Principles of Underfit Streams

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By G. H. DURY

GENERAL THEORY OF MEANDERING VALLEYS

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CONTENTS

ILLUSTRATIONS

TABLES

GENERAL THEORY OF MEANDERING VALLEYS

PRINCIPLES OF UNDERFIT STREAMS

By G. H. Dury

ABSTRACT

Meandering valleys with systematic windings are defined as a subclass of winding valleys, the bends of which can be indifferently systematic or irregular. The terms "valley meander" and "valley bend" are correspondingly applied to single features, although they are conveniently interchangeable in practice. Free meanders on a flood plain are distinguished from incised meanders, which are subclassified into intrenched and ingrown forms. Misfit streams, either too large or too small for the valleys in which they flow, are grouped as overfit and underfit. Wavelength of meanders is used as a criterion of size and is statistically referable to discharge at the bankfull stage. The term "underfit stream" also is applied to streams that either fail to describe meanders in their present channels or that lack valley meanders. Meandering streams in more amply meandering valleys are called manifestly underfit.

Stream capture or other forms of derangement of drainage are incapable of supplying the general hypothesis of the origin of underfitness that is required by the facts of distribution. A critical reexamination of W. M. Davis' attempts to explain underfitness by capture reveals grave weaknesses in his argument. Authentic diversions from the French Rivers Meuse and Bar were less effective in reducing wavelength of meanders than was the change which made all the neighboring rivers also underfit.

The Wabash and Souris Rivers, the drainage on the emerged floors of glacial Lakes Agassiz and Harrison, and the back-slope streams of the English Cotswolds provide data on spillways. These data show that overspill from proglacial lakes, or direct discharge of melt water from ice fronts, is irrelevant to the general problem of underfitness as it is separable from reduction of stream volume in either space or time, or both.

Regional development of manifestly underfit streams requires a climatic hypothesis of origin. Examples of such streams, from the till plains of Iowa, from the Humboldt, Shenandoah, Salt, and Cuivre Rivers, and from the Ozarks, show that lack of manifest underfitness can be due either to the destruction of relevant valley forms by erosion or to the failure of streams to develop meanders in their existing channels. Alternatively, this lack may be merely apparent, owing to deficiencies of map evidence. Where stream meanders are actually lacking, pool-and-riffle sequences can occur with spacing that is appropriate to stream meanders and far closer than that appropriate to valley meanders.

Davis' claim that the terraces of the Westfield River indicate no significant change in volume during terracing is directed at the views of Emerson. But the claim seems not to bear on the general problem of underfitness, especially as manifestly underfit streams occur on the emerged floor of glacial Lake Hitchcock. In Arizona, Padre and Diablo Canyons and Oraibi Wash are manifestly underfit streams, providing evidence in arid regions of reduced channel-forming discharge comparable to that noted for humid regions. In association with observations for the Humboldt River, this evidence extends the general hypothesis of underfitness to regions that are currently semiarid or arid.

Contact of streams with bedrock is provisionally rejected as a direct cause of the absence of meanders from present unbraided channels, and variation in cohesiveness of alluvium is suggested as an alternative. The view that incised meanders are necessarily inherited from free meanders is controverted. Numerous minor canyons are thought to act as flumes after heavy rain, but valley nets in dry regions are inferred to have been intitiated and developed under more humid conditions than now exist.

INTRODUCTION

The object of this paper and and subsequent papers is to present a general theory of underfit streams. Incorporated in these papers are the results of fieldwork in the United States and in England, analytic techniques applied to hydrologic and dimensional data, and inferred hydrologic changes in Quaternary chronology. Because the necessary discussion involves reference to studies of rivers in many aspects, to meteorology and climatology, and to the whole corpus of sciences that deal with Pleistocene events, it is impracticable at this point to review previous work. As far as is possible, references are concentrated in particular sections of the text, and cross references are kept to a minimum.

In the customary but too restricted sense, an underfit stream is a stream that meanders on a flood plain in a meandering valley. Figures 1 through 3 illustrate the relevant landforms in an oblique aerial view, a topographic map, and a stereoscopic vertical photograph. The writer's planned work on streams of this type began in 1946, although scattered observations had been collected for some time previously. Results obtained before 1950 were included in a thesis [1] which, relating to parts of the English Midlands, noted the widespread contrast between the surface forms of mean-

[1] Dury, G. H., 1951, Some aspects of the geomorphology of part of the Midland Jurassic belt: London Univ. Ph. D. thesis.

FIGURE 1.—Oblique aerial view of valley bends and stream meanders on the Evenlode River, Oxfordshire, England. The Evenlode is an underfit stream. View is toward the southeast; length of the railroad shown is about 1 mile. Photograph by Photoflight, Ltd., Elstree Aerodome, Elstree, Herts, England.

dering valleys and those of meandering stream channels. Subsurface exploration (Dury, 1952; 1953a,b,c) proved certain flood plains to be underlain by large meandering channels, which were taken to be the channels of the former rivers that carved the valley meanders. Investigation was later extended to parts of southeast England, which, unlike the Midland sites, was not ice covered during the Quaternary, and to the borderland of Wales. At each site explored, a large filled channel was located. These various observations were brought together in an account (Dury, 1954) that rejected all general hypotheses of the origin of underfit streams with the exception of some climatic hypotheses, that sketched an initial chronology, and that attempted to determine the discharges required by the large channels and by the valley meanders.

In the time between the writing of the 1954 paper and its publication, Leopold and Maddock (1953) published their analysis of hydraulic geometry. Dr. Leopold drew this account to the writer's attention. Both he and Mr. Maddock visited the University of London, to which the writer was then attached, to discuss implications of work then in progress; they also visited field areas and recommended lines of attack. Statistical techniques of the kind used by Leopold and Maddock were found to support the view that the large filled channels are associated with valley meanders (Dury, 1955), and these techniques were applied (Dury, 1956) to a reexamination of the diversion of the upper Moselle from the Meuse. Later (Dury, 1958), they also were applied to an amplified set of data that included the results of subsurface exploration in the Cotswold Hills (Dury, 1953a). At the suggestion of Leopold, the writer made a general review of progress (Dury, 1960) which included comments on the wide distribution of underfit streams in meandering valleys. By this time it was becoming clear that one of the main episodes of hydrologic change postulated to account for underfit streams is referable to events that occurred at end-glacial times, in the loose general significance of that expression.

Meanwhile, Leopold had arranged for the writer to be attached to the U.S. Geological Survey as a division staff scientist in the Water Resources Division, based in the Washington, D.C., office. The project, supervised by Leopold, was to last for 1 year, July 1960 through June 1961. Working with the broadest terms of reference to channel habit, valley form, and chronology, the writer executed fieldwork in the environs of Washington, D.C. (Coastal Plain, Piedmont, Appalachians); southern New England; the neighborhood of Evanston, Ill.; the Driftless Area of Wisconsin and part of its margin; parts of the till plains of Iowa; the northern Ozarks; the vicinity of Denver, Colo.; the Wasatch Mountains of Utah; parts of the Humboldt River basin in Nevada; and Arizona, mainly on tributaries of the Little Colorado River. Other visits were made to West Virginia; the vicinity of Fort Collins, Colo.; northern Michigan; and the Lake Bonneville country around Salt Lake City. Four months of the year were spent in fieldwork; the remaining 8 months were used in the collection and analysis of material, parts of which are not required by the present study and will be treated separately on another occasion.

The plan of this and the sequential papers is the following: (a) The reexamination of the connotation, usage, and overtones of the terms "underfit stream" and "meandering valley," with examples to illustrate and justify the conclusions reached, and to demonstrate the very wide occurrence of underfit streams of one type or other (it is in this part that previous work is principally cited); (b) the introduction of new field evidence, part of which supplies critical dates, and a discussion of dating in general; and (c) the discussion in some detail of the hydrologic and climatic implications of the general theory. The final part includes an

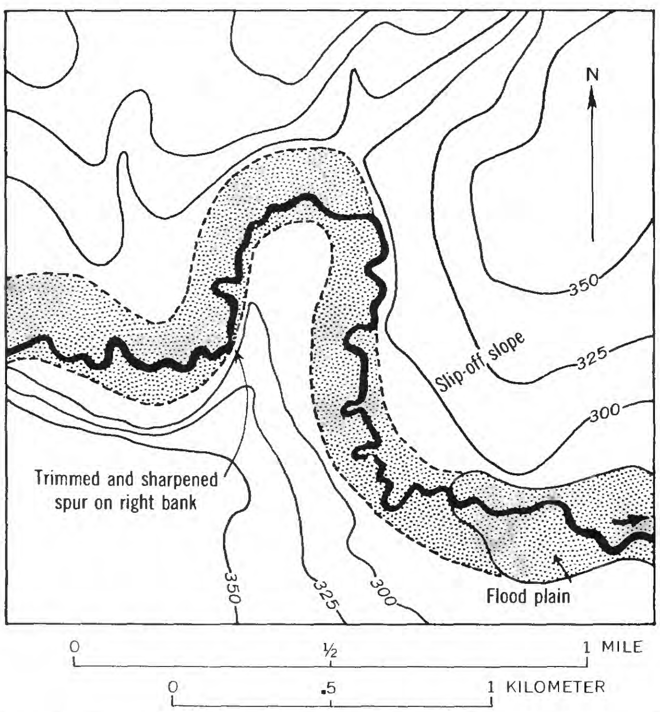

FIGURE 2.—Sketch map of part of the Windrush River, Oxfordshire, England, showing curvature of the flood plain round a valley bend. The Windrush is an underfit stream.

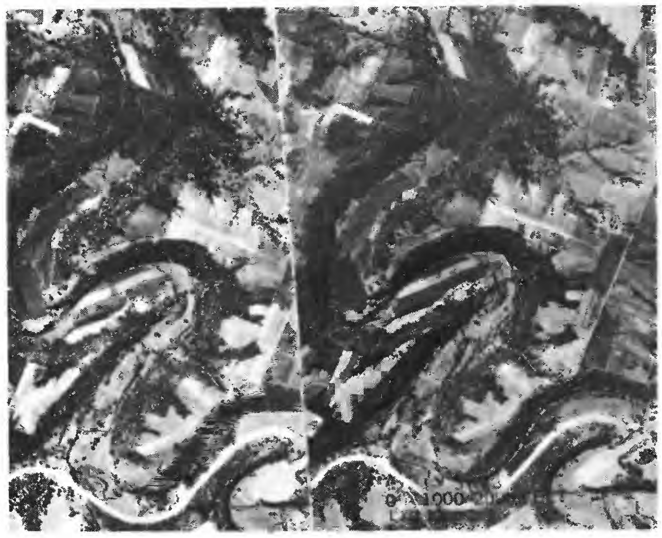

FIGURE 3.—Stereoscopic photograph of part of Bois Creek, Grant County, Wis., showing incised valley meanders, flood plain, and stream meanders. Bois Creek is an underfit stream.

amplification of existing data on the wavelength and discharge relation, which is crucial to the whole discussion, and considerably revises and extends views previously expressed on the former discharge of rivers that are now underfit.

ACKNOWLEDGMENTS

Everyone who has savored the essays of W. M. Davis will appreciate the debt of stimulation owed to that author. This debt, first incurred by the present writer in 1935, should perhaps be all the more freely admitted, for the following text includes reexamination of some of Davis' evidence, criticism of some of his hypotheses, and firm rejection of some of his conclusions.

Unreserved gratitude is due to members of the U.S. Geological Survey and of State geological surveys, to members of universities, and to private individuals for a whole range of help. The work of 1960–61 was done under the authority of Thomas B. Nolan, Director, U.S. Geological Survey; it was supervised by Luna B. Leopold, Chief Hydrologist, U.S. Geological Survey, whose encouragement, counsel, and guidance were invaluable.

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PERSPECTIVE ON TERMINOLOGY

This investigation touches on many points of doubt and controversy. Because the landforms in question can be discussed in more than one geomorphic context, a wide range of suggested interpretations is not surprising. Writers have varied in their approach to what is here the central problem, according to their environment, experience, interests, and intentions. Consequently the study of meandering valleys interlocks in a highly complex fashion with cognate topics, and attention can be limited to a desired range of material only with great difficulty. Particularly is this so, as the technical terms available for use frequently carry an unwanted charge of genetic significance, whether because they are by nature definitive, or because they have become definitive through association. Attempted or implied classification, where classification is impossible or purposeless, increase the confusion of language. Errors of fact, resulting from hasty observation or from efforts to make observation fit hypothesis, embed themselves in the literature and react on terminology.

In the broadest sense, where it implies nothing about the size of a contained stream, the term "meandering valley" is already definitive. It connotes systematic qualities that are expressed in alternate steep crescentic slopes on the outside curves and gentler lobate slopes on the opposing spurs. Even if alternate steep and gentle slopes are not obvious, roughly similar dimensions throughout a train of bends can indicate systematic qualities. As the necessary arrays of landforms are recognizable on sight in many places, the term is meaningful; but the certain presence of meanders in some valleys does not imply that their absence elsewhere can invariably be proved.

Three continuous series probably connect the three extremes of straight valleys, meandering valleys, and valleys that are not straight but yet do not meander. No convenient term exists for the third group because the term "winding valley" is preempted for valleys other than straight valleys, whether they meander or whether they are merely irregular in plan. Similarly, "valley meander" is definitive and "valley bend" merely indicative, although these terms are often interchanged for the sake of euphony. Many winding valleys are, in actuality, regular enough to be classed as meandering. Obscure instances may be illuminated by measurement—that is, by the comparison of dimensions of meanders with length of stream or with the drainage basin. Systematic variation is strong presumptive evidence of meandering as opposed to a merely irregular habit. But if continuous transition is possible from meandering valleys to straight valleys and to valleys which wind but do not meander, then criteria of whether or not a doubtful case is or is not a meandering valley become wholly arbitrary. The meandering habit remains subject to demonstration but, in a wide zone of uncertainty, not to disproof.

Words connoting the origin, form, and mode of development of meandering valleys vary in import according to the views of particular writers on tectonic and cyclic history and on the necessity for incised meanders to be inherited from a flood plain. The choice of available words is liable to vary with powers of observation. Two main distinctions, however, are usual: that between free meanders and incised meanders, and, among incised meanders, that between intrenched and ingrown forms. Free meanders are meanders on a flood plain. Incised meanders have cut down, so that projecting spurs—commonly, spurs of bedrock—obstruct their downstream sweep. It is, of course, possible for the spurs to be cut away and a continuous flood plain, wide enough to permit unobstructed sweep, to be formed; the meanders then pass from the incised to the free condition. As will be shown, however, the development of numerous trains of incised meanders has been arrested. Intrenched meanders are contained by walls that differ little or none in slope on the two sides of the valley, whereas ingrown meanders require steep slopes on the outside curves and gentle slopes on the inside curves. Intrenched meanders, by definition, result from vertical downcutting, whereas ingrown meanders result from lateral movement during incision. However, the terms cannot be allowed to retain the implication attached to them by Rich (1914), who claimed that the difference between ingrowth and intrenchment corresponds to a difference in rate of uplift. Indeed, insofar as uplift means differential tectonic movement, its relevance to the present inquiry is denied. Intrenched meanders command little attention in the literature, perhaps because erosion tends to obscure their nature, but more probably because they are rare. Field observation convinces the writer that incised meanders are normally ingrown.

The manner in which very simple descriptions of meandering valleys become entangled with cyclic history, hypotheses of planation and inheritance, and with varying nomenclature is well illustrated by one of the regions treated in this essay—the northern Ozarks. Davis (1893), discussing the valley meanders of the Osage River, postulated inheritance of the meander train from a planed-down surface and stated that the slope of the Osage in a former cycle "* * * had become very gentle, and [the river's] current had taken to a deviating path, peculiar to old streams, which so generally meander on their flat flood plains." This erroneous claim to relate a meandering habit to some condition of slope seems to be one of the earliest, equally erroneous, efforts to associate meandering with some stage in the Davisian cycle. Davis was challenged in an exchange of correspondence by Winslow (1894), who maintained that meanders can develop during incision; ironically enough, Davis himself was later criticized for incorporating simultaneous meander growth and incision in his own scheme of river development (Lehmann, 1915; Flohn, 1935; Hol, 1938, 1939). The debate concerning the Osage River resolved itself into questions of local planation and uplift. Whereas Davis undoubtedly was justified in positing one or more episodes of planation—whatever may be thought of the peneplain concept—Winslow was equally correct in his general claim that meanders can form, and grow, during the incision of an originally straight river—that is, that incised meanders are not necessarily inherited from a flood plain. Tarr (1924), writing of the Ozark rivers Gasconade and Meramec, proposed to substitute "incised" for the "ingrown" of Rich; fortunately, Tarr has not influenced usage. In opposition to Winslow, Tarr called the Gasconade and the Meramec typically intrenched. In actuality they are manifestly ingrown, as can be seen readily on the ground, from the air, and on all relevant maps so far published on the scales of 1:62,500 and 1:24,000. Already, therefore, in advance of reference to lithology and structure or to meanders of streams as distinct from meanders of valleys, errors in observation, discord in nomenclature, and complexly ramifying views on the development of meanders, valleys, and landscape have all been exemplified.

On streams, as in valleys, meander trains can often be recognized on sight. Continuous ranges of intermediate pattern, however, seem to link boldly meandering channels with braided channels on the one hand and with straight or slightly irregular single channels on the other. An equally continuous transition seems to lead from unique straight channels to highly anastomosed braided channels. Nothing said here is meant to deny that significant changes in behavior accompany changes in channel pattern, that certain patterns represent steady states (Leopold and Wolman, 1957), or that conversion from one pattern to another can be rapid. The point at issue is that any attempt to define meandering habit in terms of sinuosity must rely on arbitrary criteria. It may be possible to affirm, but not to deny, that a stream is a meandering stream.

When the terms "meandering valley" and "meandering stream" are used contradistinctively, complications multiply. Contradistinction is required by the observed fact that some meandering valleys contain flood plains, whereon the rivers trace meanders far less ample than those of the valleys. The term "meandering valley" now acquires additional significance: it implies that the valley meanders are homologues of stream meanders, but that conditions have greatly changed since they were cut.

Examples of the identity of the surface forms of meandering valleys with those associated with ingrown meandering streams are provided by Davis (1896, 1899, 1906). Reasoning from this identity and from the general circumstance that size of meanders varies with size of stream, Davis postulated a reduction in volume to explain the inferred reduction in size of meanders. He estimated size mainly by radius of curvature, which is by no means the most suitable property, and his statements about volume are so cast as to be meaningless. Furthermore, he tried on at least one occasion to hold accidental obstructions responsible for small meanders (Davis, 1913, p. 14). Nevertheless, he was correct in perceiving a disparity between the meanders of certain valleys and those of the contained streams, and justified in applying the term "underfit" to rivers that are too small for the valleys in which they flow. But if streams can be too small for their valleys, they can also be too large, hence the term "overfit." The term "misfit" includes both the overfit and the underfit classes. Overfit streams are rather difficult to imagine and would probably be unrecognizable by the criterion of radius of curvature which Johnson (1932) sought to apply. Small meander scars cut by a small ancestral river could scarcely remain long intact before the onset of large meanders developing in the stream. Observed results of dam bursts suggest that sudden natural increases in discharge—due, for example, to river capture or to the overspill of proglacial lakes—are likely to cause rapid enlargement of channels; although in some contexts the size of channel must be distinguished from the size of valley, it is improbable that overfit streams would remain identifiable for long. Streams recognized as misfit are so usually underfit that the two names are frequently interchanged.

Davis' exclusive reference to underfit streams that now meander may be responsible for Johnson's attempt to define the misfit condition in terms of meander size. In any event, Davis' examples are so well known and have been so repeatedly presented or matched that the word "underfit" has come by association to imply a meandering trace, both of valley and of stream. As a wide range of channel pattern occurs in nature, however, it seems possible that the changes which make streams underfit need not invariably preserve the meandering habit. This amounts to saying that every stream in a meandering valley is not a meandering stream, a proposition which, far less paradoxical than it may sound, will be substantiated. If it can be accepted for the time being, pending substantiation later, then the sense of meandering valley must be extended to valleys with meanders too large for the present streams, irrespective of present channel pattern, whereas underfit must be extensible to present streams, some of which fail to meander.

Criteria of size are now urgently needed. Size of meanders is best expressed as wavelength. Wavelength of meanders is known to bear a close statistical relation to bed width, which in turn is causally related to discharge (Leopold and Wolman, 1957). Later, existing evidence for a close empirical connection between wavelength and discharge will be amplified considerably. Whereas amplitude of meander belt and radius of curvature of meanders may be significant when measured on flood plains, they change during ingrowth. Ingrowing loops commonly increase both their amplitude and their radius to the limit of cutoff. In special circumstances, radius can stay sensibly constant, but amplitude then greatly increases as ingrowth continues (Strahler, 1946). Wavelength, by contrast, is suddenly fixed when incision starts, and its average value for meander trains is not greatly affected by distortions of single loops. Only where loops are completely obliterated by cutoff—an infrequent happening—does apparent wavelength change significantly.

Concentration on radius and amplitude, in preference to wavelength, has allowed confusion to enter discussions of structural, lithologic, and tectonic influences on the dimensions and forms of valley meanders. Irreconcilable views expressed by Vacher (1909), Musset (1928), Cole (1930), Masuch (1935), Flohn (1935), Blache (1939, 1940), and Wright (1942) probably give a fair sample of the work of their period. These views were previously reviewed (Dury, 1954, p. 196–197) and will not be dealt with here. It should be made clear, however, that accommodation of ingrowing meanders to structures and qualities of bedrock is not denied.

Where a meandering stream is contained in a more amply meandering valley, the disparity between the two sets of wavelengths is determinable by a plot either of one series against the other or of both against drainage area. Where the valley has meanders but the stream can be shown or suspected not to have meanders, properties additional to wavelength must be used. Additional properties are always required to test the hypothesis that underfit meandering streams have been reduced in volume and that nonmeandering underfit streams can exist in nature. Size of channel can be expressed by a range of hydraulic dimensions, of which bed width is usually the most available. In one sense, size of stream is identical with size of channel; in another sense, it is expressed as discharge, in quantity per unit time. Neither dimensions of channel nor discharge, however, possess meaning unless they are referred to a particular stage, or frequency, of flow. The appropriate stage seems to be that of discharge at bankfull; alternatively, perhaps, a rather small range of stages in which the bankfull stage is included. The reduction in volume required to make a stream underfit must therefore be taken to mean reduction in volume at bankfull. Reductions in dimensions of channel similarly relate to bankfull conditions.

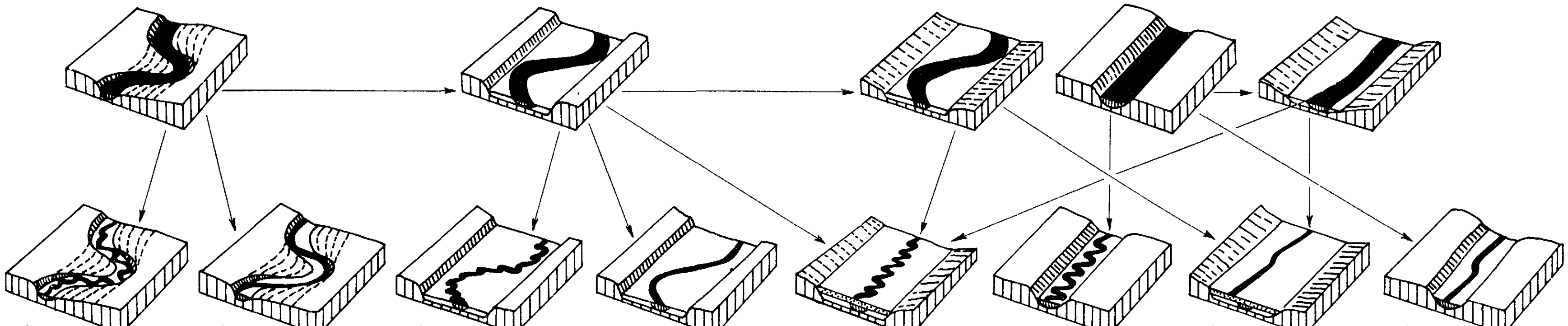
The above-mentioned interrelations of discharge, bed width, and wavelength relate specifically to the bankfull stage. They enable appropriate wavelengths to be calculated for given values of discharge and bed width and make it possible to demonstrate that certain trains of incised meanders are too large for the present streams. Conversely, that is, some existing streams are inappropriately small for the incised meanders which they occupy. In this way, the claim that a stream in a meandering valley need not be a meandering stream, and that underfit streams need not invariably meander, gains support. Confirmation will be provided later, with the aid of data on channel form and of free meanders in reaches of open valley.

The assumption that ingrown valley meanders were cut by streams of the present size—that is, that the present streams are not underfit—occurs in the work of Jefferson (1902) and Bates (1939). These writers claim that the ratio between width of meander belt and width of stream is normally greater where the rivers are incised than where meanders are free. A corresponding disparity of wavelength follows. But the general theory of meandering valleys presented in the present essay, combined with the hypothesis that underfit streams do not always meander, suggests that Jefferson and Bates were measuring wavelengths not on incised streams but on incised valleys. The relevant sites need investigation in the field.

From the inference that valley meanders were cut by former large rivers, the possibility follows that these rivers may, in places, have cut large meander troughs. If so, not all reaches of valley which contain underfit streams need themselves meander. Underfit streams in reaches of nonmeandering valley do in fact occur in nature. A leading example is the upper Evenlode in the Cotswold Hills of England (Dury, 1958; 1960, fig. 1). On the Evenlode, the large meanders had passed from the incised to the free condition before the stream became underfit; the trace of the meanders is, however, preserved, with the present meanders superimposed on it. Because the large meanders were free, they cannot properly be called valley meanders; some broader term is required. As the present essay will justify separation of the two series of meanders not only by wavelength but also by age, the contrasting terms "former meanders" and "present meanders" eventually will be adopted.

As noted previously, a meandering habit, which is expressed in pattern of channel, may be possible to affirm but not to deny. It will be shown below that a meandering tendency, recorded in the form of the bed, may operate even though it is not reflected in the channel pattern. A meandering tendency cannot be denied unless bed form is investigated and may not be open to disproof even then. Nevertheless, it remains true that some reaches of some natural single channels manifestly fail to display a meandering habit. But if nonmeandering reaches be conceded to present streams, general reasoning suggests that streams responsible for valley meanders also may have failed to meander in some places. If so, a meandering valley can in practice include reaches devoid of meanders not because intervening spurs have been destroyed but because meanders were never present to begin with. Accordingly, the possible meaning of the term "underfit stream" must be extended still further to cover at least six combinations of form of valley with trace of channel (fig. 4).

The first of the numbered combinations refers to underfit streams as described by Davis and as usually imagined. It is recognizable by surface form, as is combination 3 which has just been illustrated by the Evenlode. Combination 2, presented above as logically possible, will be exemplified from the Ozarks, from Iowa, and from the Great Basin. Comparison of size of channel at bankfull, or of rate of bankfull discharge, on the one hand to wavelength of meanders on the other has already been offered as a means of identification. In practice, observations of channel form also have been employed. These observations could be supplemented by exploration of the subsurface, as undertaken at sites representing combinations 1 and 3. Combination 4, although possible, is rare; no certain instances have yet been detected. Applicable tests would be identical with those for combination 2. Combinations 5 and 6 are required both by logic and by the general theory of meandering valleys as here presented; however, they cannot be detected by surface form nor by quantitative treatment of comparative wavelengths, for, by hypothesis, large meanders either failed to develop or have been completely destroyed. Subsurface exploration could imaginably reveal former stream channels large enough to show that existing streams are underfit, but no relevant or possibly relevant sites have yet been investigated. This study is confined to examples of the first three combinations. Nevertheless, the logically possible range of combinations shown in figure 4 requires that the possible significance of the term "underfit stream" be extended far beyond its usual limits.



Pattern of stream channel	Pattern of valley: Meandering	Pattern of valley: Nonmeandering — Trace of large free meanders preserved	Pattern of valley: Nonmeandering — Trace of large meanders not preserved or never present
Meandering	1. Meandering stream in meandering valley	3. Meandering stream in former meander trough; large meanders identifiable on surface	5. Meandering stream in (a) open valley or (b) approximately straight narrow valley
	Two series of meanders combined		
Nonmeandering	2. Nonmeandering stream in meandering valley	4. Apparently very large meanders on floor of open trough	6. Nonmeandering stream in (a) open valley or (b) approximately straight narrow valley
	Only one series of meanders present		

FIGURE 4.—Block diagrams of underfit streams, showing character and possible origin of some combinations of stream-channel and valley patterns.

PRINCIPLES OF UNDERFIT STREAMS

DIVERSION UNNECESSARY

At the same time that the sense of underfit is thus widened to admit a greater range of landform combinations than is usually envisaged, it should be narrowed in another direction. Stream capture or other types of diversion should not be regarded as a necessary, or even usual, cause of underfitness. Among writers in English, the idea that underfit streams owe their condition to beheading is due to W. M. Davis, whose comments on the matter have been so influential that, with some writers, "underfit stream" and "beheaded stream" are almost synonymous. Hypotheses involving diversions other than capture—such as derangements of drainage associated with glacial advance—are, in effect, extensions of the capture hypothesis. This hypothesis will, therefore, be challenged first. The facts of capture and glacial derangement and the changes in stream volume which they produce are freely admitted. Indeed, examples of beheaded streams and of valleys which at one time were spillways will be presented. But the tacit implication, often tacitly accepted, that underfit streams generally result from diversion of some kind is firmly rejected.

Davis based his reasoning about underfit streams on examples that represent the first of the numbered combinations in figure 4—that is, on meandering streams in more amply meandering valleys. To obviate circumlocution, underfit streams in this combination will be called manifestly underfit. So long as attention was confined to such rivers and so long as capture was regarded as the sole, or at least main, cause of underfitness, the regional distribution of underfit streams could be denied (Davis, 1913; Baulig, 1948). To counter the general hypothesis of capture, it suffices, therefore, to demonstrate that all the streams in a given region are manifestly underfit, or, alternatively, to prove that they represent some other of the combinations in figure 4. In nature, irregularities in form of valley and in pattern of channel make it unlikely that all reaches of all streams in the region will be manifestly underfit, but if the relevant landforms can be identified widely and on numerous reaches of competing streams, then underfitness at once becomes a regional problem. Capture, however, is not finally disposed of until a single degree of underfitness is proved for the whole region. Proof that a stream actually is underfit, although not manifestly so, may not be possible unless data are available on discharge, dimensions, bed form of channel, and the subsurface. Nevertheless, if manifest underfitness be accepted as resulting from a change in volume, then abrupt departures from manifest underfitness suffice to show that the change is not always manifestly expressed at the surface. Special conditions can be imagined for limestone country, in which the volume of a particular stream abruptly decreases at one point and as abruptly increases at another point farther downstream; but limestone hydrology generally is not reliable. In practice, abrupt downstream changes from or to manifest underfitness do occur, and on rocks other than limestone. This fact greatly weakens the statement that underfit streams are not developed regionally. Merely to offer regional examples, however—even those of manifestly underfit streams—would leave intact the claims of Davis that certain rivers are underfit because of capture. Such examples will therefore be deferred until the growth of the Davisian thesis has been traced and until his evidence is reexamined.

When he applied his concept of sequential erosion to the English Plain, Davis (1895) was much concerned with the growth of subsequent streams and with piracy. The apparently shrunken condition of certain rivers appeared to him a natural result of capture. Thus, dealing with the apparently contrasted habits of the Seine and the Moselle on the one hand and of the Meuse on the other, he (Davis, 1896), ascribed the so-called staggering trace of the Meuse to capture by the Seine and the Moselle, whose meanders he styled as vigorous and robust. Three years later, he claimed to identify in the Swabian Alp and in the Cotswold Hills of England consequent streams which, having been beheaded, are underfit (Davis, 1899). He named the Schmeie and the Lauchert as having lost territory—and discharge—to the Eyach [2] and the Starzel, and the Stratford Avon as having gained at the expense of the Cotswold streams Cherwell, Coln, Windrush, and Evenlode. All underfit streams were recognized by the disparity between valley meanders and meanders of the stream.

All three regions produced anomalies. In his paper of 1896, Davis noted that the deprived Meuse is out of proportion to its valley not only downstream from the point where a main headstream was lost to the Moselle but also upstream. His second French example, involving the Bar, which flows to the Meuse, and the Aisne, which belongs to the Seine system, relied on the inferred capture by the Aisne of the former head of the Bar—that is, the river now called the Aire. As he recorded at the time, the present meanders of the supposedly diverted Aire are much smaller than the valley meanders of the Bar, which are farther along the reconstructed course of the Aire-Bar as it existed before capture. Davis offered the guess that the Aire had once received the water of the Ornain (fig. 11) and that the

[2] The spellings used are those on the German 1 : 25,000 map; Davis gives Schmeicha and Ellach.

upper Meuse had experienced additional, but undetected, captures.

In his 1899 paper, Davis referred in passing to an underfit but apparently not beheaded stream in Swabia and expressed surprise that the Stratford Avon and its feeder, the Stour, which should have gained what the Cotswold streams lost, are themselves misfit (underfit). He added to the recorded anomalies in France the observation that the Aisne, a supposedly captor stream, is discordant with its valley—admittedly, above the confluence of the Aire—so that the increment of water captured from the restored Bar does not come in question. Optimistically, perhaps, he suggested that the anomalous stream in Swabia might possess a wind gap which the available maps failed to show; but, taking a more general view, he concluded that a general change in volume had superimposed its effects on those of capture. This change he thought might result either from deforestation or from some climatic change of external and obscure origin. But to retain the hypothesis of capture, he found it necessary to claim that streams of the Avon system are less underfit than their competitors on the Cotswold back-slope.

A later suggestion (Davis, 1909) that ice-dammed lakes might formerly have discharged into the Cotswold valleys will be disposed of presently. Davis himself appeared to abandon the hypothesis of overspill when, a few years later (1913), he suggested that water could be lost to underflow through alluvium. Alluviation and underflow he saw as a normal consequence of cyclic development, saying that progressive grading of hillside slopes, continuing after rivers were already graded, would ensure increasing delivery of rock waste to streams and thus cause aggradation. This is not the place to discuss the Davisian concept of grade. Suffice it to say that the postulate of automatic aggradation by mature streams has not been seriously considered by Davis' followers and that underflow cannot possibly account for the losses of water which have occurred, even when no allowance is made for the shallowness of alluvium in some valleys and for its impermeability in others. To advocate underflow as a possible cause of underfitness is, however, to concede by implication that all the streams in a given region can be simultaneously underfit—a possibility which Davis rejected in the same paper of 1913.

Finally, Davis (1923) reverted to the hypothesis of capture, naming underflow and climatic change as possible further mechanisms but advancing no fresh evidence. He wrote,

> The reduced volume of a beheaded stream cannot develop meanders of the same size as those which it followed, with larger volume before its beheading * * * hence, as the reduced meanders are too small to fit their valley curves, they may be called underfit * * *. It is believed that underfit rivers may also result from climatic change, as well as from * * * loss of surface water to underflow in the flood-plain deposits of mature valleys.

When the sites named by Davis are reexamined, much of the evidence on which he based the capture hypothesis immediately disappears. The following criticisms are largely independent of any local studies of geomorphic history made since Davis wrote, although, as will appear, these studies are themselves adverse to some part or other of the Davisian thesis. Davis' claim that the members of the Avon system are less underfit than the streams of the Cotswold back-slope cannot stand. In figure 5, concurrent readings of wavelength are plotted for valley and stream meanders. As meanders of neither series increase progressively in wavelength downstream, a plot in this form is less useful in some contexts than a plot of wavelengths against drainage areas, but the comparison made here is precisely that attempted by Davis—namely, a comparison of size of meanders. Values plotted are averages for trains. While the samples are small, they are thought capable of showing that, in fact, the streams of the Avon system are no less underfit than those of the Cotswold back-slope. At once, therefore, the need

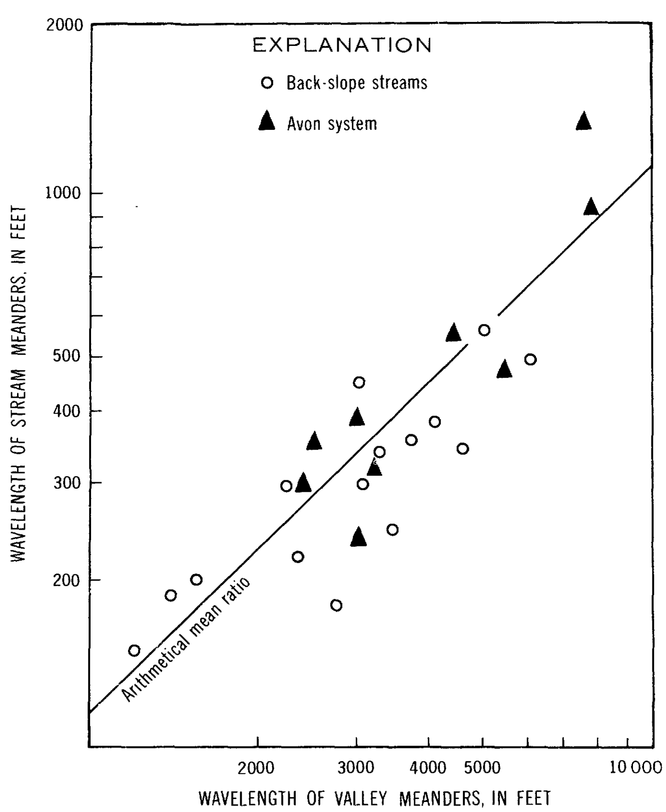


FIGURE 5.—Graph showing comparative wavelengths of valley and stream meanders of members of the Warwickshire Avon system and of streams of the Cotswold back-slope, England.

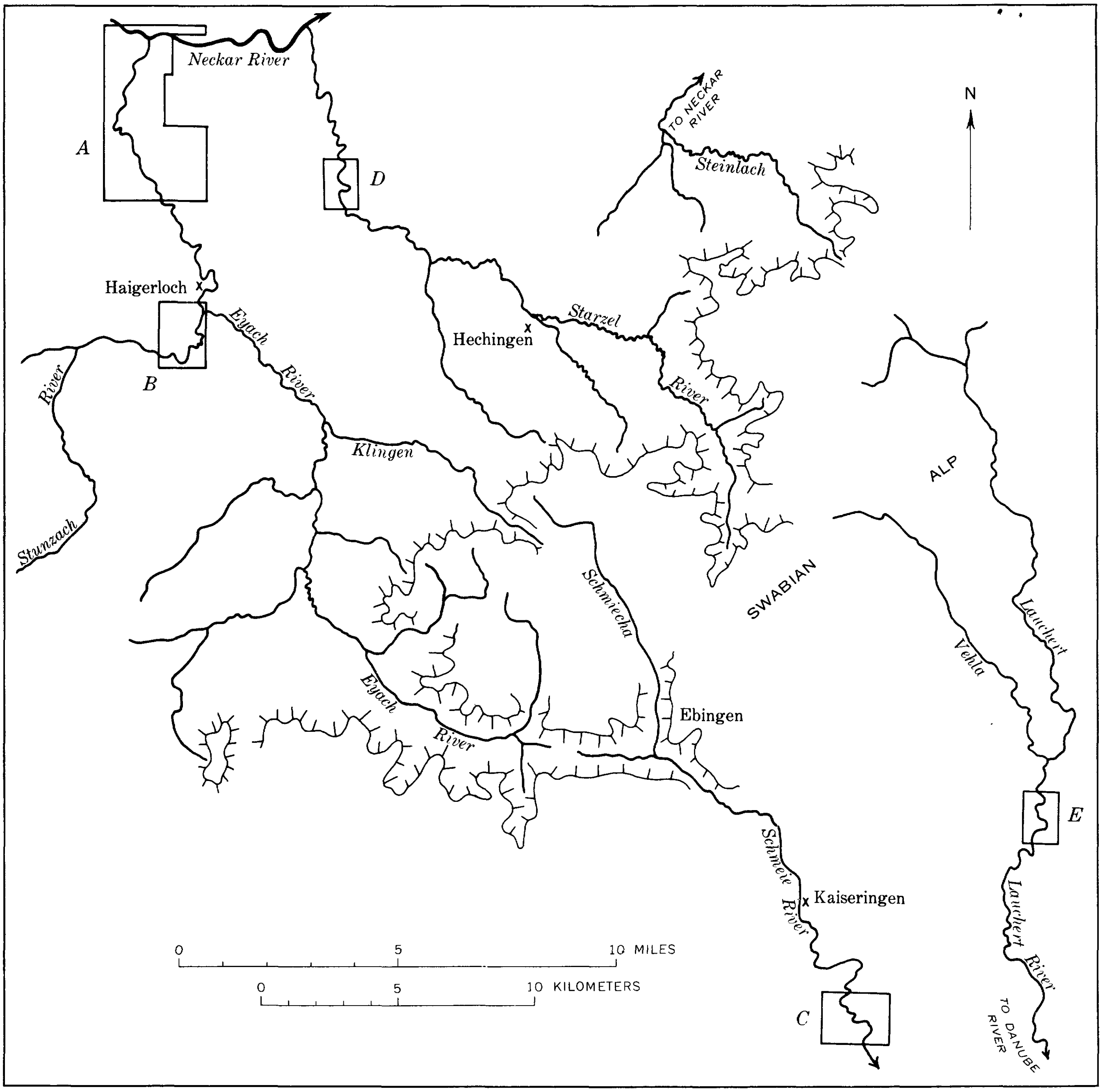


FIGURE 6.—Location map of streams in Swabia, south Germany. Outlined areas are shown in figures 7 and 8.

to appeal to capture of the Cotswold streams is removed. Dealing specifically with the Cotswold river Coln, Davis perceived signs of capture in the wind gap at each of the two heads. He maintained that the valley of the Coln displays three sets of meanders—large valley meanders, lesser scars cut into the valley walls, and the small meanders of the present stream (Davis, 1899, fig. 16). These features he supposed to have been produced, in order, by the ancestral Coln before beheading, by a river reduced by the loss of one headstream, and by the existing stream after the second feeder had also been lost. However, the alleged lesser scars do not exist (Dury, 1953a), and the main support vanishes from the postulate of successive capture. The two wind gaps at the heads of the Coln remain; but, whether or not they indicate capture, they provide no help in explaining the underfit condition of the river. The Coln is no more underfit than is the competing Avon, or than are its Cotswold neighbors. In addition to the Cherwell, Windrush, and Evenlode, the

Cotswold rivers Dorn, Glyme, Dikler, Leach, and Churn also are underfit. Some of them head either by an unbroken crest where no wind gaps can be thought to indicate capture, or midway down the smooth notch-free back-slope, where signs of capture are equally lacking. Furthermore, a single degree of underfitness is common to the whole region (Dury, 1958, fig. 8) and, as previously shown, both to the Cotswolds and to the Avon basin. None of the Cotswold evidence, therefore, sustains any part of the capture hypothesis.

The Swabian Alp is no more helpful. In point of fact, the main headstream of the Lauchert is opposed not by the Starzel but by the Steinlach, which flows to the Neckar independently of the Starzel (fig. 6, shown on page A11).

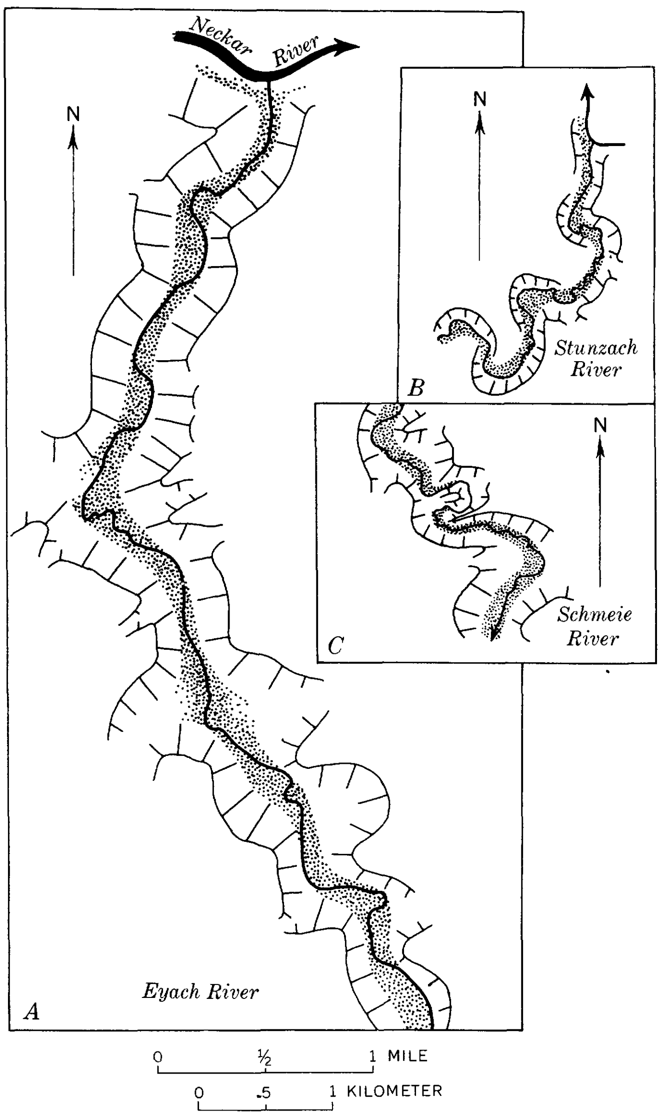


FIGURE 7.—Sketches of the Eyach, Stunzach, and Schmeie Rivers showing comparative stream-channel and valley patterns. See figure 6 for location of areas.

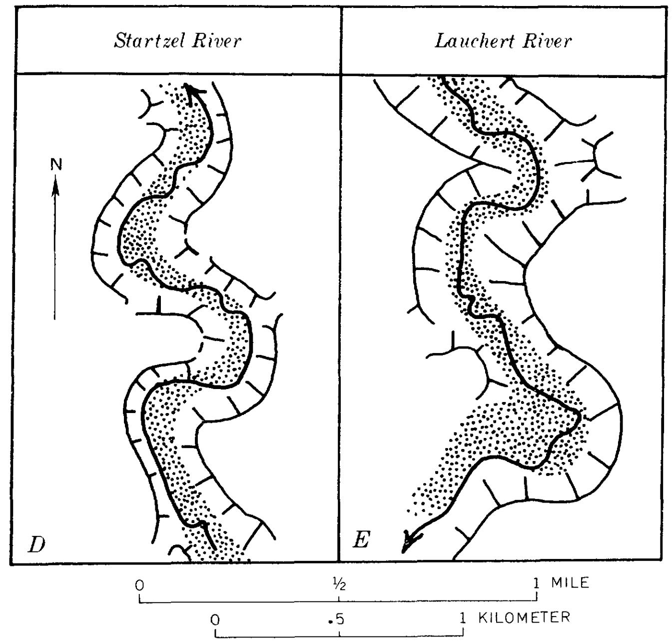


FIGURE 8.—Sketches of the Lauchert and Startzel Rivers showing comparative stream-channel and valley patterns. See figure 6 for location of areas.

The Starzel competes with the Vehla, which is a large stream but not the chief headstream of the Lauchert. The Schmiecha is the principal feeder of the Schmeie above Ebingen and contests territory not with the trunk Eyach but with the tributary Klingen. Davis' well-known block diagram can scarcely represent anything but the trunk Schmeie, as the settlement Kaiseringen is named in the caption. In all likelihood, the diagram is based on that reach of the Schmeie which is outlined as *C* in figure 6. The attempted comparison with the Eyach may therefore stand, as the general claim that back-slope feeders of the Danube have lost ground to the Neckar system is not affected by revisions of identity. The view that capture along the crestal divide is responsible for the observed underfitness is, however, false. Not only the Lauchert and the Schmeie but also the Eyach and the Starzel are underfit. Underfit streams are indeed typical of the region (Dury, 1963).

There is obviously little to choose between the condition of the Lauchert and the Schmeie on the one hand and of the Starzel and the Eyach on the other (figs. 7, 8). Stream meanders are admittedly few on the trunk Eyach, but they do occur; the tributary Stunzach is far more obviously underfit than is the Schmeie in the reach which Davis probably sketched. The Lauchert seems no more underfit than the Starzel. Although these statements are qualitative, regional analysis of meander wavelengths does not seem necessary; evidence of the kind used by Davis himself is enough to confute his views. Changes affecting the feeders of the Danube have also affected those of the Neckar. For Swabia, as for the Cotswolds, the claim that back-slope streams have become underfit through capture is not supported by fact.

Only the Meuse and the Bar now remain as possible examples of the effect of capture on stream volume. Let it be conceded at once that the upper Moselle has been diverted from the Meuse and that the Bar has lost the Aire. The anomalies of underfit captor streams have still to be explained. As will presently be shown, it is possible to define the relative influence of diversion and other change and to demonstrate that diversion was by far the less effective.

The term "diversion" is here preferred to the more specific term "capture," because Tricart (1952) has proved the derangement of the Meuse not to have been capture in the strict sense. The valley of the present upper Moselle was thickly alluviated during a cold period,[3] when thaw-freeze brought unusually large quantities of rock waste down the hillsides. Rising on its own deposits at the entrance to the Toul gap, the river spilled eastward into the adjoining valley. It became, as it has since remained, the largest member of the Moselle system. To this kind of diversion Tricart applies the name "déversement," for which spilling is probably the best English rendering. Change of mechanism, of course, does not affect the general argument from diversion; diversion, however caused, must influence discharge.

The means by which Davis sought to prove the effects of diversion on discharge are, however, mainly unreliable. His example of so-called robust meanders on the Moselle can be almost duplicated—not omitting a cutoff loop—from the Meuse near Mézières (fig. 9).

[3] During the Saale Glacial of the European sequence, corresponding to the Illinoian of North America. The full significance of the date will appear later.

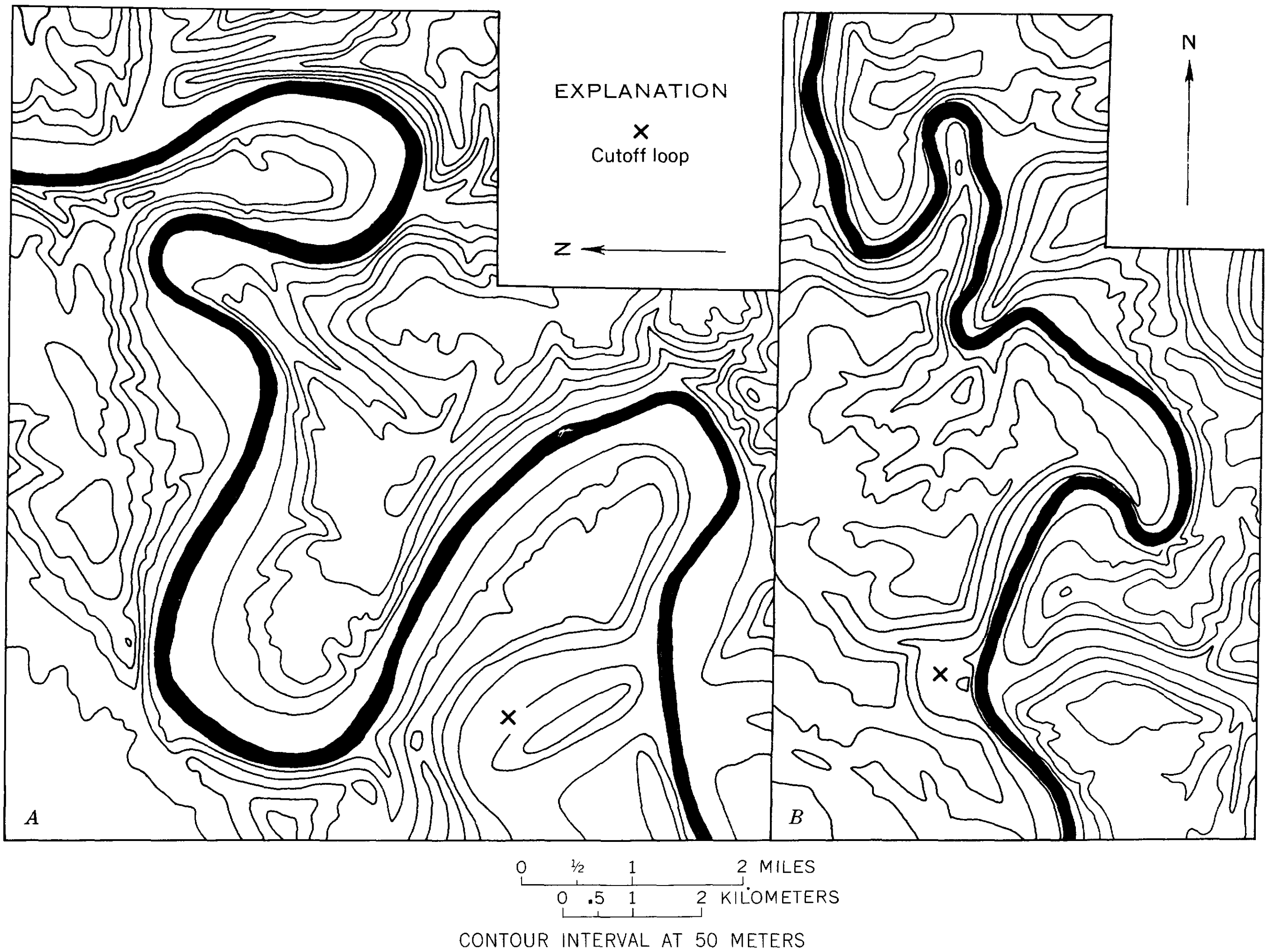


FIGURE 9.—Maps of Moselle and Meuse Rivers showing incised bends. *A*, the Moselle River near Berncastle; *B*, the Meuse River near Mézières.

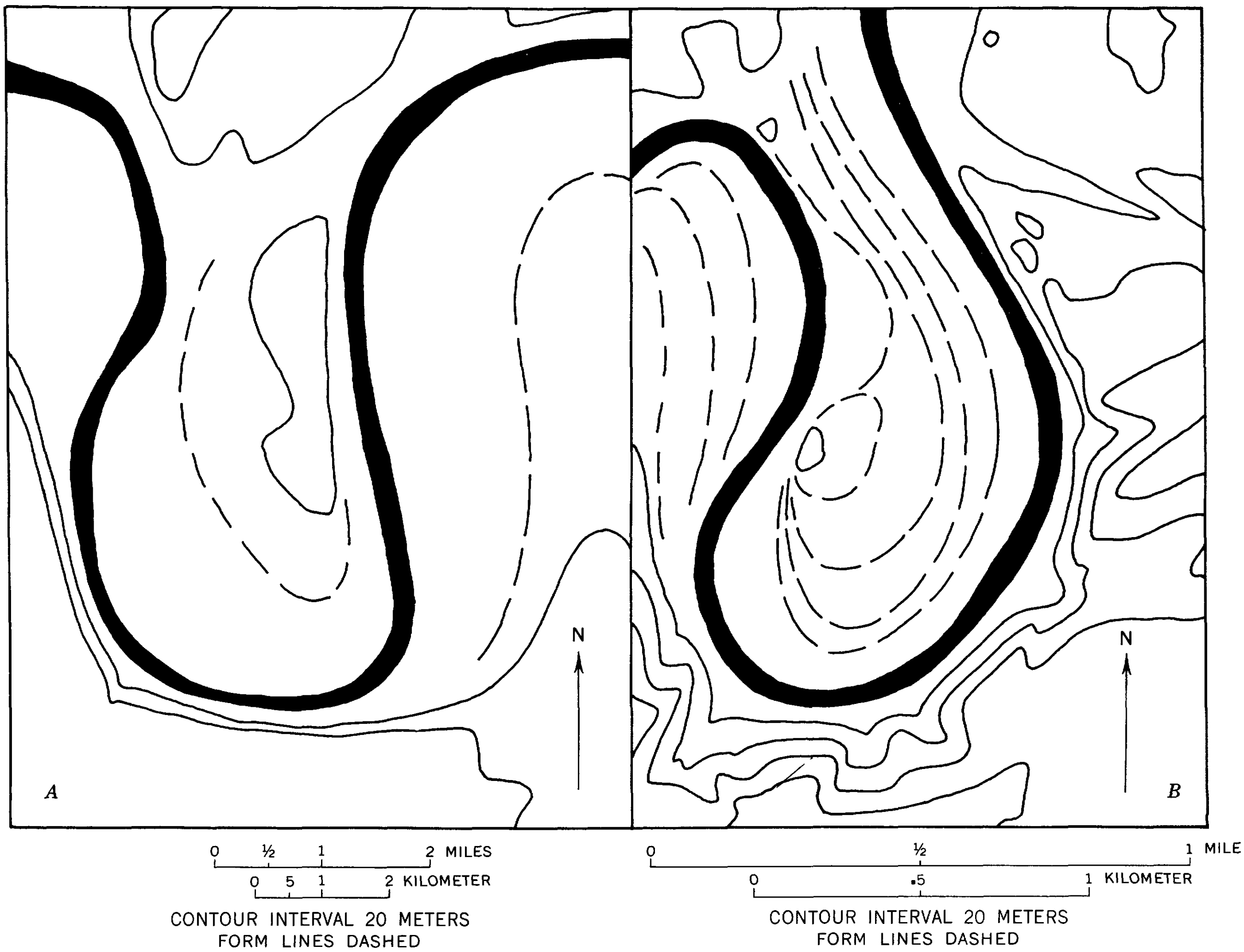


FIGURE 10.—Maps of the Seine and Meuse Rivers showing incised bends. ***A,*** **the Seine River near Duclair;** ***B,*** **the Meuse River near Givet.**

His specimen "vigorous meander" on the Seine differs little from a curve of the Meuse near Givet (fig. 10). In admitting some change of habit for the Meuse near Mézières, Davis contended that the loss of the small Aire was far less serious than the loss of the upper Moselle. This may be so, but the various derangements involve a 60-percent reduction of drainage area for the Meuse opposite the Toul gap and a 40-percent reduction near Mézières. This second reduction—surely great enough to be significant—is, nevertheless, not expressed by manifest underfitness. As has been seen, the Meuse in the relevant stretch of valley is indistinguishable from the so-called robust Moselle. Although admitting that the diversion of the Aire was of no great moment to the Seine, Davis was still able to contend that it confirmed the Seine in its boldly swinging habit. In actuality, the addition of the Aire basin could not have extended the drainage basin of the Seine by more than 1 percent. This value relates to the first point where water delivered by the Aire can enter the Seine—that is, at the confluence of the Seine and the Oise. Near Duclair, at the specimen loop, the percentage gain of drainage area would be still less.

Thus far, then, the arguments of Davis fail. Although diversion of the upper Moselle from the Meuse is authentically recorded in the Val de l'Asne, the type of evidence which Davis used does not validate an essential contrast in habit between the Meuse on the one hand and the Seine and the Moselle on the other. In logic, therefore, his contingent inferences lose all force. He was right in contending that the Meuse has been reduced in drainage area by loss of tributaries, but he did not succeed in proving reduction of discharge (Dury, 1963).

The Bar produces difficulties of a more complex kind. That part of the dismembered stream which was reversed after capture is now represented by the Moulin-Briquenay-Agron (fig. 63), which is itself manifestly underfit. Although capture can be held partly responsible for the underfit state of the remaining Bar, it cannot explain that of the Agron, the captor Aisne, the diverted Aire, or the Ornain, by which Davis sought to extend the Aire headwards. As will presently be shown, the valley meanders of the Agron belong to a series which, widely displayed in this region, bears a quantitative relation to existing drainage areas. The matter of capture does not arise. At any rate, possible capture is not relevant to the Agron. As the Agron did not exist until the Bar had been dismembered or partly reversed, the local sequence runs: diversion of the Aire, reversal of part of the beheaded Bar to form the Agron, incision of valley meanders along the Agron, and,

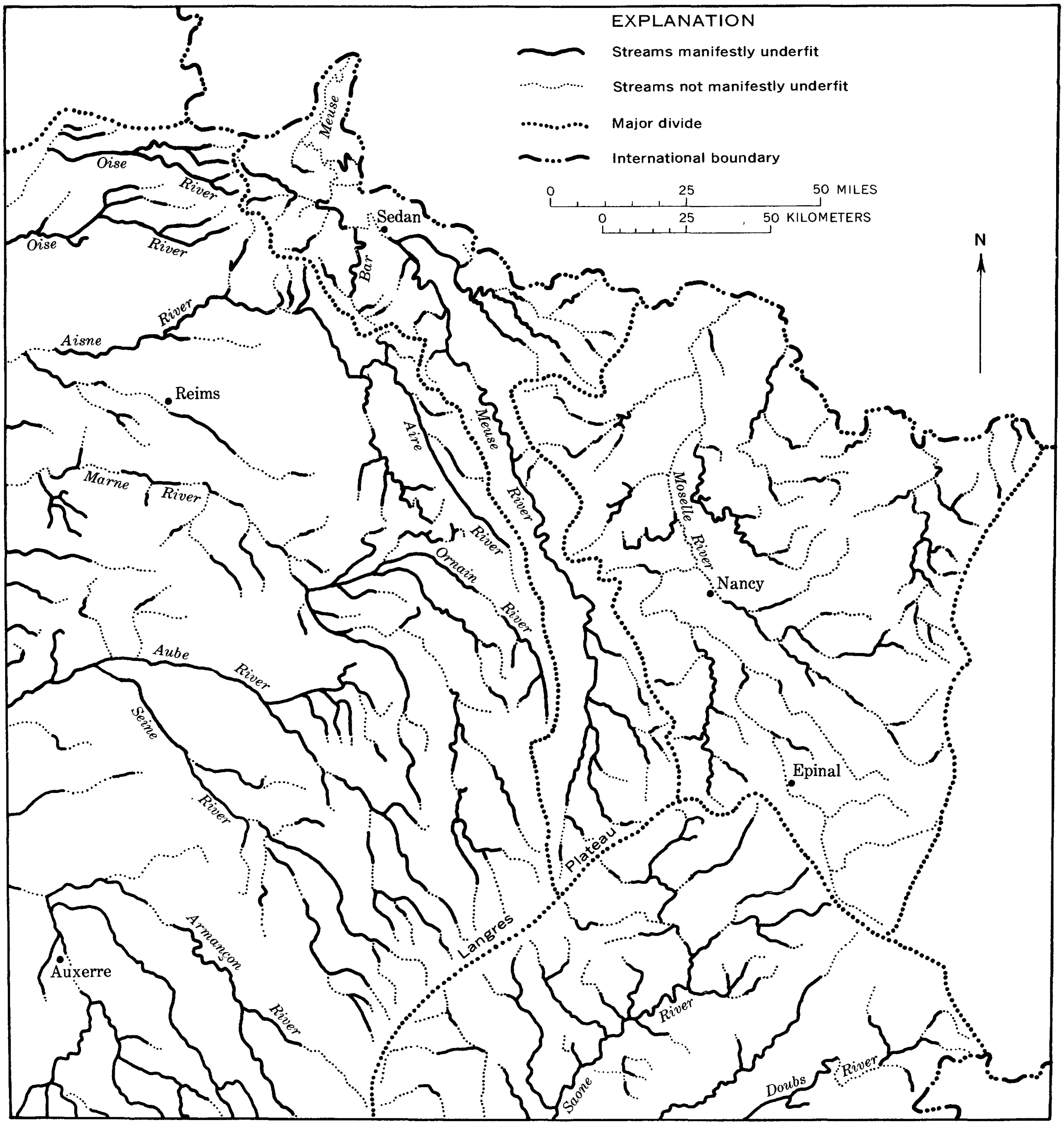


FIGURE 11.—Map of eastern France showing distribution of manifestly underfit streams.

finally, development of stream meanders. The Agron thus became underfit some time after the diversion of the Aire, thus allowing a sufficient length of time for its valley meanders to be incised 100 feet or more. Dating of the change as significantly later than the capture will shortly prove useful.

Despite what Davis wrote to the contrary, underfit streams can be regionally distributed. They are so distributed in eastern France and are well shown on the French 1 : 80,000 map from which he chose illustrations. This map is the basis of figure 11, in which manifestly underfit streams are the only type plotted. As shown, the underfit Meuse is opposed on one side by the Moselle system, parts of which are manifestly underfit, and on the other side by long manifestly underfit reaches of the Aire, Aisne, Ornain, and Marne. The underfit condition of the Saône prevents appeal to capture along the crest of the Langres Plateau. Here, as in the Cotswolds, underfitness is regional. The effects of diversion serve merely to complicate the regional pattern of underfitness. One can but regret that Davis gave first importance to diversion. His statement that some general change has superimposed its effects on those of diversion, which is incompatible in any instance with his views on distribution, is valid in a sense which he did not intend. It holds good only if it is taken to mean that diversion came first in time, and regional change second.

The shrinkage of the Agron has already been seen to postdate the diversion of the Aire. The diversion of the upper Moselle dates back to the Penultimate Glacial, whereas there is reason to place the last major regional shrinkage at the end of the last glacial. Although no dates are yet available from this area, it seems inevitable that the general change in eastern France was approximately simultaneous with that elsewhere: dates of about 10,000 years B.P. will be applied in due course to the English Cotswolds, the Great Basin, and Wisconsin, and will be associated with less precise but wholly compatible evidence from other regions. Accordingly, the relative effects of diversion and of regional shrinkage will be calculated according to the view that events occurred in this order.

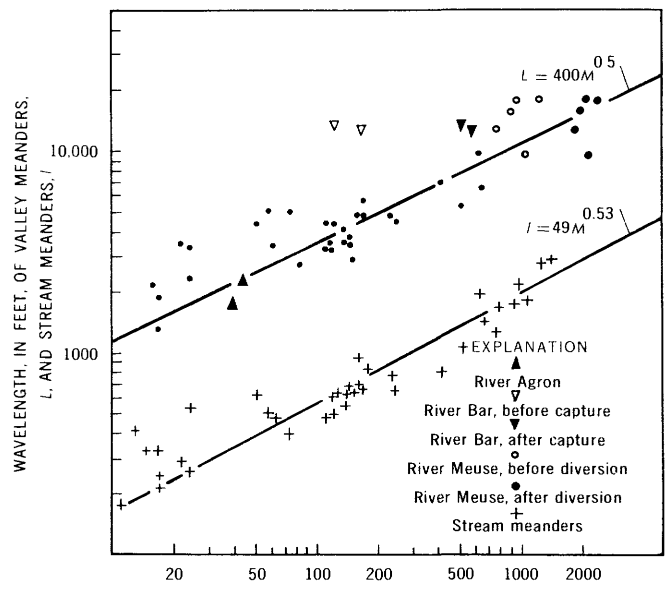


FIGURE 12.—Graph showing relation of wavelength to drainage area of selected French rivers.

Regional graphs of wavelength, both for valley meanders and for stream meanders, have been determined by the usual method of least squares from data for average wavelength in trains or groups and from areas determined by planimetry. The results appear in figure 12, where the effect of diversion on the location of points on the area scale also is shown. Between 10 and 1,000 square miles, the ratio of wavelength between valley meanders and stream meanders falls from about 7.5 to about 5.5; the disproportion resembles that observed in a number of other regions. Eastern France is closely similar to parts of the United States in respect to its degree of underfitness.

The regional graphs indicate the wavelengths of valley meanders appropriate to the Meuse and the Bar, for the basins drained immediately before and immediately after diversion. It does not follow that valley meanders of the reduced size were actually developed. Even if a meandering habit was retained by the Meuse, the shortened valley meanders might have been accommodated with no great difficulty in the existing cut. The relation among the predicted wavelengths is nevertheless instructive. Diversion could have reduced wavelength on the Meuse by about one-third and that on the Bar by about one-half; the regional shrinkage could have imposed a further reduction of five-sixths on the wavelength of both rivers. The fractional loss on the Bar was, therefore, 1½ times as great by regional shrinkage as by diversion, whereas the proportional loss was 3 times as great; corresponding values for the Meuse are 2½ and 4 times. Quite clearly, even where diversion involved loss of more than one-half the drainage area, it was potentially less effective than regional change. The hypothesis of capture, advanced in general explanation of underfit streams, should be discarded.

DIVERSIONS OTHER THAN CAPTURE—THE QUESTION OF SPILLWAYS

Regional distribution of underfit streams, once established, is in part as adverse to the hypothesis of glacial derangement as to that of capture. However, streams in general in extraglacial regions need to be proved as commonly and as markedly underfit as those in formerly glaciated areas before glacial derangement can, like capture, be reduced to a mere complicating factor. Alternatively, if underfit streams in formerly glaciated regions can be proved not to have become underfit until long after the ice had gone, then underfitness can be separated from glaciation in time. Demonstrations of the required sort will be forthcoming. Nevertheless, well-authenticated instances of glacial derangement demand something more than a general denial of the hypothesis as stated by Thornbury (1954, p. 156–157).

Country formerly invaded by ice sheets usually exhibits spillways of various kinds—in particular, melt-water channels that lead along or away from the lines of the ice front, or the outlets of proglacial lakes. Where such channels are now occupied by streams, such streams are underfit, for they are far less voluminous than were the former streams of melt water. As, however, many spillways fail to meander and as many are occupied largely by swamp, they frequently do not show the combination of valley meanders and stream meanders which characterizes manifestly underfit streams. In any event, streams flowing along former spillways represent a special type of underfitness with which the discussion in hand is not primarily concerned. The examples now to be examined have been selected to demonstrate the independence from the outpouring of melt water of those changes which reduce the drainage of an entire region to an underfit condition.

WABASH RIVER, IND., AND GLACIAL LAKE WHITTLESEY

The Wabash valley is well known to have functioned as a major sluiceway for melt water and outwash during part of the Wisconsin Glacial. In particular, it provided an outlet, in order, for the water of highest Lake Maumee (800 ft), possibly for lowest Lake Maumee (760 ft), and certainly for middle Lake Maumee (790 ft) (Hough, 1953, 1958). That is, water overflowed through the Fort Wayne gap in the Fort Wayne–Wabash complex of moraines at various times between the recession of the Erie ice lobe from the Fort Wayne moraine and the recession from the Lake Border moraines, an event dated at about 14,000 years B.P. (Flint, 1957, p. 347). As Thornbury (1958) observed, the present Wabash valley contains numerous abandoned braids above the present valley floor and minor scablands formed on buried uplands of bedrock. But, in common with some other rivers that occupy former outlets of melt water—for example, the upper Mississippi and the lower Wisconsin—the Wabash is not a finely meandering stream, nor does its valley possess well-developed valley meanders. The disparity between former and present discharge is established by evidence of a kind not to be expected from meandering valleys that were not spillways.

Streams that enter the Wabash from both left and right banks do, however, occupy meandering valleys of the usual sort; these streams have been reduced in volume independently of any cessation of overspill. But as they also lie beyond the Fort Wayne moraine, within conceivable range of the former discharge of melt water, attention may suitably be turned to the area within the moraine where streams exist which cannot possibly have carried water from any ice front.

The Maumee River, which drains the floor of glacial Lake Maumee and its successors toward the present Lake Erie, inherits the channel of no spillway. Still more certainly—if additional certainty be possible—the valleys of tributaries to the Maumee, which is well within the Fort Wayne moraine, can by no means have carried melt water. These valleys ramify across till and lake sediments, as they did not exist before the lake bottoms were exposed by receding waters. Nevertheless, numbers of them are manifestly underfit. On early topographic maps, their windings are often so generalized that the typical combination of valley meanders and stream meanders fails to appear, although the dimensions of the recorded windings are themselves great enough to suggest meanders not of streams but of valleys. When aerial photographs are consulted, the patterns of stream channels emerge in full. Figures 13 through 15 contrast the patterns of a sample area, some 15 to 20 miles south of Defiance, Ohio, according to evidence from topographic mapping and mapping from photographs, respectively. Figure 14*A* shows the two sets of meanders as well as the remains of scars cut by, and point bars deposited in, the large meanders despite the irregular development of both sets of meanders and despite also the extensive scalloping effected by meanders of the present stream. Former traces, including cutoffs, are reconstructed in figure 14*B*.

The flat interfluves of the sample area rise to slightly more than 700 feet above sea level and were certainly inundated not only by the three Lakes Maumee but also by glacial Lake Whittlesey (738 ft). Between the stands of middle Lake Maumee and Lake Whittlesey there intervened the stand of Lake Arkona (710–695 ft), but this episode was brief. Consequently, the valley meanders south of Defiance are considered to postdate the recession of the lake from the Whittlesey shore. As wood from beach sediments of Lake Whittlesey has been radiocarbon dated to 12,800±250 years (Barendsen, Deevey, and Gralenski, 1957) and as highest Lake Warren (690 ft) succeeded Lake Whittlesey

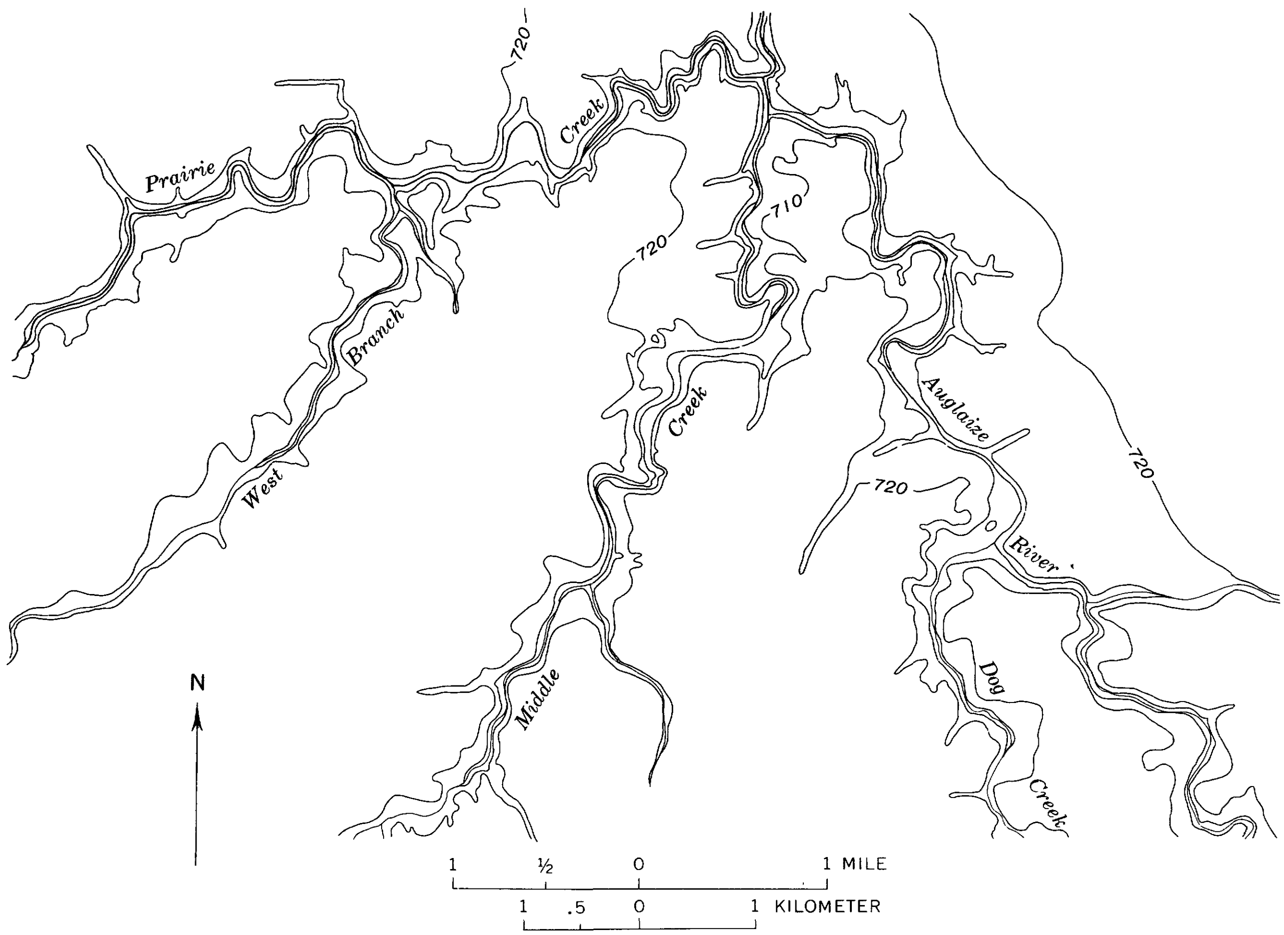


FIGURE 13.—Map of the Auglaize River system, Ohio, showing stream-channel patterns.

slightly before 12,000 years ago, with a renewed clearing of the Grand River link between the Huron and Michigan basins, the earliest date for the cutting of valley meanders into the emergent floor of Lake Whittlesey may be taken, in round figures, as 12,500 years ago, some 1,500 years after spill water had ceased to flow in the Wabash valley.

SOURIS RIVER AT MINOT, N. DAK.

The Souris River at Minot, N. Dak., provides a neat demonstration of the combined effects of the cessation of outspill of melt water and a subsequent independent reduction in channel-forming discharge. Its valley is part of a concentric system of melt-water channels that lies well within the Martin moraine and west of the former glacial Lake Souris. At Minot, where the valley swings first to the right and then to the left, former point bars now form patches of terrace on the insides of bends (fig. 16); the point bars were deposited by the broad, but meandering, stream of melt water. The present stream, which is cutting irregular meanders on the valley floor, is signally misfit; but its present loops are arranged not in a simple meander belt but in a meander belt which itself meanders. The reconstructed sequence (which should be read in conjunction with that given below for the Sheyenne) is: Cutting of a very large meandering channel by melt water; cutting of large meanders, equivalent to valley meanders in unglaciated regions, by an ordinary stream; and cutting of the present meanders by the reduced stream.

SHEYENNE RIVER, N. DAK., AND GLACIAL LAKE AGASSIZ

The interpretation placed upon the foregoing example accords precisely with that now to be given for the Sheyenne River. On this river, unmistakable signs exist that meanders significantly larger than those of today were developed after melt water had ceased to flow down a great outlet.

The Sheyenne River, which heads at an ill-marked divide that coincides roughly with the Martin moraine enclosing the Souris basin, traverses some 175 miles of

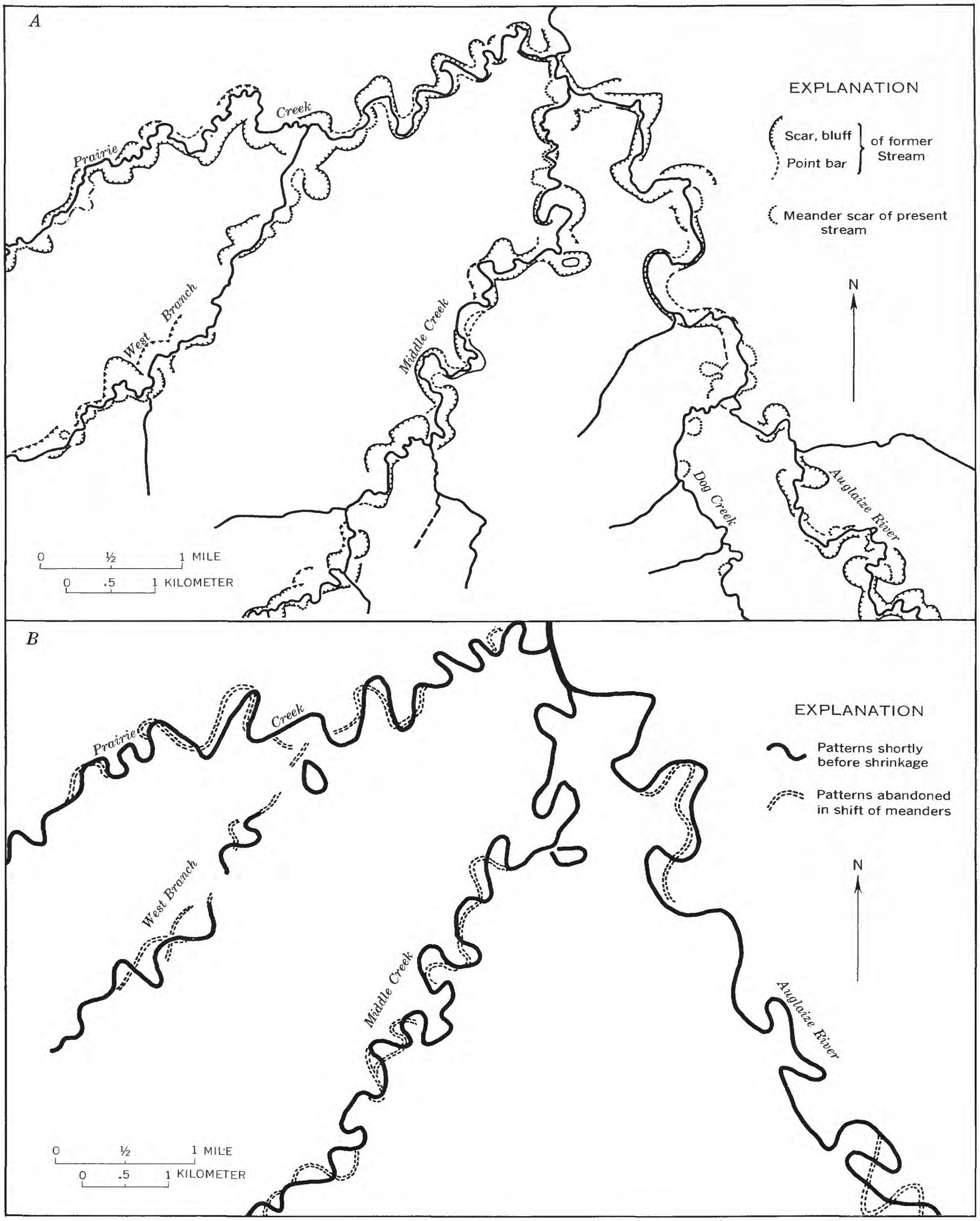


FIGURE 14.—Auglaize River system, Ohio, as mapped from aerial photographs. *A*, stream-channel patterns and lateral features; *B*, restored patterns of former streams.

FIGURE 15.—Aerial photograph of part of the Auglaize River, Ohio, showing valley and stream meanders.

glaciated country before breaking through the last morainic barrier into the basin of glacial Lake Agassiz (pl. 2). Its upper basin includes a nexus of melt-water channels, not all of which functioned simultaneously. A tangle of complications in the sequence of events responsible for the channels arises from the competition of two ice lobes, from the variable relation between the Sheyenne and the James Rivers, and from the fluctuations of glacial Lakes Souris and Agassiz. At times, water from glacial Lake Souris spilled into the valleys of the James and the Sheyenne. At times also, cross connections led melt water from country now drained by the Sheyenne into the basin of the James, where it flowed southward, eventually reaching the Mississippi at Yankton (Geol. Soc. America, 1959). But, as the Souris lobe receded and as the Agassiz lobe melted back toward Devils Lake, something like a master outlet established itself. This channel, which passes through the Heimdal and Hillsdale moraines, is distinctly trenched and meandering. Between moraines, it tends to become braided across belts (or fans) of outwash, but after entering the next moraine downstream it resumes its meandering habit and swings boldly from side to side through the whole north-south reach downstream from Valley City. The great meanders persist as far downstream as the point where the channel reaches the topmost beach of glacial Lake Agassiz.

Unlike meandering valleys of unglaciated areas and postglacial meandering valleys of glaciated areas, the Sheyenne channel shows little sign of increasing the wavelength of its meanders except in its lowermost reaches. The apparent abrupt increase in wavelength at the lower end (table 1), if it is truly significant, seems hardly explicable by an increment of melt water supplied by the not particularly well-marked channel leading in from Eccelston Lake, 13 miles west of Valley City. However this may be, the uniformity of wavelength along most of the channel suggests that when the bends were being cut, melt water was being supplied principally at the channel's head—for instance, by overflow from Lake Souris.

TABLE 1.—*Wavelengths of meanders of the Sheyenne River spillway*

[Queried areas are interpolated, with the aid of planimetry, in the series of values cited by McCabe and Crosby (1959). Total areas for localities downstream of Warwick include 3,940 square miles in the closed Devils Lake basin]

Locality	Drainage area, in square miles		Number of meanders	Mean wavelength, in feet
	Total	Probably contributing		
Harvey (South Fork)	535	171	2	21, 125
Lower North Fork	700(?)	200(?)	2	29, 050
Below confluence of the two forks	1, 600(?)	500(?)	3	22, 700
Above Warwick	1, 790	560	2	27, 450
Warwick	2, 070	660	3	25, 350
Lake Ashtabula:				
Upstream end	7, 750(?)	1, 850(?)	4	25, 075
Downstream end	7, 880	1, 900	3	28, 500
Below Valley City	8, 300(?)	2, 100(?)	3	23, 750
Between Valley City and Lisbon	8, 400(?)	2, 200(?)	2	31, 700
Lisbon	8, 500(?)	2, 300(?)	4	37, 000
Kindred [1]	9, 150	2, 970	5	15, 300

[1] The wavelengths listed for Kindred are those of ordinary valley meanders, not of meanders of the spillway; they are inserted for comparison.

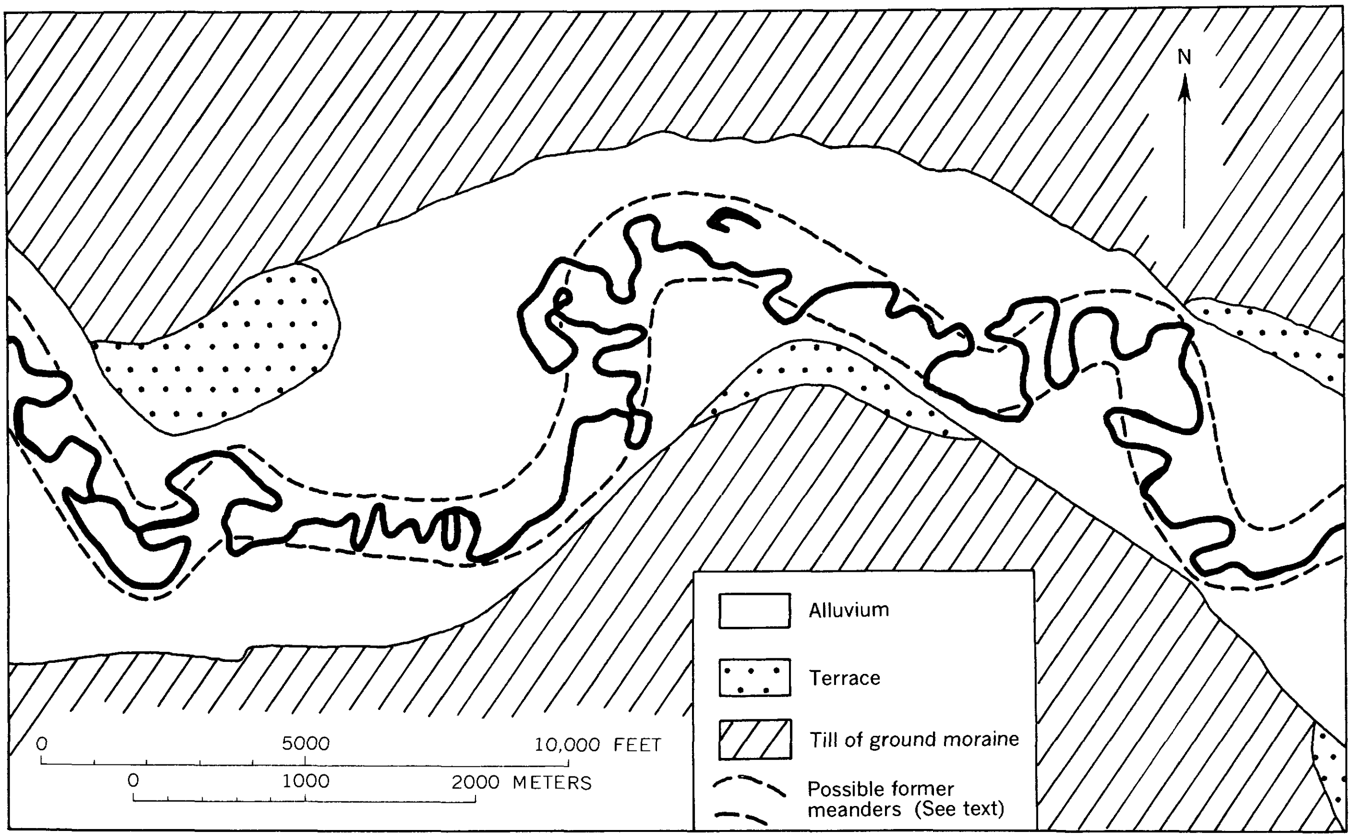


FIGURE 16.—Sketch of the Souris River valley at Minot, N. Dak.

As the meanders of the present Sheyenne increase in wavelength with drainage area, whether total drainage or probably contributing drainage be considered, the river becomes progressively underfit in the meanders of the melt-water channel as it is traced headward. Even in the reaches downstream of Valley City, it is far more underfit than is usual with rivers in nonglaciated regions: the last 5 bends of the melt-water channel contain some 100 stream meanders. But when the Sheyenne passes onto the emerged floor of glacial Lake Agassiz, it becomes an underfit stream of the usual type, with a wavelength ratio between valley meanders and stream meanders of about 5 : 1 (pl. 2).

The valley meanders of normal type occur mainly on that reach of the Sheyenne which runs somewhat north of east from the line of the Herman Beach of glacial Lake Agassiz northeast of Lisbon to and through the Wahpeton moraine and the Campbell Beach. Relative to the local chronology, the earliest possible time for the inception of this train of valley meanders can be fixed within quite narrow limits. When the lake stood at the Milnor Beach, the basin of Lake Agassiz was still almost filled with ice, and water discharged eventually to the south into the valley of the Minnesota River near the south end of Lake Traverse (Leverett, 1932; U.S. Army Map Service 1:250,000, Milbank and Fargo sheets, NL 14–6 and NL 14–9). With further recession of the ice and the formation but progressive fall in level of Lake Agassiz 1, Cottonwood Slough and the Lake Traverse outlet took over the southward outlet of water, which, after an early cessation, recommenced when readvancing ice in the north created Lake Agassiz 2. The Campbell Beach, which crosses the present Sheyenne on the inner border of the Wahpeton moraine, extends into the broad southern gateway leading to Lake Traverse; but, before this beach was cut, the huge lacustrine delta of the Sheyenne, opposite the mouth at the Milnor and Herman Beaches, was already exposed. Thus, the extension of the Sheyenne across the delta as far as the Wahpeton moraine occurred in the interval between the Herman and Campbell stands of the lake. When the water level descended still lower, valley meanders were cut by the still extending Sheyenne for an additional 5 miles, bringing them below the 950-foot contour and well within the Campbell Beach.

The lower end of the train of valley meanders on the Sheyenne is too ill-defined to show whether or not there is a sharp change from two sets of meanders to only one. If such a change were demonstrated and were found to occur also at corresponding positions on other rivers, then a useful fix could be obtained; for, in this northern region, the conversion from large to small meanders may have occurred later than in regions farther to the south. As matters stand, it is possible merely to observe that the Red River, the trunk stream flowing along the axis of the former lake basin, is not underfit. In this respect, as in its setting, the Red River resembles the Maumee. Two obvious possibilities are that the trunk streams did not begin to incise themselves until after their laterals had become underfit or that the forms of valley meanders have not been preserved in the weak materials of the bottoms of the two basins.

Some other rivers resemble the Sheyenne in having cut valley meanders across part of the lake floor. Rivers tributary from the west display the relevant features better than do those tributary from the east, and they also make possible an extension of dating. Until the ground has been carefully examined for signs of beaches below the Campbell—the McCauleyville Beach—the interpretation of possible valley meanders on the Dakota Wild Rice River, west and northwest of Wahpeton, must remain in doubt. Valley meanders on the Maple River, west-southwest of Fargo, go slightly lower (to about 920 feet above sea level) than do those on the nearby Sheyenne. If the large bends on the Minnesota Wild Rice River, about 25 miles north of Fargo, are valley meanders, then such meanders were cut into the lake bed at 850 feet; the bends on the lower Buffalo River, which enters the Red River 15 miles north of Fargo, seem likely to be authentic valley meanders, and they also are cut below the 850-foot mark. The North Branch of Elm River describes unmistakable valley bends a little above this level yet well inside not only the Campbell and McCauleyville but also the succeeding Blanchard and Hillsboro Beaches. There is room, however, in the sequence of events since ice receded across the basin of Lake Agassiz for more than one fluctuation of discharge, and it is most desirable that, in due course, the local valley meanders should be dated. As yet, all that can be said is that the local rivers have been reduced to an underfit condition, subsequent to the emergence of the lake bed; comparison between the middle and lower reaches of the Goose River, next northward from the Elm River, suggests that more than one generation of valley meanders may be present, those upstream being larger and earlier than those downstream. Because the largest of the indubitable valley meanders (meanders of spillways always excepted) are but some five times as long as the stream meanders, even these valley meanders are likely to be savagely bitten by the loops of the present streams, and any valley meanders of a lesser order promise to be identifiable only by means of very detailed investigation.

Still farther north, however, useful observations can be made on the Park, Tongue, and Pembina Rivers (U.S. Army Map Service 1:250,000, Thief River Falls Sheet, NM 14–12). The Pembina describes valley meanders of a normal size, clearly distinguishable from irregularities of trace associated with lake beaches, at least as far downstream as Neche, N. Dak.—that is, within the Burnside Beach. The old lake bed here stands at about 835 feet above sea level; the present flood plain, some 25 feet lower, is underlain by as much as 40 feet of silt, clay, and sand—river deposits which, in a belt as much as three-fourths of a mile in width, are included in the silt of Lake Agassiz (Paulson, 1951). If these deposits correspond to the fills of large channels in meandering valleys, then the Pembina, when it had large meanders, cut its large bed perhaps as low as 770 feet above sea level at Neche.

Although the course of the Tongue River is manifestly affected by old shorelines, valley meanders as low as 800 feet above sea level appear between the Ossawa and Stonewall Beaches. But the most clearly developed valley meanders at low level occur on the Park River, where they are below 800 feet above sea level and extend at least 10 miles beyond the Gladstone Beach and possibly the whole way to the Red River.

In summary, the site of glacial Lake Agassiz south of the United States–Canadian border appears to record the extension, with varying strength and with varying subsequent preservation, of large meanders across the progressively emerging floor, in places at least as late as the date of the Ossawa Beach, and below the 800-foot level. The examples cited all refer to the floor of Lake Agassiz 2, the history of which begins with the 1,080-foot (Herman Beach) stand, dated at about 11,200 years B.P. (Flint, 1957, p. 347). As yet, it is not possible to indicate what proportion of the recession period of that lake—a period extending from about 11,200 to perhaps 7,500 years B.P.—included the new establishment of large meanders. This matter must await the dating of relevant deposits; but the evidence adduced here is at least sufficient to emphasize the distinction between the valley meanders of spillways and those of rivers which did not receive spill water, even when both sets of conditions are exemplified on a single stream.

STRATFORD AVON, ENGLAND, AND GLACIAL LAKE HARRISON

For the basin of the Stratford Avon, the conversion of rivers to underfitness is clearly separable in time from the presence of ice and the operation of spillways. Some trains of valley meanders were initiated during the last interglacial (Holstein of northern Germany, Sangamon of North America), whereas the shrinkage which made

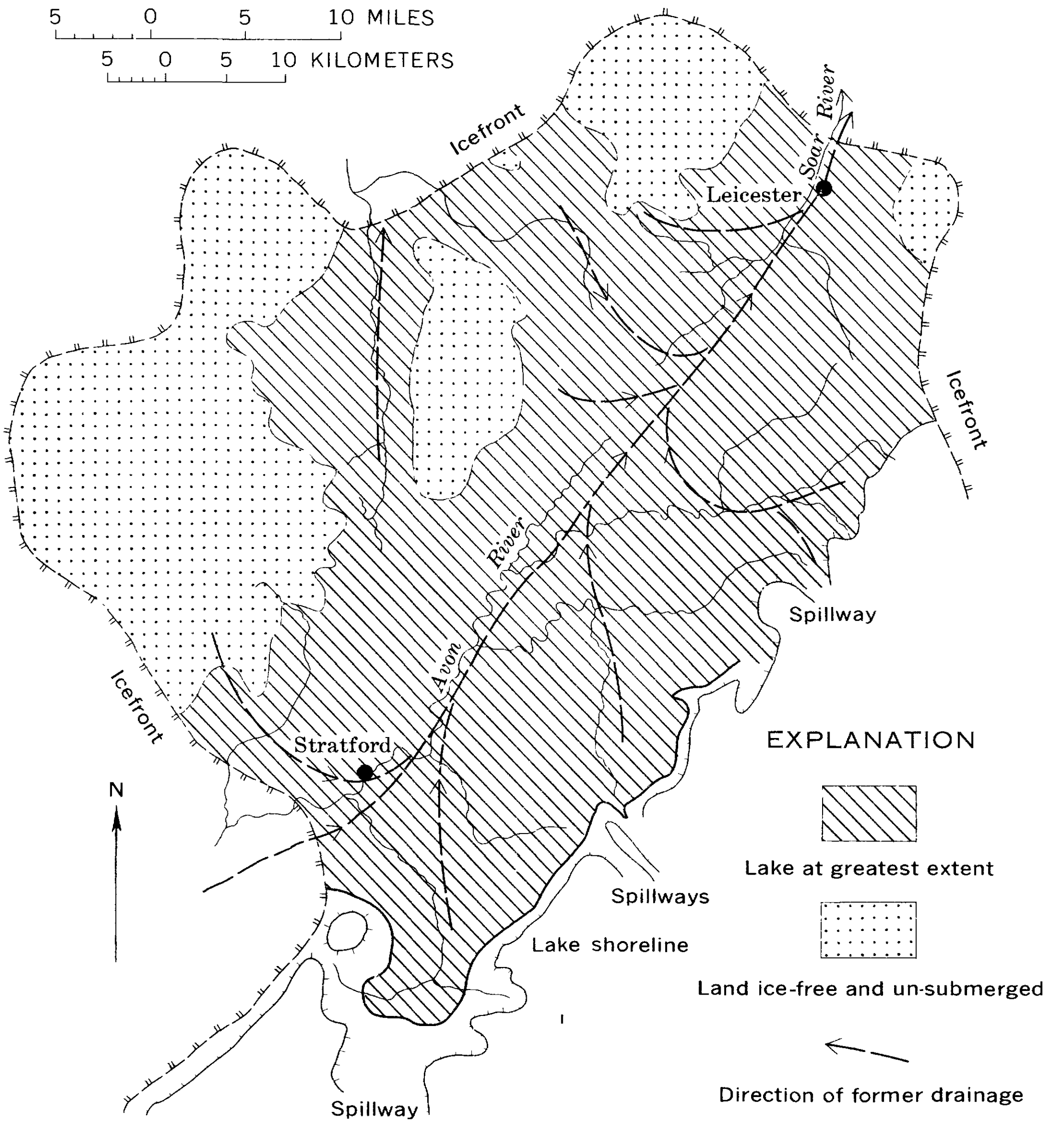


FIGURE 17.—Sketch map showing former drainage basin of the Avon River, Warwickshire, England, in relation to glacial Lake Harrison.

the rivers underfit was deferred until quite late in the last glacial (Weichsel, Wisconsin). Although ice-dammed lakes once existed in the region, they date from the Penultimate Glacial (Saale, Illinoian) and can have no part in explaining either the valley meanders or the reduction in discharge. Ice did not invade the Avon drainage basin during the last glacial, nor did melt water spill into it. In these circumstances, the time gap between the last local glaciation and the conversion to underfitness is readily demonstrated; the necessary outline of the evidence can be far shorter than that for the Lake Agassiz region, where, as seen above, active spillways and the induction of underfitness belong to a single part of the glacial sequence. At the same time, the extended time span applicable to events in the Avon basin demands that the expression "conversion to underfitness" be qualified. The conversion in question is that responsible for the present condition of rivers. It will be mentioned as if it were a unique event, without prejudice to the possibility that similar conversions may have occurred earlier. All that is required now is to show that valley meanders were still developing late in Last Glacial times, regardless of fluctuations of discharge that had occurred previously.

Before the Penultimate Glacial, most of the area now drained by the Avon was tributary to the River Trent. It was included in the drainage basin of the Soar, which was then considerably longer than it is today (fig. 17). Advancing ice impounded a series of lakes against the Cotswold scarp and its continuation to the northeast.

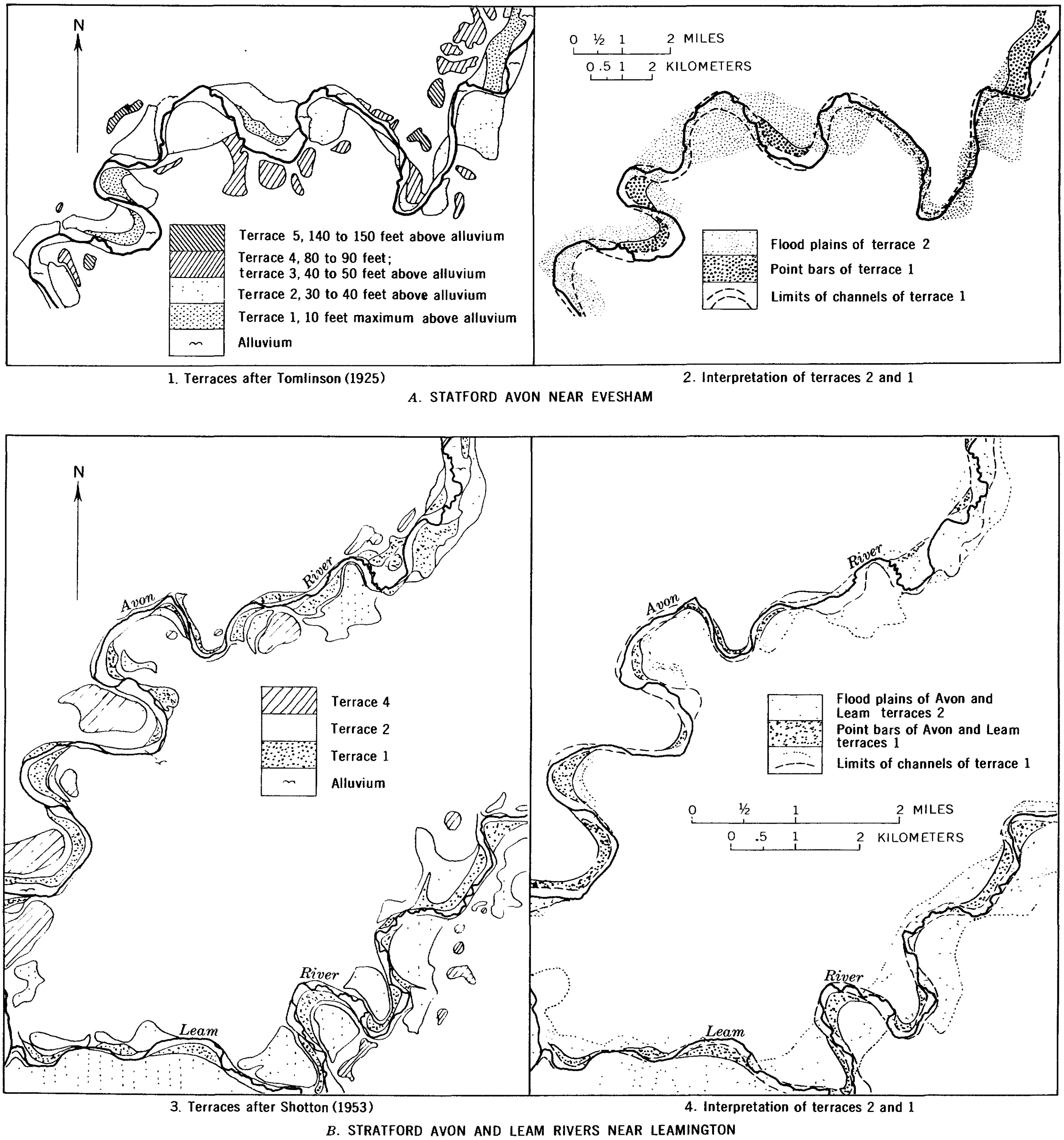


FIGURE 18.—Sketches of the Avon River, Warwickshire, England, showing river terraces and two interpretations of these terraces. *A*, Stratford Avon near Evesham; *B*, Stratford Avon and Leam Rivers near Leamington.

Collectively, these lakes are called glacial Lake Harrison (Shotton, 1953); various extents and levels are distinguished as named stages (Bishop, 1958). The detailed history of Lake Harrison is not material here: the essentials are that while the lake existed, spill water discharged through gaps in the bounding scarp on the southeast; and when the lake was finally drained, the Stratford Avon came into being on the bulky fill of glacial, proglacial, and lacustrine sediments in the temporary basin.

The development of the Avon system is well recorded by a series of terraces (Tomlinson, 1925, 1935; Shotton, 1929, 1953; Bishop, 1958). (See fig. 18.) Avon terrace 5, the highest and oldest, was assigned by Shotton and Bishop to the Penultimate Glacial; it may well consist of outwash provided by the receding ice. Terraces 4 and 3 are younger and lower than 5. Both date from the last interglacial, and both are fluvial in origin. Their somewhat dubious interrelation does not concern the present argument nor affect the circumstance that terrace 4 was deposited in a broad open valley. If significant downcutting had already occurred before the completion of terrace 4, it had been largely offset by subsequent infilling. Partly for this reason and partly because terraces 4 and 3 are but scantily preserved in most of the valley, there are few reliable signs that the meanders (valley meanders) of Avon 4 had ingrown. Terrace 2, lower and younger still, is by contrast extensively preserved. Enough remains to show that, in some reaches, Avon 2 had swept out a meander trough almost as broad as the existing belt of valley meanders, whereas elsewhere the great bends were still confined by spurs on which crescentic patches of terrace 2 represent point bars. Avon 2, that is to say, displayed the two arrays of landform which are diagrammatically illustrated in figure 4 at sites 1 and 3. Ingrowth of valley meanders continued when the river cut through terrace 2, for the reconstructed trace of Avon 1 transgresses the limits (only in part reconstructed) of terrace 2; the meander belt of Avon 1 was broader than that of Avon 2 (fig. 18*B*). On the tributary Itchen, valley meanders are cut through terrace 1 (Shotton, 1953, fig. 9; Bishop, 1958, fig. 6). A former larger stream postdates Avon 1, so that reduction of discharge and conversion to the present state of underfitness must be placed later still.

The absolute gap of time between the disappearance of ice and the appearance of stream meanders on the existing rivers cannot be assessed precisely. Something depends on the span allocated to the Pleistocene as a whole. For example, Zeuner's data (1959, chaps. 4, 6) suggest an age of at least 185,000 years for Lake Harrison and terrace 5, and age of about 125,000 years for part at least of terrace 4 (and 3?), and an age of 75,000 years for terrace 1. As terrace 1 does not represent the final incision of valley meanders, the interval of about 110,000 years between the last local deglaciation and the last conversion to underfitness is too short. Although Emiliani (1955, fig. 15) requires but half the length which Zeuner gives to the whole Pleistocene, his correlation does not greatly reduce the interval under consideration. On Emiliani's scale, the end of Lake Harrison and the deposition of terrace 5 fall at about 105,000 years B.P., whereas terrace 1 cannot be referred to anything but Emiliani's position for Würm II of the Alps and the Wisconsin of North America—say, at about 15,000 years B.P. The gap is still no less than 90,000 years, even without allowance for the persistence of large meanders after the formation of terrace 1. Glacial events in this region have no possible bearing on the regionally underfit state of the existing rivers.

The spillways on the southeast ceased to function when Lake Harrison was drained. In the Cotswolds, as on the Avon, there is good evidence that the rivers did not become underfit until much later. Although spill water discharged from Lake Harrison into the valleys of the Evenlode and Cherwell (Shotton, 1953; Bishop, 1958; Dury, 1951), these rivers are no more underfit than are other rivers which, draining parts of the Cotswold back-slope, emphatically did not carry overspill. As the maximum height of Lake Harrison was 435 feet above sea level, discharge could not have occurred except through gaps leading to the Evenlode and the Cherwell and possibly also to the east-flowing Nene. No appeal can be made to hypothetical lakes formed during glacials earlier than the Penultimate, for the valley meanders of the Evenlode did not then exist. Despite the correlation attempted by Arkell (1947, table 2), these meanders had probably been formed, and had begun their ingrowth, before Lake Harrison overflowed into the Evenlode valley (Bishop, 1958, fig. 12). The first incision of the Evenlode through a fanlike spread of gravel—the Hanborough Terrace—seems likely to belong late in the Penultimate Glacial and certainly to antedate the first outspilling of the lake. Furthermore, the main headstream of the Cherwell rises near an unbroken crest more than 600 feet above sea level and well out of reach of Lake Harrison; but the stream is manifestly underfit, just as much underfit as those reaches which occupy the spillway (Dury, 1953c). The synoptic profiles drawn by Bishop (1958, fig. 8) put the existing flood plain at 25 to 45 feet below the floor of the spillway. A descending sequence of terraces proves that erosion continued after the spillway ceased to function. Indeed, the valley meanders go below the surface of the flood plain into the so-called sunk channel, and this is an indication that they were incised by 40 to 60 feet after Lake Harrison had fallen for the last time below the col which linked it with the Cherwell valley.

Because the Cotswold rivers are equally underfit and because their condition cannot be explained by derangement of drainage, it seems likely that a date for the shrinkage of one stream would apply to all. A date is forthcoming from the Cotswold River Dorn, where the valley meanders were finally abandoned about 10,000 or 9,000 years ago (Dury, 1958). If this date applies at all widely—as, in the writer's view, it does—

then the onset of underfitness is more widely separated than ever in time from the last local discharge of spill water and from the last local glaciation. Just as with the site and borders of Lake Agassiz, glacial derangements of drainage can be seen to have no general bearing on the origin of underfit streams.

REGIONAL DISTRIBUTION AND A REGIONAL HYPOTHESIS

At the same time that the wide distribution of manifestly underfit streams in a given region conflicts with hypotheses of derangement, it supports the claim that underfitness need not always be manifest. Even where they are highly characteristic, meandering streams are rarely exclusive; but there is no purpose in contending that a stream, manifestly underfit in most of its length, ceases to be underfit in a single reach where either valley meanders or stream meanders are absent. If reaches upstream and downstream have been affected by a change in discharge, then the intermediate reach must have been similarly affected. Again, reaches are easy to locate where the present channel, meandering in the natural state, has been regularized, so that the combination of forms essential to manifest underfitness has been destroyed. Natural irregularities combine with artificial works to reduce the numbers of streams and the lengths of reaches which are manifestly underfit; distributional maps such as figure 11 tend to understate the facts.

Minor allowances for occasional reaches cause no difficulty. Regions such as eastern France demand a regional hypothesis, which cannot be other than climatic. But if a climatic hypothesis is adopted, then it becomes applicable wherever manifestly underfit streams are usual. An apparently obvious procedure is to map the distribution of manifestly underfit streams so that spatial limits can be fixed for the hypothesis of climatic change.

Practical difficulties arise here. One is that the task of distributional mapping is tedious and involves nothing more than the expenditure on routine work of time which could be more profitably spent otherwise. A second and related difficulty is that every gradation seems possible from regions where all streams are manifestly underfit to regions where none of the streams are underfit. It therefore becomes necessary to use some kind of index of manifest underfitness if regions are to be described as possessing streams that are mainly underfit. Such an index could, for example, express the total length of manifestly underfit reaches as a percentage of the total length of all streams. But, if a continuous range extends from total to zero underfitness, any such index could serve no purpose except that of description. For reasons which shortly will be obvious, no attempt has been made either to define or to apply an index of underfitness.

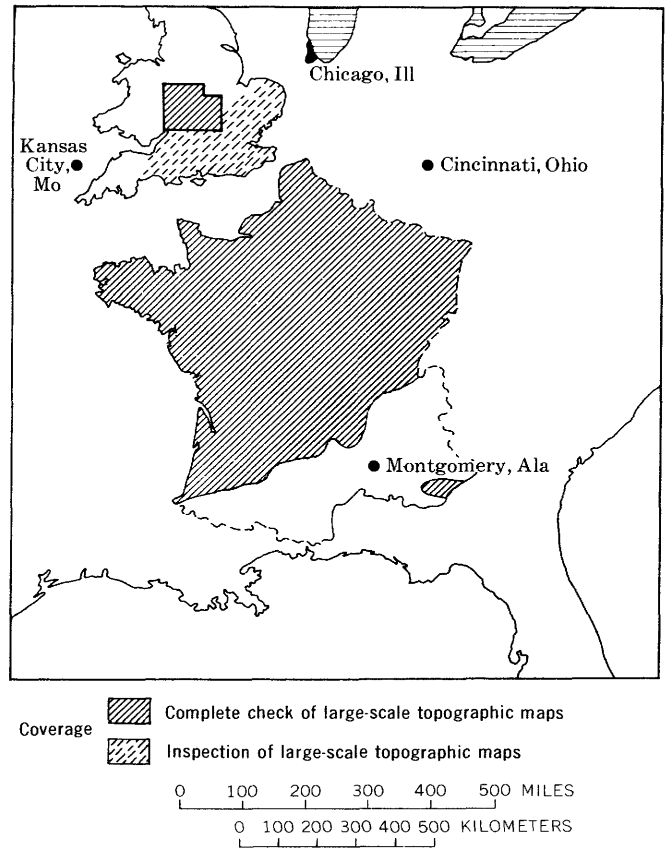


FIGURE 19.—Known areal extent of manifestly underfit streams in France and southeast England superimposed on comparable areas of the United States.

In western Europe, manifestly underfit streams are typical of large areas. In view of what has just been said about the use of an index, the word "typical" should perhaps be taken to signify that an estimated minimum of 50 percent of the total length of streams of the second and higher orders is manifestly underfit. Distributional maps (fig. 11 above; Dury, 1953d, fig. 2; Dury, 1954, fig. 2) give samples of the incidence in question. Topographical maps on scales ranging from 1:20,000 to 1:80,000 have been examined for the whole of France and for a large part of the English Plain; these maps reveal that manifest underfitness characterizes many reaches of many streams in an area that extends about 600 miles from north to south and 500 miles from west to east (fig. 19). These distances, which are roughly equal to the distances from Chicago, Ill., to Montgomery, Ala., and from Kansas City, Mo., to Cincinnati, Ohio, are thought sufficient to demonstrate that manifest underfitness in France and England can be explained only by a shift in climate.

A third practical difficulty arises when attempts are made to trace the distribution of manifestly underfit streams eastward across Europe and southward toward the Mediterranean. Whereas the German 1:25,000 map is excellently suited to record the relevant combination of forms, some other surveys do less well, either because they do not purport to represent the necessary fine detail of channel pattern or because their cartographic techniques do not permit such detail to be shown. Consequently, certain rivers can be identified as manifestly underfit, but proof that other rivers are not so may be impossible. In the United States, where topographic coverage on scales no smaller than 1:62,500 is incomplete, it also is impossible to deny—or to confirm—the regional development of manifestly underfit streams in considerable areas. Moreover, even where maps exist, they can be misleading.

On occasion the forms of valley meanders are misrepresented, and not merely because the interval and incidence of contours prove unhelpful. The valley of the Kickapoo River near Soldiers Grove, Wis., is by no means well shown by the 1:62,500 map (Gays Mills quadrangle, Wisconsin, surveyed 1923–24, published 1924). The topographic sheet indicates one clear left-hand swing of the flood plain at Soldiers Grove, a broad bowing to the right on the next 4 miles downstream, and a second left-hand swing at the confluence of Bear Creek. Aerial photographs reveal that low hills rising from the valley floor on the east side of the stream are the old cores of valley meanders, that the open lower end of the valley of Bear Creek is the curve of a valley meander, that the side of Mother Lot Point is the opposing scar next upstream, and that the succeeding left-hand scar occurs on the north flank of Bear Point (figs. 20, 21). In addition, the photographs show a large scar on the right of the stream, immediately west of Soldiers Grove; although this scar is suggested by the map, the large upstanding core in its center is omitted.

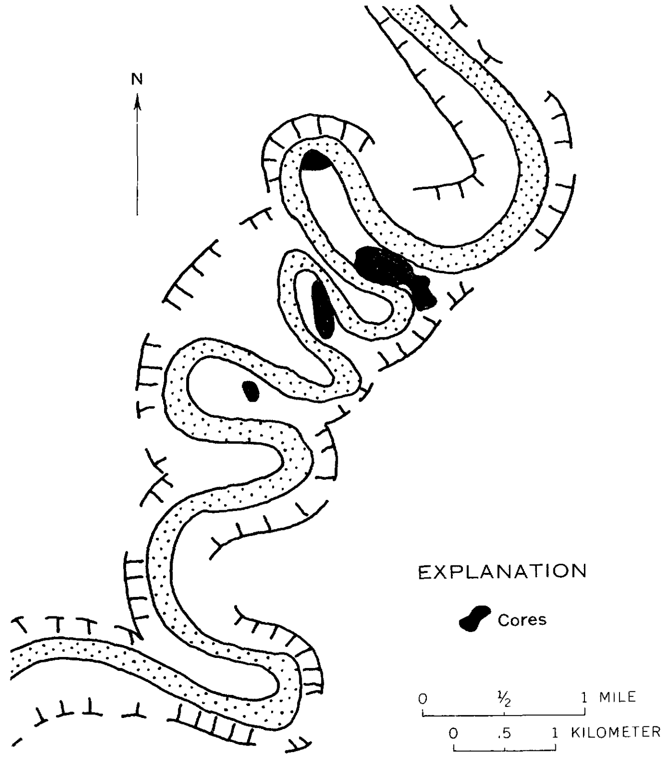


FIGURE 21.—Sketch of the Kickapoo River showing former meanders reconstructed from aerial photographs.

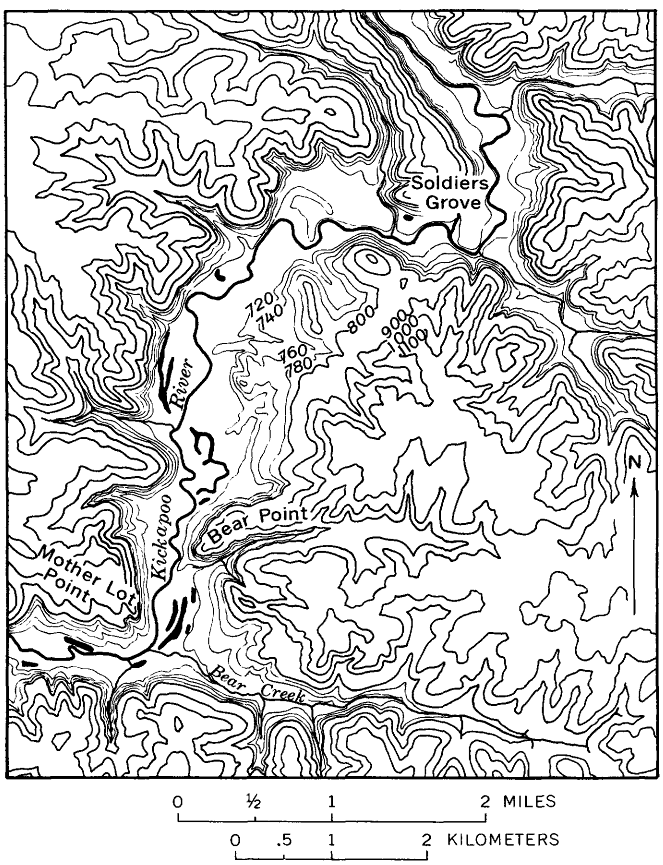


FIGURE 20.—Map of the Kickapoo River near Soldiers Grove, Wis.

Stream meanders seem most liable to omission or to misrepresentation. An example has already been given of streams on the emerged floor of Lake Whittlesey-Warren which are manifestly underfit on aerial photographs but have their present meanders obscured by the topographic sheets. Even where maps are drawn from aerial photographs, the trace of present channels is not invariably shown with great accuracy. Little streams can be wholly concealed by overhanging trees, and the fine detail of small rivers generally seems capable of becoming generalized in the process of cartography. In some localities, rivers cannot justly be identified as not manifestly underfit until their trace and the forms of the valley sides have been checked from aerial photographs and possibly also on the ground.

A further practical limitation to map evidence is that, in places, erosion has largely destroyed the forms of meandering valleys. Manifest underfitness cannot be ruled out, unless whole blocks of sheets are available for inspection. Many examples are possible. One may perhaps suffice to indicate how rapidly the form of the ground can change within a short distance.

The Delaware River of Kansas, which occupies a

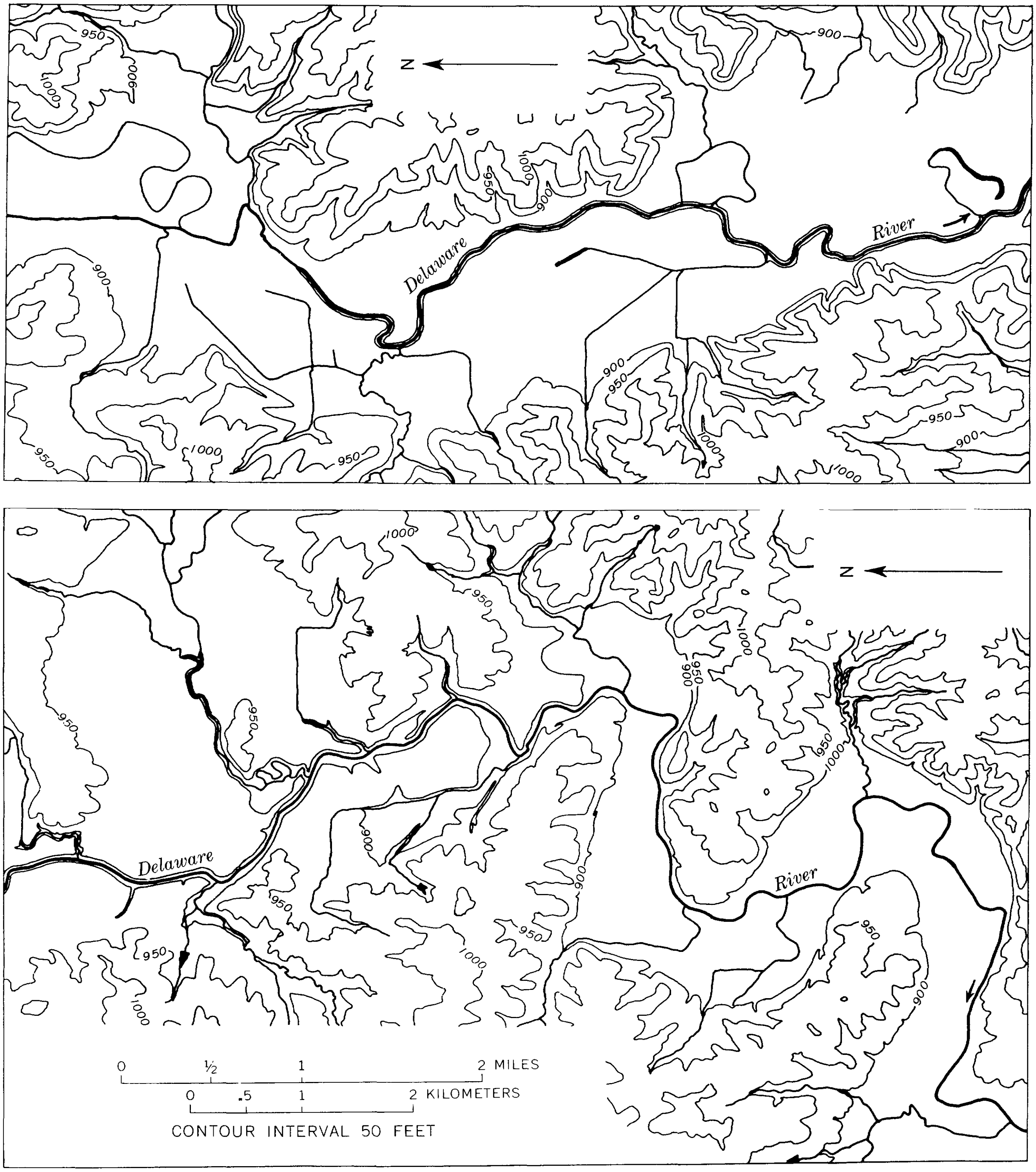


FIGURE 22.—Contrasted valley patterns on the Delaware River, Kans.

valley 65 miles long that trends from north-northwest to south-southeast, enters the Kansas River 15 miles downstream of Topeka, Kans. The valley makes an angle of some 45° with generalized outcrop boundaries; the river passes in the downstream direction onto progressively older rocks, heading in the Council Grove Group of the Permian System, traversing the outcrop of the Admire Group of the same age, and subsequently reaching rocks of the Wabaunsee and Shawnee Groups of the Virgil Series of the Pennsylvanian. (See, for outcrops, Kansas State Geol. Survey, 1937; for lithologic description, Moore and others, 1951.) Broad morphologic contrasts match the broad contrasts in rock strength.

Parts of the upper 25 miles of valley, which is incised into the Council Grove and Admire Groups and into the upper members of the Wabaunsee Group, combine valley meanders with meanders of the stream: the Delaware River is clearly underfit. In the 20 miles or so above Valley Falls, however, the valley widens, having a broad floor and gentle side slopes developed on the mainly shaly rocks of the lower part of the Wabaunsee succession. Valley bends, if present at all in this reach, are but vestigially preserved. Downstream from Valley Falls, resistant rocks reappear in the Shawnee Group and sustain steep walls which rise as much as 100 feet on the outsides of valley bends (fig. 22). The Valley Falls, Kans., quadrangle of the lower U.S. Geological Survey, 1:24,000 map, on part of which the panel of figure 22 is based, well illustrates the entry of the Delaware into a belt of outcrops where the rocks are, in the main, resistant. Near the actual entry, the 950-foot contour marks the bedrock core of a cutoff valley bend; but a little farther downstream, no very marked sweep has occurred; valley meanders are ingrown, but their intervening spurs are no more than trimmed.

Downstream again, however, resistant beds rise gradually above river level so that the valley bends are cut into increasing thicknesses of shale. The upper panel of figure 22, based on part of the Ozawkie quadrangle of the 1:24,000 map, illustrates the landforms formed in these conditions. A distance of 2 miles between the two reaches introduces a most striking alteration in the form of the valley. In this southern (downstream) reach, a number of curved recesses in the valley wall are scallops cut by the former large meanders, but the projecting spurs of the upstream reach are here replaced by the bluntest of cusps. The local rocks clearly offered little resistance to the free downstream sweep of the former large bends. Consequently, whereas the underfit character of the Delaware is manifest in one reach it would be obscure or dubious in the other if this second reach were considered in isolation.

This example returns the immediate argument to its starting point, that the absence of manifest underfitness from a particular reach is no obstacle to the claim that such underfitness can be a regional characteristic. Where manifestly underfit streams occur in widely separated regions, any climatic hypothesis invoked to explain them must be held to apply also to intervening regions. When all possible allowance is made for erosion, for the local breakdown of manifest underfitness, and for deficiencies of maps both in accuracy and coverage, it remains true that the streams of certain areas are not at all manifestly underfit or are but exceptionally so at the most. Consequently, a means must be sought for bringing rivers generally within the scope of underfitness and of climatic change.

CLIMATIC HYPOTHESIS AND UNDERFITNESS OTHER THAN MANIFEST

In conterminous United States, manifestly underfit streams have been identified in locations ranging from the Great Lakes to the gulf coast, and from the Pacific Northwest to the Atlantic coast (figs. 23, 24). The distribution shown in the figures is by no means complete. It is presented merely to emphasize that any hypothesis of climatic change invoked to explain underfitness should apply to most of the country, if not indeed to the whole. Manifestly underfit streams, however, are far less common in the United States than in France or on the English Plain. Examples described in this section will be of combination 2 of figure 4—that is, of nonmeandering streams in meandering valleys.

Hitherto, with manifestly underfit streams taken as the stereotype—indeed, with most writers, as the only type—it has been possible to regard nonmeandering streams in meandering valleys as evidence for hypertrophy of stream meanders; for the influence of structure, lithology, and crustal movement; and for the absence of underfitness. The examples described here are meant to show that some rivers in meandering valleys devoid of stream meanders are underfit. The corollary inference is that, within the limits of distribution of underfit streams in general, all streams in meandering valleys may be underfit, even though they display but one series of bends. Although underfitness cannot be demonstrated unless bed form is known, comparative measurements of bed width and of wavelength (wavelength of valley meanders) give strong general support to the corollary stated. The observations and conclusions presented here are considered to shift the onus of proof. The underfitness of streams in incised meandering valleys can no longer be denied, either ex-

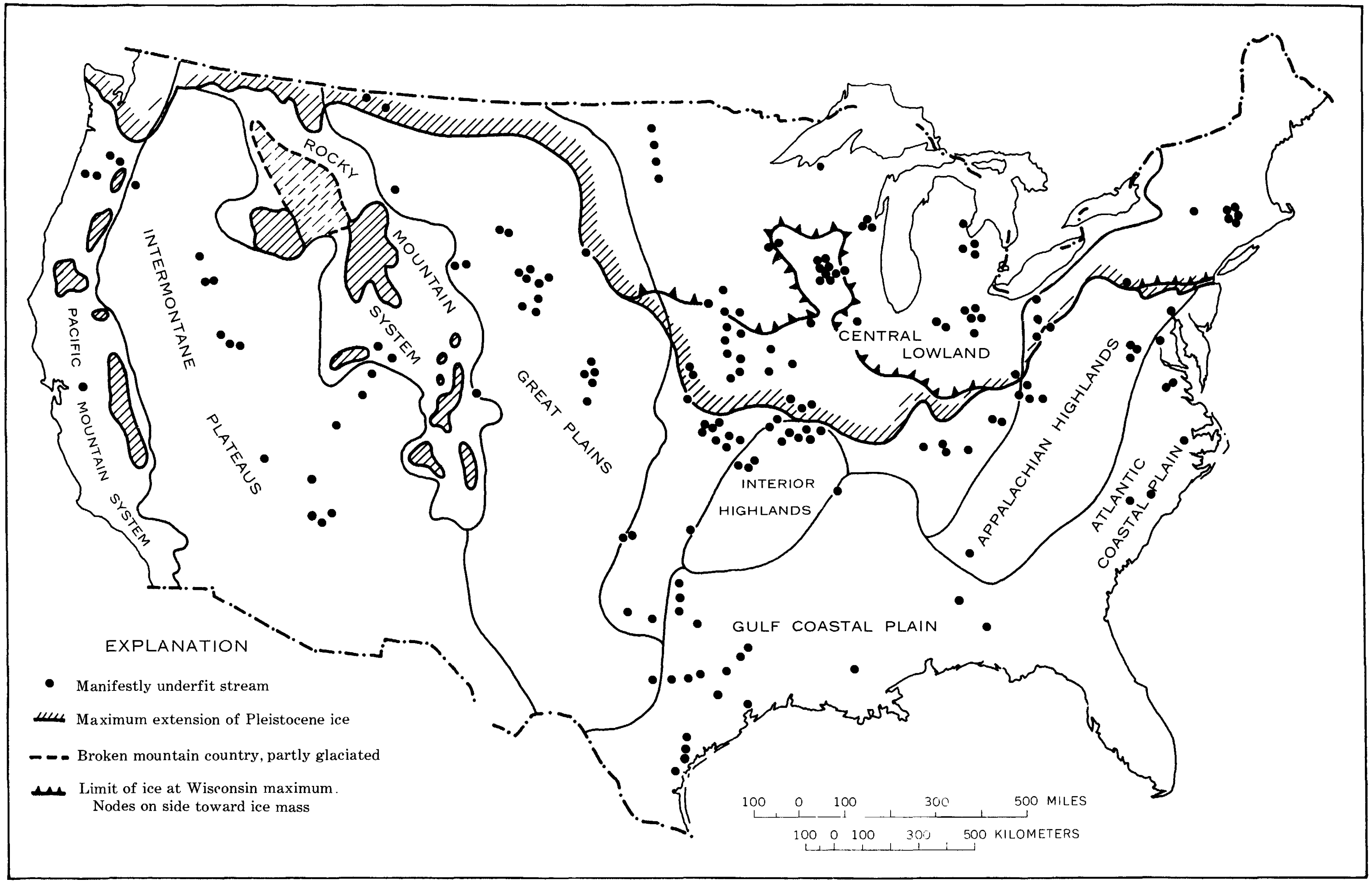
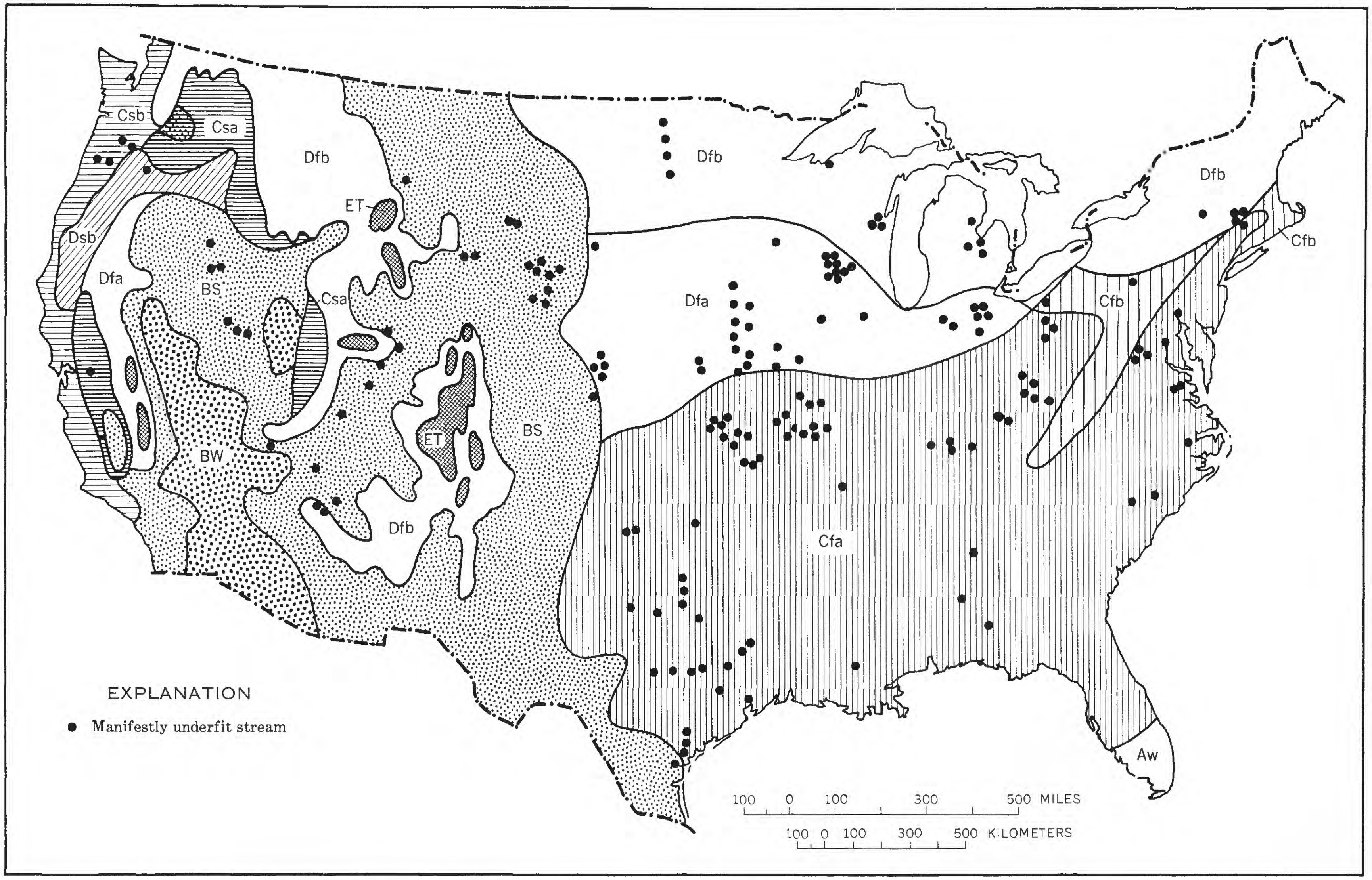


FIGURE 23.—Map of conterminous United States showing areal range of manifestly underfit streams in relation to physical subdivision.



AW, tropical rainy, with dry low-sun season.
BW, arid.
BS, semiarid.
Cfa, warm temperate rainy, with no dry season and hot summer.
Cfb, warm temperate rainy, with no dry season and cool summer.
Csa, warm temperate rainy, with hot dry summer.
Csb, warm temperate rainy, with dry cool summer.
Dfa, cold snowy, with no dry season and hot summer.
Dfb, cold snowy, with no dry season and cool summer.
Dsb, cold snowy, with cool dry summer.
ET, tundra.

FIGURE 24.—Map of conterminous United States showing areal range of manifestly underfit streams in relation to climatic subdivisions. After Köppen (1931).

plicitly or by implicit assumption, unless some kind of disproof be attempted. If, on the other hand, the present thesis is correct, then incised winding valleys containing streams not manifestly underfit cease to conflict with the hypothesis that underfitness is common throughout large areas.

The basic principles concerned are two: that wavelength of meanders is causally related to bed width of stream, and that meandering begins not with swinging of the channel in plan but with deformation of the bed in the vertical plane. The first principle is considered to be sustained by the quantitative data supplied by Leopold and Wolman (1960) and by the theoretical analysis of Bagnold (1960). The second was stated by C. M. White (1939), who, summarizing the results of laboratory study up to that time, wrote "two distinct stages can be recognized, one in which the bed controls the banks, and another in which the banks control the bed, as in fully developed meander in nature." Subsequent work has shown that, in nature as in the laboratory, a sequence of pools and riffles can occur in straight channels, and that their spacing is appropriate to a meandering habit. Appropriateness of spacing amounts to a distance from one pool, or one riffle, to the next of about 5 times the bed width, corresponding to a distance of 10 times the bed width for a whole wavelength. But as rhythmic deformation of the bed can be associated with braiding and with straight single channels in addition to meandering, such deformation does not always mean that a channel is in the process of developing meanders (Leopold and Wolman, 1957, p. 53–57). At the same time, if rhythmic deformation occurs and if its interval can be shown appropriate to stream meanders as opposed to valley meanders, then large incised bends can be dissociated from nonmeandering streams contained in them. If these were simple incised meanders cut by the rivers which now flow round them, one series of pools ought to occur near the extremities of bends, and one series of riffles near the inflections between bends. If, however, pools and riffles are more closely spaced than is required by the wavelength of valley meanders and if, in addition, the channel is narrower than would be expected from the approximate 10:1 ratio of wavelength to bed width, then nonmeandering streams can be identified within meandering valleys. Braided courses of present streams present no difficulty of recognition; single nonmeandering channels, on the other hand, require bed form to be studied. Equally, however, their presence cannot be denied unless pools and riffles are demonstrated to be spaced in relation not to the channel of the present stream but to the bends of the valley. In the examples now to be described, spacing is appropriate not to valleys but to streams.

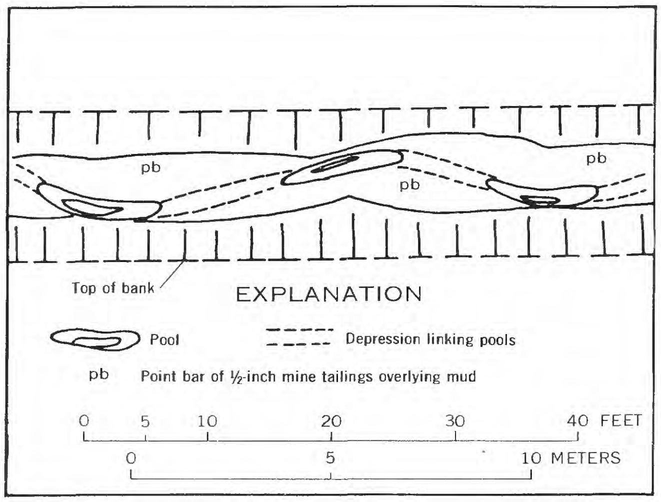


FIGURE 26.—Sketch of ditch shown in figure 25.

FIGURE 25.—View of drainage ditch of Eagle-Pitcher mine near Shullsburg, Wis. See figure 26 for sketch of ditch.

MEANDERING TENDENCY OF A DRAINAGE DITCH

An instance which seems to illustrate an actual tendency to meander on the part of a straight stream is that of the ditch at the Eagle-Pitcher Co.'s mine near Shullsburg, Wis. The ditch was cut through a thin layer of tailings and through topsoil into Maquoketa Shale of Ordovician age; the ditch is about 8 feet deep, and its width decreases from about 12 feet at the top to 4 feet at the bottom. Water pumped from the mine since 1952 ran along the ditch into settling pits. In 1960 the lower end of the ditch was blocked off. The dry bed of the lower reach was formed into pools and riffles (figs. 25, 26), which alternated along the sides of the cut and were associated with faint scalloping of the sides. Comparison with the still-flowing stream in the upper reach suggested a bed width of about 5 feet—that is, one-eighth the length of the single wavelength indicated in figure 26. If the riffles were bulky enough and high enough to reduce the width, then the wavelength and width ratio was greater than 8:1; but even at that value, it is within the range observed on natural meandering streams (Leopold and Wolman, 1960). Strong deformation of the bed, contrasting with very slight development of meander scars, suggests that a meandering tendency may by no means be reflected in the channel pattern.

CREEKS IN IOWA

In many parts of the till plains of Iowa, valley meanders are better developed than are stream meanders. The distinction between the two series can in fact be obscured by the poor development of stream meanders. Reaches of Sugar Creek (Cedar County) and of McDonald Creek (Scott County) were among the sites observed, all of which showed that where the stream is mapped as not meandering on a valley bend, the bed is deformed at shorter intervals than those set by the curves of the valley.

Sugar Creek, in T. 79 N., R. 2 W., secs. 15 and 22, is incised about 75 feet below the general level of the surrounding terrain. Although its channel as shown on the topographic map (Lime City quadrangle, Iowa, 1:24,000) does not curve smoothly round the valley bends, there is no continuous train of present meanders (fig. 27). However, as the annotations in figure 27 show, the channel on the long north-south limb of a valley bend is by no means regular in form. Although the survey does not justify a claim that the deformation is rhythmic, the presence of lumplike islets in midstream suggests that this reach of streambed is influ-

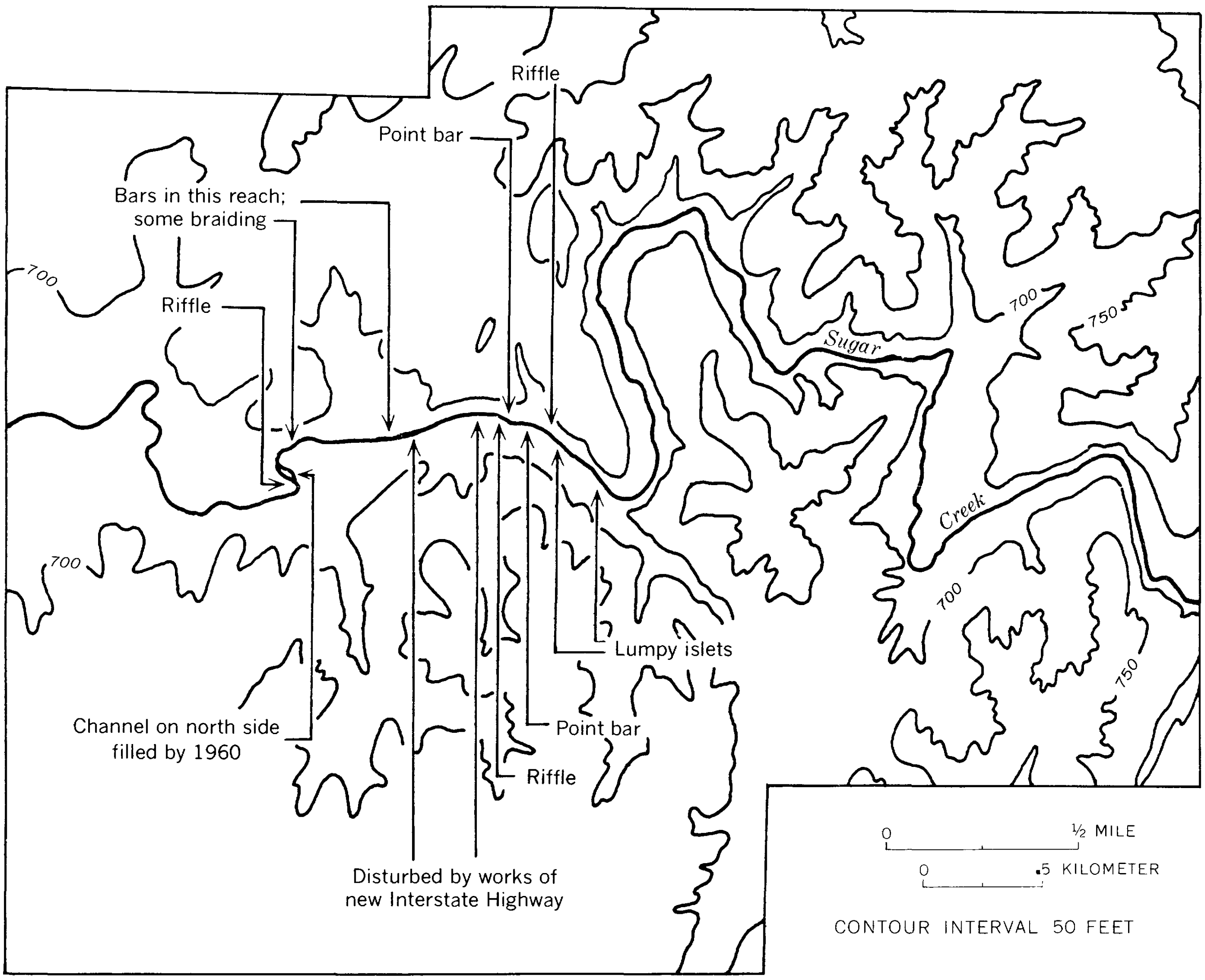


FIGURE 27.—Map of part of Sugar Creek, Cedar County, Iowa.

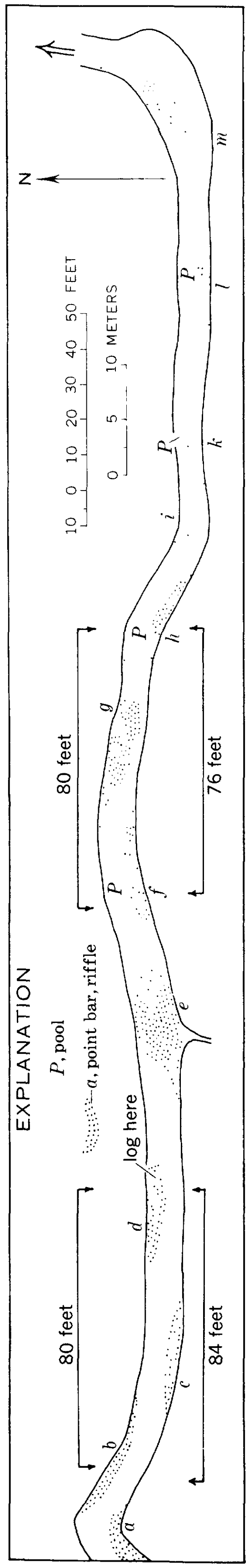


FIGURE 28.—Sketch of part of McDonald Creek, Scott County, Iowa. Letter symbols explained in text.

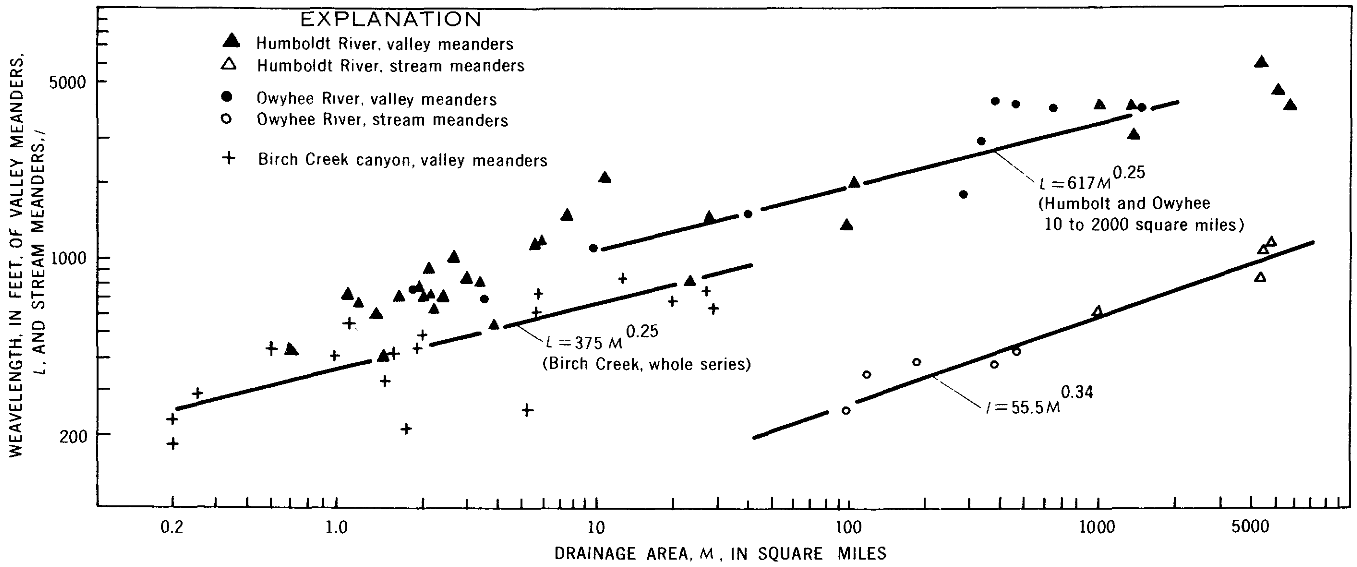


Figure 29.—Graph showing relation of wavelength to drainage area of the Humboldt and Owyhee Rivers and Birch Creek.

enced by factors additional to the curvature round valley bends.

McDonald Creek (Eldbridge quadrangles, Iowa, 1:24,000, T. 80 N., R. 3 E., sec. 24) was traversed along the west-east limb of a valley bend, with the results shown in figure 28. Although the channel is not sinuous in this reach, the bars are distributed according to a rough system. Bars *a* through *d* and *f* through *i* seem to display a true alternation; they permit the measurement of four wavelengths, as shown in figure 28, which average 80 feet—that is, about eight times the bed width.

HUMBOLDT RIVER, NEV.

The Humboldt River, Nev., which cuts from place to place through upstanding blocks of hills, is excellently adapted to illustrate the contrast between stream meanders and valley meanders, even though the two rarely occur on a single reach. On the open floors of basins, long reaches of the Humboldt meander considerably, with bends about 10 times as long as the channel is wide. Where the river enters a canyon, however, apparent wavelength suddenly increases (fig. 29). The streams curve round valley meanders, wherein stream meanders are unusual. The distinction of magnitude between the two series is well displayed by the regional graph (fig. 29), but separation of the two series from one another does not in itself dispose of the hypothesis that the large meanders are in some way a response to cutting into bedrock. When the present channels are inspected, however, they are found to contain pools and riffles much more closely spaced than the bends and inflection of the canyons. Such is true for the South Fork of the Humboldt where it trenches across the end of Grindstone Mountain, 8 miles southwest of Elko, Nev. (Dixie Flats quadrangle, Nevada, 1:62,500; fig. 30). Both upstream and downstream from the canyon, the river describes meanders of the size expectable from its bed width. Within the canyon, the stream is certainly braided in part, although any systematic qualities which its bed form may display cannot be detected without instrumental survey.

In Carlin Canyon, 6 miles east of Carlin, Nev., the trunk Humboldt is in places somewhat confined by highway and railroad embankments (Carlin quadrangle, Nevada, 1:62,500). Nevertheless, braiding can be observed to set in at the approaches to the canyon and to occur in places within it, whereas a meandering habit is resumed farther downstream (fig. 31). In the next succeeding canyon, Palisades Canyon, wherein the stream is much compressed by the railroad embankments, braiding again occurs near the entry of Pine Creek, where the railroads cut through a lobe of rock and the channel is unconfined. The two intervals in a succession of three braids average about one-fifth of the mean wavelength of valley bends in this reach of canyon. Toward the downstream end, a section through the local valley fill was provided in 1960 by the strip mine near Barth (Beowawe quadrangle, Nevada, 1:62,500). Gravelly alluvium was seen to extend at least 35 feet below the river bed, opposite the mouth of the lateral Safford Canyon. Before mining caused the Humboldt to be diverted, the river had a strong tendency in this reach to form meanders, as is suggested by the topographic sheet and clearly displayed on the ground. One possible inference, shortly to be confirmed by observations on the Shenandoah, is that out-

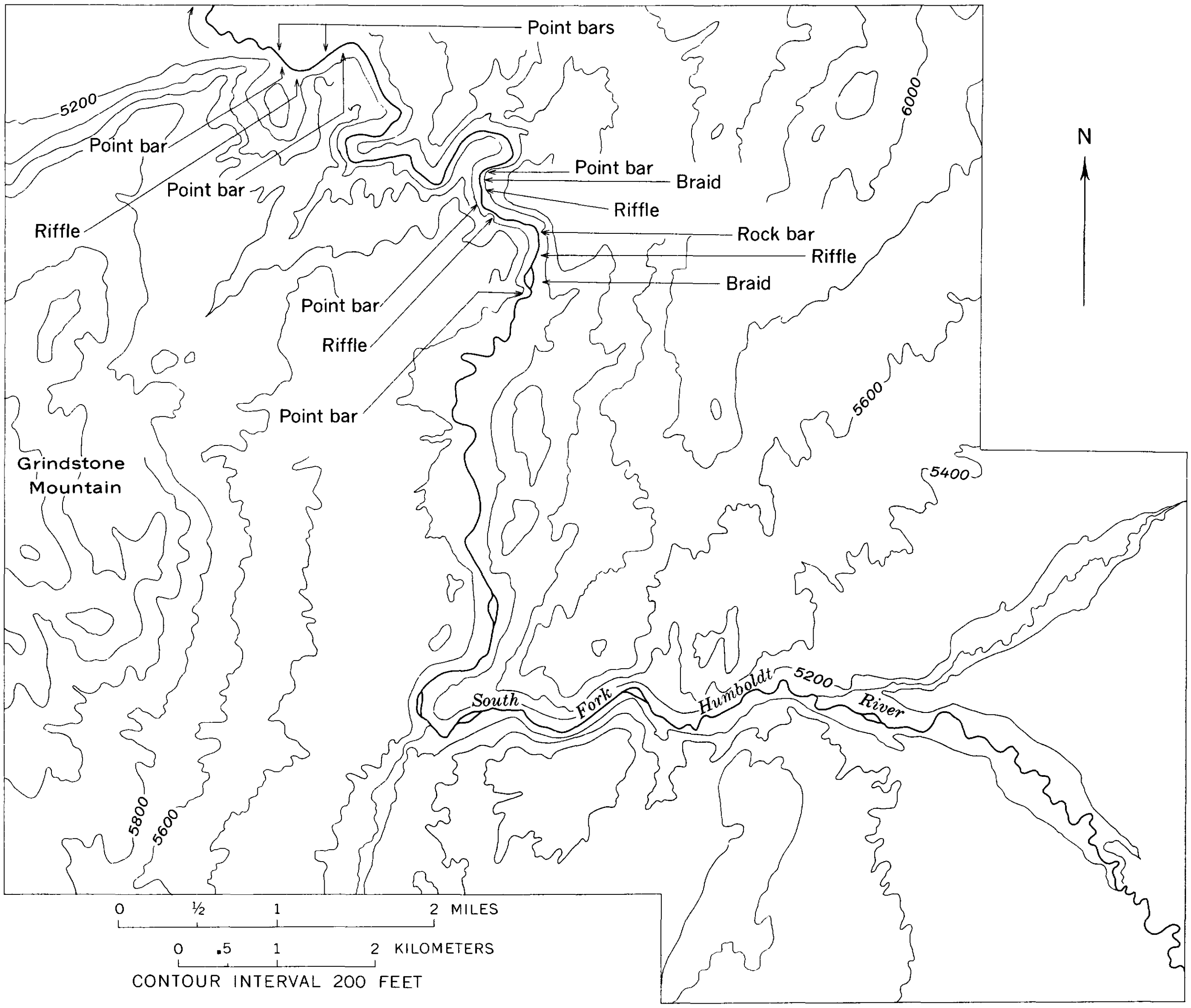


FIGURE 30.—Map of part of the South Fork of the Humboldt River near Carlin, Nev.

cropping bedrock in some way inhibits the development of stream meanders; but this inference should be treated with reserve, as will be explained.

SHENANDOAH RIVER, VIRGINIA

In large part, the Shenandoah River flows in great incised bends. Similar bends occur on a number of its laterals, although they seem more liable to distortion by structural influences than are those of the trunk stream. Two of the most regular trains, respectively on the North and South Forks of the Shenandoah, occur in the area represented by the Strasburg (Virginia) quadrangle of the U.S. Geological Survey 1:62,500 map. Here, as on the Conodoguinet (Strahler, 1946), some bends are much ingrown: the amplitude of the meander trains has increased, without an accompanying change in wavelength, even where three spurs have been breached in the several miles of valley on the North Fork above Strasburg.

Although each of the two forks describes but one series of bends, these are valley meanders. They seem to illustrate with especial clarity the habit assumed by a meandering river, already incised into bedrock, when its channel-forming discharge is reduced. Stream meanders simply are not present. The two forks have been reduced in width, and presumably also in depth, and now display characteristics typical of some groups of straight channels. As Hack and Young (1959, p. 7) observed for the North Fork, crossovers occur not only on the bends but also in the straight reaches.

Although, however, the two forks in most of their length display but one series of bends, most of their laterals have two. Stream meanders in combination with valley meanders are well seen in the field on Toms Brook, which enters the North Fork on the left, 5 airline miles upstream of Strasburg; stream meanders are incipiently developed on the North Fork itself in the area represented on the Mount Jackson (Virginia) quadrangle of the 1:62,500 map; and valley meanders are combined with stream meanders on Smith Creek, which joins North Fork just above Mount Jackson (fig. 32). The Mount Jackson and Strasburg quadrangles provide numerous instances of the way in which standard topographic maps omit fine detail of stream course—detail

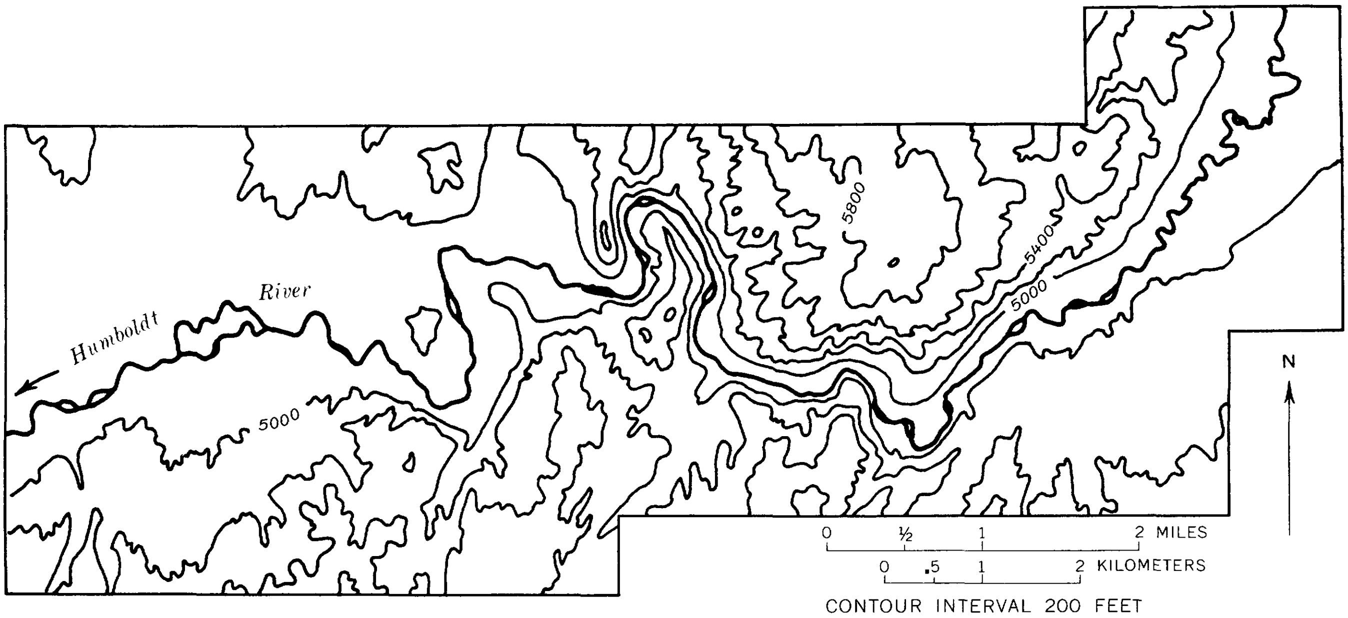


FIGURE 31.—Map of part of the Humboldt River, including Carlin Canyon, near Carlin, Nev.

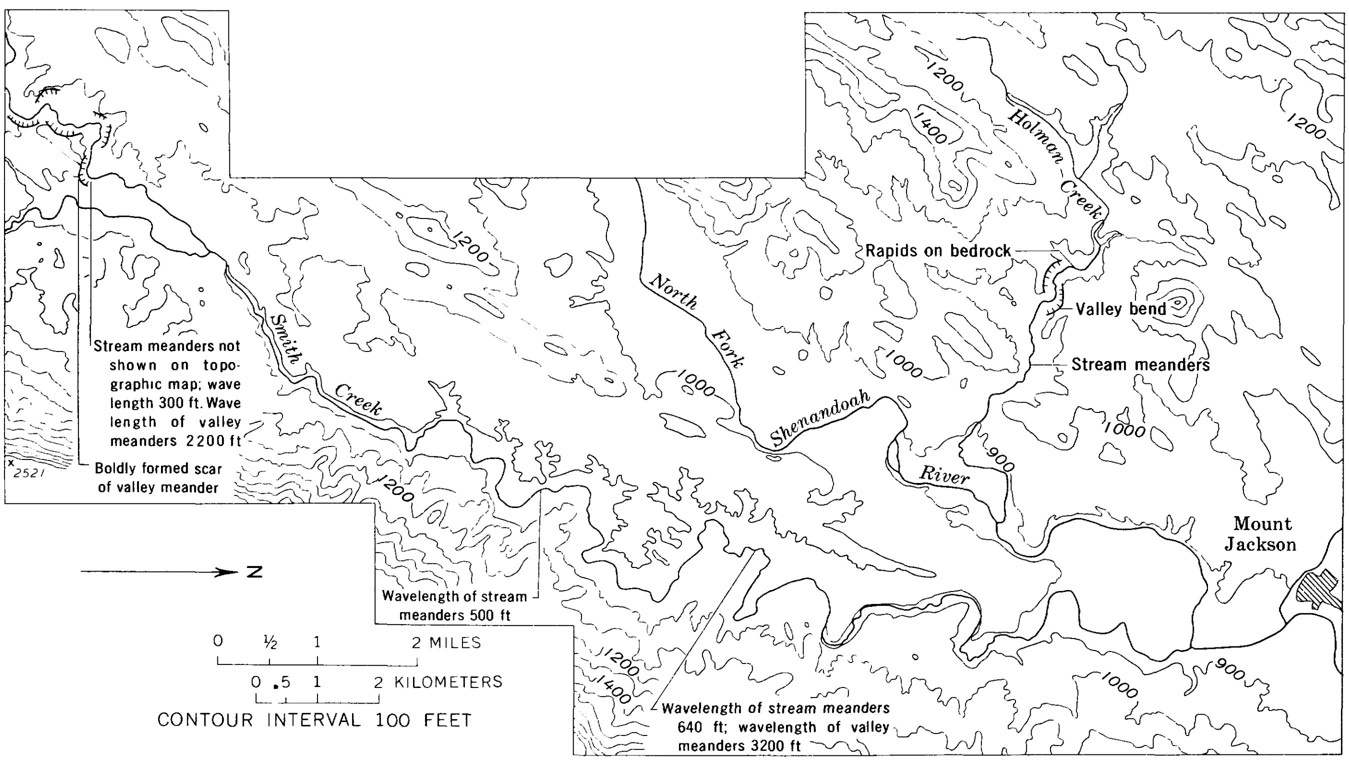


FIGURE 32.—Map of part of the North Fork of the Shenandoah River near Mount Jackson, Va.

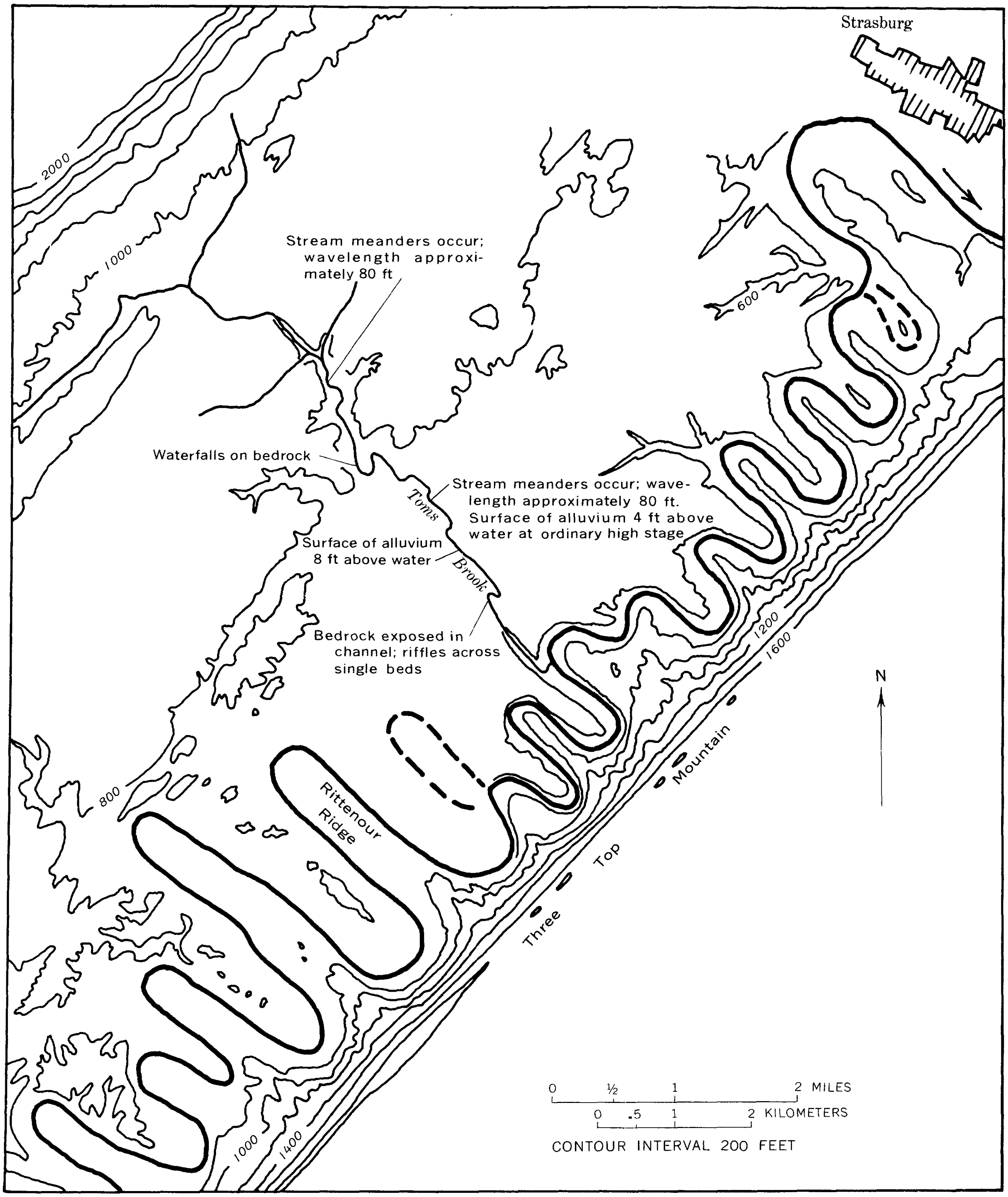


FIGURE 33.—Map of part of the North Fork of the Shenandoah River near Strasburg, Va.

which is highly relevant to the present inquiry. The main fork of Smith Creek, southwest of the Mount Jackson quadrangle, possesses actual stream meanders in addition to the valley meanders which are alone indicated by the map, as also does Holman Creek in a reach $3\frac{1}{2}$ miles southwest of Mount Jackson; even on lower Smith Creek, the actual meanders of the stream are more boldly formed than the map suggests. None of the present meanders of Toms Brook (fig. 33) are recorded on the Strasburg quadrangle. Instances of this kind could be multiplied in great number; there is no doubt that stream meanders are more common on streams of modest size than the maps show. That is to say, manifestly underfit streams are far more numerous in the Shenandoah River basin than can be demonstrated without the aid of field inspection or of large-scale aerial photographs.

Although few data of wavelength of present meanders have been collected, it is clear from the observations made that the large incised bends belong to the local family of valley meanders. At the mark of 100 square miles, the valley bends seem to be about five times as long as present meanders—that is, the relevant members of the Shenandoah system have been affected in similar proportion to streams in certain other regions. In this way, the immediate problem reduces itself to one of explaining why the North and South Forks fail to possess stream meanders for much of their length.

For about a mile upstream from its confluence with the North Fork, Toms Brook does not now meander. As with other laterals of comparable size, the lowest reach has been quite strongly rejuvenated. The channel is cut in bedrock; single resistant beds crop out as bars in the channel, which is shallow in proportion to its width at medium-high stages and which, if not regular in cross section, is at least patternless. One and one-half miles above the confluence, however, the valley floor is lined with alluvium, wherein stream meanders are developed. One mile upstream again, the Toms Brook falls over a group of resistant beds; but half a mile above the fall the valley floor widens for the second time in a strip of alluvium, and stream meanders occur. As valley bends complete with valley-meander scars typify all this part of the valley, Toms Brook combines a complete train of valley meanders with discontinuous trains of present meanders. The interpretation is not that the valley bends are ordinary meanders enlarged under the control of bedrock but that Toms Brook cannot develop, or has not yet had time to develop, present meanders where its channel is formed not in alluvium but in solid rock in place.

That part of the South Fork represented on the Strasburg quadrangle is broken by numerous riffles. The stream crosses and recrosses outcrop boundaries, or single resistant beds, and is in contact with bedrock along the whole base of its channel. This channel does not meander. However, the river is by no means everywhere in contact with bedrock at the channel side; it does not press vigorously against the valley-meander scars as it presumably did when these were being eroded. The North Fork, similarly, although incised into the Martinsburg Shale of Ordovician age, reaches limestone in places. Not all the resulting shallows and bars appear on the topographic map. On the upstream side of Rittenour Ridge, the spur 8 miles southwest of Strasburg, only one set of rapids is marked; but in actuality a second bar, prominent enough to reduce the water depth to some 3 feet at normal high spring stage and to make the water surface choppy, occurs half a mile above. Like the South Fork, the North Fork appears to have retreated from a number of its spurs.

On both forks, the present stream width is disproportionately small in relation to wavelengths of the valley bends; sample measurements give the ratio $L:w$ as 47 on the South Fork and 48 on the North Fork. This second result is at variance with the findings of Hack and Young (1959) but accords with observations on numerous other streams of similar type. On the principle that ratio of length and width should normally be about 10:1, the valley bends of the Shenandoah seem to be some 4.75 times too large for the channel, a value close to the approximate 5:1 reduction of wavelength on manifestly underfit members of this river system.

OZARKS AND SALT AND CUIVRE RIVER BASINS, MISSOURI

The northeast Ozarks exemplify meandering valleys with bends distorted in many places and present streams on which meanders are unusual but not absent. The Osage River seems capable of representing the type of stream which, although not now meandering, is enclosed in valley bends and possesses a well-defined sequence of pools and riffles.

On the Meramec River, just east of Pacific (St. Louis County, Mo., Pacific quadrangle, 1:24,000), occurs a fine cutoff valley bend, with its core rising about 170 feet above the flood plain (fig. 34). Meanders of the present channel, supplemented by the recent cutoff traced by the county boundary and by the abandoned scars and channels reflected in the contours, make clear the disparity of wavelength between valley and stream. The 10-foot contours on the topographic sheet permit a likely measurement of bed width between bank tops at a generous figure, 400 feet. As the mean wavelength of valley meanders on this reach of the Meramec is about 11,500 feet, a stream of the present size could not have been responsible for the large bends unless it pos-

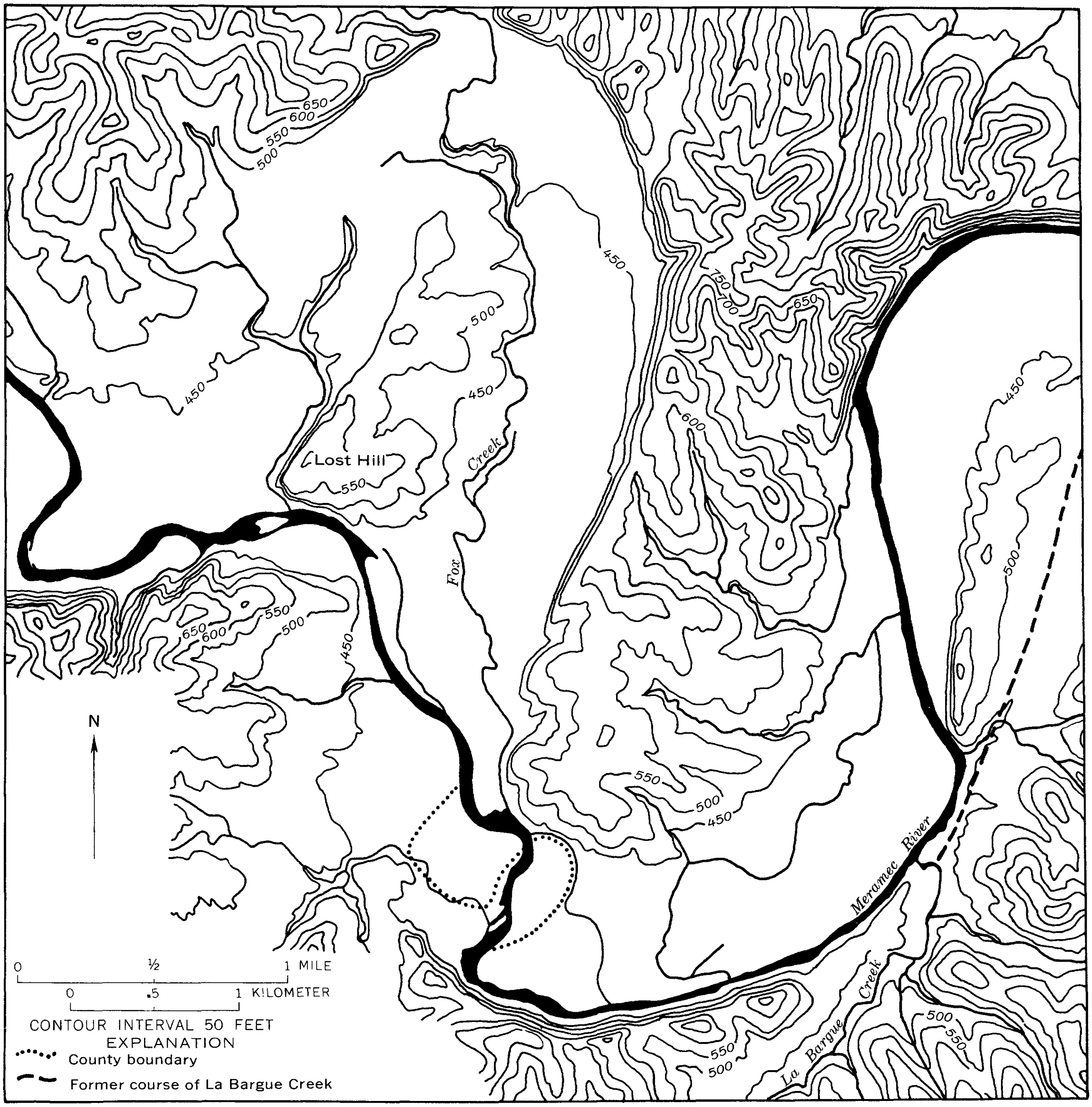


FIGURE 34.—Map of the Meramec River near Pacific, Mo., showing incised valley meanders.

sessed a wavelength and width ratio of at least 30:1. But as river meanders are actually present, there is no need to postulate a ratio of this order. On the contrary, the ratio of 30:1 between wavelength of valley meanders and bed width of present stream can reasonably be used to support the inference that the stream has been reduced in width since the valley bends were cut—that is, that it is underfit.

An alternative view which is urged from time to time is that valley bends are cut by high floods. In actuality, field observation shows that quite exceptionally high floods do not erode the valley walls except where the present channel impinges on them. In May 1961, the rivers of the northeast Ozarks rose 20 feet or more above normal, deeply inundating their flood plains; but the floodwater neither shifted the alluvium in the valley bottoms nor scoured the bases of the valley walls. So much was evident on the ground at the time and is recorded in photographs where trees and brush, rooted in the flood plains or at the outside edges of bends, are seen still in place (figs. 35, 36). In any event, downstream velocities in water which inundates a flood plain are typically low. The fact of evulsion can be admitted without implying any concession of general scour. Accordingly, no hypothesis of erosion by floodwater can be used to bring the ratio between wavelength of valley meanders and bed width of present streams down to the value of wavelength and width ratios appropriate to streams alone.

FIGURE 35.—Aerial view of the Gasconade River, Mo., in flood, May 1961.

FIGURE 36.—Ground view of the Gasconade River in flood, May 1961.

On the Gasconade River near Rich Fountain (Washington County, Mo., Linn quadrangle, 1:62,500) is a cutoff valley bend with an exceptionally bulky core (fig. 37). Although a certain ingrowth is indicated by the contours, the steep sides of the core testify to downcutting rather than to lateral enlargement during the period recorded by existing landforms. The markedly irregular valley meanders of this whole area suggest, however, that the influence of bedrock has been strong. Meanders on the present stream are little if at all developed on this reach of the Gasconade but can be identified about 5 miles upstream.

Near their confluence in Jackson County, Mo. (Florida quadrangle, 1:62,500) the Middle and Elk Forks of the Salt River possess stream meanders well-enough developed to permit reliable averaging of wavelength: exceptionally for this region, a continuous train of four meanders occurs on Elk Fork (fig. 38). Immediately upstream from the confluence, Salt Fork has withdrawn from the outer curve of a large left-hand bend, which appears to be devoid of core. A similar site lies 3½ miles downvalley. At both sites, the river seems to have undergone rapid lateral development after it was already well incised; this is in direct contrast to the behavior of the Gasconade near Rich Fountain.

The Bourbeuse and the Meramec, at short distances above their confluence 1 mile northeast of Moselle (Central County, Mo.; St. Clair quadrangle, 1:62,500), possess highly distorted valley bends (figs. 39, 40).

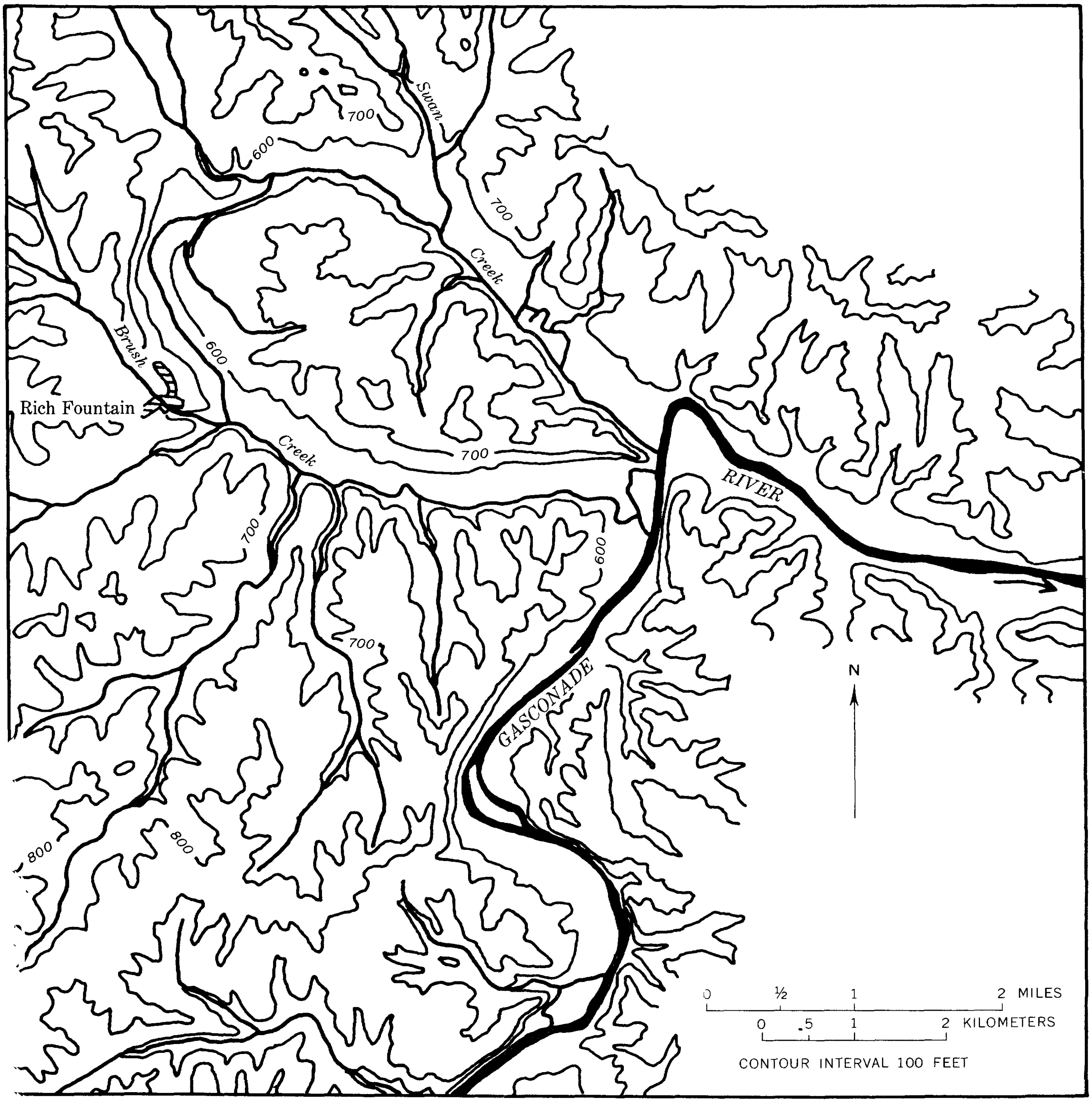


FIGURE 37.—Map of the Gasconade River south of Linn, Mo., showing cutoff valley bend.

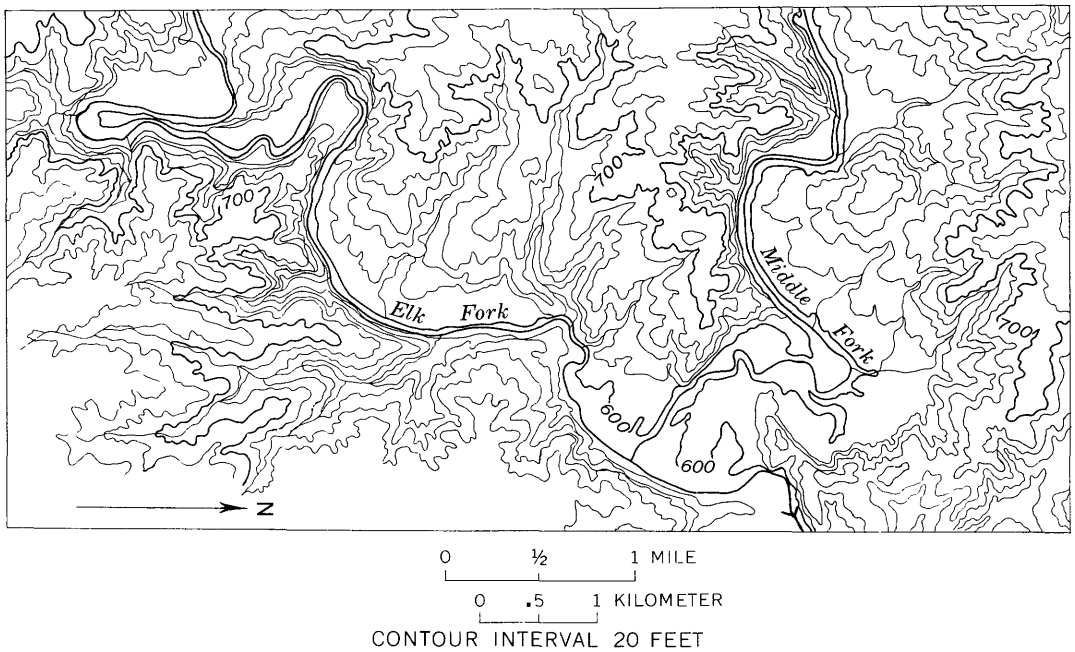


FIGURE 38.—Map of parts of the Elk and Middle Forks of the Salt River, Mo.

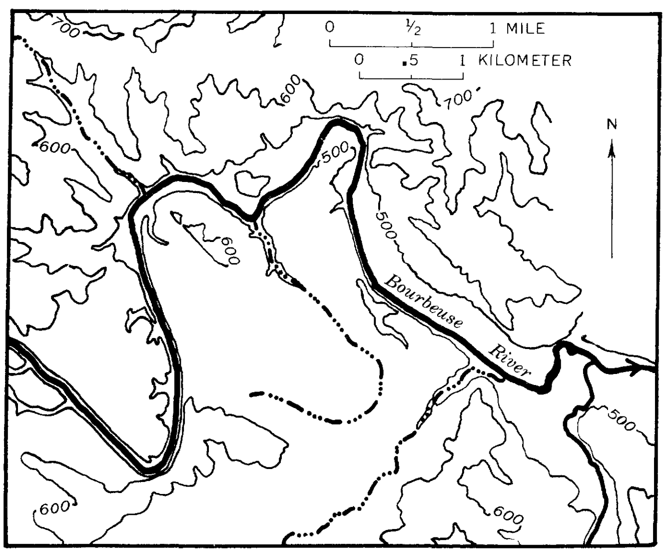


FIGURE 39.—Map of part of the Bourbeuse River, Mo.

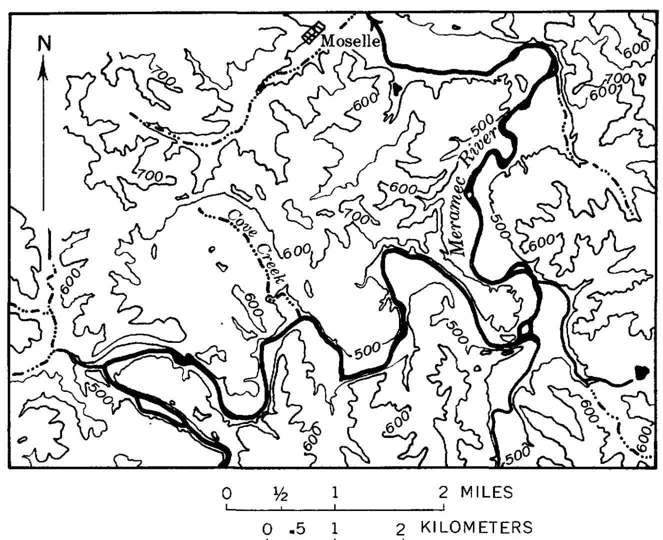


FIGURE 40.—Map of part of the Meramec River, Mo.

Measurements of wavelength are dubious here. Distortion does not, however, altogether obscure the trimming and undercutting which result from downstream sweep and from ingrowth. The present channels display a certain tendency to wind, and the Meramec has unmistakable stream meanders both upstream and downstream from the illustrated reach.

Because stream meanders are uncommon and because valley meanders are usually distorted, concurrent values of wavelength in the two series are difficult to obtain and give a considerable scatter when plotted (fig. 41; table 2). Nevertheless, plots can be obtained. They suggest a downstream decrease from 8 : 1 to 4 : 1 in the wavelength ratio between valleys and streams, within the limits of observation for the northeast Ozarks, and corresponding values of 7.5 : 1 to 3.5 : 1 for the Cuivre and Salt Rivers. In both areas, the wavelength ratio ranges upward to values typical of regions where streams are highly and manifestly underfit—the Driftless Area of Wisconsin and the Cotswolds of England. A regional average value of 5 : 1 seems reasonable. But although the two series of meanders can be distinguished one from the the other, it remains true that in many reaches of many valleys, the rivers of the northeast Ozarks and the Cuivre and Salt Rivers are far from being manifestly underfit. Their underfit condition can be identified in plan only with difficulty.

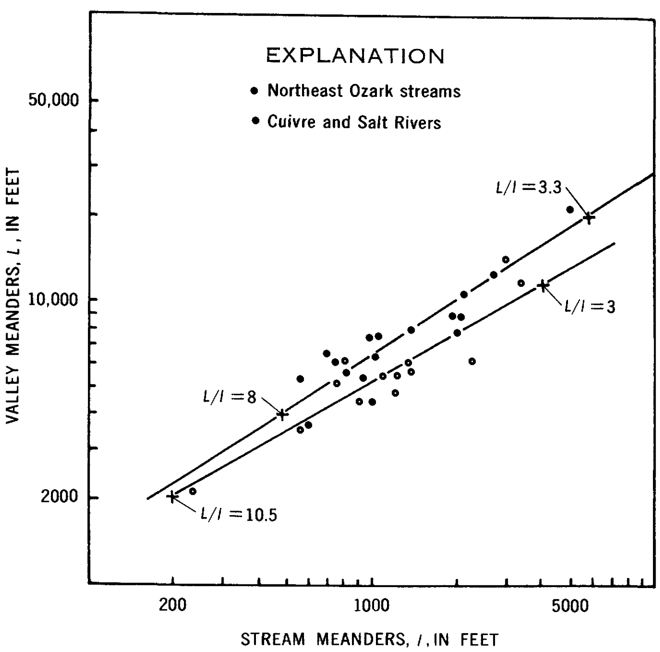


FIGURE 41.—Graph showing comparative wavelengths of streams in the northeast Ozarks and of the Salt and Cuivre Rivers.

TABLE 2.—*Comparative wavelengths of valley meanders and stream meanders on individual reaches of rivers in the northeast Ozarks and on the Salt and Cuivre Rivers*

[Entries are listed in order of wavelength of valley meanders]

	Valley meanders		Stream meanders	
	Number of meanders	Mean wave length, in feet	Number of meanders	Mean wave length, in feet
Northeast Ozarks				
Gasconade River	3	22, 000	4	5, 000
Meramec River	3	12, 300	3	2, 740
Big River	2	10, 550	4	2, 125
Do	3	9, 000	5	2, 000
Big Piney River	3	8, 825	5	2, 100
Bourbeuse River	4	8, 000	6	1, 400
Meramec River	4	7, 700	4	2, 000
Do	4	7, 500	6	1, 030
Dry Fork River	3	7, 500	5	1, 000
Do	2	6, 750	5	700
Big Piney River	3	6, 350	4	1, 025
Meramec River	3	6, 200	8	750
Roubidoux Creek	3	5, 600	3	(?) 835
Little Piney Creek	3	5, 400	5	(?) 560
Dry Fork River	4	5, 400	6	930
Do	4	3, 700	8	600
Salt and Cuivre Rivers				
Salt River	4	14, 250	5	2, 900
Cuivre River	1	11, 900	4	3, 300
West Fork Cuivre River	4	6, 200	5	800
North Fork Cuivre River	3	6, 175	5	2, 270
Elk Fork Salt River	2	6, 000	5	750
Do	3	6, 000	5	1, 350
North Fork Cuivre River	4	5, 755	5	1, 350
Middle Fork Salt River	4	5, 500	4	1, 250
Big Creek	2	5, 400	5	1, 100
Cuivre River	3	5, 125	5	750
South Fork Salt River	5	4, 725	5	1, 200
Do	3	4, 425	5	1, 000
Salt River	3	4, 400	5	900
Do	3	3, 600	6	560
Briar Creek	4	2, 125	5	230

On long reaches of the Osage River, all signs of a presently meandering trace appear to be absent.[4] The ingrown valley meanders of the Osage and the river which they contain thus represent the other extreme from such forms as those of the Kickapoo River of Wisconsin, with the sites of the northeast Ozarks intermediate (fig. 42). However, one reach of the Osage is revealed by detailed survey to have a well-defined sequence of pools and riffles. (See figs. 43, 44.)

The reach in question is now flooded by the Lake of the Ozarks, but the habit of the river both downstream from Bagnell Dam at the lower end of the lake and upstream from the upper end near the surveyed reach is

[4] Stream meanders occur, however, farther up the valley; they are developed on a few valley bends south of Kansas City, Mo.

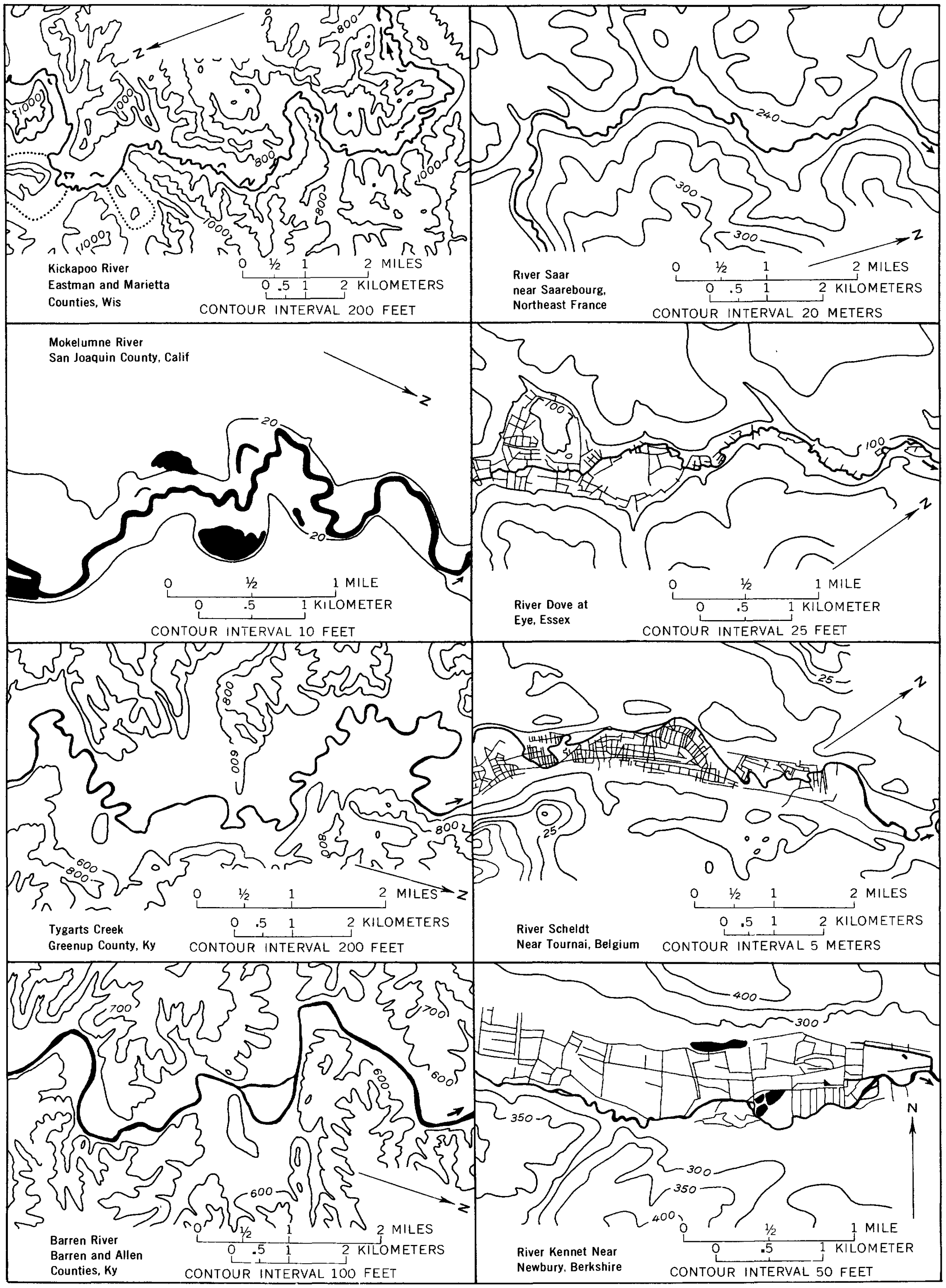


FIGURE 42.—Maps showing ranges of stream-channel and valley patterns on underfit streams. The Kickapoo and Saar Rivers, in the reaches shown, are manifestly underfit in incised meandering valleys. The Mokelumne River is manifestly underfit, although shallowly incised; and the valley meanders of Tygarts Creek have shifted considerably downstream, although through less than one wavelength. Stream meanders are very poorly developed on the Barren River. The present stream-channel pattern on the River Dove is partly obscured by numerous artificial ditches, as is that on the River Scheldt. Large bends of former meanders are identifiable on the Scheldt even though the stream occupies a former large meander trough. No trace of former meanders remains on the Kennet River, but the former large channel is proved here by excavations and boreholes.

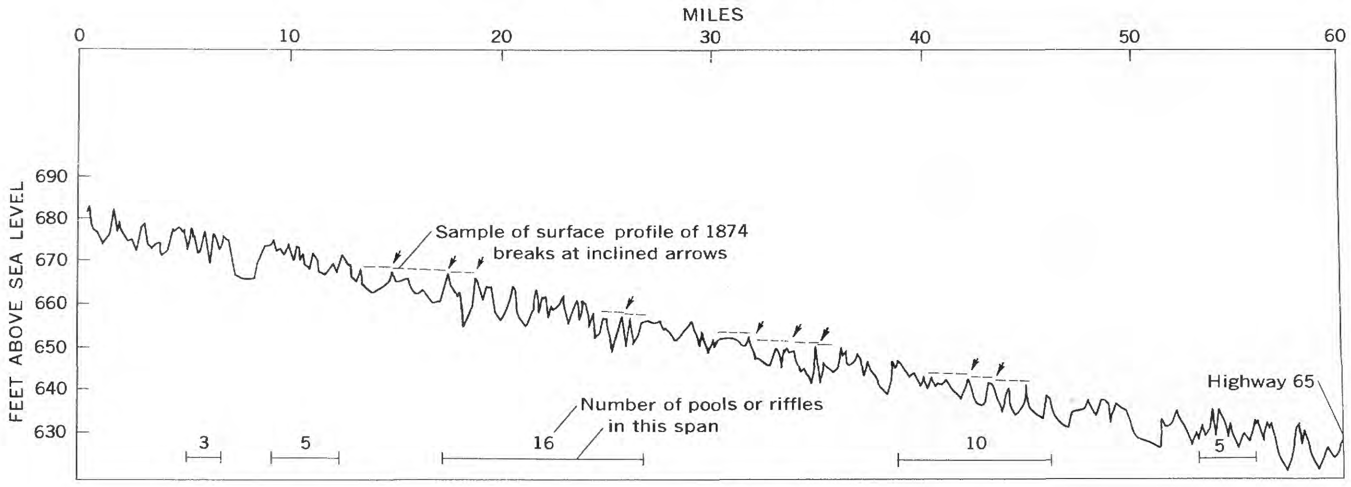


FIGURE 43.—Channel-bed profile of a reach of the Osage River, Mo., in 1874.

not a meandering one (Bagnell quadrangle, Missouri, 1:24,000; Shawnee Bend quadrangle, Missouri, 1:24,000). Furthermore, Deer Creek and Niangua River, which enter the lake from the south, are manifestly underfit in scarcely any reaches (Edwards quadrangle, Missouri, 1:24,000; Macks Creek quadrangle, Missouri, 1:24,000). It seems most unlikely that the surveyed reach possessed trains of stream meanders before the lake filled.

The pools and riffles are far more closely spaced than are the bends and inflections of the valley. How much more closely depends on how many of the peaks on the surveyed profile are classed as individual riffles and on how many of the troughs are classed as pools. The tally of hydraulic jumps in the low-water profile of 1874 is 50 for the 60-mile length, giving an average spacing of 1.2 miles from jump to jump. This value is, however, too great to represent a half a wavelength, for a number of low peaks were not reflected by jumps. When close-set groups of small peaks are counted as single peaks, the total becomes 75, identical with that for troughs. The spacing of 0.8 mile indicates a wavelength of 1.6 miles. This is already less than half the wavelength of valley meanders, but it is probably too large because of the irregularities in the sequence observed, which suggests imperfect development. When readings are taken on distinctive parts of the sequence (bottom of fig. 43), they give an average of 0.56 mile for 39 intervals, corresponding to a full wavelength of 1.12 miles. The wavelength of the locally distorted valley meanders of the Osage is measurable with difficulty but appears to be some 3.8 miles—nearly 3½ times as great as the wavelength for the streambed. The ratio of 3.5:1 is within the range of regional value for meander wavelength in the northeast Ozarks. The Osage, therefore, like the rivers of the northeast Ozarks, supports the thesis that a stream in a meandering valley need not be a meandering stream.

RIVERS IN NEW ENGLAND

Where a meandering stream in a nonmeandering valley passes into a reach of incised meandering valley where stream meanders do not occur, and where also it begins to meander again on the far side of the incised reach, the distinction between the two sets of windings cannot be gainsaid (fig. 42). But in New England, the winding valleys which dissect the upland are in many parts angular in plan, whereas stream meanders are largely confined to the irregular and drift-encumbered low ground of the coastal belt. Manifestly underfit streams can be identified in few places. Nevertheless, when wavelengths are averaged on trains of valley windings in the uplands, they plot against the drainage area in the usual fashion (fig. 45). Wavelengths of stream meanders constitute a second family, whether they are determined for lowland drainage areas or for the rare sinuosities of the channels of upland streams. Both the absolute dimensions of valley bends and their relation to the wavelengths of indubitable stream meanders show that underfit rivers occur also in New England.

Some 8 miles north of North Adams, Mass., the Deerfield River occupies a magnificently winding valley that is cut as much as 1,000 feet below the levels of nearby summits (fig. 46). The stream channel has but a slight tendency to wind, even though the valley floor is wide enough in places to accommodate stream meanders. Farther downstream, near the confluence with the trunk Connecticut, stream meanders appear in weak glacial and fluvial sediments (fig. 47) where valley

FIGURE 44.—Aerial oblique view of part of the Osage River, upstream from the Lake of the Ozarks, at very low stage, showing bars spaced along one limb of a valley bend. Photograph by Missouri Conservation Commission.

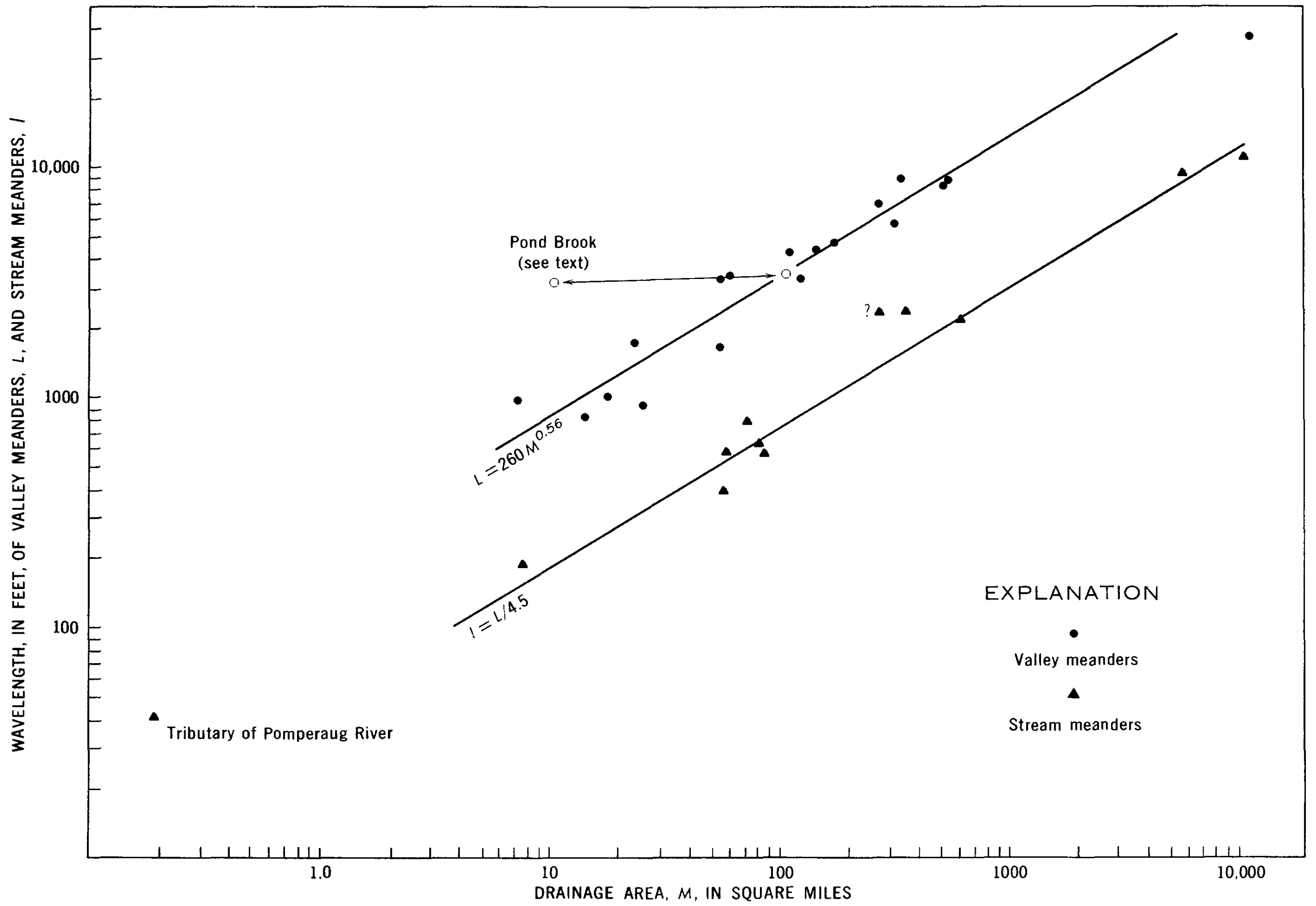


FIGURE 45.—Graph showing relation of wavelength to drainage area of streams in southern New England.

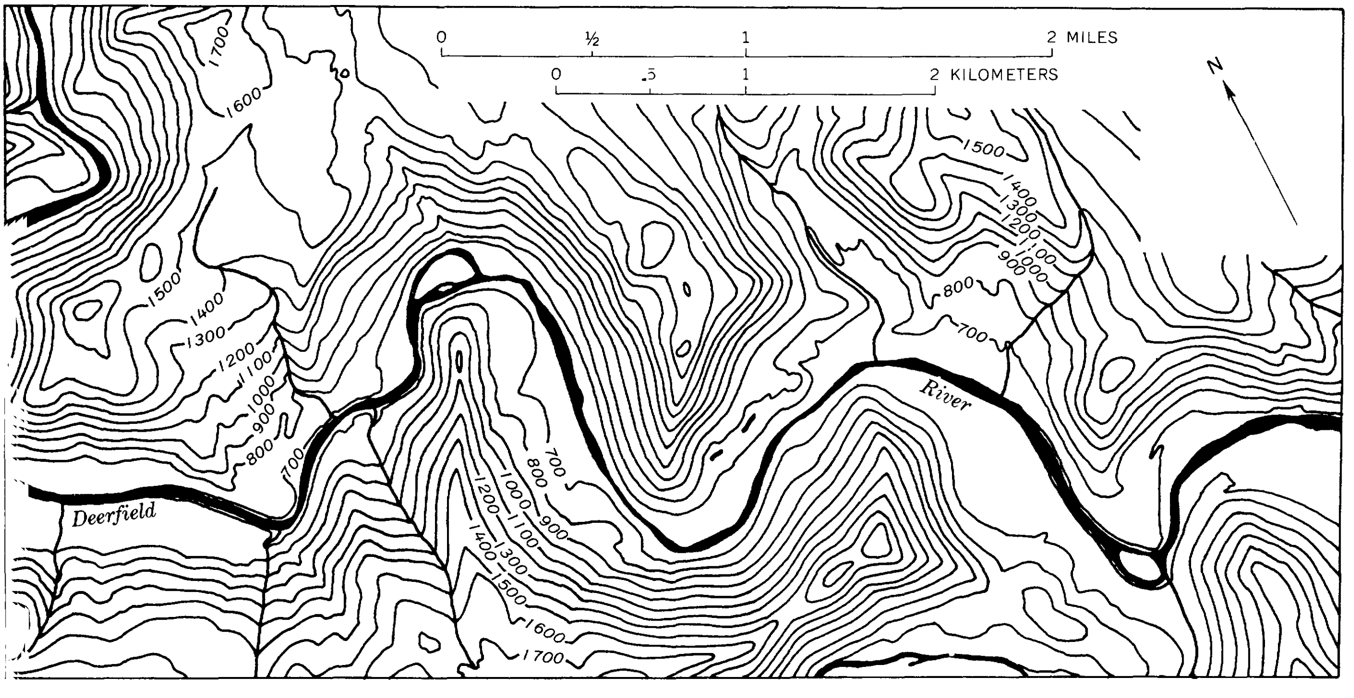


FIGURE 46.—Map of the Deerfield River, Mass., showing valley bends on an upland reach.

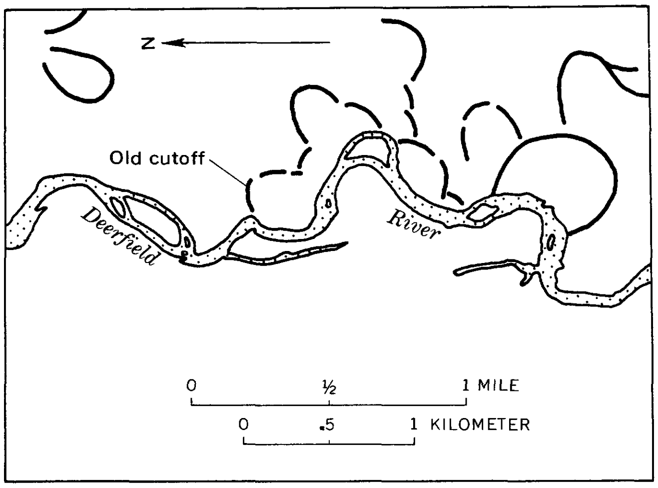


FIGURE 47.—Sketch of the Deerfield River, Mass., showing stream meanders on a lowland reach.

meanders are absent. The valley bends of the upstream reach have a mean wavelength of 6,600 feet at 300 square miles, whereas somewhat dubious stream meanders average 2,300 feet (table 3). In the downstream reach, at 560 square miles, stream meanders average 2,025 feet in wavelength. In this humid region, where bankfull discharge cannot fail to increase with increasing drainage area, the wavelength of valley meanders appropriate to a drainage area of 560 square miles is likely to be much greater than 6,600 feet; by extrapolation, therefore, the disparity between the two series of wavelengths is considerable.

TABLE 3.—*Wavelengths for rivers in southern New England*

River	Drainage area, in square miles	Valley meanders		Stream meanders	
		Number of meanders	Mean wavelength, in feet	Number of meanders	Mean wavelength, in feet
Housatonic	57	2	3, 425		
Do	132	4	4, 225		
Do	517	4	8, 050		
Eightmile Creek (to Housatonic)	21	4	1, 805		
Pomperaug	74			7	750
Hoosic	71			8	640
Pond Brook [1]	9. 6	2	3, 400		
White, Vt.	101	4	4, 200		
Westfield	115	5	3, 060		
Do	160	3	4, 500		
Do	328	2	8, 350	2	2, 310
West	300	5	5, 140		
Deerfield	257	2	6, 600	3	(?)2, 305
Do	500	2	7, 900		
Do	562. 5			4	(?)2, 025
South (to Deerfield)	22. 5	4	960		
Bear (to Deerfield)	13	3	870		
Cold (to Deerfield)	16	3	1, 060		
Green (to Deerfield)	66			5	815
Connecticut	5, 400			3	8, 400
Do	10, 624			4	9, 750
Do	11, 600	2	30, 600		
Mill (to Connecticut)	53	2	3, 400	6	600
Fort (to Connecticut)	50	3	1, 625	5	400
Bachelor Brook (to Connecticut)	6. 5	2	1, 070	6	210

[1] See text discussion.

Similarly, the Westfield River upstream from the well-known terraces near the town of Westfield curves inside the great sweeping recesses of an incised valley, with a mean wavelength of 8, 350 feet at 430 square miles (fig. 45). Scanty readings on the stream channel give a value of 2,310 feet for stream meanders here. Farther upstream, about 15 miles northwest of Northampton, Mass., the valley of the Westfield River simply leaves no room for stream meanders (fig. 48). But the appearance of regional values in the regional graph leaves no doubt that valley meanders and stream meanders are separable from one another. The windings of the New England valleys are strictly comparable to those of the Ozarks, despite their angularity.

Davis (1902a) chose to present the terraces of the Westfield and others rivers as evidence against reduction in stream volume. Two points arise immediately. First, Davis seems to have directed his main attack against the changes of volume postulated by Emerson (1898), who was discussing discharge of melt water rather than changes produced by climatic change subsequent to the recession of ice; and second, even if Davis proved correct in maintaining that no significant change in volume had occurred since the Westfield River first began to cut into its topmost terrace, he would not necessarily confute the general reduction in volume which is here claimed to have occurred since the meandering valleys were cut through bedrock. Furthermore, Davis is open to challenge on his own ground, as will now be shown.

Davis advocated the defense of terraces by outcropping bedrock, as opposed to reduction in volume, reduction in load, or increase in slope. His general conclusion, that the several arrays of terrace fronts are meander scars, is not disputed, although he is open to correction on points of detail. For example, his perspective diagram of the terraces at Westfield (Davis, 1902a, fig. 82) omits several scars, as may readily be seen from the aerial photographs now available or from inspection of wooded parts of the terrace fronts. He may have mistaken tiny remnants of low terraces for slumped masses, for he stated (p. 91) that recently abandoned scarps are uneven with landslides. If this were so, the oldest (uppermost) scarps should be particularly uneven, as they have had the longest time to yield by slumping; in actuality, they are nearly everywhere smooth and unbroken. Again, Davis seems to have overstressed the role of bedrock in defending surviving

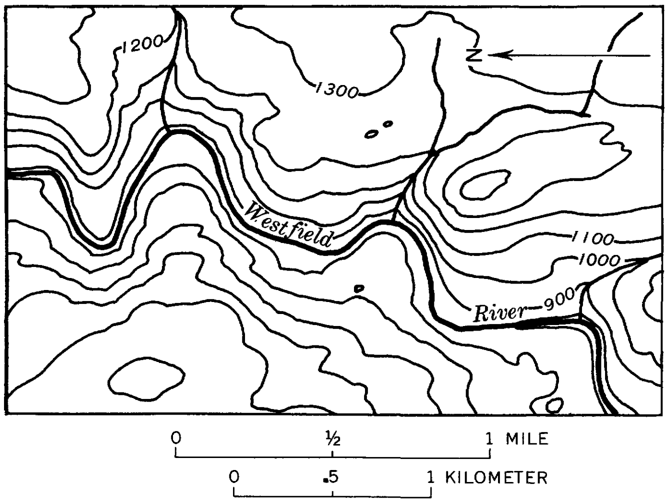


FIGURE 48.—Map of the Westfield River, Mass., showing valley bends on an upland reach.

parts of terrace (Jahns and Willard, 1942, p. 283). Perhaps he was a little too greatly influenced by the principle that "observation is greatly aided by the discovery of a successful theory; for the essential facts are then quickly acquired by well-directed research" (Davis, 1902a, p. 93).

Davis' comments upon the hypothetical effects of increasing slope (1902b, p. 290–293) seem to refer mainly to Emerson's conclusion (1898) that the lake clays of the Connecticut Valley were deposited close to the sea level of the time, so that their present altitude indicates crustal warping. Although little is yet known of the details of late-glacial and postglacial movements of the strandline in southern New England, warping has certainly occurred. J. E. Upson's studies (written and oral communications, 1960–61) of bedrock valleys, Flint's assemblage (1957, fig. 14–16) of evidence for crustal movement, and tilting of the lake floor in the Connecticut Valley (Jahns and Willard, 1942 p. 272–274) show that south-flowing streams have been submerged at their mouths and uplifted in the north. Whatever the interplay of crustal movement with eustatic rise in sea level, rivers debouching along the southern coast of New England have undoubtedly had their downstream slopes increasingly steepened since deglaciation. Consequently, Davis' view that uplift is inconsistent with the formation and preservation of whole flights of terraces must be rejected, the more so as it relies on the elusive concept of grade—to be specific, on the indefensible notion that a meandering habit is in some way associated with the attaining of grade, whatever the state of grade may be.

Davis' brief treatment of diminishing load (1902b, p. 293–294) is little more than guesswork. In fact, according to Davis' own theory of grade, load, and therefore slope, should still be increasing on the New England rivers today as the various stream nets become progressively better organized and the laterals—which Davis regards as developing tardily by comparison with the trunk streams—come to feed increasing bulks of sediment into the main rivers.

On the subject of diminishing volume, Davis wrote (1902b, p. 288),

The best indication of the volume of the stream by which a terrace has been carved is afforded by the curvature of its frontal scarp. If the scarps of the low-level terraces have a radius and an arc of curvature similar to these elements in the existing river meanders, and significantly smaller than in the high-level scarps, while curves at intermediate levels show intermediate values, a diminution of stream volume may be fairly inferred. If the radius and arc of curvature are of about the same measure in the three cases, no change in stream volume is indicated * * * [but] a graded river on a strong slope does not develop curves of as small radius as it would when subsequently flowing with the same volume but with a finer load on a gentler slope; hence a large radius of curvature in the uppermost terraces should not alone be taken as an indication of large volume; large arc of curvature should also be found before large volume is inferred.

These comments seem to go too far in some directions and not far enough in others. Davis is clearly challenging the hypothesis of a progressive decrease in volume—at unspecified but presumably constant stage—in the context of the progressive downward narrowing of the remaining spreads of terrace. But, as is repeatedly observed, the conversion from large to small meanders which makes rivers manifestly underfit seems to occur swiftly, leaving no time for the production of scars of intermediate size. Absence of intermediate forms is thus not relevant to the present discussion. The question is simply whether or not large scars exist at high levels. However, although the reference to radius of curvature accords with the modern views of the behavior of meandering streams, Davis seems to make no allowance for the possible effects of downstream sweep in elongating particular scars or for the usual hypertrophy of single loops in weak proglacial sediments. As the curves in his diagrams do not appear to have been determined by instrumental survey, and as Davis fails to state what he means by significantly smaller, he is not equipped to decide whether or not there is a difference in the size of scars at high and at low levels. If, moreover, the coarse valley trains were deposited or partly worked over by braided streams, the relation which Davis postulates, between coarse and bulky load on the one hand and strong downstream slope on the other, ceases to be relevant to the behavior of the meandering streams which carved the terraces. In any event, it is not permissible to compare the present downstream slope of the outwash with the present downstream slope

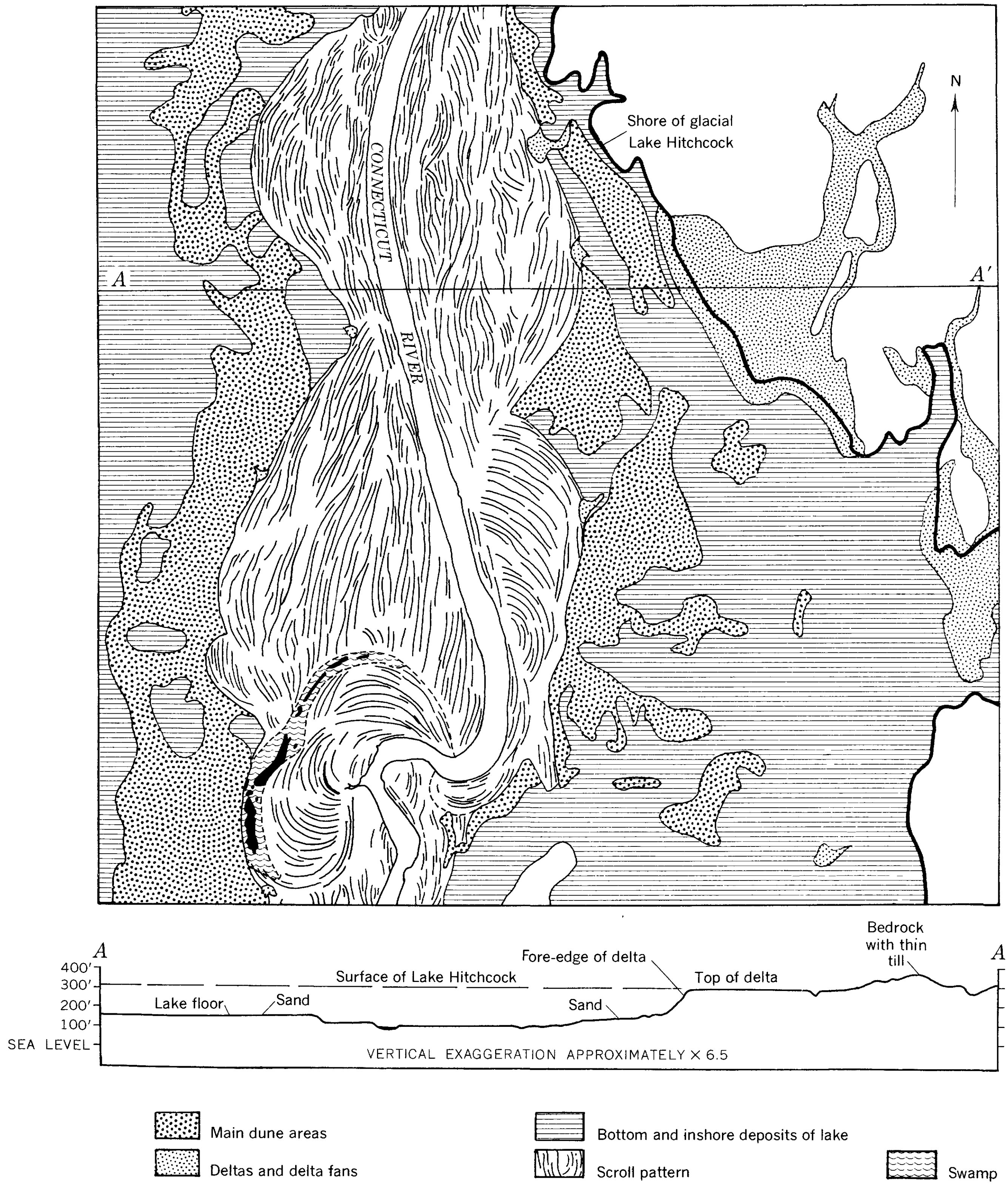


FIGURE 49.—Map of the Connecticut River valley near Amherst, Mass., showing scrolls. Simplified from Mount Toby quadrangle, scale 1 : 31,680.

of the south-flowing rivers; allowance should be made for crustal warping, which cannot fail to have altered the profiles of the outwash trains. In this same connection, Davis' claim that a steeply descending graded river with a heavy load develops curves of unusually large radius can also be recognized as irrelevant. The distribution of old scrolls on the Connecticut River (Mount Toby quadrangle, Massachusetts, 1:31,680) [5] suggests that, at times and in some reaches, the Connecticut River has been a braided stream, laying down scrolls more or less parallel to the axis of the valley but at the same time cutting long arcs into the terrace fronts (fig. 49). Here also the criteria suggested by Davis are not conclusive enough for use in this area.

Although Davis did not cite the authors of the hypothesis that the volume of New England rivers was once greater than it now is, his main objection seems to be directed at Emerson. Emerson (1898) made free and sometimes incautious use of the term "flood"; in addition, he was mistaken in regarding erosional terraces as usually paired across the valleys (1898, pl. 25, sheets A–D), as is readily seen from the results of instrumental leveling by Fisher (1906). But Emerson fully comprehended the nature and origin of the valley fills. Apart from lake sediments and deltas, these consist almost wholly of outwash trains and kames, dimpled in many places (as Emerson observed) by kettles. The valley fills were laid down at the time when local glaciers were in an advanced state of decay, and when streams of melt water carried outwash around, and over, detached blocks of ice. The melt water streams, however effective in smoothing the tops of the outwash trains, were temporary phenomena, irrevalent to the question of whether or not postglacial meandering streams have undergone a reduction of volume.

To summarize, Davis' views on the likely effects of changes in slope and load of New England rivers are in part inconsistent with his own hypothesis of grade; his criteria for separating large from small meander scars are insufficiently rigorous; and, in discussing possible reduction in volume, he seems to have been challenging the limited concept of melt-water discharge.

It would be unreasonable to expect Davis to refer his conclusions to scales of chronology comparable to those now in use, but this circumstance should not prevent correction of his inferences in the light of modern findings. On the other hand, Davis can justly be criticized for omitting reference to meandering valleys in bedrock, such as are readily visible from viewpoints overlooking the New England Peneplain. As stated, these valleys have wavelengths which relate them to the family of valley meanders. The streams in them are underfit.

The streams which cut the valley bends removed a great bulk of bedrock. Postglacial streams, operating since the last deglaciation, have not yet succeeded in removing the valley fills of unconsolidated outwash, deltaic beds, and lake sediments. The valley bends are referable chiefly to a period earlier than, and much longer than, postglacial time. As they were overridden and occupied by ice, and as they are fluvial, not glacial, features, they must be regarded as produced mainly before the last local glaciation—that is, as having a long history comparable to that of the valley meanders of the Ozarks, the Driftless Area of Wisconsin, and the English Cotswolds. This is not to say, however, that large streams capable of assuming wavelengths of the valley-bend size did not reestablish themselves in postglacial New England; this matter will be discussed presently.

The regional graphs of wavelength and area can be used to classify some of the trains of bends on the Connecticut River. The bends near Hartford and North Walpole are stream meanders, whereas those cut through bedrock near the estuary are valley meanders, even though their wavelength runs a little short by comparison to wavelengths from smaller drainage areas. The graphs also enable the anomalously large windings of Pond Brook to be interpreted. Pond Brook enters the Housatonic River 8.5 miles northeast of Danbury, Conn., occupying a valley with the usual distorted windings but also with recessed curves on the outside bends which are unmistakable on the ground. The wavelength of these bends—more than 3,000 feet near the confluence—is, however, excessive by regional standards for the present drainage area of about 10 square miles (fig. 50). As the bends cut down 300 feet into bedrock. they relate to erosion before the last local glaciation.

This may well be an instance of capture in the normal cycle (Harvey, 1920). If capture has occurred, the captor stream is Still River, which now flows northward across the head of Pond Brook valley to join the Housatonic near New Milford (fig. 50). If Pond Brook before capture drained the complex depression which now includes Lake Candelwood, its former drainage basin was about 100 square miles, a value which would locate the point graphed for wavelength and area almost exactly on the best-fit line for the region (fig. 45).

Although underfit streams can be recognized within the winding valleys of New England, the question of when the last general shrinkage occurred in this region remains open. All that has been established so far is

[5] Although the scrolls are described in the key as being shown diagrammatically, recent aerial photographs at 1:7,200 confirm the accuracy of the trends represented.

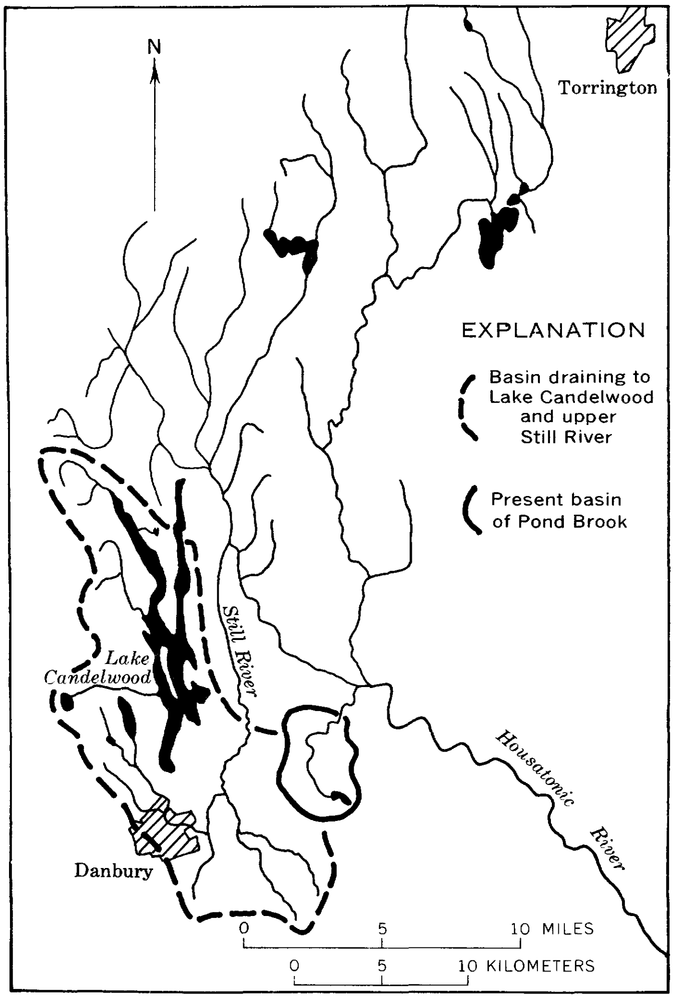


FIGURE 50.—Sketch map showing the possible capture of Pond Brook, Conn.

that the valley meanders were shaped almost wholly before the last local glaciation: postglacial erosion, apart from some clearance of surficial material, has been slight. Postglacial dates for large bends are demonstrable only if these bends are cut into glacial or proglacial deposits, and the dates bear on the argument only if they were cut by ordinary streams and not by melt water or spill water.

Relative dates of erosional features can be obtained, with some precision, from the sequence of surficial deposits. Difficulties in the low ground and in upland valleys open enough for stream meanders arise less in dating than in identification. Kettles generally, and kettles in kame terraces in particular, can produce steep slopes of curved plan like those of scallops due to meanders. Problems of identification are well illustrated by the valley of the lower Pomperaug River (Newton and Southbury quadrangles, Massachusetts, 1:31,680 and 1:24,000). Five miles above its confluence with the Housatonic, the Pomperaug is eroding kettle-pitted outwash on its right bank. A recess in the outwash at the edge of the flood plain resembles in diameter a number of kettles in the top of the kame and could itself be a kettle even though its enclosing slope is steep (fig. 51). In actuality, auger holes and inspection pits show that a former stream channel, now filled with humified slope wash, curves round the outside of the recess, which is therefore identifiable as a scallop cut by a meander. Three miles downstream, immediately north of the abrupt bend of the Pomperaug at South Britain, a swampy recess on the right bank is neither a kettle nor the cut of a meander but the site of a mill reservoir that dried out when the enclosing dam failed. In this second instance, the recess shown by contour lines on the topographic map is large enough to be a valley meander; but independently of local reports on the history of the site, augering proves a flat surface of sand beneath a thin cover of humified topsoil across the whole width of the recess, which lacks either the peat-filled center that might be expected from a kettle or the large channel that might occur in an abandoned valley meander. The two examples illustrate the need for extreme caution in the interpretation of topographic maps of New England.

Aerial photographs, however, supply a check. They confirm that some laterals of the Connecticut River in the general neighborhood of the Holyoke Range are manifestly underfit (fig. 52). On the left bank, manifestly underfit reaches occur on the Scantic River, Podunk River, Fort River, and Bachelor Brook systems; on the right bank, they occur on feeders of the Manhan River. Where comparative wavelengths can be measured, a ratio of about 5:1 is apparent, as in the regional graph for small drainage areas. There is nothing to suggest that the forms identified as valley meanders are due either to the discharge of melt water or to the formation of kettles. Because numbers of the large scallops are cut into the bottom sediments of glacial Lake Hitchcock, their origin must be set later than the draining of that lake. And although kettles lie close to some trains, it would be a remarkable coincidence indeed if kettles formed continuous winding trains, and if the wavelengths of these trains were accidentally the same as the wavelength appropriate to valley meanders. The reaches shown in figure 52 are, then, claimed to display authentic valley meanders. Numbers of large scallops elsewhere seem probably to be valley meanders, but the effects of rapid downstream shift and the distortion of some loops ensure that in many places the valley constitutes a trough bordered with blunted cusps,

FIGURE 51.—View of scallop of stream meander in kame, Pomperaug River, Conn.

not a winding cut on which wavelength can be reliably measured; in opposition to Davis, no use is here made of radius of curvature.

Because some parts of some valleys are straight and other parts are widely opened, the evidence of manifest underfitness is fragmentary. It is nevertheless consistent with that obtained elsewhere in suggesting that the last onset of underfitness came late—late enough for Lake Hitchcock already to have disappeared. Davis' claim that the New England rivers have not shrunken is therefore rejected, independently of the reference of that claim to the views earlier expressed by Emerson. Poorly developed though they are, manifestly underfit streams exist. Because similar streams occur in the uplands, shrinkage is taken to have been regional. In spite of the difficulties of its terrain, New England is thus brought within the scope of the general theory of underfit streams.

CANYONS IN ARIZONA

Canyon Padre and Canyon Diablo, respectively crossed by U.S. Highway 66 at 21 miles and 33.5 miles east of Flagstaff, Ariz., are tributary to the Little Colorado River. At the crossings they are cut into a stripped surface of the Kaibab Limestone of Permian age, which hereabouts consists largely of dolomitic limestone (Childs, 1948; Strahler, 1948). Each canyon describes large bends, with undercut slopes on the outside curves and gentler lobate slopes on the inside curves (figs. 53–56). In the bottom of each valley, large terraces or berms composed of reddish-brown sandy and silty material contrast strongly with the pale much jointed rocks of the Kaibab Limestone; the surficial deposits are presumably derived from the red beds of the Moenkopi Formation, which succeeds the Kaibab upward. The tops of the terraces or berms slope regularly downvalley; the fore-edges are slightly dissected in places by tiny gullies. The present stream channels, which cut into the deposits, are about 15 feet wide and 3 to 4 feet deep; they themselves include faintly developed berms in places. The channel in Canyon Diablo swings a little in some reaches and includes very bulky islets or braids in others.

These assemblages of features are taken to indicate reduction in bankfull discharge. The present channels, like those in the Ozarks, are far narrower than would be expected from the approximate 10:1 ratio of wavelength to bed width, when the wavelength used is that

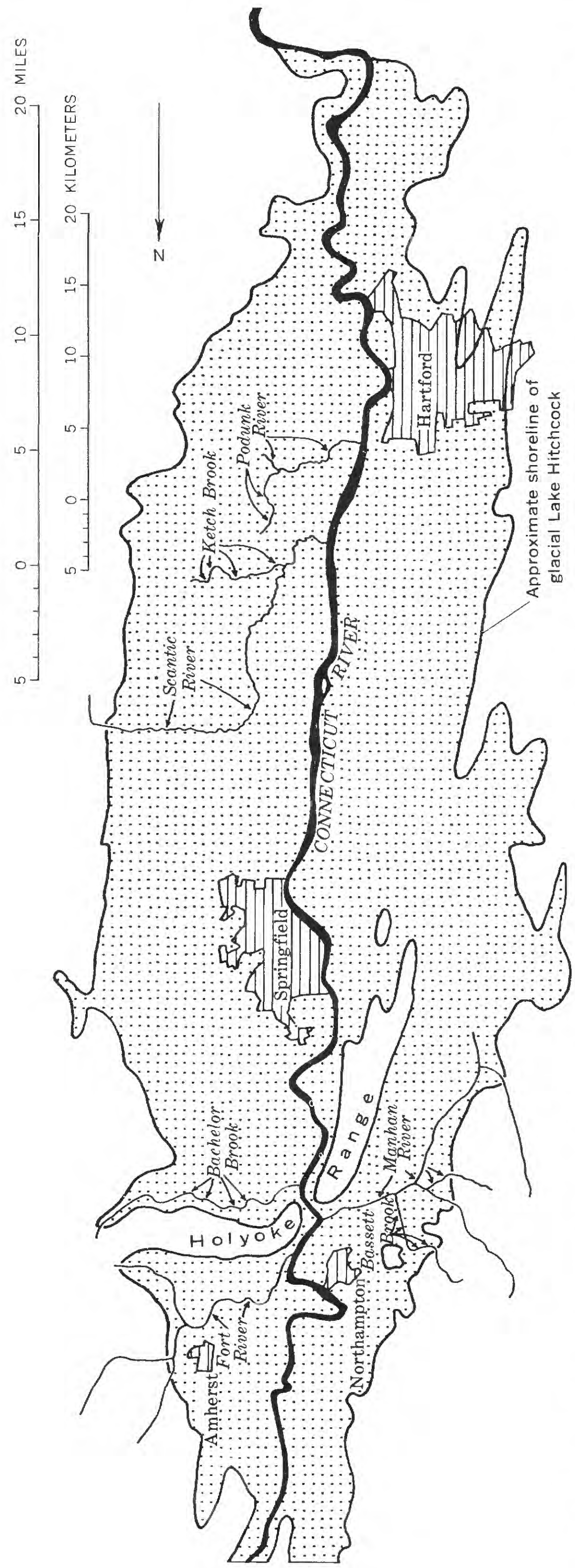


Figure 52.—Sketch of the Connecticut River valley showing manifestly underfit streams on the drained floor of glacial Lake Hitchcock. Shoreline drawn after Jahns and Willard (1942) and Cushman (1961) to include deltas and other littoral deposits.

FIGURE 53.—View of valley bend in Canyon Padre, Ariz.

FIGURE 54.—View of berms and stream channel in Canyon Diablo, Ariz.

FIGURE 55.—View of point bar of valley meander in Canyon Diablo, Ariz.

FIGURE 56.—View of point bar of valley bend, undercut outer slope, and shedding of joint blocks in Canyon Diablo, Ariz.

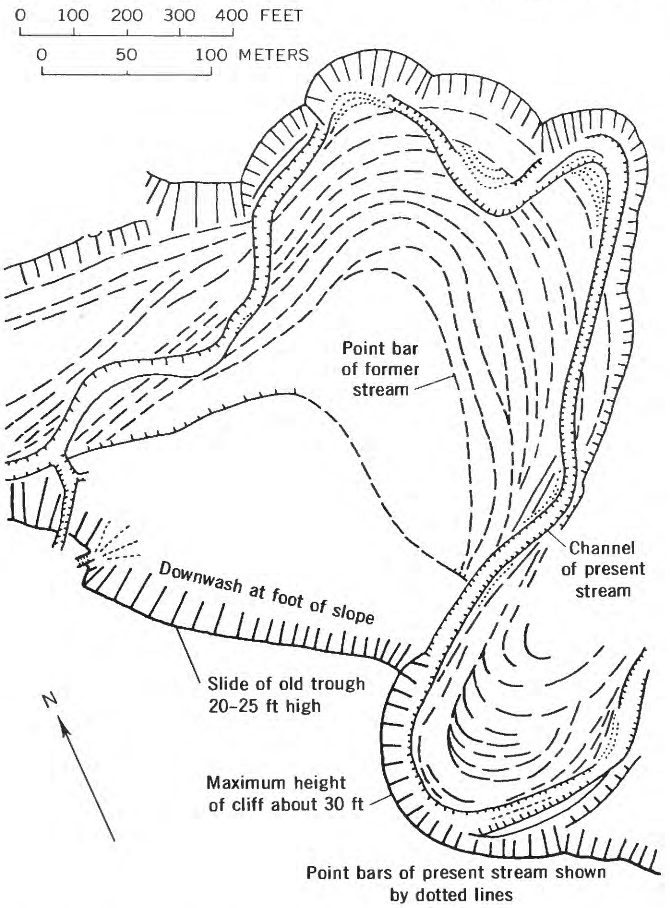


FIGURE 57.—Sketch of Oraibi Wash., Ariz., showing scrolls and scars.

of the bends in the canyons. The occasional faint swings and islets of the present channels reproduce features noted for the Ozarks. Much of the reddish-brown sediment is regarded as point-bar deposits of the former rivers. Those narrow accumulations which line parts of the outside curves cannot, however, be fully explained until the whole nature and origin of berms are understood.

The Oraibi Wash [6] in northeastern Arizona drains part of the Black Mesa and Tusayan Washes country toward the Little Colorado. At the crossing of the highway between Moenkopi and Keams Canyon, close to Oraibi village, the wash is enclosed in a terraced valley where outcrops of bedrock are visible beneath dunes on the higher terraces but where the stream channel appears to be underlain by some 30 feet of fill. The drainage area here is about 425 square miles. Upstream, in the Black Mesa, the tributaries of the Oraibi Wash flow in steep rock-walled canyons; downstream, the main valley opens out, and many tributaries fail to reach the trunk river. The Wash is ephemeral, usually flowing only in response to thunderstorms in July and August.

At the highway crossing, the stream is manifestly underfit. Its present meanders are superimposed on a previous trace of considerably bigger loops (figs. 57, 58), cutting in places into former meander scars and elsewhere across the former point bars. The present channel has point bars and berms of its own, but these are mostly distinguishable from the older series into which the present channel is slightly incised. As figure 57 shows, the large bends are contained in a large meander trough, not so wide that its walls are free from scalloping. Inspection of the ground accords with the record of aerial photographs to indicate that the large meanders swept downstream at higher levels but underwent ingrowth before their last abandonment. The older parts of the trough wall are now being dissected by short gullies, some of which discharge fans at their lower ends.

As Hack (1942) has shown, this whole area has experienced alternate cutting and filling of valleys such as is widely known from dry regions in the West. The site description presented here is not meant to prejudice either the chronologies obtained by Hack or by other writers or to suggest that the last conversion of the Oraibi Wash to an underfit condition was contemporary with the corresponding change affecting rivers in other regions; the dry West may offer problems which do not recur elsewhere. This is a topic to be pursued later. All that is intended at this juncture is to offer the present condition of the Oraibi Wash as essentially similar to the condition of many rivers in humid regions.

PROBLEMS OF THE INFLUENCE OF BEDROCK

As will be described later, a number of manifestly underfit streams are underlain by large channels which, winding round the valley bends, contain alluvial fills of which the present flood plains constitute the topmost parts. Streams of this kind are illustrated in generalized fashion in figure 4 at no. 1, where the large channel is marked. A similar channel can occur beneath streams which combine two sets of meanders of contrasting order of size, even though neither set is incised, as in figure 4 at no. 3. Underfit streams of either type make no contact with bedrock even at times of maximum scour, unless they impinge on the valley wall. Their meanders are alluvial meanders in the fullest possible sense.

Incised rivers of the kind exemplified by the middle Humboldt in its canyons, by much of the upper Shenan-

[6] This account of the setting is based closely upon information kindly communicated by Richard F. Hadley, of the U.S. Geological Survey (WRD) Denver office, who initially suggested the site here described as likely to be instructive.

Figure 58.—Aerial view of Oraibi Wash, Ariz.

doah, by long reaches of the Ozark streams, by the New England rivers in most upland stretches, and by Padre and Diablo Canyons—all of which possess few or no stream meanders—set the question of whether or not the meandering of present-day channels is inhibited by contact of the streams with bedrock. As has been observed, small feeders of the Shenandoah meander across alluvial fills but fail to meander where they cross bedrock. Hack and Young (1959) take a contrasted view that meanders (valley meanders) on the trunk North Fork are caused by structures in the Martinsburg Shale; but although structures appear to be responsible for greatly enlarged amplitude, they can scarcely explain a wavelength and area relation which is appropriate to the region as a whole.

Outcrops of bedrock are known to occur in the bed of the Humboldt in more than one canyon, as also in certain rivers in the Ozarks. Logs of boreholes at highway crossings suggest that, generally speaking, bedrock commonly lies close below the present-day beds of the Ozark streams,[7] whether or not it is actually exposed in them. The contrast between meandering valleys and meandering streams in New England corresponds to the contrast between uplands carved in bedrock and lowlands extensively mantled by surficial material. Examples could be multiplied by reference to the Hercynian massifs of Europe, to parts of the Appalachians additional to the Shenandoah Basin, and also to parts of the Piedmont. The Meuse has been noted as failing to produce stream meanders where it crosses the Ardennes; the great loops described by the Conodoguinet (Strahler, 1946) are valley meanders; and Rock Creek, where it passes through the suburbs and city of Washington, D.C., pursues a nonmeandering course along a rock-lined bed, within the meanderings of an incised valley. The relevant landforms are so common that they appear to have misled some previous writers, especially those responsible for hypotheses of the hypertrophy of meanders during incision. Although enlargement and distortion are admitted, they should not be allowed to obscure the distinction between meanders of the valleys and the trace, meandering or not, of the present stream. The foregoing observations show that a number of streams in meandering valleys are actually underfit, although not manifestly so, and they open the possibility that many others may be underfit, as required by an hypothesis of climatic change. Hence the problem of the absence of stream meanders from incised reaches despite their presence elsewhere.

Contact with bedrock does not conflict with the development of meanders after incision has begun. The whole array of ingrown forms and the deep trenching of valley meanders through firm rock in place accord with the evidence of terraces in proving that neither lateral growth nor downcutting, nor the meandering habit itself, are suppressed by contact of the stream with the solid. When terraces are used to reconstruct former traces of valley meanders, they commonly show that these traces become less and less sinuous with increasing age, as would be expected from the very fact of ingrowth. At high levels and with the earliest terraces, however, the evidence is usually so fragmentary that it cannot be used either to justify or to confute a claim that, when incision began, any given river had an essentially straight channel. In the well-studied valleys of parts of Europe, the sinuosities which became incised valley meanders developed first on trains of outwash or reworked crytoturbate (Troll, 1954). The immediate forerunners of the large meandering streams were braided, and the braided deposits could have been thick enough to insulate the initial meanders from bedrock. Similar considerations probably apply to the Stratford Avon, where the highest terrace has been noted as probably consisting of outwash. It is therefore not possible to use valley meanders as proof that a river already in contact with bedrock, and not already possessing a meandering trace, can spontaneously develop meanders.

Nevertheless, the claim which is sometimes made that all trains of incised meanders are inherited from free meanders need not be conceded. Numerous observations on initially straight gullies, which assume a meandering habit as they cut into heaps of spoil, demonstrate that systematic winding before incision is not essential. (See figs. 59–60.) Any possible objection

FIGURE 59.—View of meandering gully on highway bank near Iowa City, Iowa. Pack gives scale.

[7] The records will be discussed and illustrated in a succeeding paper.

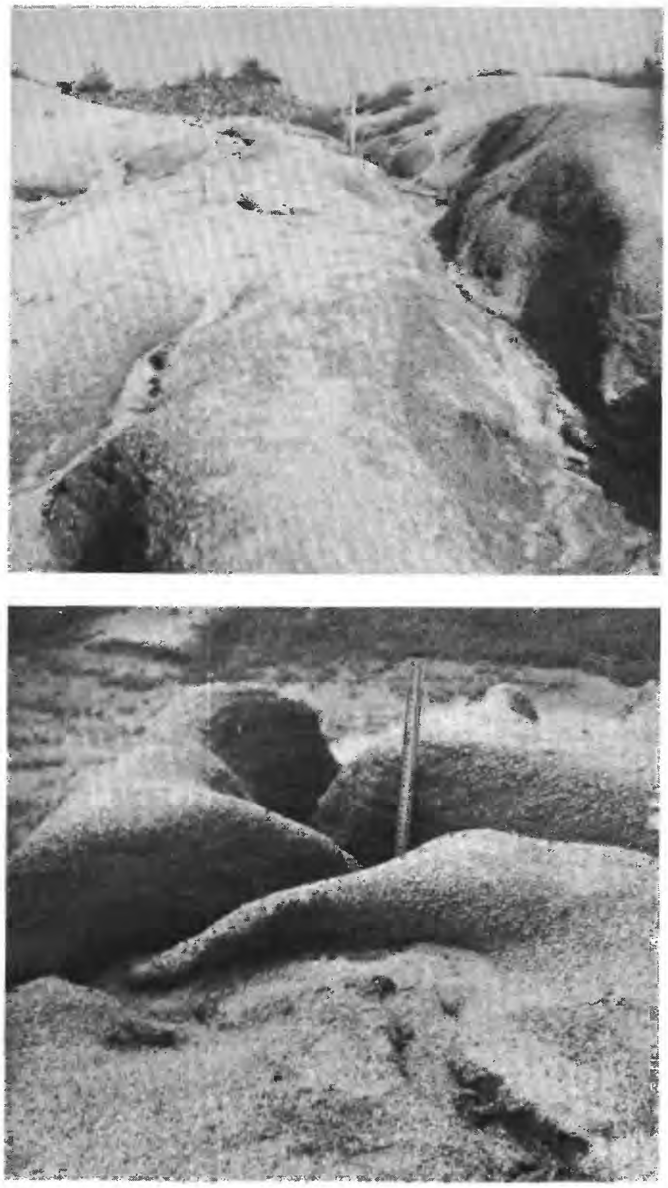


FIGURE 60.—Views of meandering gullies on mine tailings near Shullsburgh, Wis. Staff gives scale.

that the gullies are sunk into unconsolidated material—natural streams are being considered in relation to bedrock—is easily overcome by reference to natural rivulets which, originally alined on straight dikes, faults, and master joints, begin swinging only after they have cut straight trenches. Just as meanders can develop initially when the stream is in contact with bedrock, so they can persist not only when the meanders are being incised but also when a continuous flood plain has been constructed. The Garren Brook on the Welsh Border of England can perhaps be regarded as superimposing its stream meanders onto bedrock through the alluvial fill of the large underlying channel (Dury, 1954, fig. 11), but a different interpretation is required for the Cotswold Coln. Below a nickpoint, the Coln illustrates the stereotype of the alluvial trough (Dury, 1953c); its meanders are sweeping downstream, the bottoms of meander pools reaching the planed-off surface of rock beneath the flood-plain alluvium. Mere contact with bedrock is here insufficient either to prevent the retention of a meandering trace or to stop new meanders from forming in a reach where cutoff is frequent.

Conversely, nonmeandering reaches can occur on streams where bedrock lies far underground. McDonald Creek, Iowa, used above to illustrate the absence of the meandering pattern, is a case in point. Augering proves it to be underlain not directly by till but by the fill of just such a large channel as elsewhere contains the flood plain of a presently meandering stream. Parallel instances can be adduced from rivers which, in the main, are manifestly underfit. Just as contact with bedrock does not prevent meandering, so lack of meanders does not necessarily imply contact with bedrock.

This is not to deny that meanders develop more easily in alluvium than in bedrock or that the very steep slopes where feeders of the Shenandoah cross solid outcrops have nothing to do with channel habit. The difference may, in part, be one of time: meanders perhaps take longer to form in bedrock than in alluvium. But dates to be supplied for the general onset of underfitness give a span of about 10,000 years, in which stream meanders could presumably have developed, if they were to develop at all, on such rivers as the North Fork of the Shenandoah, the incised rivers of the Ozarks, and the canyon reaches of the Humboldt. The very fact that stream meanders occur outside the canyons, but only exceptionally inside, suggests that the incised character of the valley and the lack of meanders on the streams are in some way connected. Where a stream which is elsewhere manifestly underfit passes through an alluviated reach of the valley, it is at least possible that the trace of former large meanders has been lost during alluviation. But where the valley is incised and winding, the trace of stream meanders is the one lacking. As contact with bedrock appears to supply no sufficient reason, another cause of inhibition must be sought.

The possibility that the walls of incised valleys deliver material too coarse to permit meandering is not attractive in that form. Meanders can be initiated, develop, and persist both in coarse till and in coarse alluvium. The first instance is best illustrated, within the writer's experience, by streams in the glaciated, till-choked valleys of Wales and along the Scottish Border—in particular, of the Cheviot. The second is well exemplified by the draw, its margins boldly scalloped, alongside the highway which descends from the ghost

FIGURE 61.—View of joint blocks of dolomite shed from valley wall, Mineral Point Branch of the East Pecatonica River, Wis.

town of Jerome, Ariz. Moreover, the undercut slopes of some meandering valleys can scarcely have failed to shed large joint blocks when being eroded by the former rivers. Examples include the outside curves of Canyon Diablo and Canyon Padre in Arizona (figs. 53–56) and those of many winding valleys in the Driftless Area of Wisconsin, wherever the upper slopes are cut in widely joined dolomitic limestones. (See fig. 61.) At the same time, bed material in the Humboldt canyons appears to be, as reported, perceptibly coarser than that in reaches upstream and downstream where river meanders occur. As Hack (1957) has observed for another region, the caliber of loose material transported by streams declines rapidly with distance from the outcrops which supply coarse fragments. It therefore seems entirely practicable for coarse debris to be concentrated almost exclusively in the incised reaches. An hypothesis is possible that, because the lack of stream meanders in incised reaches ensures a shorter trace and a steeper slope than in meandering reaches, steepness, coarseness of bed material, and a tendency to braid are reasonably associable with one another.

Such an hypothesis must be taken with reserve, however, as soon as allowance is made for the winding thalweg which accompanies the development of pools and riffles in a straight channel (Leopold and Wolman, 1957, p. 53–55). It has yet to be proved that thalweg slopes are steeper within the canyons of the Humboldt than outside. And, if the Ozark rivers are generally in or near contact with bedrock, the change from the former large meanders to the present narrowed channels and nonmeandering traces would involve an actual reduction in downstream slope. Additional problems arise when caliber of bedload is compared from stream to stream. Numbers of lesser streams in the Ozarks fail to meander, even though they transport very little material larger than medium gravel—for example, Little Piney Creek upstream from its confluence with the Gasconade. By contrast, the Mineral Point Branch of the Pecatonica in Wisconsin, in its upper reaches where it is smaller than Little Piney Creek in that stream's lower reaches, is shifting coarse gravel along a distinctly meandering channel. The fact that the coarse gravel in Mineral Point Branch comes not directly off the valley walls but from an alluvial fill under the silty flood plain does not seem relevant to the maintenance of a meandering habit. Mineral Point Branch does move coarse gravel and does meander; the larger Little Piney Creek transports medium gravel and fails to meander.

In other respects, however, caliber may be strictly relevant to the immediate problem. Mineral Point Branch may be capable of meandering, not in spite of its coarse bedload, but specifically because its bank material consists largely of silt. If, on rivers not wholly confined by bedrock, braiding is favored by lack of cohesiveness of beds and banks and maintenance of a single channel by cohesiveness, then the lack of stream meanders in the canyons of the Humboldt may be due simply to the high erodibility of the debris present. Lack of fine-grained waste in the Ozark valleys may perhaps be widely ensured by the preponderance of limestone among outcropping rocks, which can readily supply fragments but not particles. In all the valleys so far investigated which contain manifestly underfit streams, the alluvium contains a high silt-clay fraction. This whole matter obviously requires further study, but the suggestions made are perhaps capable of pointing investigation away from the direct influence of outcropping bedrock, except insofar as the cohesive properties of bedrock may be held to have encouraged the persistence of meanders on the former streams which cut the valley bends.

CANYONS AS FLUMES

On steep hillsides in the Great Basin, and in the Cordillera generally, short canyons with steep downstream gradients are numerous. In actuality, there is a continuous range from canyons with near-vertical sides to steep-walled valleys of the form common in humid regions; the second type is well displayed in the Ruby Mountains of Nevada. The steeply descending canyons and the ordinary deep-cut valleys usually tend to wind. Their windings appear to be valley meanders, for plots

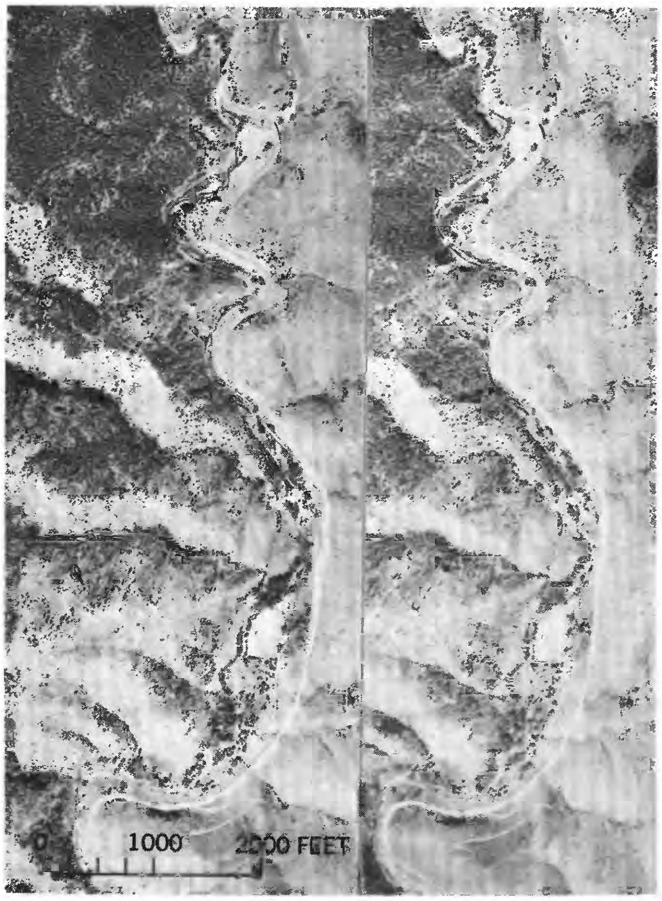


FIGURE 62.—Stereoscopic photograph of part of Bear Creek Canyon, near Denver, Colo.

of wavelength against area bring them into the family which includes, for instance, the incised systematic windings of reaches of the Humboldt (fig. 30).

Where perennial streams flow, as in Bear Creek Canyon in the Front Range near Denver, Colo., it may be possible to compare the wavelengths of stream meanders with those of the valley; in one short reach, and exceptionally, the floor of Bear Creek Canyon is wide enough to accommodate a flood plain, on which stream meanders occur (fig. 62). Although these are too few to justify a comparative plot of wavelength, and although the limb of valley bend on which they lie appears to be elongated in response to structure, the disparity of size between the ingrown windings of the canyon and the meanders of the present stream is beyond doubt.

Where present streams are ephemeral, the floor of a canyon may be encumbered with rock waste on which braided streams flow after rain. Even then, a plot of wavelength against area may be capable of revealing a systematic relation between the two sets of data and of showing that the bends of the canyon are valley meanders. Such is the instance with Birch Creek Canyon (fig. 63), which enters Deep Spring Valley, Calif., from the west. The present stream rarely flows to the mouth of the canyon; but the valley bends, although considerably distorted by the structures of bedrock, closely accord with those of the Humboldt (fig. 30).

Numerous canyons, however, are so narrow at the base that, far from providing room for meanders, they do not contain a streambed in the usual sense. The valley acts as a notch or flume, and the stream level rises on the valley wall at times of high discharge. Examples of this kind are provided notably by the inner canyon of the Colorado, which does not wind, and by the systematically winding canyons of the Wasatch Front north of Salt Lake City. Cloudbursts on the Wasatch Front promote torrential streams which, flowing down the canyons, undergo very marked superelevation at bends.

The torrents resulting from infrequent heavy rains can be strongly erosive, in the sense that they carry great amounts of coarse debris from the canyons and discharge it on to the fans at the canyon mouths. However, it seems unnecessary to hold such rains responsible for the initiation of the canyons, as wavelengths belong to the regional family of valley bends. Alluvial meanders are related primarily to discharge at bankfull. Where streams are manifestly underfit, bankfull discharges higher than those of today are held to account for the initiation and the incision of valley meanders. There is no reason to seperate incised winding canyons with steep downstream gradients from the general family of incised meandering valleys or to postulate for them an origin referable to some other type of discharge than that which produced valley meanders generally. At the same time, the function as flumes suggests that short canyons may, from time to time, carry discharges of an order similar to that of the discharges which initiated them; if so, the windings of the canyons are still developing in their original manner, in contrast to valley meanders on lower and more gently sloping ground, which are currently in a state of arrested development.

An ancillary problem which still awaits investigation is that of stream density in dry regions. According to the views expressed here, the existing network of valleys is denser than the present climate requires. Because canyons in well-dissected terrain provide ready-made routes of discharge, they inevitably carry streams from time to time, but it by no means follows that the valley systems were first developed in conditions like those of today. Canyons which do carry streams ought to be studied in association with valleys which do not. Strahler (1944, 1948) infers that the systems of dry

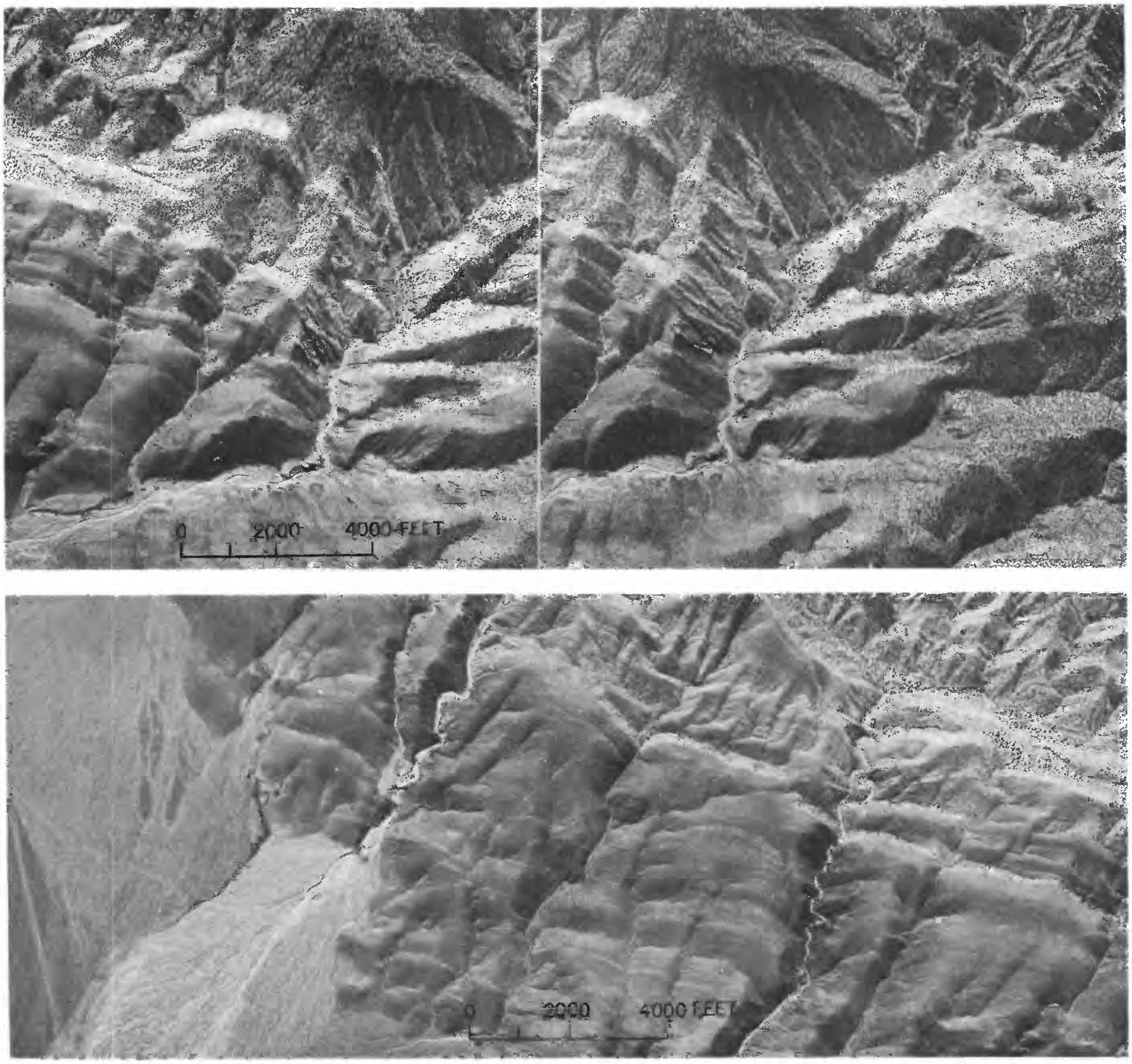


FIGURE 63.—Views of canyons on west side of Deep Spring Valley, Calif. Upper, stereoscopic photograph of Birch Creek Canyon; lower, aerial view of nearby canyons to the south.

valleys on the Kaibab Plateau result from the disappearance of water along lines of underground drainage. If, however, this region has been influenced by climatic change powerful enough to reduce streams to underfitness, then its limestone hydrology is comparable to that of the Chalklands of the English Plain; in both areas, the peculiarities of limestone are responsible for absolute streamlessness, whereas the valley systems and the rivers which cut them are related to a former period of high surface discharge. Rapid percolation superadds its effects to those of climatic change.

SUMMARY

This development of the general theory of underfit streams will be continued in subsequent professional papers, with reference to large meandering channels, to chronology, to calculations of former discharges, and to reconstructed conditions for the occurrence of those discharges. Meanwhile, the conclusions reached so far can be summarized as follows:

1. Underfit streams are those which have undergone a marked reduction in bankfull (channel-forming) discharge.

2. Derangement of drainage cannot supply the required regionally applicable hypothesis of the cause of underfitness.
3. Certain authenticated derangements serve merely to complicate the pattern of underfitness.
4. Underfit streams in more amply meandering valleys—manifestly underfit streams—are not the only underfit type, even when braided streams are left out of account.
5. Manifestly underfit streams are appropriately specified in terms of wavelength ratio between valley and stream, which gives an index of underfitness.
6. In the absence of stream meanders, valley meanders can often be recognized from wavelength and drainage area values and by comparison with the valley meanders of manifestly underfit streams elsewhere.
7. Study of nonmeandering underfit streams with unbraided single channels should include measurement of the long profiles of the beds. Subregular deformation of the bed in long profile appears capable of substituting for a meandering habit.
8. Nets of canyons in dry regions appear comparable to systems of dry valleys in limestone country, in that both series relate to high surface discharges in former times. Canyons, however, can be sufficiently narrow at the bottom to act as flumes at times of high discharge, so that the bends of some of them may still be undergoing erosion.

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