years.

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