Subsurface Exploration and Chronology of Underfit Streams

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By G. H. DURY

GENERAL THEORY OF MEANDERING VALLEYS

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ABSTRACT

Field investigation of valley bottoms of underfit streams by means of augering or of seismic refraction demonstrates large channels that meander around valley bends. Information from miscellaneous sources—that is, civil-engineering records from damsites—supplements and confirms the writer's findings. The large channels are taken as the beds of former large streams; their infilling is ascribed to stream shrinkage rather than to aggradation.

In areas not covered by ice at the last glacial maximum, dates for the initiation of valley meanders range from early Pleistocene to late in the last glacial. Some trains of valley meanders are deeply incised into bedrock and date at least as far back as early (Nebraskan) glacial times. Other trains, cut into till sheets or littoral deposits, were initiated in the mid-Pleistocene, whereas still others slightly postdate the outermost ice stand of the last (classical Wisconsin) glacial. The last abandonment of the largest channels and the valley meanders for these groups appears to be associated either with the Two Creeks Interstade or with the opening of Zone V (Boreal), according to locality. Areas covered by ice or by proglacial lakes at the last glacial maximum or during part of the last deglacial display valley meanders whose date of first possible initiation is perhaps as much as 2,000 years ago. Reduction to underfitness of streams in this group is provisionally equated with infilling of minor channels by streams of the former group.

Comparison of humid regions with arid or semiarid regions sets questions of the cause of accelerated erosion. Generally speaking, this erosion should correspond to increases in surface water, which could, however, be effected by an increase in precipitation or a decrease in temperature. The brief very high stands of glacial Lake Lahontan shortly before and shortly after the Two Creeks interval seem to have resulted from climatic changes of both types; these high stands are correlated with the last clearance of large channels, respectively, in the Driftless Area of Wisconsin and its margins and in southern England. The hypsithermal maximum (Zone VII) was a time of increases both of temperature and of precipitation; precipitation increased sufficiently to renew erosion both in humid regions and in large parts, at least, of dry regions. Infilling of large channels in humid regions during Zone V (Boreal) resulted from decreased precipitation, which more than offset a simultaneous reduction in temperature.

Down to the limits of magnitude involved in the partial reexcavation of channels in Zone VII, the respective successions of cutting and filling in dry and humid regions appear synchronous and parallel. Lesser sequences of cut and fill, on the other hand, may be out of phase.

INTRODUCTION

This paper continues the development of the general theory of underfit streams begun in Professional Paper 452–A (Dury, 1964). That account was meant principally to review terminology, to establish the widespread occurrence of underfit streams, to demonstrate that not all underfit streams need possess meandering channels at the present time. and to show that derangements of drainage cannot supply the general hypothesis of origin which facts of distribution and chronology require. Neither the introduction to the series nor the acknowledgments of extensive help will be repeated here, except for a general statement that many individuals—in particular, both full-time and part-time members of the U.S. Geological Survey—have been most generous with assistance in the field, with discussion, and with constructive criticism.

The following text extends Professional Paper 452–A by reference to subsurface exploration and to dating. The two matters are closely related, for alluvial fills proved and sampled during exploration of the subsurface provide certain critical dates. The large channels that contain these fills support the interpretation of valley meanders as the products of erosion by former large streams. In addition, observations on valley meanders in relation to records of terracing, sedimentation, and the draining of proglacial lakes combine with results obtained in various connections by other workers to elaborate the sequence of incision and channeling. Although the presented material is organized under subheadings, there is in actuality considerable overlap from section to section, but the correlation eventually reached is meant to give a synoptic view of the whole.

FIELD EXPLORATION OF FILLED CHANNELS

ENGLAND

Other than the mapping of landforms, hand augering has been the writer's principal technique of investigation at sites on the English Plain and its borders. This technique is well suited to the local conditions of fine-grained alluvium. The valley fills contain little material coarser in grade than sand; they consist mainly of silt and clay, varied in places by peat, sapropel, tufa, and malm (earthy, amorphous calcium carbonate). A person working alone can auger to depths of 30 feet with a screw auger 1½ or 2 inches in diameter and to depths of 20 feet with a bucket auger 3½ inches in diameter. Reaching depths greater than 16 feet with the screw auger or greater than 12 feet with the bucket auger requires however, usually some dismantling of the shafting each time the auger is drawn up. No form of sheerlegs or derrick was found necessary. The normal bit of the screw auger can be made to penetrate a mixture of gravel and mud and can be screwed through self-cemented limestone gravel, but this auger is checked by uncemented gravel of resistant material, even when a special bit is used. Both the screw and the bucket types of auger seem capable of extracting clean samples from coherent deposits, although great care is needed in cutting away the crumbs and sludge that cling to the outsides of all samples. Experiments with a specially constructed corer, fitted with a piston to prevent collection of sediment during lowering, were discontinued when the piston was found to jam repeatedly. There seems to be no advantage in using corers of the type made for sampling peat, for they cannot be kept free of water and mud during descent. The screw-bit and, probably to a lesser extent, the bucket types clean themselves as they are driven in.

At the outset, samples were logged in detail at depth intervals of a few inches. As work progressed and the alluvial sequence was established for a given valley, it became possible to use the screw auger as a probe which could be forced through the weak fill and turned for a short distance at the base for a sample of bedrock. The junction between the base of the fill and the underlying rock almost everywhere was found to be sharp. First trials in the valley of the Itchen River of Warwickshire fortunately involved an abrupt transition from moist, gleyed alluvium to dry well-indurated shale or marl. Cemented bedrock can in places be identified from small fragments obtained with the bucket auger or from grains adhering to the pilot screw of the screw bit. For example, the alluvial fill of the valley of the River Perry in Shropshire consists of dull brown clayey silt, thin layers of intercalated gravel, and peat, all contrasting strongly with the bright-red grains of dry sand obtained from the underlying Triassic sandstone, whereas dry well-indurated oolitic fragments in the Cotswold valleys differ markedly from the moist yellow grains of decemented ooliths.

In a first series of field explorations, 53 cross profiles were determined by means of 290 boreholes in 6 valleys that contained manifestly underfit rivers (Dury, 1952; 1953a, b, c; 1954). The work was designed initially to test the hypothesis that if valley meanders are homologues of stream meanders, then homologues of stream channels could be associated in nature with valley meanders. Such homologues were identified at every site explored.

Subsequent work provided a further 27 profiles, determined from 216 boreholes in an additional 6 valleys (Dury, 1958). This second field exploration showed that the degree of underfitness is constant throughout the Cotswold region and permitted the onset of underfitness to be dated relatively to the beheading of the River Evenlode, to the spreading of congeliturbate on the floor of the Evenlode valley, and to the infilling of the large channel beneath the River Dorn. Records in addition to those published bring the writer's tally of profiles to 93, determined by some 600 boreholes in 18 English valleys; work now in hand by graduate students raises the total to more than 100 profiles in 22 valleys, without appeal to incidental records obtained by researchers in other studies or by civil engineers. Not all the additional material need be presented here, as part of it merely duplicates what is otherwise known; the record of channeling and filling will, however, be amplified below when chronology is discussed. The general outcome of subsurface exploration is to show that manifestly underfit streams on the English Plain are characteristically underlain by large channels which wind round the bends of valleys.

The large channels reach their greatest depths at or near the extremities of valley bends. At these sites they are asymmetrical in profile, sloping steeply down from the outside of the curve and less steeply across the inside curve—that is, they are identical in habit with the beds of meandering streams (fig. 1). The channels are much wider than the present streambeds, even when all possible allowance is made for difficulty in identifying their banktops, and they widen considerably at some valley bends; for use in comparison, widths have accordingly been taken at inflections between bends, where they are least. The average ratio of width between the large channels and the present channels, for a first series of nine determinations, is 11.5:1 (Dury, 1954, table 1). Such a ratio, or the convenient but approximate value of 10:1, immediately suggests discharges for the large channels of an order entirely different from that applicable to present channels. A firm suggestion that bed widths of the large channels have not been overestimated comes from the 13:1 ratio between the wavelengths of valley meanders and the determined bed widths (Dury, 1955). A wavelength and bed-width ratio of about 10:1 seems the most

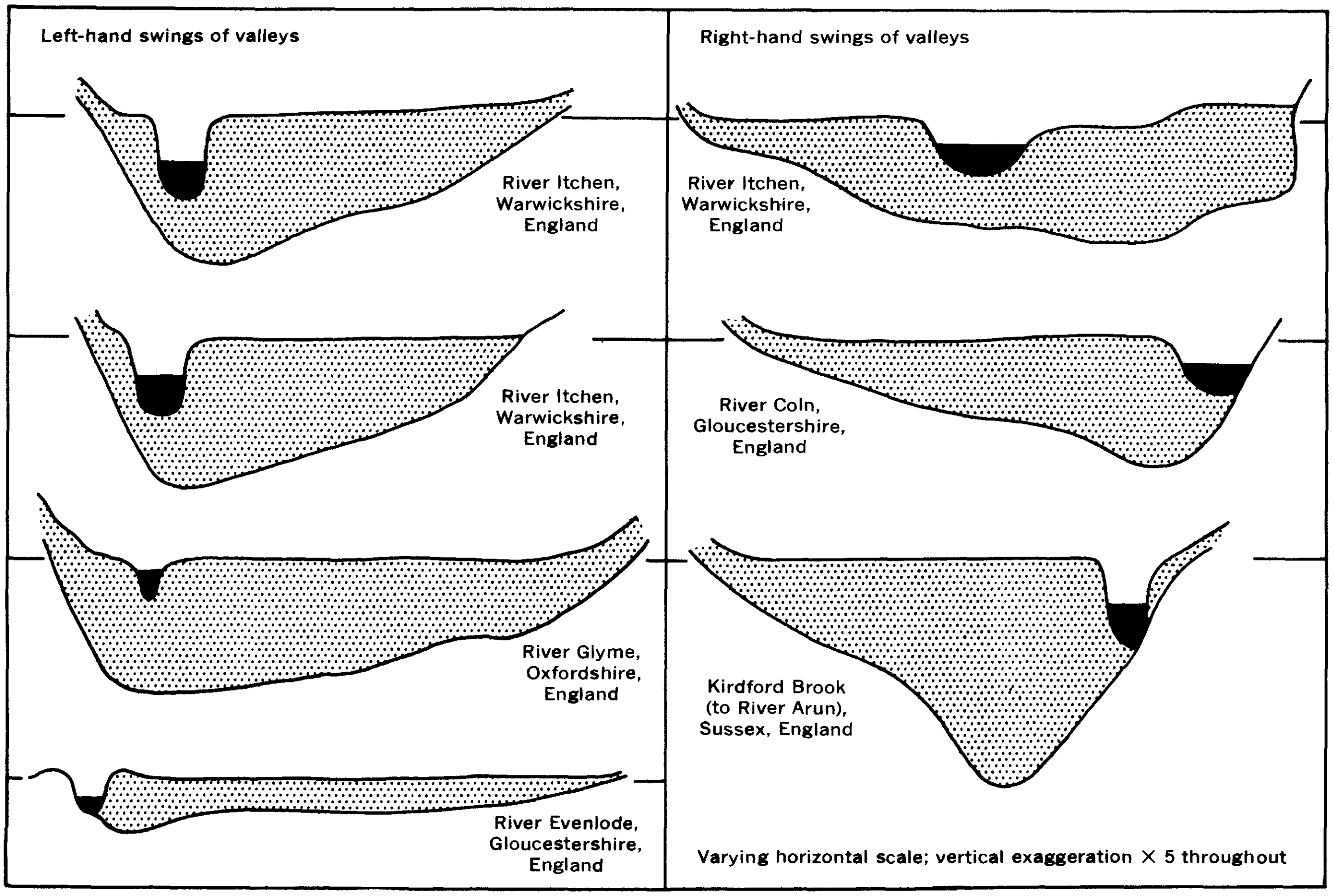

FIGURE 1.—Profile sections of filled channels beneath manifestly underfit streams showing asymmetry at valley bends. Views are downstream.

likely to apply to rivers in general (Leopold and Wolman, 1960; Bagnold, 1960). As wavelengths can be measured with some accuracy, the difference between 13:1 and 10:1 could be explicable by values of bed width that are too small. On the other hand, the measured channels are cut into coherent material, so that the high wavelength to width ratio may reflect nothing more than proportionally narrow channels with a somewhat high depth to width ratio.

Records for the Itchen River valley are now available from four reaches and have been used to make a graphic comparison of bed width and drainage area (fig. 2). It seems at least possible that the bed widths of the large channels on the Itchen system vary with drainage area in the form $W \propto M^b$,

where

W=width of channel bed, in feet;
M=drainage area, in square feet;
and b is a numerical constant.

Variation of the same type seems to apply also to the bed width and to the wetted perimeter of the present channels. More evidence of this kind, if it were available, could usefully be employed, but these observations do at least indicate that the large channels can be traced far up the valleys toward the heads. They also suggest that the disparity between bed widths increases headwards, as the disparity between wavelengths will later be seen to do. If so, the unusually high value of 11.5:1 for the ratio between respective bed widths of large channels and present channels may result, in part, merely from the smallness of the drainage areas involved. Even within the low range of observations on the Itchen, the bed-width ratio appears to fall from about 15:1 at 3 square miles to 9:1 at 40 square miles.

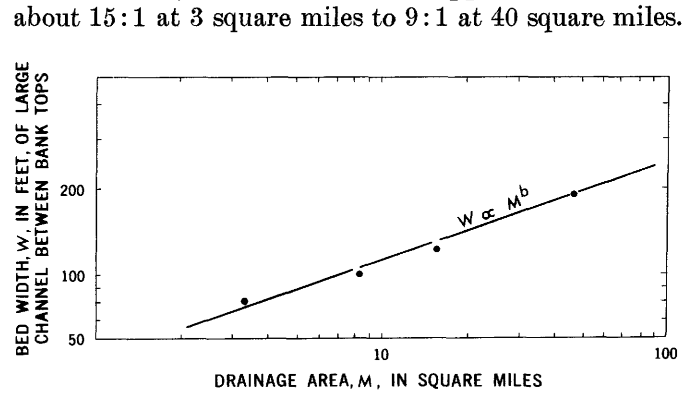

FIGURE 2.—Graph showing relation of bed width to drainage area of the River Itchen, Warwickshire, England.

However, as wavelengths and bed width are closely related and as the wavelength ratio between valleys and streams is normally found to be systematic, there is no great point in determining the bed width of large channels merely for purposes of dimensional record. Determination of cross-sectional area, on the other hand, has uses of its own, whereas analysis of sedimentary fills can obviously be instructive.

CHARACTER OF THE FILLS

On the Itchen, the sole consistent change in the vertical succession of alluvium is that from dull-brown cloddy columnar or prismatic clayey silt at the top to moist, blue-gray, gleyed clayey silt in the lower part. When the first records were made, the significance of gleying was not taken fully into account, and the two types of deposit were recorded as distinct. Subsequently, it has become clear that the difference is one between permanent waterlogging and seasonal waterlogging. In the absence of lithologic change it is impossible to define the base of the present flood plain, although the base of the large channel lies well below the maximum depth of scour in present conditions. Aquatic plants rooted in the streambed are not swept away by discharges at high stage, nor do the banks undergo general erosion at times of flood: the bed is not scoured severely enough to permit the stream to reach the base of the underlying filled channel, nor does the present channel widen sufficiently to provide the width to depth ratio which, on any reasonable view of channel form, would be needed if scour were to go down to the underlying bedrock.

In some other valleys the distinction between the alluvium of the flood plain and the underlying remainder of the fill is abundantly clear, especially where the fill beneath the flood plain is stratified. Such is the case with the Cotswold Rivers Glyme and Dorn, where the alluvial succession includes calcareous deposits that could not remain uncontaminated unless they were now out of reach of the streams which are reworking the silty clay of their flood plains and are carrying bedloads of sand. Sandy layers that extend horizontally through the fill at about the depth of the bottoms of pools mark the bases of the flood plains and indicate the present limit of scour. The fact that the fill of the Dorn valley remains undisturbed below the flood-plain base is confirmed by the fill's pollen content, which includes much birch, pine, and hazel, with elm becoming evident toward the top but with alder absent. Infilling began late enough for birch-pine forest to be established and, as shown by elm pollen, extended into the Boreal phase; but as alder is lacking, the sedimentary record does not reach the top (end) of the Boreal. Whether sedimentation did continue into the latest Boreal, to be partly obliterated by later erosion, is not material at this point. The preservation of a pollen assemblage notably different from that of today shows that the remaining sediments have not been reworked since they first accumulated.

Confirmatory observations come from the English River Rib, in Hertfordshire. The Rib flows off the back slope of the Chalk which rims the London Basin on the north. In its upper reaches, the valley is cut through or into thick outwash gravel that dates from the Penultimate Glacial—at least 30 feet, and possibly 40 feet, of gravel is exposed in a disused and overgrown working in the side of the valley. Four profiles (fig. 3) indicate a rather shallow filled channel occupied by clayey silt and floored by gravel. Natural changes of course and artificial straightening complicate the site, but at the same time they make it possible to discover that the fragmented bed load in an abandoned natural channel is separated from the underlying gravel by a layer of fine-grained fill (fig. 3, line 2). Here again, the signs are that scour in present conditions does not reach the floor of the large channel. Three and one-half miles downstream, where both the valley and the stream are larger, the Rib has entered a train of valley bends cut through the gravel into the underlying solid formation of Chalk, which is exposed in small quarries on both sides of the valley. A line of boreholes across the curve of a valley bend prove muck and peat to depths of nearly 30 feet below the surface of the flood plain (fig. 4). In some holes the auger was used mainly as a probe, but detailed logging at seven points reveals the wide extension of what seems to be a horizontal layer of peat. This, like the assorted fills of the Cotswold valleys, could scarcely have remained intact if it had been scoured by the present-day stream.

MODE OF INFILLING

To apply the term "aggradation" to the infilling of large channels is to beg the question. Reduction of a stream to a manifestly underfit condition necessarily lengthens the trace and thus tends to reduce the slope. Reduction of slope could be offset in part by degradation of downstream reaches and by aggradation of upstream reaches, but changes of this kind could not compensate in full, in numerous valleys, for the lengthening of trace. Lengthening must occur when stream meanders are superadded to the trace of valley meanders. The magnitude of lengthening is given by the ratio between distances measured along the curves of the valley and those measured along the present meanders of the stream; alternatively, straight-line distances from bend to bend or from bend to inflection to bend

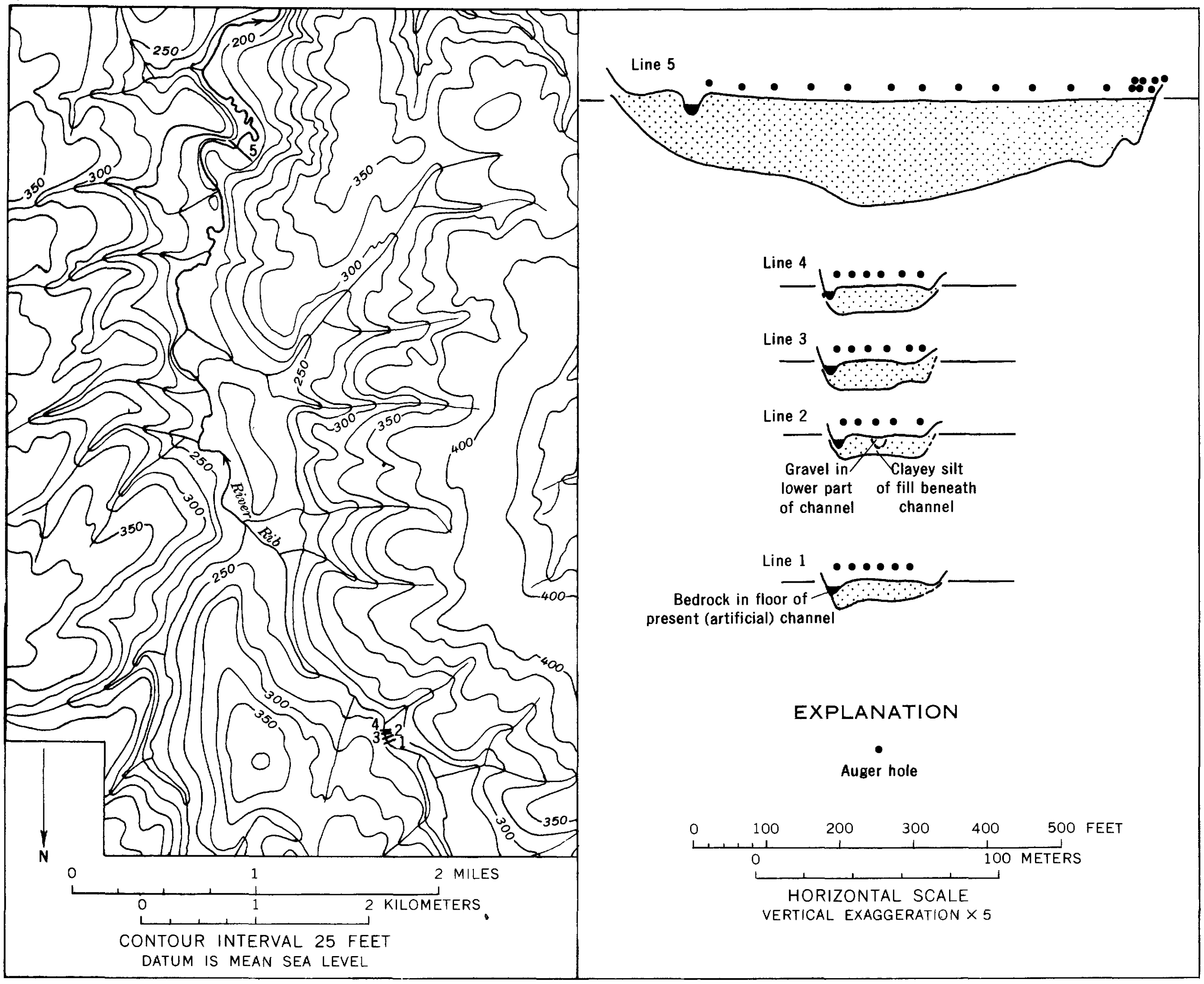

FIGURE 3.—Index map of the River Rib, Hertfordshire, England, and profile sections of channels, arranged in downstream order.

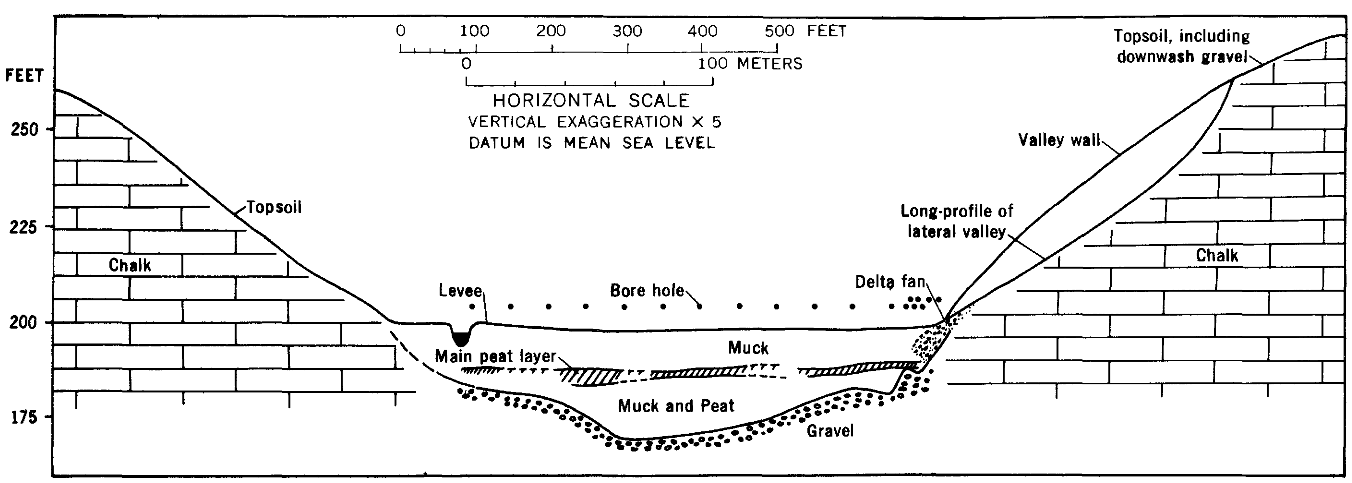

FIGURE 4.—Profile section of valley and channel of the River Rib. See figure 3, line 5.

may be used, according to understanding of the term "thalweg." A third possibility is to use axial distances, measured on straight lines where the axis of the valley is reasonably straight and on curves of the valley where the axis is that of an existing train of meanders. On any of the three reckonings, a modest estimate of the lengthening of Cotswold streams is that specified by a factor of 1.2; to compensate fully for this lengthening, the vertical difference between sources and mouths would need to increase in the same proportion (fig. 5).

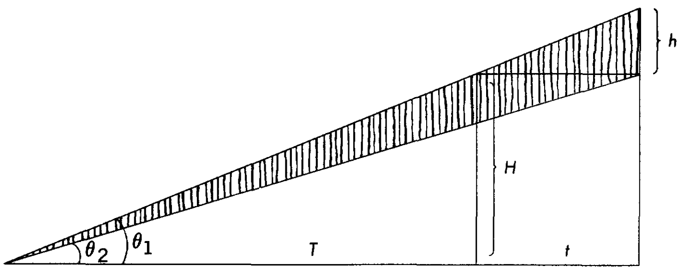

FIGURE 5.—Diagram illustrating hypothetical infilling as compensatory for lengthening of trace. Let T and H be, respectively, the length of trace and the total descent of a stream before the onset of underfitness; then $H/T=\tan\,\theta_1$, where θ_1 is the angle of downstream slope between source and mouth. If the onset of underfitness lengthens the trace to $(T+t)$, the angle of total downstream slope is reduced to θ_2, which i less than θ_1. The slope will be fully restored if H is increased by h where $H/(H+h)=T/(T+t)$. The required depth of infilling increases in the upstream direction, as shown by the shaded segment.

Now, there is no scope for degradation at the downstream ends, where levels are controlled by confluence with the trunk Thames, and all compensation would therefore need to be performed by infilling on the upper reaches. As shown in table 1, the depths of fill required by full compensation for lengthening of trace are great.

TABLE 1.—*Depths of infill required to compensate, on Cotswold streams, for the lengthening of trace induced by reduction to underfitness*

Stream	Approximate height, in feet above sea level		Vertical difference, in feet	Required depth of infill at source,[1] in feet, determined as ×0.2 vertical difference
	Confluence	Source [1]		
Cherwell	190	575	385	77
Churn	260	700	440	88
Coln	240	650	410	82
Evenlode	200	450	250	50
Dorn (to Evenlode)	200	650	450	90
Glyme (to Evenlode)	200	650	450	90
Leach	235	600	365	73
Windrush	210	750	540	108
Dikler (to Windrush)	210	750	540	108

[1] Present source: use of heights at the actual valley heads, upstream from the presently dry-head reaches, would increase the vertical differences and the required depths of fill.

No such deep fills have been located in the field. Indeed, the fills in some Cotswold head valleys are distinctly shallow (Dury, 1958, figs. 3–6). The fills on the Itchen increase in depth in a downstream direction and appear, moreover, to do so regularly. In actuality, there is a considerable range in depth of fill from valley to valley and also in the level of the floor of the present channel relative to that of bedrock (fig. 6).

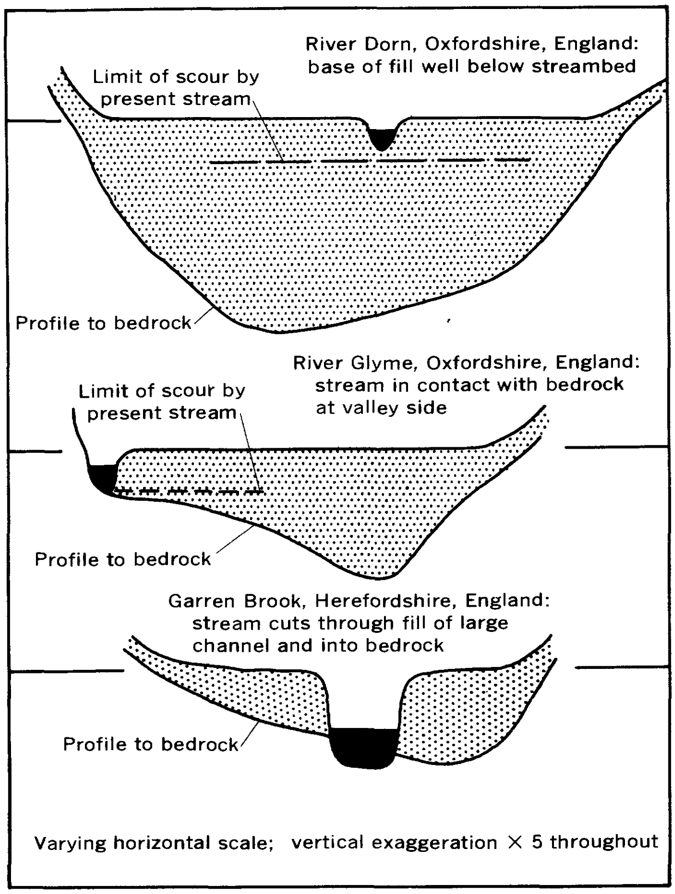

FIGURE 6.—Profile sections of English rivers showing relation of large channels to bedrock. Views are downstream.

The Cotswold Dorn is separated from bedrock in midvalley by 14 feet of sediment, whereas more than 20 feet of sediment intervene between the base of the present channel of the Rib and the gravel that lines the underlying large channel (fig. 4). The Cotswold Coln at the downstream end of the investigated reach is now scouring the bedrock at the base of its flood plain, and the Garren Brook of Herefordshire has cut through its valley fill and occupies a bed floored, and partly walled, by bedrock in place (fig. 6).

In the Rib valley the peaty layer, which is now some 10 feet below the surface of the flood plain, seems to indicate a pause of filling during which swamp established itself. In this respect, the investigated reach can be called aggraded. In general, however, a distinction between vertical and lateral accretion does not seem justified by the evidence. Vertical filling in many valleys seems to be no more than the counterpart of scour. The reduction in discharge at bankfull—strictly, in this context, at the frequency associated with bankfull flow—that made rivers underfit is thought to have involved constriction of the large channels in both planes while still providing scope for additional filling or for continued or subsequently resumed downcutting, according to site.

Vertical and lateral accretion are both possible where the fill is remarkably weak. Epping Forest, on the northern outskirts of London, provides illustrations of this circumstance every fall. Dead leaves shed copiously by hornbeam and beech collect in the channels of small streams in the forest; where fallen timber acts as dams, the leaves accumulate both at the bottoms and at the sides of the ponds, lining channels very similar in dimensions to those immediately above and below the ponded reaches. The beds and banks of channels formed in this manner consist, indeed, not so much of masses of leaves as of a loose mixture of leaves and water. Although infilling here results directly from damming and may thus be classed with aggradation, it nevertheless provides useful illustrations of possibilities. Parallel illustrations come from a drainage ditch, some miles to the northeast on the till plains of Essex, where the stream nourished by base flow has been observed to meander between banks of algae. Given a marked reduction in bankfull discharge, vertical accretion on the bed seems as practicable as lateral accretion on the banks. Accordingly, the infilling of the large channels ought not to be identified as aggradation unless the tops of the fills surpass in height the banktops of the large channels.

UNITED STATES

The fieldwork of 1960 began in the general neighborhood of Washington, D. C., with augering trials in small valleys in the Piedmont, in the eastern borders of the Appalachians, and on the Coastal Plain. The initial object was to test equipment and technique against a new set of conditions and to compare those conditions with the conditions of the English Plain. Results of the first trials were in the main limited and unhelpful, partly because the selected streams of the Piedmont and the Appalachians are working close to bedrock and partly because their alluvium includes gravel, cobbles, and boulders. Because the fills are shallow, any filled channels that may underlie small rivers cannot easily be distinguished from simple flood plains. Bed material of streams 10–20 feet wide commonly includes fragments measurable in inches along the *b* axis, whereas temporary sections revealed cobbles 6 inches in diameter in the alluvium of the Piedmont and boulders 1½–2 feet across (originating as congelifracts?) in that of the Appalachian foothills. Only near the heads of small estuaries of the Coastal Plain in the Delmarva Peninsula was the hand anger passed significantly lower than the base of the stream channels. The greatest depth below this base reached in any one borehole was 12 feet. Further penetration was prevented by gravel, and the base of the fill was not reached. Hand augering, so well adapted to the English Plain, was accordingly discontinued in the Washington region.

Trials were next made in the Driftless Area of Wisconsin, where manifestly underfit streams are numerous and where deep valley fills are reported. The Driftless Area is a plateau cut in Cambrian, Ordovician, and Silurian rocks, among which dolomite and sandstone are predominant. Dips are gentle; many of the steep-sided valleys are well capable of preserving the forms of valley meanders, and stream meanders occur in trains and are actively migrating along many flood plains. Debates on the number, identity, and origin of erosional platforms (see Trowbridge, 1921; Martin, 1932; Bates, 1939) do not immediately concern the present investigation.

Two examples of manifestly underfit streams from this region had already been cited by the writer (Dury, 1954, figure 1b, c), and the Kickapoo basin had been discussed by Bates (1939), who though recording a fill 50–125 feet deep and describing terraces, supposed the underfit character of the Kickapoo River to result from the sudden introduction of a flood plain by aggradation. Reconnaissance in 1960 and reference to well logs suggested that fills are indeed bulky, but many streams were found to resemble those of the Washington district in that they transport bed loads of gravel. Although the flood plains of the Driftless Area are typically silty and penetrable without difficulty by either type of hand auger, the cherty gravel that occupies the bottoms of many valleys cannot be drilled without power tools. A bucket auger will collect and raise fragments of rock, but boreholes cave rapidly below depths of 1 foot or so; no experiments were made with casing. Powered rigs seemed likely to involve difficulties of negotiation with farmers and also practical difficulties of access, for the determination of cross profiles usually requires drilling on both sides of a stream and, in some places, drilling into swamp. In these circumstances, a series of tests was performed with seismographic equipment light enough to be carried by hand across the streams. First results justified extension of the work, which, as will now be described, enabled four profiles to be determined. The seismic equipment also proved effective in valleys where the fill consists partly of quicksand; this material, although penetrable by auger to depths of about 20 feet, makes working very difficult by closing-in the boreholes and by clinging to the shaft.

SEISMIC REFRACTION

The principal seismic work was executed in the valley of the East Pecatonica near Argyle, Wis., and the valley of Mineral Point Branch near Mineral Point, Wis. (South Wayne quadrangle, Wisconsin-Illinois, 1:62,500, and Mineral Point quadrangle, Wisconsin, 1:24,000). As the tabulated results have been given elsewhere (Dury, 1962), the present account will be limited to a description of the equipment used, an outline of the two sites, and a summary of the results obtained.

The equipment consists essentially of a portable oscilloscope powered by a 12-volt wet battery. Operation requires a team of two—one to observe and record and one to operate the tamper by which shock waves are generated. The tamper is connected by cable to the oscilloscope; a jump switch in the handle closes the circuit when the tamper is beaten on the ground, causing a wave train to flash across the screen of the instrument. Delay time to a selected point on the wave train is read from a dial that controls the position of a marker on the screen. Shock waves are generated at selected distances along a graduated tape pagged on the line of sounding, which normally runs upvalley or downvalley—that is, at right angles to the desired line of cross profile.

In the vicinity of Argyle, the flood plain of the present river is some 200 feet below the level of the nearby plateau top. Immediately northwest of the town is a valley bend devoid of upstanding core, succeeded upstream by a second bend in the center of which the core survives (fig. 7). This second bend, in the angle made by the East Pecatonica and the tributary Mud Branch, was the one chosen for seismic exploration. As there is little or no channeled surface drainage, this abandoned loop seemed likely to retain in a sensibly intact condition any fill that might occupy a large channel. Because bedrock is accessible both on the meander core and on the steep outer slope of the curve, the site promised to allow some augering as a check on seismic observations. Three lines of sounding were run as a first trial, and 2 complete lines of cross section were subsequently determined by means of 22 lines of sounding and checked by 8 boreholes (fig. 8).

The sections indicate that a large channel is present, descending as low as 35 feet beneath the present surface of the ground. Its fill consists partly of fine- to medium-grained sand and partly of silt; where augering was possible, the sand appeared to underlie the silt. Infilling of the old loop appears not quite complete, for the ground is slightly hollow along the very bottom of the cutoff; however, it is difficult to decide what allowance should be made for downwash either from the hillside directly or from the remnants of silty terrace that line some parts of the outer curve. Like certain patches of terrace on Mounds Creeks (to be described below), these remnants appear to have originated as loess, although the precise mode of their emplacement is in doubt. On any reasonable view of the effects of downwash, the large channel seems to be not less than 800 feet in width at the minimum—that is, it seems to be more than 7 times as wide as the present stream between banktops.

No augering was possible on Mineral Point Branch, because the silt of the flood plain is underlain by coarse cherty gravel. Immediately upstream from the sounded reach, the valley is widely opened and parallel sided; but at the upstream line of sounding, at an inflection of the valley, it narrows to a width of 330 feet across the surface of the flood plain. The downstream line is near the extremity of a valley bend, where the floor widens to about 600 feet. After 3 trials, 12 lines of sounding were run; and most were checked by reverse spreads, connecting spreads, or both.

On the upstream section, where bedrock is exposed on both flanks of the valley, a large channel some 300 feet wide descends as low as 39 feet beneath the surface

FIGURE 7.—Panoramic view of cutoff valley bend near Argyle, Wis. Hill in center, middle distance, is meander core of bedrock; foreground is floor of cutoff.

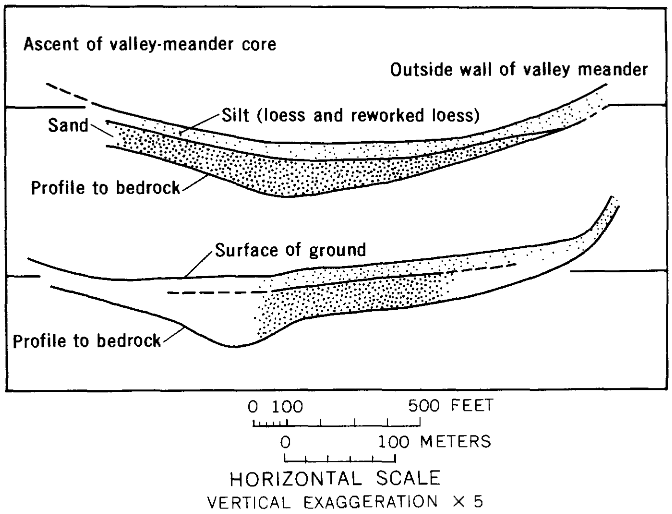

FIGURE 8.—Profile sections of large channel of the East Pecatonica River near Argyle, Wis. Views are downstream.

of the flood plain (fig. 9). The present limit of scour appears to be some 10 feet below the flood plain surface, judging by the depth of a pool excavated in 1960 by high discharges at a particularly abrupt bend. If, however, the dark bed in the silty alluvium that overlies the gravel at a depth of about 4 feet below the flood-plain level corresponds to the buried first-bottom soils identified by Happ (1944) on the Kickapoo River, then the maximum depth from the flood plain of the base of the large channel was but 35 feet in the middle of last century. This is still not to say that the flood-plain surface of 1850 corresponded to the bankfull level of the large channel when it was occupied by the former stream, but a width of a little less than 300 feet appears probable, no matter where the former bankfull level is established.

On the downstream section (fig. 9), the large channel broadens, deepens, and becomes directly asymmetrical in cross section. Its maximum depth below the surface of the flood plain is 45 feet, reached close to the outside of the valley bend. The cross section defined in figure 9 by the profile to bedrock undoubtedly includes a massive point bar similar to those on other rivers where the filled channels widen greatly at valley bends.

Both Mineral Point Branch and the East Pecatonica near Argyle are manifestly underfit. Large channels occur on both that are similar in their relation to valley bends and their disparity with present channels to the large channels proved on the English Plain. No stream now flows in the cutoff loop near Argyle; but on Mineral Point Branch, where a stream exists above the valley fill, it seems impossible that the fill is subject to reworking except in its topmost part, which supplies the present bed load. Here, as in most of the investigated valleys of England, conversion to underfitness has been accompanied by infilling and by insulation of the stream from the underlying bedrock.

ALLUVIAL SECTIONS

BLACK EARTH CREEK, WISCONSIN

Hand augering proved effective in the valley of Black Earth Creek and the neighboring valley of Mounds Creek, Wis. Ten alluvial profiles were determined from 93 boreholes on Black Earth Creek in the 6 miles between Cross Plains and Black Earth (fig. 10).

Whereas many valleys in the Driftless Area describe bold well-formed incised meanders, the valleys of Black Earth Creek does not. If the valley of Black Earth Creek contains large meandering forms in depth, these are concealed by a deep fill of surficial material.

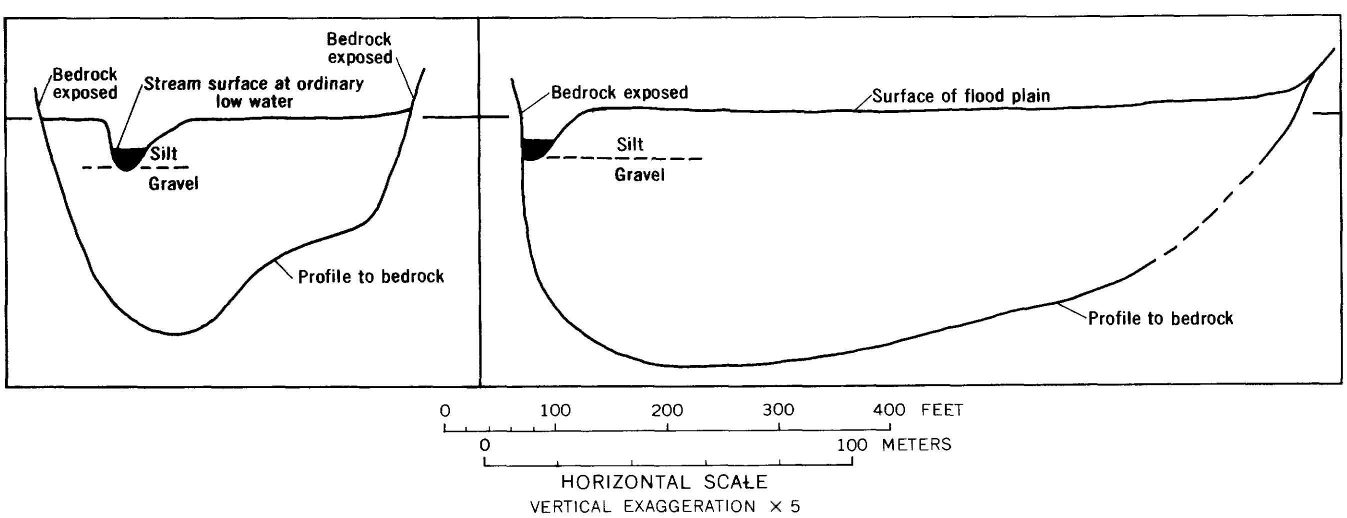

FIGURE 9.—Profile sections of large channel of Mineral Point Branch, East Pecatonica River, near Mineral Point, Wis. Views are downstream.

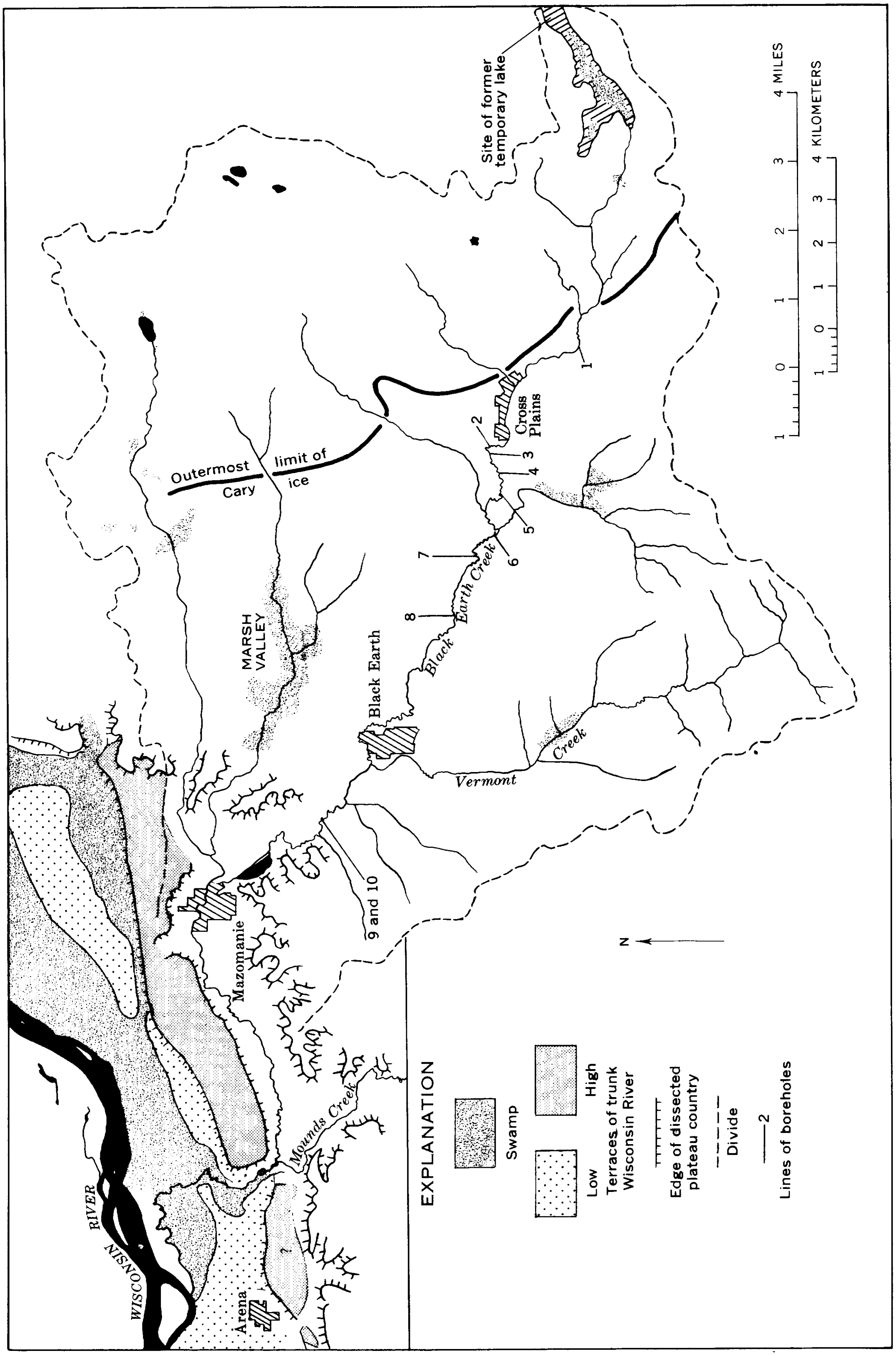

FIGURE 10.—Index map of the area of Black Earth Creek, Wis.

Straight elements in the local valley system probably result from structures that strike roughly southwest, west, or west-northwest (Judson and Andrews, 1955; Heyl and others, 1959, p. 31 ff.). As the Precambrian lies at most a few hundred feet below sea level, linear elements in the structures of exposed Cambrian and Ordovician rocks are not surprising; subdued hills flanking Black Earth valley rise but to 1,050 to 1,200 feet. The bounding divide is capped in places by Ordovician dolomite, but the bulk of the hills consists of Ordovician or late Cambrian dolomite and sandstone which are carved into steep valley walls that rise abruptly from the valley floors. Although its valley is almost straight, Black Earth Creek displays two sets of meanders. The existing river winds on a flood plain that is itself sinuous (fig. 11). Black Earth Creek is manifestly underfit.

Now certain fixes on the local scale of chronology, which are easily obtained by reference to the sequence and distribution of surficial deposits, make Black Earth Creek particularly suitable for detailed study. During the maximum of the Wisconsin Glaciation, the trunk Wisconsin River was a major outlet for melt water and outwash, which it led across the Driftless Area to the Mississippi River near Prairie du Chien. The outermost limit of Wisconsin ice is marked locally by the Johnstown Moraine (Alden, 1918), which is referable to the Cary Stade as understood by Thwaites (1943) and probably to the Valparaiso Moraines in the Woodfordian substage of Frye and Willman (1960). Names of glaciations and stades are less significant here than the placing of the Johnstown ice stand not long before the Two Creeks Interstade. Ice standing on the line of the Johnstown Moraine discharged melt water and outwash not only along the Wisconsin River valley but also along certain feeder valleys, including the Black Earth valley (fig. 12). Backwater flooded the downstream ends of some laterals, depositing sediment in them. The topmost surface of the fill constitutes the High Terrace of the Wisconsin River (MacClintock, 1922).

The Johnstown Moraine crosses the Black Earth valley about 2 miles east of Cross Plains, and the valley downstream of the moraine is thickly infilled with outwash. Alden (1918) conjectures that the fill may be 250 or 300 feet thick in the Wisconsin valley near Mazomanie; the grestest known depths of fill in Black Earth valley are 130 feet in a well at Black Earth village, 45 feet (unbottomed) at Cross Plains, and 50 feet reported for the gravel workings between Cross Plains and Black Earth. Because all three sites are close to the valley wall, the stated thickness are minimal, as is the 30 feet somewhat dubiously indicated by seismic readings (fig. 13). The seismic-sounding sites were near the left-hand [1] edge of the flood plain, about halfway between Black Earth and Mazomanie, and as shown on line 10 in figure 10.

Not all the fill of Black Earth valley need be of Cary (Valparaiso) age, but the topmost part certainly

[1] Right hand and left hand, here and throughout, are referenced to the downstream direction.

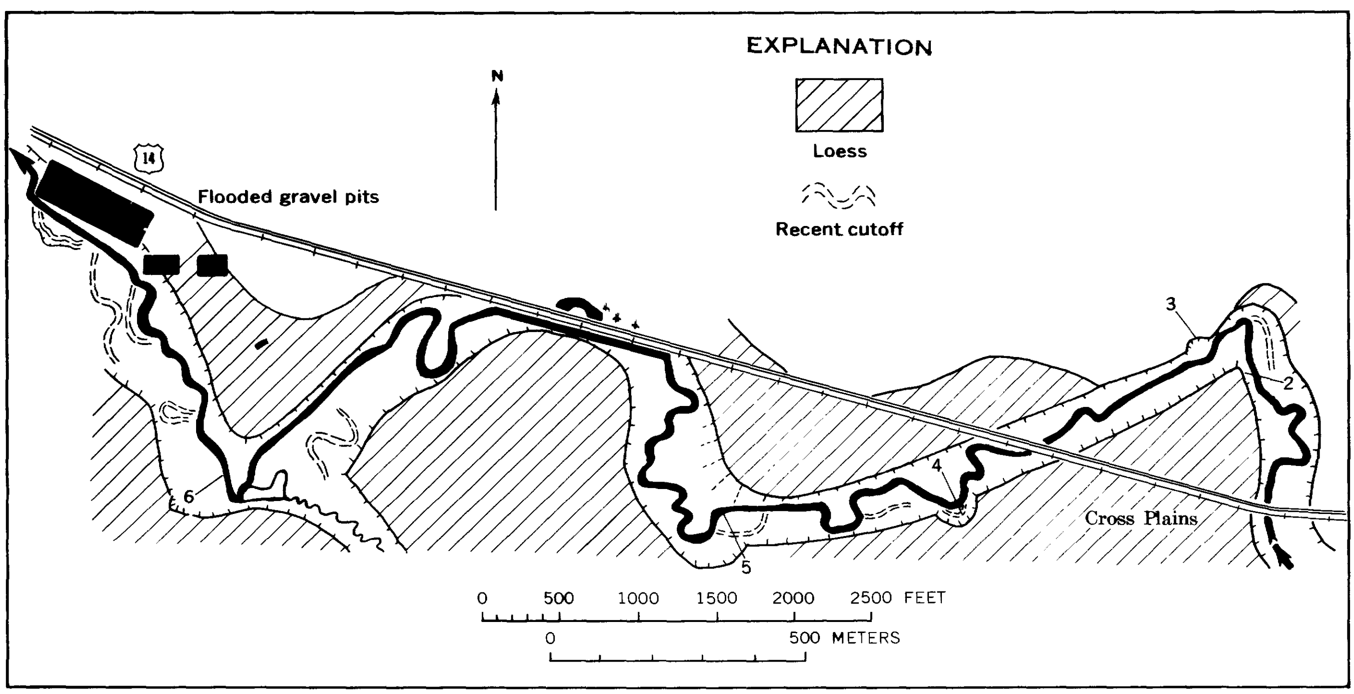

FIGURE 11.—Sketch map of part of Black Earth Creek showing valley meanders. Mapped from aerial photographs and planetable survey.

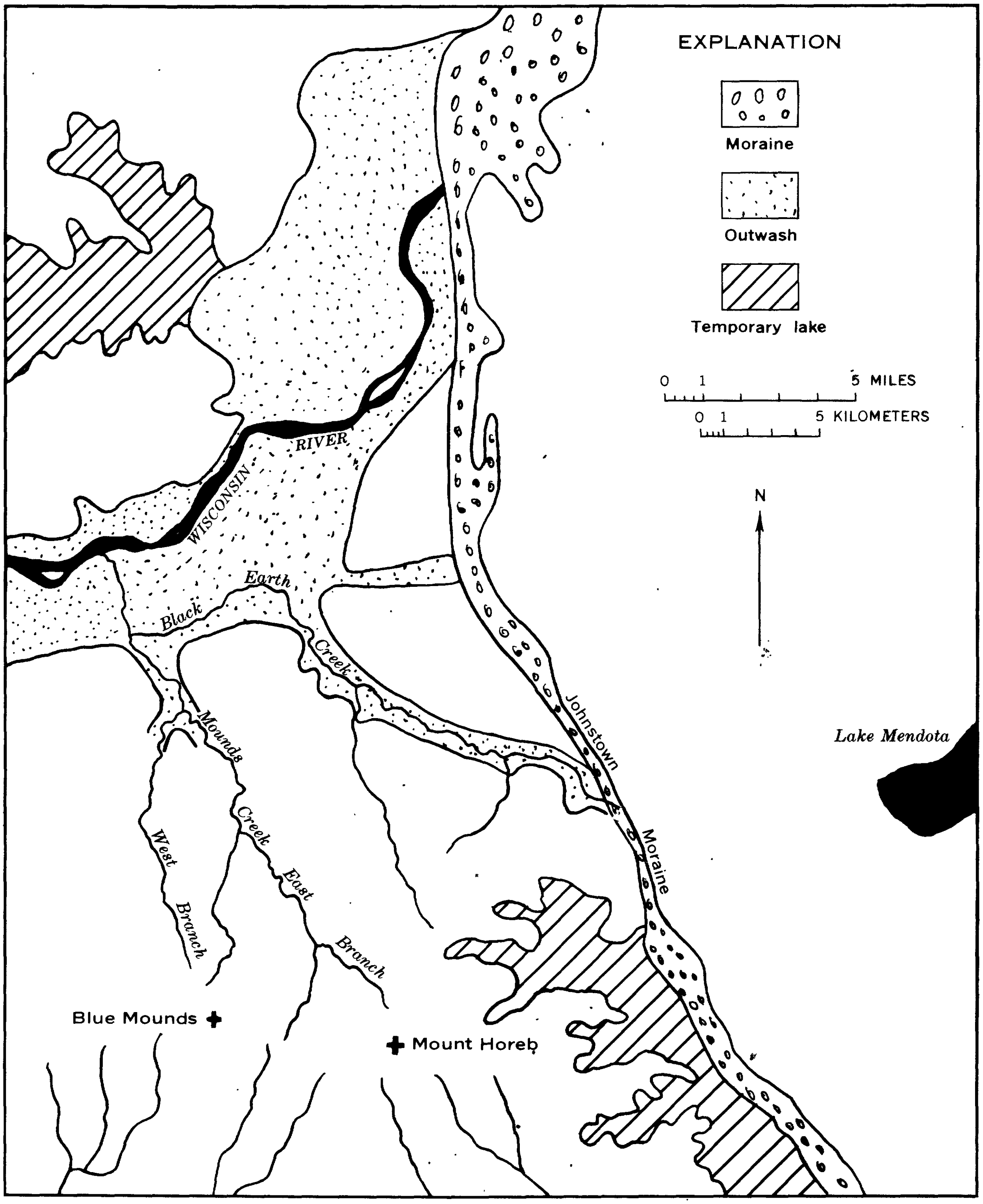

FIGURE 12.—Sketch map showing relation of ice front to Black Earth Creek and Mounds Creek, Wis.

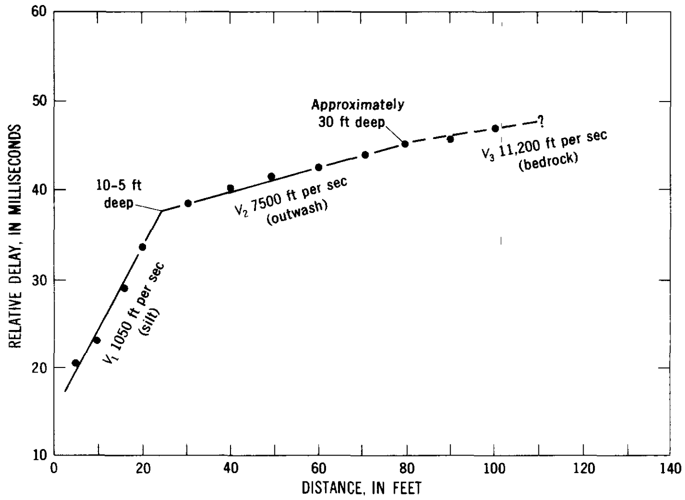

FIGURE 13.—Graph showing relation of time to distance in seismic refraction sounding at Black Earth Creek, 55 feet from left-hand edge of flood plain midway between Black Earth and Mazomanie.

is. The continuity of Johnstown Moraine with the outwash train was well shown in 1960 in the gravel working on the north side of U.S. Highway 14. So much outwash passed down Black Earth valley that the mouths of laterals were choked. Silt accumulated thickly behind the obstructing sand and gravel and eventually provided the foundations of swamp. In Marsh valley, which is tributary at Mazomanie, 8 feet of peat has been proved to overlie 33 feet of silt, which in turn rests on surficial sand (Mississippi Univ., 1957). The middle reaches of the valley of Vermont Creek are notably peaty, and a sizable peat bog occurs in the large feeder valley next downstream from Cross Plains on the left-hand side of Black Earth Creek. The mouth of the Black Earth valley may have been similarly choked as the trunk Wisconsin valley was infilled, but outwash in Black Earth valley was deposited thickly enough to provide a continuous downstream slope from the Johnstown Moraine at about 900 feet above sea level to the top of the High Terrace near Mazomanie at about 800 feet above sea level. The one possible sign of obstruction is the right angle that Black Earth Creek makes where it leaves the plateau, but this angle may result from nothing more than the growth of a levee on the Wisconsin River—that is, it could be associated with a deferred tributary junction.

So far as is known, the topmost surface of outwash in Black Earth valley is remarkably flat in cross section except beneath the flood plain, where it has been slightly eroded. The flatness is probably referable to the reworking and deposition of outwash by a braided stream similar to many of the streams that now discharge from ice fronts. Cessation of outwash and abandonment of the braided habit cannot be dated precisely to the withdrawal of ice from the Johnstown line but cannot have been long delayed thereafter. The first withdrawal produced a temporary lake at the head of the valley about 4 miles east of Cross Plains (fig. 10); the site is now marked by a drained bog that is crossed by the present divide near its east end. Although melt water could still have passed into the valley by way of the lake, and presumably did so, there is nothing to show that the flat outwash surface relates to the lake level of about 920 feet above sea level rather than to the stand of ice at the Johnstown line. The outwash is covered across the whole width of the valley by loess which, lying banked against the bases of the valley walls, rises onto and passes across the hummocks of the Johnstown Moraine. At least in part, therefore, this loess postdates the withdrawal of Wisconsin ice from its local extreme limit. By the time loess deposition was completed, the ancestral creek was flowing not in braids but in large meanders. These are developed in, and cut slightly through, the loses. They are thought not to have been cut by a melt-water stream and thus to postdate in origin the last discharge of melt water and outwash. If a braided stream flowed from the temporary lake, they postdate the lake also. The view that the creek which developed and incised the large meanders was not a stream of melt water is supported not merely by comparison with existing melt-water streams but also, as will be seen shortly, by the behavior of the neighboring Mounds Creek and the mode of development of certain laterals of Black Earth Creek itself.

Because the outwash train in the Black Earth valley is correlative with the High Terrace of the Wisconsin River, it is neither necessary nor possible to follow Alden (1918) in ascribing the High Terrace to a substade earlier than that responsible for the Johnstown Moraine. Reference of the large meanders of Black Earth Creek to a time rather later than the Johnstown ice stand is supported by the relation between Black Earth Creek and the High Terrace near Mazomanie. Immediately northwest of this settlement, a large abandoned bend cuts into the High Terrace. Traces of other comparable loops may exist farther downstream, but the lower part of the creek is so strongly rejuvenated that little of such loops remains. The floor of the single intact bend, however, lies more than 30 feet below the level of the High Terrace and falls below the projected line of the profile above Mazomanie (fig. 14), evidently having been cut after the lower part of Black Earth Creek was rejuvenated by the fall of the trunk Wisconsin from the High Terrace level. Without very detailed leveling it is impossible to say what traces of the Low Wisconsin Terrace may exist along the lower, strongly rejuvenated part of Black Earth Creek, but the

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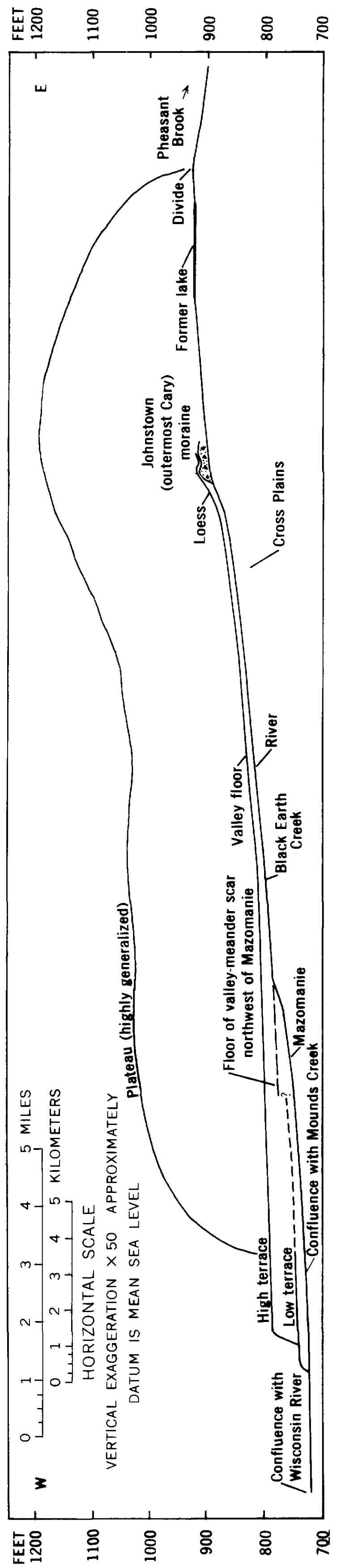

FIGURE 14.—Longitudinal profile of Black Earth Creek, Wis.

evidence available is at least sufficient to show that the large meanders persisted here after the High Terrace had been abandoned.

The large meanders of Black Earth Creek are more regular than many of the windings of the present channel (fig. 11), and their slip-off slopes can be identified in places, mainly in the reach midway between Black Earth and Cross Plains. The trough that contains the present flood plain is regarded as modified from the large channel associated with the large meanders. That channel can have been about 10 times as wide as the present channel, just as its meanders are about 10 times as long as the meanders of the existing stream, area for area of drainage. The 10:1 ration ensures that the present meanders fit rather neatly into the trough provided by the large channel.

Rejuvenation affects the present stream almost as far upstream as Cross Plains, so that it is only near Cross Plains itself that the base of the former channel can be demonstrated to survive. Lines and groups of boreholes drilled at intervals from a point 2 miles upstream from Mazomanie to 1 mile downstream from Cross Plains all show the present stream in direct contact with the outwash and tending at most places to shift the outwash (fig. 10; fig. 15, lines 5–10). At lines 9 and 10 the present meanders are sweeping downvalley while at the same time tending slightly to incise themselves. Consequently, the surface of the flood plain is scalloped by the tiny curved bluffs of recent cutoffs, and the top of the outwash is distinctly irregular in detail, as shown by the profile on line 10. Although sections through recent cutoffs suggest that fragments transported through the present meanders are as much as 2 inches across, much of the outwash is far coarser than this and includes blocks 1 foot or more long. Cobbles removed from some existing pools accumulate as bars on the downstream limbs of meanders. Islet building or incipient braiding occurs 2 miles above Mazomanie and again at 2 miles and 3 miles above Black Earth village. Within the large right-hand loop at this last site—that is, between lines 6 and 7 (fig. 15) and opposite the flooded gravel pits (fig. 11)—come the last obviously ingrown meanders of the present series, with the outer bank perceptibly higher to the unaided eye than the inner bank. This is not yet the upstream limit of rejuvenation, however. On line 5, at the apex of the large left-hand bend next below Cross Plains, the pool of a stream meander descends into the gravel; the surface of the gravel lies 4 to 4½ feet beneath the top of the flood plain, whereas the pool goes down to 5½ feet. Still farther upstream, on line 4, the present stream has cut into and again retreated from the side of the trough. Instrumental leveling discloses a faint slip-off slope and suggests that slight rejuvenation is felt as far upstream as this line.

On lines 6 and 5 (fig. 15), the base of the flood plain is so nearly flat that the present alluvium seems to be contained in a well-defined meander trough. On line 4, however, details of a new kind appear. Borings reveal a broad spread of medium- to coarse-grain sand at the base of the peaty alluvium of the flood plain. Beneath this sand, in a shallow depression, is a layer of clayey silt that reappears in greater thickness on line 2. The vertical succession in this reach is striking—dark peaty silt above is followed downward by jet-black somewhat silty spongy peat; next comes a thin layer of sand that is yellowbrown to gray, wet, and incoherent; and then comes the clayey silt, which is dark on line 4 but light gray, compact, and no more than moist on line 2.

These various deposits are interpreted as follows: The clayey silt is the remnant of a valley fill, contained in the pool of a large former meander; the sand represents the base of the present flood plain; and the high proportion of peat in the lower flood-plain alluvium results largely from growth in place, whereas the silty content of the upper alluvium indicates deposition by the spilling river. This last contention is supported by the presence of faint levees indicated by instrumental survey.

On Black Earth Creek, therefore, as on numerous other streams of the manifestly underfit type, the alluvium of the flood plain rests unconformably on the fill of a large channel. What here remains of the former pool and its fill seems to have been preserved by a combination of favorable circumstances—the very slight extent of the downcutting now in progress, and the resistance of solid rock at the apex of the large bend. At the right-hand end of line 3, the present stream has cut a meander scar into the solid rock of the valley wall, the channel perhaps shifting across a bedding plane. The former large stream was compelled to make an abrupt turn through 90°. It is possible, therefore, that this particular large pool was unusually deep and also that it has been to some extent defended by firm rock in place.

No additional pools have been found higher upstream, but numerous boreholes in the very swampy flood plain immediately above Cross Plains have penetrated gravel at a fairly uniform depth.[2] A line across the left-hand side of the flood plain on the last possible large bend 1 mile southeast of Cross Plains (line 1) produced inconclusive results. Although the present stream bed stands a little higher than the base of the alluvium, powerful

[2] Leveling was impracticable at this site, and no transverse line of boreholes conld be run.

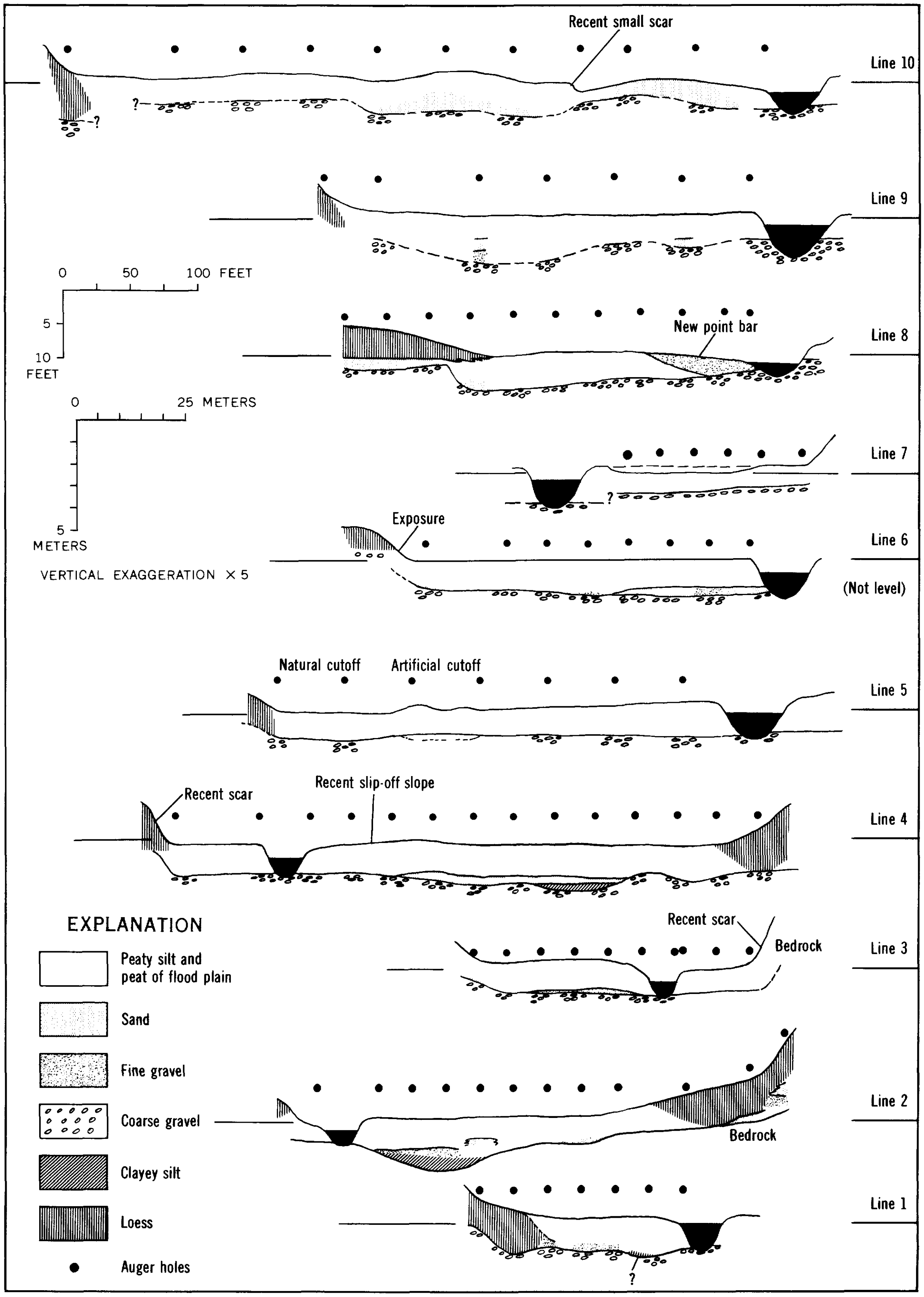

FIGURE 15.—Profile sections showing flood plain and associated features, Black Earth Creek. Views are downstream.

seepage from an adjoining hill makes the site very swampy; and it is impossible to say whether or not the gray peaty clayey silt penetrated near the stream represents the fill of the old channel or whether it results from contamination of present alluvium by loessal material from the nearby hillside. If part of the old channel does survive here, then the present stream is fluming pebble gravel through a silt-lined bed.

Large meanders occur on some of the laterals of Black Earth Creek, in valleys which were emphatically not invaded by ice during the Wisconsin Glaciation[3] (fig. 16). Any suggestion that these valleys may have

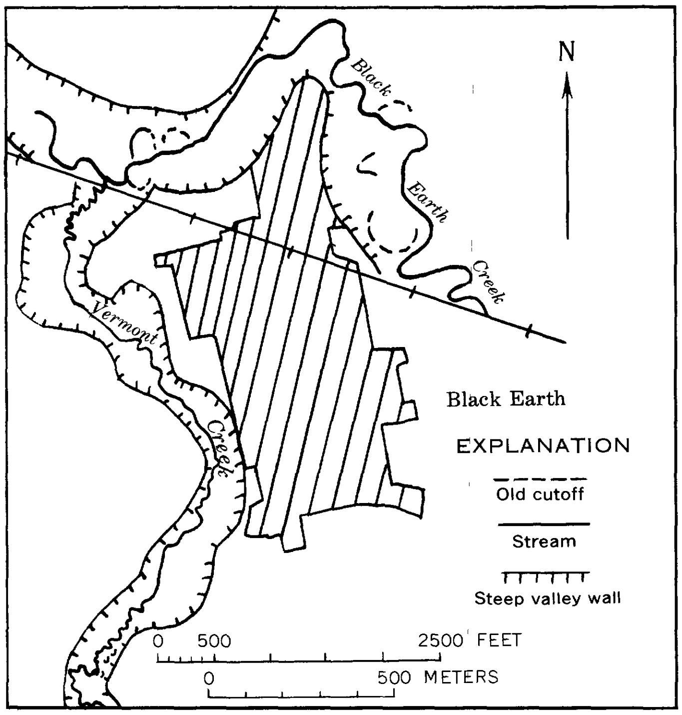

FIGURE 16.—Sketch map showing entry of Vermont Creek, a lateral stream, into Black Earth Creek. Valley bends of Vermont Creek are cut through loess.

been invaded by pre-Wisconsin ice and received large increments of melt water at some early time is not relevant to the present investigation; for their large meanders are cut through lateral extensions of the latest loess down to the level of the existing flood plain of Black Earth Creek. Like the large meanders of the trunk stream, those of the feeder streams postdate the Johnstown ice stand and the subsequent episode of loess deposition. Moreover, the wavelength of valley meanders in the Driftless Area as a whole, at 50 square miles of drainage, is about 8 times that of present meanders; to explain the large meanders of Black Earth Creek, there is no reason to appeal to direct outwash. Those meanders, like the large meanders of lateral streams, constitute a sample of the phenomena typical of the whole region, which are dissociable from the discharge of melt water.

The minimum outline sequence required by the observed landforms is therefore the following:

1. Discharge of melt water and outwash from the Johnstown ice front, with construction of the High Terrace on the Wisconsin River and the correlative outwash train in Black Earth valley; choking of the mouths of valleys lateral to Black Earth Creek.
2. Recession of ice from the Johnstown line, with formation of temporary lake; deposition of loess, continuing after the draining of the temporary lake; conversion of the ancestral Black Earth Creek from a braided to a meandering habit.
3. Considerable lateral growth and slight incision of large meanders.
4. Rejuvenation of the lower reaches, referable to a fall in level of the trunk Wisconsin. (See below.)
5. Reduction in volume (at bankfull), with conversion to small meanders and formation of existing flood plain; continued rejuvenation of lower reaches and slight rejuvenation along much of the river.

MOUNDS CREEK, WISCONSIN

Mounds Creek heads in the high ground near Blue Mounds and Mount Horeb. Its drainage basin was not invaded by ice during the Wisconsin Glaciation (fig. 12) nor is it thought to have been invaded during earlier glacials. In consequence, Mounds Creek serves to demonstrate the landforms produced by periglacial conditions, those which occur very close to the ice front but in the absence of outwash and melt water. Like the valley system of Black Earth Creek, that of Mounds Creek hints very strongly at guidance by structures in the solid; many of its elements are alined from south-southeast to north-northwest or from south-southwest to north-northeast. In their middle and lower parts, the valleys both of West Branch and of East Branch are steep sided and wide bottomed. There is room—but perhaps not ample room—for large meanders, to the trace of which the present meanders are superadded. Like Black Earth Creek, both branches of Mounds Creek are underfit, although they cannot be described as flowing in meandering valleys unless the semblance of valley bends on the upper reaches of East Branch is authentic.

As Mounds Creek received no melt water or outwash from its valley heads, the High Terrace simply invades the valley from the lower end. The Low Terrace

[3] This statement does not prejudice, nor is it prejudiced by, the revisions which Prof. Robert F. Black, University of Wisconsin, is making in the location of former ice fronts on the margins of the Driftless Area.

(MacClintock, 1922) is also present, as it is upon the lower reaches of Black Earth Creek; but whereas the relation of the Low Terrace to the present flood plain on Black Earth Creek is obscure, on Mounds Creek it is clear. In consequence, the sequence definable for Mounds Creek elaborates that presented above for Black Earth Creek.

Augering at four sites, seismic sounding at one, reports of bridge piling, and inspection of the ground combine to show that Mounds Creek occupies a cut that descends well below the surface of the flood plain and contains an assorted fill of loess, sand, silt, gravel, and peat. The gravel visible in the stream bed, on the line of the Elvers profile, rises upstream above the banktop level but descends downstream to lie beneath the flood plain at Grim's Farm (fig. 17). That is to say, the gravel slopes more steeply downstream than does the present stream. As far as is known, the gravel consists wholly of local material, mainly chert and dolomite rock.[4] On various grounds, this gravel can be referred to periglacial weathering, and its latest production can be referred to a time slightly predating the formation of the High Terrace. As on Black Earth Creek and the Wisconsin River, the High Terrace results from flooding by sediment-laden melt water. On Mounds Creek the gravel descends across the line of the High Terrace surface—which is here horizontal—and also across the profile of the later Low Terrace. It thus appears to predate both.

Such information as was established by 33 boreholes on 3 lines of profile on East Branch is illustrated in figure 18. Although the cross sections fail to reveal much distinct evidence for any former channel associated with the large meanders, they contribute to the understanding of the valley fill.

The slight depression in the surface of the gravel on the line of the Pigpen profile may well be a former channel floor, in which case the rise of the gravel towards the present streambank is an old point bar; this profile was taken across a bend of the valley to the right. Here, as on the line of the Elvers profile next downstream, the present flood plain is but slightly developed; near Elvers it consists merely of discontinuous berms in a narrow trench, the valley floor being almost completely occupied by terrace. Where exposed in section, the terrace appears to consist of interstratified peat and silt, but augering shows that the upper part is mainly silty whereas the lower part is mainly peaty; the silt is regarded as reworked loess. Toward the right-hand side of the Elvers profile, a second peaty layer, containing partly humified brushwood, occurs near the base of the fill, separated from the main peaty layer by a thin deposit of loess which, thickening towards the right-hand valley wall, merges into the bank of loess against the hillside. The very slight depression in which the lower peat lies may possibly be part of a former large channel.

Although Mounds Creek near Elvers is in contact with bedrock along its left side and with the underlying gravel on the streambed, little gravel seems to be undergoing downstream transport. At Grim's Farm, downstream of the Elvers site, the banks of the present channel consist of silt, and the bedload consists of nothing coarser than sand. Furthermore, the alluvium beneath the present streambed is almost wholly silt, down to a depth below the surface 2½ times as great as the depth to the bottom of the channel. At its base, the silt becomes admixed with small gravel, which appears at a depth of about 10 feet across most of the line. The recorded base of the silt and gravel comes where the auger was finally obstructed, so that its irregularity may not be particularly significant. Although this site is not especially propitious for seismic work—at least it proved not to be in the wet conditions of September 1960—two satisfactory lines of seismic sounding indicate a depth to bedrock of more than 50 feet roughly in midsection (figs. 19, 20), so that the gravel may be more than 40 feet thick.

Both near Elvers and at Grim's Farm, loess and sand complicate the identification of terraces. On the Elvers profile as on the profiles taken on Black Earth Creek and in the Pecatonica valley near Argyle, sandy bands appear within, and especially at the base of, deposits of loess. These may originally have been windborne, at least in part. At the left-hand end of the Grim's Farm profile, simple downwashed sand appears to occur both at the base and at the top of the augered section, but sand at the right-hand end forms parts of a remnantal terrace. As the scrap of terrace lies perceptibly below the level of the High Terrace, its top is here referred to the Low Terrace.

The whole valley fill near Grim's Farm is too wet, too weak, and too obscurely assorted to permit identification of any former large channel; and patches of terrace that remain along the sides of the valley are too small to indicate the trace of the former large meanders. Near Orcutt Farm, however, there is a broad strip of Low Terrace that extends upstream to and beyond the confluence of the two branches. Although the present meanders are migrating freely and the river is cutting slightly downward so that the fore edge of the Low Terrace is scalloped at more than one level, the large meanders are manifestly sunk into the Low

[4] George F. Hanson of the Wisconsin State Geological Survey kindly examined a 15-pound sample taken from the streambed a little way upstream of the Elvers profile.

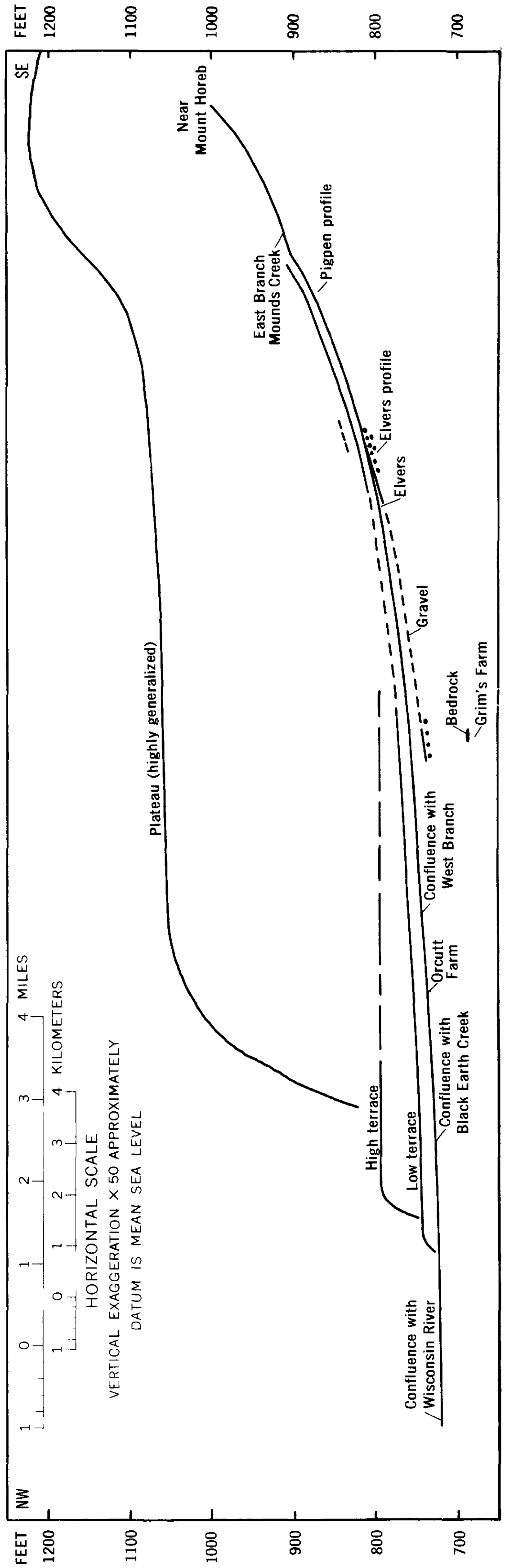

FIGURE 17.—Longitudinal profile of East Branch Mounds Creek, Wis.

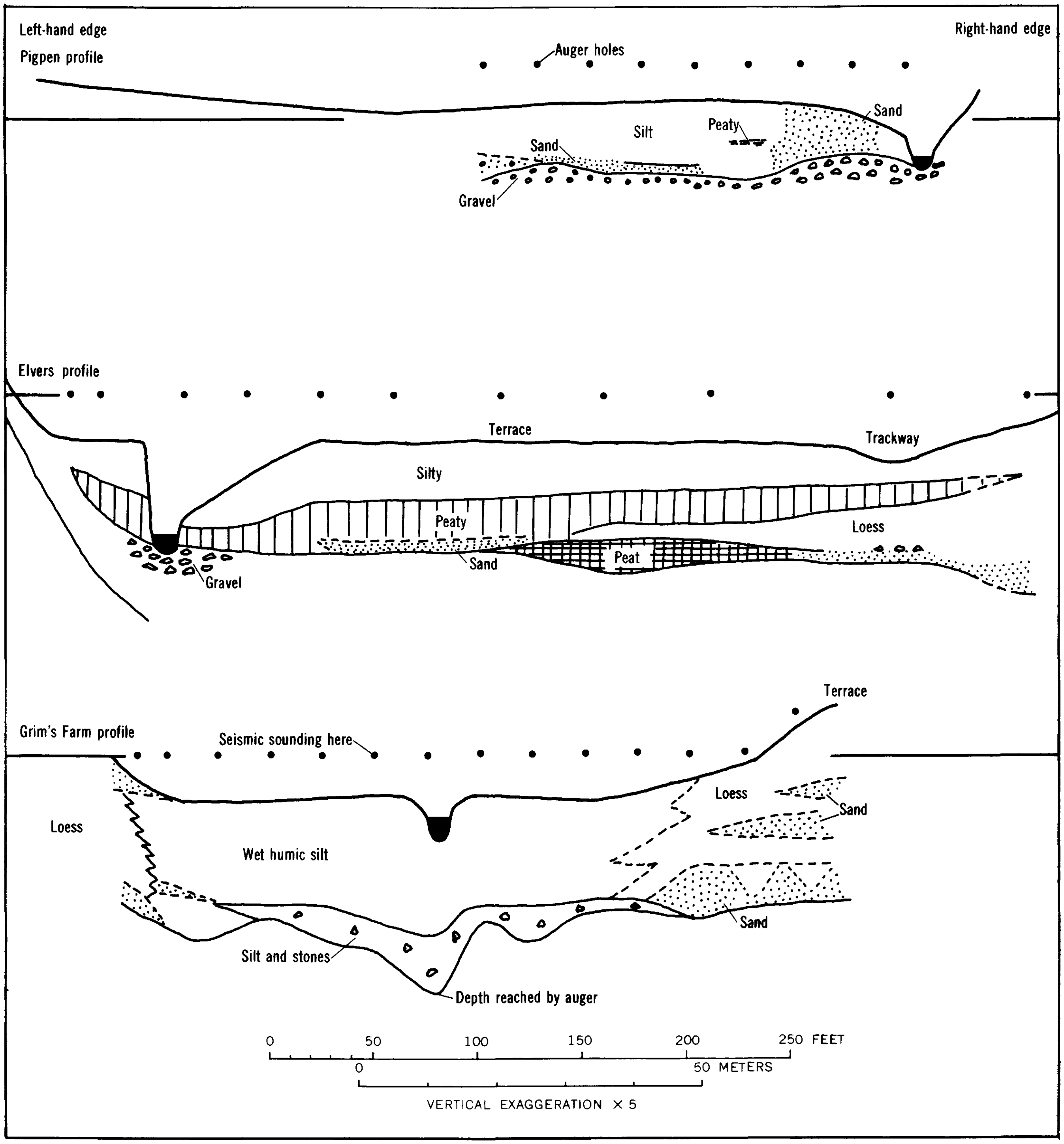

FIGURE 18.—Profile sections of East Branch Mounds Creek, Wis. Views are downstream.

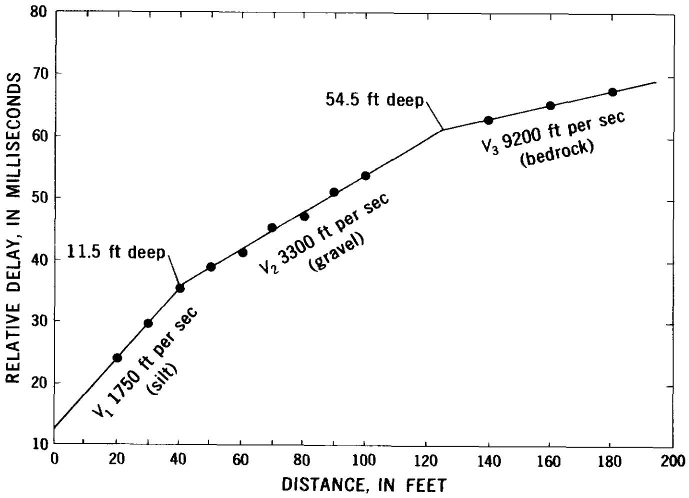

FIGURE 19.—Graph showing relation of time to distance in seismic refraction sounding at Mounds Creek, from valley bottom near Grim's Farm. Second borehole from left-hand edge of channel, figure 18.

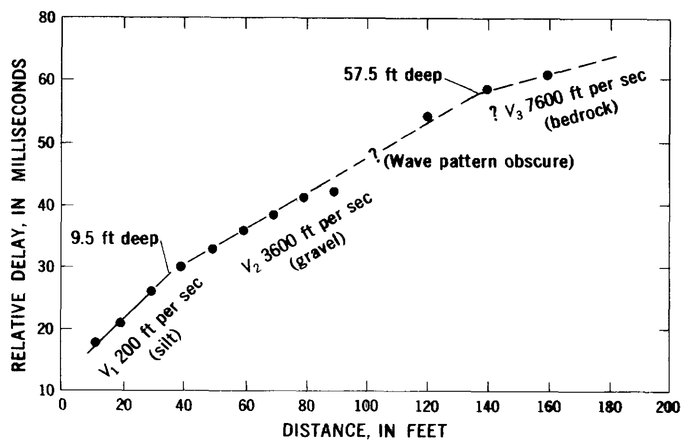

FIGURE 20.—Graph showing relation of time to distance in seismic refraction sounding at Mounds Creek (second example). First borehole from right-hand edge of channel, figure 18.

Terrace. Immediately upstream of Orcutt Farm, moreover, a tiny right-hand lateral has cut large meander scars into its own strip of Low Terrace almost down to the level of the present flood plain (fig. 21). On Mounds Creek, that is to say, the former large meanders can be seen to postdate the Low Terrace.

Exploratory boreholes at the site of the highway bridge near Orcutt Farm reached a depth of 40 feet before penetrating bedrock. As the bridge is close to the valley side, the bedrock surface could lie much lower in the center of the valley. Both in the main valley of Mounds Creek and in the valley of the tiny lateral, quicksand greatly handicapped augering; it closed in so rapidly that no borehole went deeper than 21 feet. However, it was possible with the aid of 22 boreholes to trace the sharp descent of the right-hand wall of rock to depths well below the level of the present streambed and to discover that quicksand occurs also beneath the Low Terrace and underlies the lowermost part of the lateral stream to a depth of more than 8 feet. In all probability this quicksand was swilled into the valley of Mounds Creek from the Wisconsin River when the latter was building up its High Terrace.

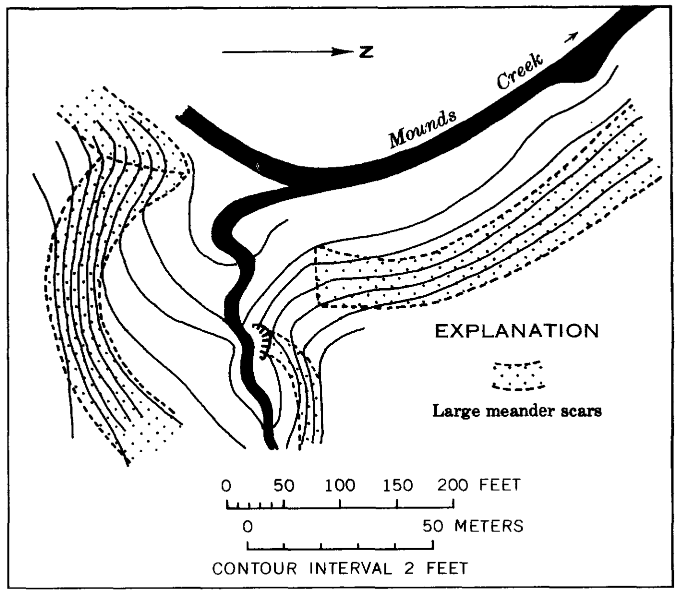

FIGURE 21.—Sketch map showing entry of lateral stream into Mounds Creek.

The outline sequence of development of Mounds Creek thus becomes:

1. Deep cutting of valley in bedrock.
2. Onset of periglacial conditions with the approach of Cary ice; discharge of frost-shattered gravel from the valley sides.
3. Infilling of the Wisconsin River valley and the lower part of Mounds Creek valley by sandy outwash—that is, formation of the High Terrace.
4. Deposition of loess (compare sequence established for Black Earth Creek).
5. Deposition of peat near Elvers.
6. Completion of the Low Terrace by erosion in the lower reaches, but probably also by considerable reworking of loess.
7. Entrenchment of large meanders through the Low Terrace.
8. Reduction of channel-forming discharge, with reduction in size of meanders; scalloping of the fore edge of the Low Terrace by small meanders, accompanied by slight rejuvenation at least as far upstream as Orcutt Farm.

The two sequences, for Black Earth Creek and Mounds Creek respectively, will be referred in a later section to the scale of absolute time.

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MISCELLANEOUS ADDITIONAL RECORDS

Reconnaissance trials on the till plains of Iowa provided further evidence of large filled channels, although some locations were not easy to explore. Crooked Creek, near Lime City (Lime City quadrangle, Iowa, 1:24,000, T. 79 N., R. 2 W., sec. 5), describes stream meanders within a meandering valley. Eight inches of light silt covers the flood plain and overlies dark material which in its stratigraphic relations resembles the alluviated first-bottom land described by Happ (1944) in Wisconsin. Below the streambed is dark muck containing medium- to coarse-grained sand and humified fragments of wood; this muck is penetrable with difficulty because of a gravel band at about the level of pools in the present channel. The dark muck, however, continues beneath the gravel and, in one borehole, changes after another 3½ feet of depth to light uniform light-brown loess. Gravel at this location prevents definition of a complete profile; but the indications, as far as they go, match those of the two sections next described.

The upper profile in figure 22 relates to an unnamed right-hand lateral of North River near Winterset (Winterset quadrangle, Iowa, 1:62,500, T. 76 N., R. 30 W., sec. 6, bordering R. 29 W., sec. 1). On the line of profile the stream is cutting slightly into the right-hand bank, where downwash probably obscures the bedrock that a natural section exposes farther downstream. A quarter of a mile from the augered line, limestone and shale are visible to 8 feet above stream level, mantled by weathered till with abundant Kansan erratics; loessic slope wash drapes the whole valley side. Augering proves a large channel that is filled with dark muck, silt, and sand; contains the present stream channel and old cutoff channels; and bottoms either in loess or against bedrock. Taken at the inflection of a valley bend, this profile reveals a disproportion between large channels and present channels similar to that on the upper Rib (see above).

Certainly on this stream, and apparently also on Crooked Creek, the large channel is trenched into loess. The loess of Iowa, however, permits a wider range of possible dates for trenching than does the loess at Black Earth Creek. All that can be said is that the general relations of large and small channels to the spread of loess are similar in all three places.

McDonald Creek (Eldridge quadrangle, Iowa, 1:24,000, T. 80 N., R. 3 E., sec. 24) was used in Professional Paper 452–A to exemplify a pool-and-riffle sequence on the limb of a valley bend. The incomplete profile on the lower part of figure 22 herewith lies near the downstream end of that bend, which cuts through sandy outwash. The steep slope on the right-hand side of the profile in figure 22 is the right-hand turn.

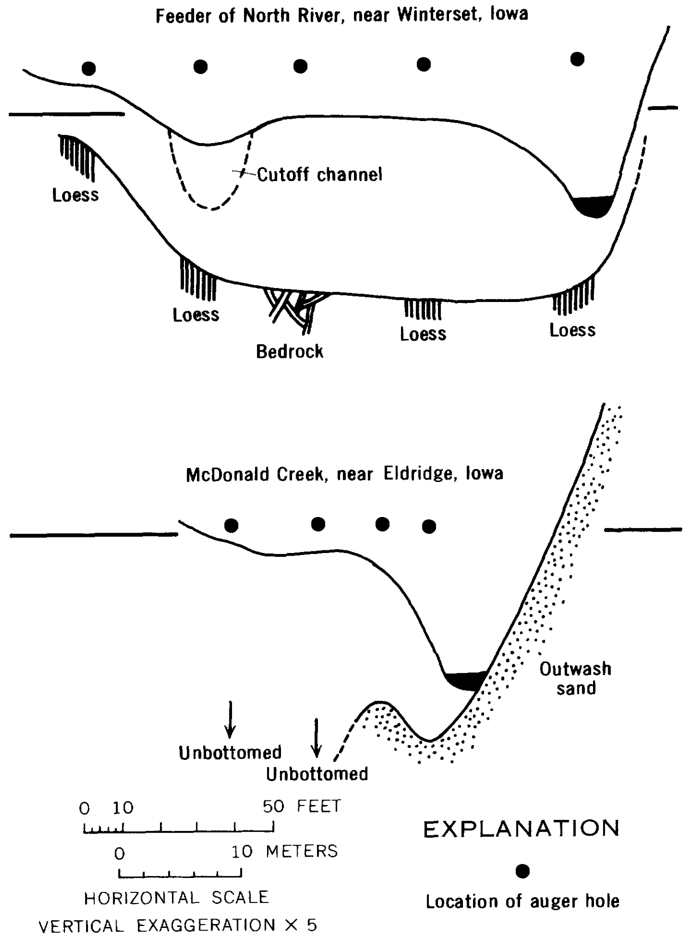

FIGURE 22.—Profile sections of large channels of two streams on till plains in Iowa. From field exploration.

Whereas the outwash sand is bright orange, the fill is dark and in part silty. On the line of profile, the outwash appears to include a berm or point bar of the former large stream. Although two boreholes failed to reach the bottom of the fill, they descended well below the level of the present streambed. This site appears more complicated than a number of others, but it once again reveals part at least of a filled channel that was much larger than the channel of the existing stream.

Exploration by civil engineers, particularly at damsites, is obviously capable of revealing the depth and form of alluvial fills in the valley bottoms of underfit streams. But because many of the records remain unpublished and relate in part to irrelevant instances or to inappropriate lines of cross profile, engineering work supplies less information than might be hoped.

Borings undertaken in conjunction with highway construction in the Ozarks are mainly confined to the centers of valleys. Nevertheless, their results suggest that a number of head valleys contain alluvial fills, even though streams are in contact with bedrock elsewhere, and even though recorded depths from surface of flood plain to bed rock in the filled valleys are nowhere great. Figure 23 illustrates a common type of situation, where depth to bedrock beneath the streams is certainly greater than the depth on the step valley sides. Each of the two outline profiles resembles profiles determined on other rivers by close-spaced augering; at least on Branch of Woods Fork Creek, the fill appears too deep for the existing stream to scour to bedrock at the bankfull stage.

The Yellowstone damsite in Lafayette County, Wis. (figs. 24, 25), lies in a meandering valley with steep sides but shallow fill. Here again, however, the 20 feet or so of fill seems too great for the present stream to scour. As the explored site lies at the inflection of a valley bend, either the former large stream had an unusually high width to depth ratio or it widened its bed in the course of downstream shift.

Drilling logs from the damsite at Governor Dodge State Park, Wis. (fig. 26), are too few and too generalized to supply a detailed profile. Nevertheless, the local conditions strongly resemble those described elsewhere and become more clearly understandable by comparison with the Mill Creek site illustrated below. In the State Park, a large channel trenches the St. Peter Sandstone; the alluvial fill of the channel contains basal gravel and interfingers with the loess or loessic downwash of the valley walls. Unless the present stream assumes the improbable cross section that would permit it to scour 20 feet below the flood plain, it cannot now reach bedrock.

Records from the Mill Creek damsite, Wisconsin (fig. 27), are especially valuable in identifying loess and colluvium, showing how the colluvium wedges into the fill in the valley bottom, and recording that the loess forms low terraces. This site recalls profiles taken on Mounds Creek (Elvers; Grim's Farm) and near Argyle. (See figs. 8, 18.) The large channel beneath Mill Creek is partly filled with loess. In addition, however, the likely profile of the base of the loess suggests a channel intermediate in size between the channel cut in bedrock and the channel of the present stream. A possible sequence of development is the following:

1. Incision of valley, cutting of large channel into bedrock.
2. Shrinkage of stream, partial infilling with colluvium, cutting of intermediate channel (by somewhat reenlarged stream?).
3. Loess fall, filling of intermediate channel (implying renewed shrinkage of stream); loessic alluvium spread as flood plain.
4. Slight rejuvenation, fill of intermediate channel terraced.

Variations on this sequence, or elaborations of it, are easy to make. Suggested correlations with the outline sequences for Black Earth Creek and Mounds Creek occur in a later section. For the present, it suffices to observe that Mill Creek illustrates the common circumstance that by the time of the last heavy loess fall in Wisconsin the deep incision of valleys into bedrock had already taken place. The slightly rejuvenated condition of the present stream belongs, perhaps, with the widely observed epicycle of slight erosion now in progress.

Logs for the Brighton damsite, Maryland, on the Patuxent River, supply a complete profile across the valley (fig. 28). In the valley bottom is a trench, about five times as wide as the present channel of the Patuxent, cut into residual rock waste and containing sand and gravel below an upper layer of finer alluvium. Although the Patuxent, in common with many other rivers that cross the Piedmont, displays poorly developed or

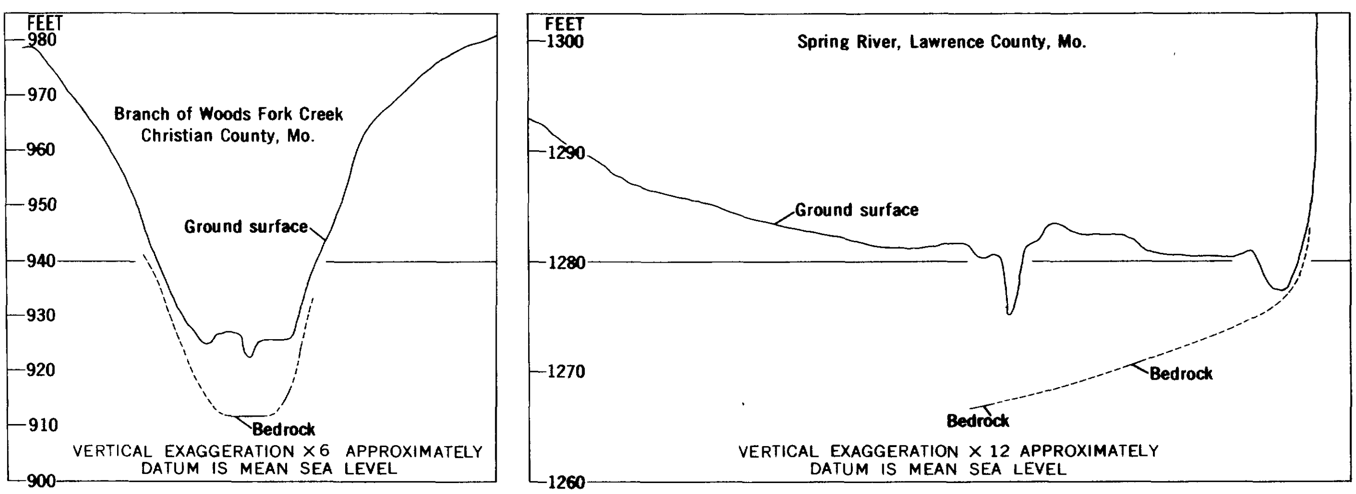

FIGURE 23.—Profile sections of valley bottoms of two streams in the Ozarks. From civil-engineering records. Views are downstream.

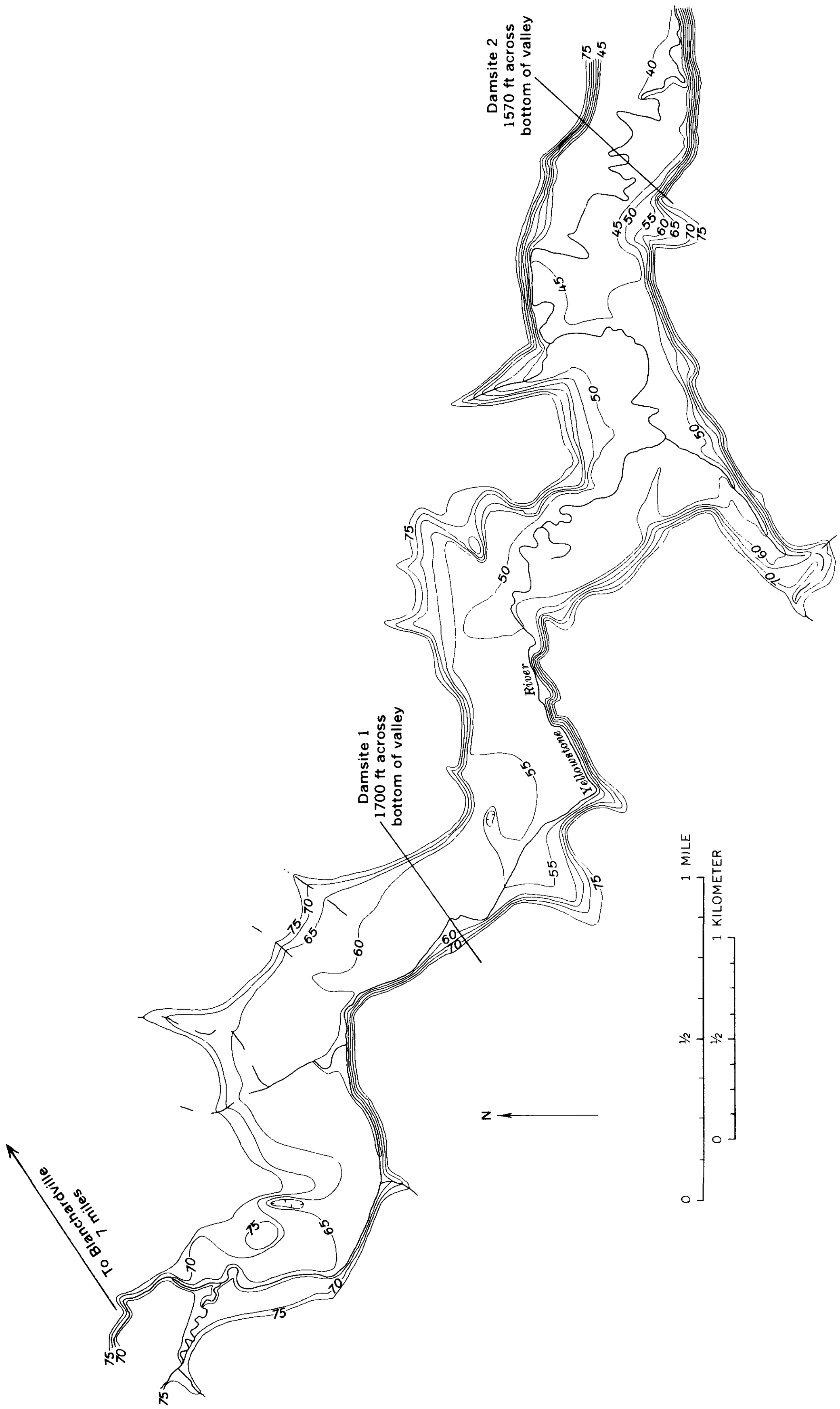

FIGURE 24.—Contour map of the Yellowstone damsite, Wisconsin. Data from Wisconsin Conservation Dept.

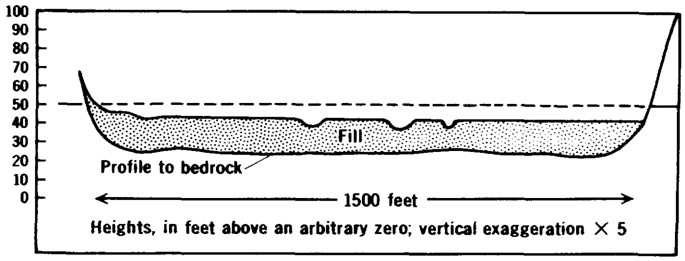

FIGURE 25.—Profile section of damsite 2, Yellowstone area, Wisconsin. See figure 24 for location of section. View is downstream.

no stream meanders, its valley bends in some reaches are cut boldly and incised deeply. The 5:1 ratio between the width of filled trench and that of present channel is identical with a widely distributed wavelength ratio between the valley meanders and stream meanders of manifestly underfit streams. The filled trench is accordingly taken as a former stream channel, cut when bankfull discharge was greater than it now is. Without study of the present river, the coarse basal part of the fill cannot positively be distinguished from the existing bed load—which, in fact, it could supply, just as outwash gravel supplies bed load to the present Black Earth Creek. But the difference in caliber between this material on the one hand and the bulk of the uppermost alluvium on the other at least invites comparison with the widely reported coarseness of former alluvium and the fineness of material undergoing transport today. The residual material beneath the fill suggests that, in this reach, the large Patuxent of former times failed to scour to bedrock in the latest stage of its history.

None of the instances specified here relates to infilled spillways. All six rivers drain basins that remained ice free at glacial maximum. The profiles exemplify what, in the writer's view, should be a common circumstance: if underfit streams, whether manifestly underfit or not, are regionally developed, then alluvial fills in former channels should be widespread. The profile described by Lattman (1960) is a case in point. That author shows that Beaverdam Run, Cambria County, Pa., occupies a valley where the fill is 20–25 feet deep whereas the stream is but 4–4½ feet deep at bankfull. A deposit of rounded boulders as much as 1 foot in diameter, resting directly on the bedrock floor, can represent the bed load of the former large stream. The writer consequently inclines to reject Lattman's view that infilling resulted from aggradation, especially aggradation resulting from forest clearance. Beaverdam Run closely resembles Mineral Point Branch of the East Pecatonica where, upstream from the reach explored by seismic means, a reach widened and straightened by the downstream sweep of valley meanders has been infilled; Lattman's cross profile closely resembles the profiles described here for the Brighton, Governor Dodge, and Mill Creek damsites. Conditions of this sort appear to be very widely represented in head valleys throughout the Driftless Area and can be matched repeatedly in small valleys on the English Plain.

CHRONOLOGY

Three specifications of time apply to underfit streams: that of the initiation of large meanders or large channels, that of the onset of underfitness and the abandonment of large meanders or channels, and that of duration between initiation and abandonment. In practice, initiation can often be dated solely by reference to an erosional platform or a depositional spread, with no certainty that large meanders existed upon the platform or on the sheet of sediment. Streams that now possess incised valley meanders need not have been meandering

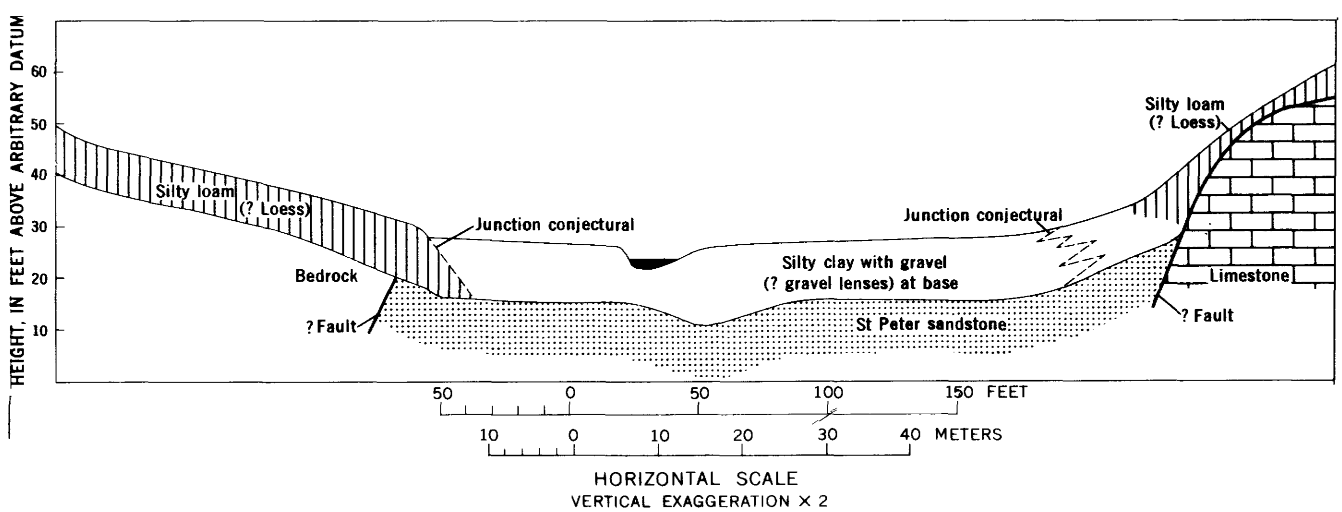

FIGURE 26.—Profile section of damsite in Governor Dodge State Park, Wis. View is downstream.

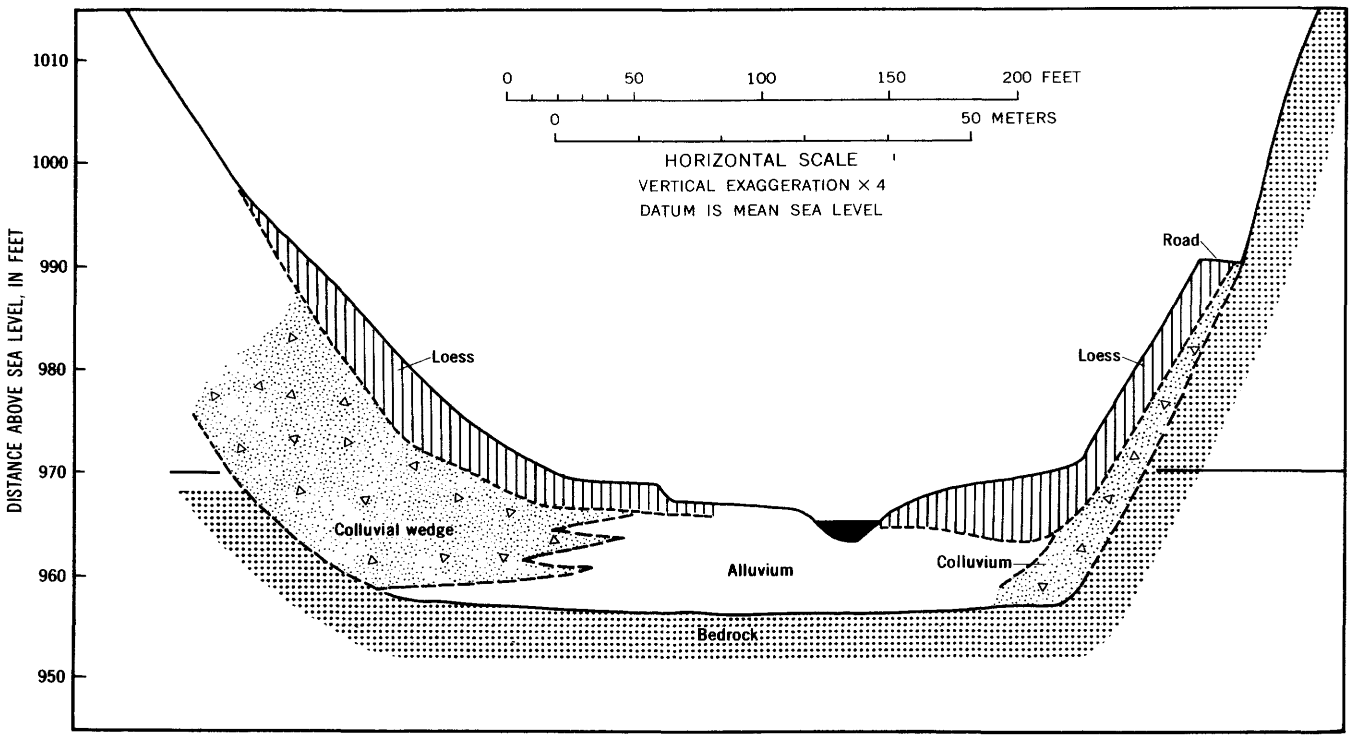

FIGURE 27.—Profile section of Mill Creek, Richland County, Wis. Site 10, drainage area 2.10 square miles. View is downstream.

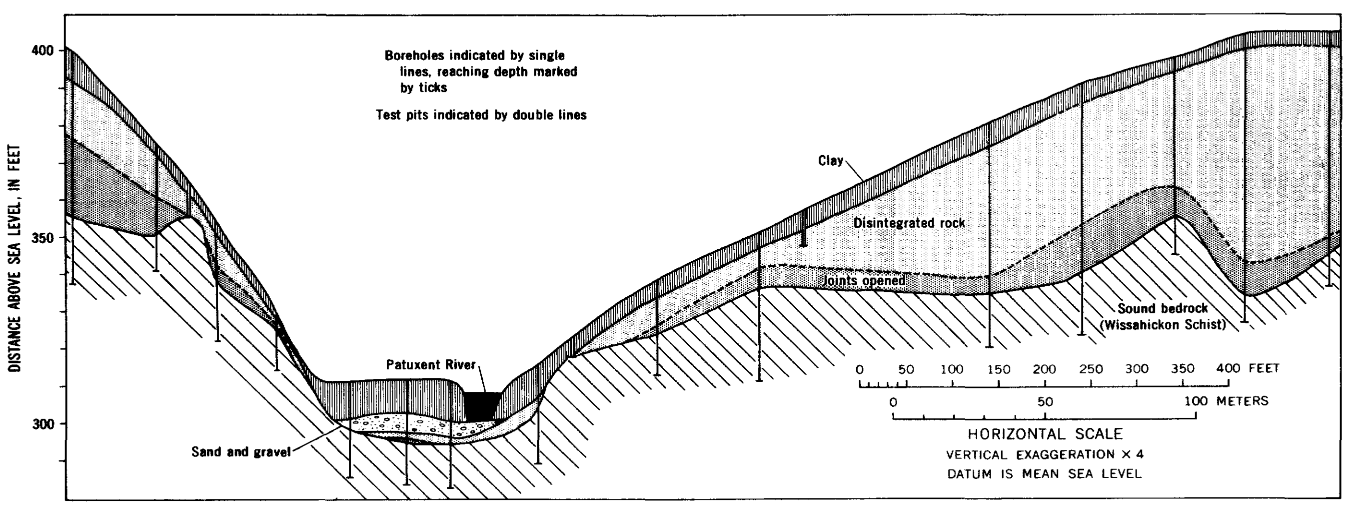

FIGURE 28.—Profile section of valley of the Patuxent River, Md., at Brighton Dam. Data from records of core borings and test pits. View is downstream.

streams when they flowed at (or near) the level of plateau tops. Platforms and sediments, therefore, frequently do no more than set limits before which the relevant trains of valley meanders could not have existed. On the other hand, terraces contained in meandering valleys, especially those formed as point bars on the ingrowing loops, can fix points on the time scale when large meanders were certainly in being. In this way the dubious gap between incision of stream and appearance of large meanders can often be much narrowed.

Duration, expressed as the span between initiation and abandonment, does not imply that large meanders or large channels continued in use throughout any span defined. On the contrary, the climatic hypothesis gives strong general reasons to suppose that the last onset of underfitness was but one episode of several. Especially is this so, as the event which has hitherto been treated as single will now be shown to have been multiple; the record of cutting and filling in a number of valleys requires the term "last onset of underfitness" to connote, in actuality, a complex series of fluctuations.

Not all the instances described below supply dates—whether relative or absolute—for initiation, duration, and abandonment of large meanders, but overlapping sequences are useful in this context as in stratigraphy in general. To relate one sequence to another, however, some common scale of reference is needed; and because the span of time involved in abandonment is that from a well-marked glacial maximum to the present day, questions of nomenclature, succession, and absolute dating at once arise. The scales of stratigraphy and time used in this report derive respectively from the zonal scheme of Blytt (1876) and Sernander (1910) and from radiocarbon dating. As shown in table 4, the scales allow for parallelism, if not for strict simultaneity, between events in Europe and those in North America. In the form stated, they rely on the findings of Firbras (1949), Deevey (1949, 1951), Gross (1954), Emiliani (1955), Suess (1956), Barendsen, Deevey and Gralenski (1957), Wright (1957), Deevey and Flint (1957), and Fairbridge (1961). The use of a general schema is not meant to prejudice any evdience of opposed or compensatory change according to location, as for instance in northwest Europe as against the Mediterranean; but, as will appear, considerable similarity seems to be indicated for the main episodes of channeling and filling, respectively, in northwest Europe and in the United States.

In addition to scales of reference, discussion also requires some rather general terms indicative of the location of events in some bracket of the whole sequence. For example, Godwin (1956, fig. 29) places the Lower (= Older) Dryas, the Allerød, and the succeeding Upper (= Younger) Dryas in the late glacial, extending the postglacial from the beginning of the pre-Boreal to the present. Deevey and Flint (1957) reject the terms "postglacial climatic optimum," "thermal maximum," "altithermal," and "megathermal" and propose "hypsithermal" for the time interval embracing pollen Zones V through VIII of the Danish sequence or Boreal through sub-Boreal in the sequence of climatic phases. Morrison and others (1957) defend the use of the term "Recent," whereas Frye and William (1960) apply Recent to their post-Wisconsin time—that is, to the last 5,000 years. Cooper (1958) calls the whole span from Zone III (Younger Dryas) onward the Neothermal (see also Antevs, 1953), subdividing it into Anathermal (Zones III and IV), Hypsithermal (V through VIII), and Hypothermal (IX). In the text which follows here, the well-documented rise of temperature during hypsithermal times (the hypsithermal maximum) will be regarded as belonging to peak interglacial conditions. Accordingly, the whole span between the last preceding maximum of glaciation on the one hand and the hypsithermal peak on the other will be styled "deglacial." No difficulty will arise from questions of the number and relative severity of stadial maximums within the last (Wisconsin, Weichsel) glacial, as all that is needed is a term indicating the net trend of amelioration through some 15,000 years or through a shorter period during which ice sheets or proglacial lakes persisted in northern latitudes. It is principally in the context of deglacial time that the last recorded abandonments of valley meanders and large channels will be discussed.

EXAMPLES OF EARLY INITIATION OF MEANDERING VALLEYS

The examples immediately following are those of meandering valleys where the first incision has been dated to early Pleistocene times, where a sequence of terraces extends well back into the Pleistocene, or where a dated record of slight excavation contrasts with the presumably much longer span of time needed to carve the whole trains of deeply ingrown bends. In all instances, the total possible duration of cutting is long, on the Pleistocene time scale.

In discussing the Belgian River Ourthe, Alexandre (in Macar and others, 1957) holds that free meanders appeared above the level of the highest terrace—that is, at the beginning of Pleistocene time and upon the last incompletely developed erosion platform of the local Tertiary sequence. His opinion that this platform formed in a subarid climate need not be examined; as Alexandre observes, the earliest series of meanders is incompatible with such a climate, whatever the conditions immediately before their appearance. At the present time, the Ourthe lies 300 feet or more below the flat adjacent summits. Its history includes the downstream sweep of some large meanders, although sweep through a whole wavelength characterized single loops rather than complete trains. The valley, therefore, retains much of its original meandering trace, modified by ingrowth. Alexandre neglects to state that the present stream in some reaches is manifestly underfit (his fig. 1).

Seret (in Macar and others, 1957) distinguishes 11 successive flood plains on the River Lesse, a tributary of the Meuse; he correlates his succession with that on the trunk stream and accepts shifts in climate as the dominant cause of spasmodic downcutting. Lateral migration of the whole river, distortion by structural guidance during incision, and certain derangements of drainage obscure the earliest traces of the large meanders; but they had certainly appeared by the time Seret's terrace 4 was formed (his fig. 6)—that is, at a height of 200 feet above river level in the lower reaches.

Troll (1954) shows that certain incised meandering valleys in the Hercynian massifs of Europe and in the Alpine Foreland came into being early in the Pleistocene. Kremer (1954) refers the highest terrace of the Moselle to infilling during the Gunz (=Early, Nebraskan) glacial; she places the initiation of the large cutoff loop near Kommlingen in this glacial, so that the history of incised valley meanders on the Moselle spans much of glacial time. Ingrowth rather than downstream sweep ensures that the meandering trace of the incised Moselle is in general well preserved, although modified in places; terraces provide the means of dating single episodes of cutoff (fig. 29). Both on the Moselle and on the other rivers that Troll examined, the record is one of alternate braiding in times of cold and meandering at other times; braiding was independent of the presence or absence of ice in the headwater basins. Although Troll calls the great incised bends valley meanders, he appears not to use this term in contradistinction to stream meanders and to overlook the essential disparity between the two series, perhaps because most of the rivers which he considers are not manifestly underfit. He seems, by implication, to ignore the possibility that braiding in cold periods may have been a response to infilling by congeliturbate which, charging the valley bottoms with incohesive and coarse material, inhibited the retention of single meandering channels.

According to Peltier (1949), the Susquehanna River scours during high stages without cutting down to bedrock. Matters are different in the lowermost 30 miles above tidehead, for which reach Mathews (1917) describes islets of bedrock in midstream and long spoon-shaped depressions in the channel floor. In neither part is a meandering trace well, or at all, developed on the present channel. Conditions in the reach discussed by Peltier seem to resemble those described above for the Patuxent at Brighton Dam.

Terraces, preserved chiefly on the insides of valley bends, record little but slight ingrowth since an episode of filling correlated by Peltier with the Illinoian glacial maximum. Greater coarseness of terrace material than of the present alluvium indicates, in Peltier's view, a reduction in the magnitude of floods since the terraces were formed. Such an inference is independent of invasion of the upper basin by ice, which occurred at least once during the Illinoian and three times during the Wisconsin Glaciation; for the 15-foot terrace of North Branch, which was not fed directly from ice, is also coarser than the present alluvium. Peltier concludes that filling occurred during cold periods, for which he posits ET (Tundra) climate (Köppen classification) over much of the Appalachians. Although the widespread evidence of severe frost action accords with the charging of coarse debris into the valley bottoms, it does not suggest a means of transporting the materials so delivered; transportation requires a change of regimen, such as that which Peltier infers. Conclusions about the Susquehanna thus accord with those about European rivers, especially when allowance is made for the already incised condition of the Susquehanna at the time when Peltier's earliest (=Illinoian) terrace was formed.

There is no reason to think that the geomorphic histories of the North and South Forks of the Shenandoah have differed in any major way. If not, then the great incised bends on the North Fork extend the observations of King (1949) on the South Fork near Elkton, Va. King finds that the valley floor of the South Fork, on the east side of Massanutten Mountain, consists mainly of a series of gravel-topped benches, which he refers to alternate erosion and deposition during the Pleistocene. Three series of gravels occur: an older gravel, 300 to 700 feet above river level, that thickens laterally into coalescent fans at the foot of the mountain; a thin intermediate sheet resting on broad benches; and a younger sheet, also thin, that forms terraces 50 to 75 feet above the river. Because thick residual clays are present beneath the gravels, King separates the origin of the existing loops from the cutting of the so-called Valley Floor Peneplain; and because many of the benches occupied by the younger gravels lie within the loops of entrenched (valley) meanders, he considers that the meanders did not form until near the end of the period when the intermediate gravels were laid down. However, the North Fork above Strasburg is cut as much as 250 feet below the floor of the Great Valley of Virginia—a floor which, although now much dissected, appears formerly to have been sensibly intact and gently sloping. Beyond 8 airline miles upstream from Strasburg, remnants of the floor extend along spurs in the incised bends, suggesting that the loops already existed here—although less developed laterally than they now are—when the river flowed very little below the general level of the valley floor. (See also Hack and Young, 1959.) Incision to a depth of 250 feet or more along the whole length of a sizable reach indicates a long history of cutting. Nevertheless, a local history of ingrowth by part of the North Fork does not oppose the sweeping out of a large meander trough on part of the South Fork, nor does it deny the possibility that both rivers alternated

NAME OF TERRACE	SERIAL Nº	CORRELATIONS WITH GLACIAL SEQUENCES		
		ALPINE	CONTINENTAL U.S.	GENERAL
HOHEN	7	GÜNZ	NEBRASKAN	EARLY
OBERE HAUPT	6			
MITTLERE HAUPT	5	MINDEL	KANSAN	ANTEPENULTIMATE
UNTERE HAUPT	4			
OBERE MITTEL	3	RISS I	ILLINOIAN	PENULTIMATE
UNTERE MITTEL	2	RISS II		
NIEDER (in part subdivided)	1 b, a	WÜRM	WISCONSIN	LAST

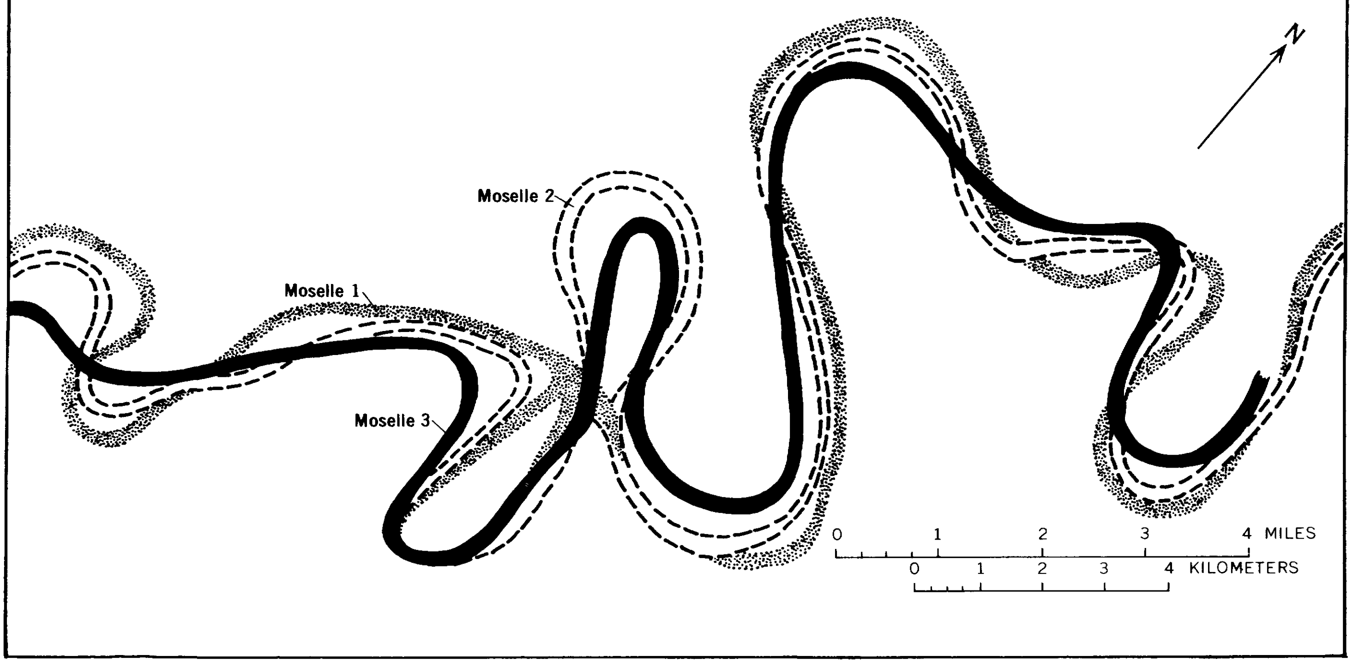

FIGURE 29.—Sketch map of the middle Moselle River. Above, arrangement of terraces; below an interpretation of ingrowth from end of deposition of terrace 3 to end of deposition of terrace 1. Data after Kremer (1954).

in time between braiding and meandering. On the Shenandoah, as elsewhere, the most deeply incised valley bends seem to have been initiated well back in Pleistocene time. Again, like many similar bends elsewhere, they have failed to modify their original wavelength during their long history of ingrowth.

In Wisconsin the Driftless Area and its margins support the customary doubt surrounding the age of summit platforms, though clearly exemplifying the contrast between the extent of downcutting in the last deglacial and that recorded in incised meandering valleys. No review of the disputed platforms in Wisconsin seems necessary, for definitive conclusions of identity, number, age, and origin have yet to emerge. Similar uncertainties apply to the Ozarks, where, however, a thick regolith with ghosts of original bedding seems to record prolonged weathering and conditions unlike those responsible for the incised valleys and advanced dissection which typify parts of the region. In the Driftless Area, as in the Ozarks and in the Hercynian massifs of Europe, deeply cut valleys contrast powerfully with subdued tops. Whatever hypotheses of planation be adopted, and whatever sequence of platforms be distinguished, the existing valleys have undergone marked rejuvenation.

When it rose to form the High Terrace, the Wisconsin River caused choking of lateral valleys, as noted previously for Black Earth Creek and Mounds Creek. Mounds Creek has cut through some 60 feet of weak material in its lower reaches, (since the formation of the High Terrace), whereas its valley descends 350–400 feet through solid rock. No means exist to extrapolate from shallow incision through a weak fill to deep cutting through rock in place, especially because changes in discharge are involved; but the disparity of effect is at least great enough to require a long span for the development of the whole valley. The High Terrace dates from the last (classical Wisconsin) glacial—say, from about 14,000 years B.P., if the Johnstown moraine is correlative with the Valparaiso system.

Identical signs come from the Kickapoo River, where the High Terrace occupies valley meanders (fig. 30). All the six valleys named in the diagram are cutoff valley meanders; Haney Valley, Steuben Valley, and Pine Creek Valley still have upstanding cores of bedrock, but Barnum Valley and Posey School Valley do not. Citron Valley may be not one cutoff, but two. The inflection on its west side may well be a left-hand valley bend, formed on the downstream limb of a greatly hypertrophied northward swing. This reach of the Kickapoo illustrates with unusual freedom the modification by cutoff of an incised meandering trace. The contrast between cored and coreless loops corresponds to the difference between prolonged ingrowth on the one hand and rapid lateral enlargement at low levels on the other. All six loops contain patches of High Terrace; all six, therefore, predate High Terrace times, whether or not they had already suffered cutoff by then. Piney Creek, tributary along the southern limb of Piney Creek Valley, and Citron Creek, tributary near the downstream end of Citron Valley, are manifestly underfit. As their valley bends cut through the High Terrace, some time must have elapsed between the formation of that Terrace and their reduction to underfitness. This part of the record, as far as it goes, corresponds with that established for Black Earth Creek and Mounds Creek. On the Kickapoo, as on Mounds Creek, the incomplete removal of the High Terrace contrasts with the bulky excavation of bedrock from the river valley.

INITIATION OF MEANDERING VALLEYS DURING MID-PLEISTOCENE TIMES

Certain meandering valleys were first cut before the last (Wisconsin) glacial but later than the early (Nebraskan) glacial. Their occurrence shows that hydrologic conditions generally similar to those responsible for the earliest dated meandering valleys obtained in mid-Pleistocene times, in the broad sense of this term. Moreover, since the wavelength to area relations of meandering valleys initiated during the mid-Pleistocene very closely resemble those of early Pleistocene valleys, region for region, there is nothing to choose between the conditions responsible for the earlier series and those responsible for the later.

Trains of valley bends on the River Avon, Warwickshire, England, were noted in Professional Paper 452–A (Dury, 1964) as originating in the last interglacial—not long, perhaps, after the formation of the outwash train which, predating them, belongs to the recession phase of Penultimate (= Illinoian) ice. Incised bends on the competing Evenlode, also described in the earlier report, date from at least as early as the valley meanders of the Avon, and probably from the Penultimate Glacial itself. The Avon, its tributary Itchen, the Evenlode, and neighboring streams on the Cotswold back slope are all highly underfit, with a wavelength ratio between valley and stream of about 9:1. (See Dury, 1964.) Their shrinkage was no less marked than that of streams in the Driftless area of Wisconsin. Although the wavelength of valley meanders is difficult to compare from region to region because of variable wavelength to area relations, comparative degrees of underfitness suggest that, climate for climate, valley meanders initiated at about the end of the Penultimate Glacial were as large as those dating from earlier times. The Avon is especially instructive in this connection. Working in weak

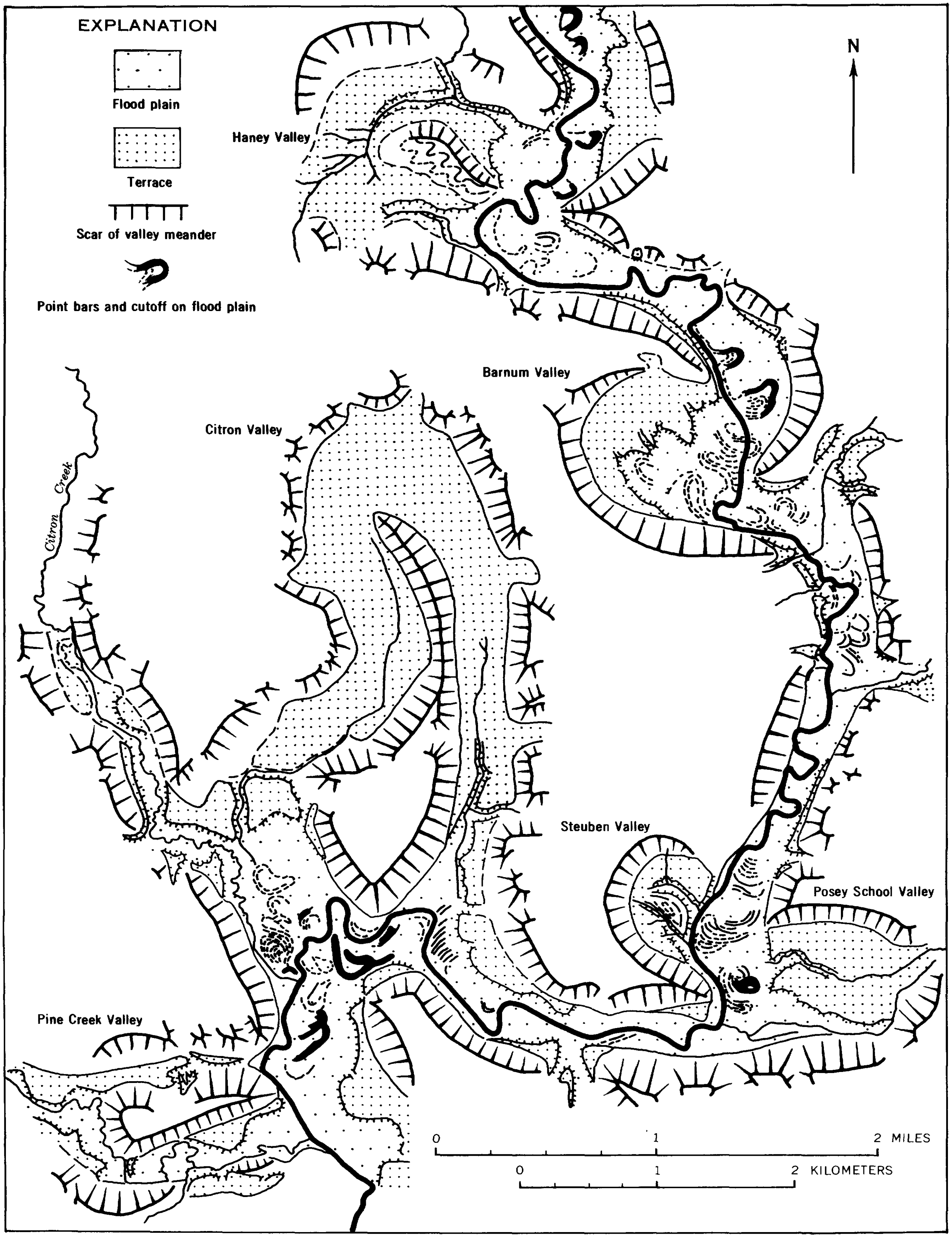

FIGURE 30.—Morphologic sketch map of part of the lower Kickapoo River, Wis.

rock where confinement by resistant valley walls does not come in question, the Avon should have been able to accommodate its wavelength to changes in regimen; in actuality, the wavelengths recorded by the lowest terrace are identical with those at the highest level known for the great bends. Each episode of high discharge at the bankfull stage in valleys with long histories of ingrowth seems to have produced rivers comparable in size with those produced in earlier episodes. A similar set of circumstances exists for channels; Sandford (1924; written communication, 1955) regards the channels beneath terraces in the Oxford district as similar in dimension throughout the range of terrace stages, including that stage when the filled channel beneath the present alluvium was cut.

Streams on parts of the Atlantic Coastal Plain underwent extension during the Pleistocene, developing valley meanders on the emerging sea floor. Relevant fixes come from the work of Doering (1960) in the range Georgia to Virginia. Doering identifies six offlapping surface formations—the Citronelle, Sunderland, Wicomico, Penholoway, Talbot, and Pamlico, listed in order of ascending age and descending height. He assigns an early Pleistocene (preglacial) age to the Citronelle by reference to plant fossils from Alabama and cold-water Foraminifera from Louisiana and tentatively places the Pamlico Formation and its associated shoreline in a mid-Wisconsin interstade.

Because the Foraminifera belong specifically to the Calabrian, the Citronelle formation correlates with the 600-foot shoreline of the European Mediterranean and with the base of the Pleistocene succession. Fairbridge (1961), in a broadly ranging review of published material, gives reasons for regarding the Pamlico as Sangamon, thus reducing the interval spanned by the whole sequence to slightly below that inferred by Doering. Even so, much of Pleistocene and glacial time is involved.

Valley meanders trench the whole series of six formations, descending well below the Pamlico level near the coast. Doering's figure 12 shows the Roanoke River entering Albemarle Sound at Plymouth as a manifestly underfit stream, 50 feet lower than the Talbot Shoreline and 25 feet lower than the Pamlico shoreline; indeed, valley bends continue below present sea level. Whatever the earliest history of excavation, valley cutting through the local Quaternary succession is mainly the work of former large streams. These, lengthening across the Coastal Plain in response to emergence, continued in being until the time of low sea level during the Wisconsin Glaciation. As in other regions, the known record does not require that the large streams persisted continuously from initiation to abandonment of their meanders. But because there is nothing to choose between extended and original reaches in terms of wavelengths to area value or degree of underfitness, there is no evidence for large meanders of pre-Pleistocene date on the original reaches; and because the age of origin of extended reaches decreases downvalley without disturbing wavelenth to area relations of the valley bends, some trains of valley meanders are likely to have come into being earlier than others. The alternative view that all originated simultaneously raises insuperable difficulties and, moreover, conflicts directly with the long-continued use, or repeated re-use, of valley meanders elsewhere. The record of initiation of valley meanders on the Coastal Plain is therefore taken to include part, and possibly all, of the glacial Pleistocene and to refer in part to trains first developed in mid-Pleistocene times.

Till sheets in the Midwest set earliest possible limits for the origin of streams which now drain them. There is no suggestion that the reconnoitered streams, mentioned in a previous section and in Professional Paper 452–A (Dury, 1964), occupy former spillways; on the contrary, they represent common habits of normal drainage. Reasoning similar to that applied to the Coastal Plain holds good here also. Unless the initiation of valley meanders be referred to about the end of the last glacial, numerous meandering valleys of the Midwest have histories beginning before the Wisconsin advance.

INITIATION OF MEANDERING VALLEYS DURING THE LAST DEGLACIAL

Just as valley meanders initiated in the mid-Pleistocene testify to the continuance or reestablishment of hydrologic conditions similar to those of the early Pleistocene, so do valley meanders initiated later than the last glacial maximum indicate the similar continuance or reestablishment of similar conditions late in the Pleistocene sequence as a whole.

Professional Paper 452–A (Dury, 1964) uses radiocarbon dates for glacial Lake Whittlesey to date the initiation of valley meanders on the Auglaize River System as not earlier than 12,500 years ago. Similarly, the draining of Lake Agassiz II sets an earliest limit for the development of valley meanders on the Sheyenne, Elm, Park, Tongue, and Pembina Rivers where they cut into the lake floor; the limit coincides with the recession of Valders ice (Elson, 1957). But whereas valley meanders can have formed on upstream reaches within the once-flooded area soon after draining began, those at low levels must be later. The date of final draining is yet uncertain, but it lies between the 7,500 years B.P. mentioned in the foregoing paper and the latest limit of 3,600 years B.P. set by Elson.

Valley meanders on the site of glacial Lake Souris are also relevant here. They occur, for example, on Deep River and Cut Bank Creek, within 2 miles of the Souris River; both streams are manifestly underfit (Paulson and Powell, 1957, pl. 1). Although dates are not forthcoming, the location of these particular trains denies their appearance at least until very late in the history of the final draining of Lake Souris.

Manifestly underfit streams on the Shropshire-Cheshire Plain of England cannot fail to postdate the sheet of till into which they cut. Barendsen, Deevey, and Gralenski (1957) report a radiocarbon date of 10,670±130 years for peat in a kettle near the outer margin of the sheet; so that, in round figures, the relevant streams can be taken as not older than 11,000 years B.P. Valley meanders on the floor of glacial Lake Hitchcock, in the valley of the Connecticut River (see Dury, 1964), can be as early as those of the Auglaize; Rubin and Alexander (1960) give 12,200±350 years for the base of a bog formed, when Lake Hitchcock drained, on a delta near Suffield, Conn. By contrast, some of the trains near Green Bay, Wis., date from late in the descending sequence of lake levels in that region.

In certain respects, the country around the head of Green Bay is well documented. Recent maps on the scales of 1:62,500 and 1:24,000 clearly portray the meanders of existing streams and, in addition, the winding valleys in which these streams are contained (Appleton, Chilton, Denmark, De Pere, Green Bay, Neenah, and New Franken, Wis., quadrangles, 1:62,500; see also De Pere, Wis., quadrangle, 1:24,000). Prepared as they were with the aid of aerial photographs and contoured at intervals of 10 or 20 feet, the maps are commendably detailed. Although the trunk Fox River, leading from Lake Winnebago north-northeastward into Green Bay, is broad and shallow, irregular rather than sinuous in plan in its lower reaches, and, moreover, affected by dredging and by damming, numerous lateral streams are manifestly underfit. They drain areas where the glacial geology has been mapped in detail, the East River crossing the shorelines of three former lakes above the level of the present shore.

Wavelengths of valley and stream meanders have been measured on stereoscopic photographs and plotted against drainage area for three tributaries of the Fox River—Plum Creek, Apple Creek, and East River—which enter the Fox respectively 10, 8, and nearly 2 miles above its mouth at Green Bay (figs. 31, 32). The ratio of wavelengths between valley and stream meanders is almost exactly 5:1; but the two clusters of plotted points are less regular than usual, probably mainly because the meanders themselves are irregular, having been developed rapidly in weak sediments. Cutoff valley meanders, distinguishable by upstanding cores, are not uncommon; although the reduction of parts of the sides of the large trenches to blunt cusps suggests, in combination with the irregular plan of the side slopes in general, that cutoff was quite frequent on the former large streams. The 5:1 ratio of wavelength associated with hypertrophy of some existing loops ensures that valley-meander scars are considerably eroded, but the clear separation of the two meander series and the almost perfect parallelism of the two best-fit graphs are reassuring.

The valley meanders near the head of Green Bay cannot have originated before the recession of Valders ice, as is demonstrated by the work of Thwaites (1943) and Thwaites and Bertrand (1957). Flint (1957), Hough (1958), Frye and Willman (1960), and Zumberge and Potzger (1956) supply relevant dates, which the following discussion incorporates (see also Crane and Griffin, 1960).

In the advance before the Two Creeks Interstade, ice in the Michigan basin reached points 40 miles beyond the present southern tip of Lake Michigan and 130 miles beyond the head of Green Bay (fig. 33). During its recession, this lobe blocked an extensive lake, early Lake Oshkosh, which drained to the Wisconsin River through an outlet near Portage at about 800 feet above sea level. Such a level indicates that most of the country now drained by Apple and Plum Creeks and the East River was drowned. Further recession of the ice front back to the straits of Mackinac allowed the water in the Michigan basin to fall below its present level, to the Bowmanville low-water phase which corresponds to the Two Creeks Interstade. The closing date for this interval is about 11,000 years B.P.

When ice readvanced during the Valders Stade, the Green Bay lobe eventually reached a limit at least 60 miles southwest of the head of Green Bay. It seems likely on general grounds that water was impounded in front of the spreading Valders ice (compare Bishop's (1958) account of glacial Lake Harrison in the English Midlands); Thwaites and Bertrand do in fact identify pro-Valders lake beds in places. The best-known body of water referable to this part of the sequence is, however, later Lake Oshkosh, which established itself against the eventually receding Valders ice. Later Lake Oshkosh possessed a first outlet near Portage, once again at the approximate 800-foot level, but was in time drained by successive spillways across the Door Peninsula until the ice front cleared Sturgeon Bay, at which time the southern half of the Green Bay basin was united with the main water body in the

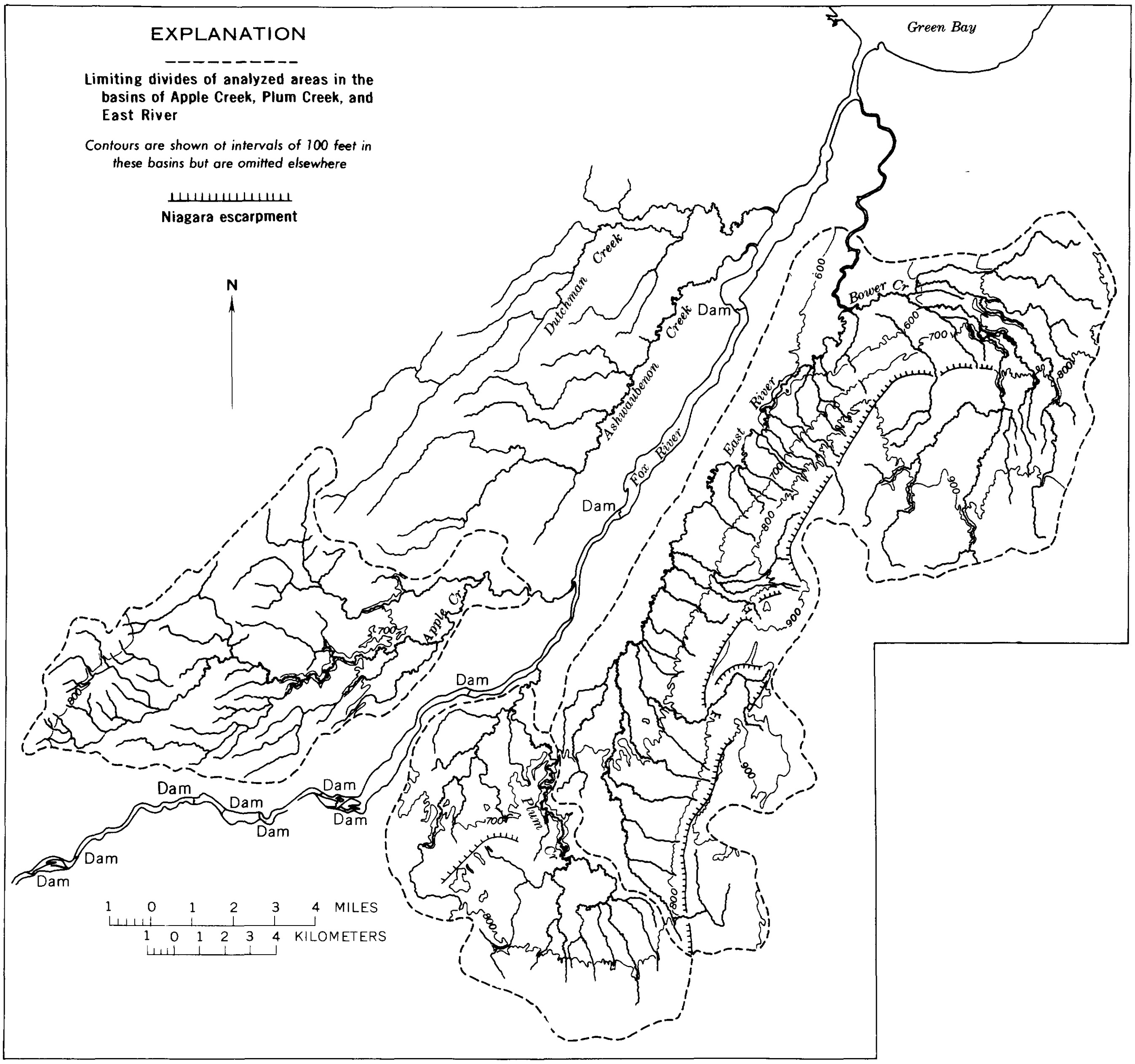

FIGURE 31.—Index map of streams near the head of Green Bay, Wis.

Michigan basin. Meanwhile, this main lake had fallen from the Calumet level of 620 feet to the Algonquin (=Tolleston) level of 605 feet. The first late-glacial exposure to subaerial processes of much of the basins of Plum and Apple Creeks and the East River—that is, the land between altitudes of 800 and 605 feet that was drained by these streams—occurred not earlier than about 10,000 years B.P. However, as will now be shown, parts of the meandering valleys began to form much later than this, so much later that their cutting did not begin until long after the large bends on Black Earth Creek on the margin of the Driftless Area were already disused.

Although the flat interfluves of Plum and Apple Creeks near their confluences with the Fox River rise respectively above altitudes of 660 and 640 feet, the scars of valley meanders on these streams are cut down past the 620-foot level. On Ashwaubenon and Dutchman Creeks, left-bank laterals entering the Fox between De Pere and Green Bay, corresponding scars are cut below the 600-foot contour; indeed, on Ashwaubenon Creek they are cut below the 590-foot contour. Sim-

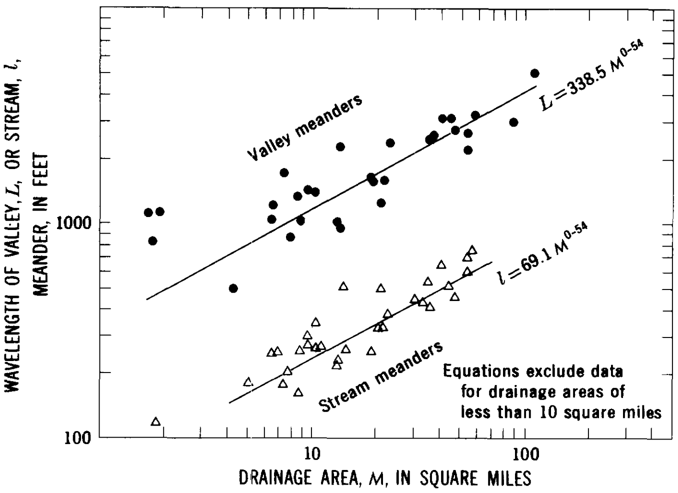

FIGURE 32.—Graph showing relation of wavelength to drainage area of streams (Apple Creek, Plain Creek, and East River) near Green Bay, Wis. See figure 31 for location of streams.

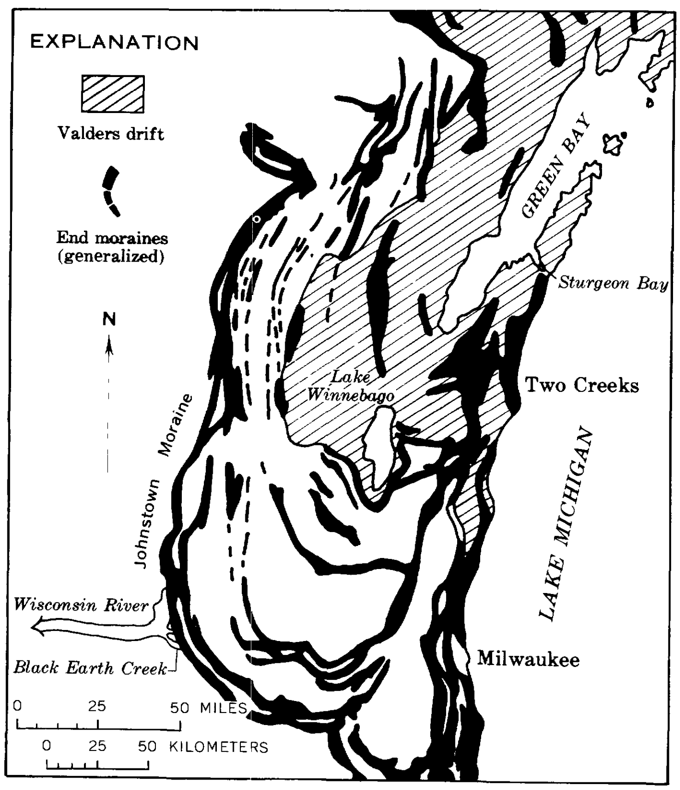

FIGURE 33.—Sketch map showing glacial setting of country near the head of Green Bay, Wis.

ilarly, large meanders on the East River reach along the floor of the wide, lowermost valley almost to the confluence with the Fox, if indeed they do not run the whole way down. These large bends must, it would seem, have been cut not only after the recession of Valders ice but also after the fall of the lake from the 605-foot level. Any allowance made for warping of the Algonquin shoreline would increase the extent of submergence indicated for Algonquin time by present-day contours; without such allowance, a stand of the lake at 605 feet would inundate more than 3 miles of Dutchman Creek, nearly 4 miles of Ashwaubenon Creek, and nearly 10 miles of the East River. However, as the present streams tend to cut into the floors of the enclosing valley meanders, measurements related to interfluves are preferable to those referred to the valley bottoms; a lake standing at 605 feet would inundate more than 1 mile of the whole valley of Dutchman Creek, 1½ miles of the valley of Ashwaubenon Creek, and 7 miles of the valley of the East River.

The Algonquin phase ended about 8,000 years B.P. with a spasmodic fall in water level that eventually reduced the water body in the Michigan basin to Lake Chippewa, which stood at about 230 feet above sea level and is dated to about 5,000 years B.P. The 605-foot level was later reestablished when the Nipissing Great Lakes came into existence as warping raised the North Bay outlet of the whole Superior-Michigan-Huron system. As a group, the Nipissing beaches are strongly developed, indicating a lengthy stillstand; they can be distinguished from the Algonquin beaches, and thus compared in respect of strength of development, in those northern areas where the two series are upwarped in different degrees. Because of the inferred long stillstand, the radiocarbon date of 3,656±640 years for peat from a Nipissing beach is merely a sample from a long span of time. In view of its lateness by comparison with Algonquin dates, and especially in view of the presence of the Nipissing shoreline in the East River basin, this date, or span of dates, is significant in the present context. The succeeding beach in the Michigan sequence, the Algoma Beach at 596 feet, dates from about 2,500 years B.P. and may have continued to develop even as late as 2,000 years ago. Very little of Dutchman Creek or Ashwaubenon Creek would be flooded at the Algoma level, but the valley of the East River would be occupied by water for at least 7 miles above the river mouth. It seems unlikely that large meanders on the East River have been neatly re-excavated after the long stand of water at the Nipissing level. Furthermore, the patches of swamp (indicated on the 1:24,000 map) alongside the lowermost reaches of the stream are seen on aerial photographs to be associated with large point bars and with large cutoffs downstream from the 590-foot contour (fig. 34). The inference is that these particular large bends were cut in the emergent floors of Lakes Nipissing and Algoma. This means that the necessary climatic conditions for large meanders were prevalent here as late as about 2,000 or 2,500 years B.P. Subsequent slight upwarp-

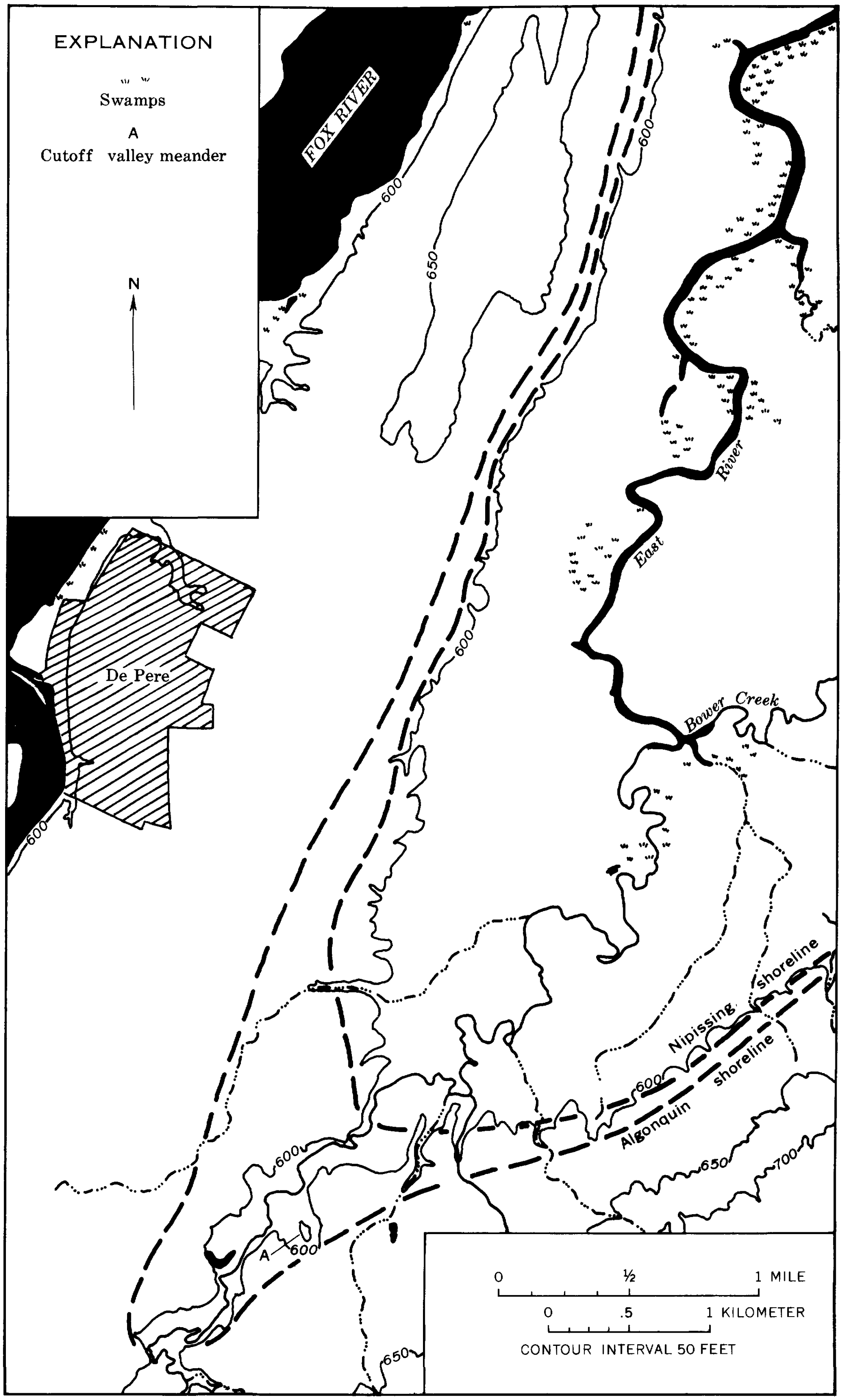

FIGURE 34.—Sketch map showing relation of the lower East River to glacial-lake shorelines.

ing can be held to account for the apparent drowning of the East River, perhaps as far upstream as the confluence of Bower Creek 5 miles from the mouth of East River, and for the drowning of the extremities of Dutchman Creek and Ashwaubenon Creek. Drowning seems responsible for the failure of the streams to convert in their lowermost reaches from large to small meanders.

DATES FOR THE ABANDONMENT OF VALLEY MEANDERS AND LARGE CHANNELS

In this context, abandonment means infilling sufficient to separate a stream channel from underlying bedrock, always provided that the infilling is associated with stream shrinkage. Alternatively, of course, abandonment of valley meanders merely constitutes reduction of wavelength sufficient to produce stream meanders upon the ample meandering trace of the valley. In practice, the dates available are those supplied by studies of channel fills. In practice, also, these dates depend largely upon the analysis of fossil pollen and on correlation of pollen data with the data of radiocarbon analysis.

This section will review the evidence from Wisconsin and from a number of well-documented sites on the English Plain. The Mission River of Texas will be used to exemplify valley meanders drowned by the deglacial rise of sea level. The general outcome of this part of the discussion will be that, although great alternations between cutting and filling are recorded for humid regions, the last abandonment of large channels—that is, the end of the last episode of complete scouring—occurred not later than some 9,000 years ago, except in regions such as parts of the Lake Borders where still-receding continental glaciers were able to influence the regional hydrology until much later dates.

Unless a streamless interval be postulated for Black Earth valley between the outwashing of a braided stream of melt water and the initiation of the stream that cut large meanders into the loess, it must follow that the change from braids to large meanders was nothing more than a change of habit by a stream which continued in being. Changes of this type are well known from other regions. Fisk and McFarland (1955, fig. 2) show the Mississippi Trench at the head of the deltaic plain as filled by late Quaternary (=late Wisconsin) deposits; the lower part of the trench is referred to sedimentation by a braided river. Their text (p. 292) states that the channel characteristics of the Mississippi at the time of late Wisconsin low sea level were probably similar to those of the braided present-day Willamette River. Change from braiding to flow in valley meanders was noticed above for certain rivers on the European mainland and, in Professional Paper 452–A (Dury, 1964), for the English streams Avon and Evenlode. The postulated braided ancestor of Black Earth Creek was probably capable of dealing with silt, because it could transport large blocks. Conversion from braids to meanders should therefore be placed at about the time that loess fall began; the top of the outwash supplies an earliest possible fix for the origin of large meanders.

The cause of change in habit may be somewhat more complex than a simple retreat of the ice front and a cessation of the discharge of melt water. Some of the rivers described by Troll were not supplied from ice fronts. It is possible, therefore, that Black Earth Creek continued to braid after the ice had withdrawn so far as to discharge no more sediment or melt water into the valley head. On the other hand, because the train of outwash is stratigraphically continuous with the Johnstown Moraine, the change of habit appears to have followed swiftly upon the first withdrawal of ice. If the Johnstown ice stand equals the Cary of the traditional subdivision of the Wisconsin Glaciation, then it belongs in the interval 14,000–12,000 years B.P. (see Horberg, 1955; Ruhe, Rubin, and Scholtes, 1957); if it belongs with the Valparaiso Moraines, the earlier rather than the later date applies. The base of the present flood plain seems to date from not later than 10,000 years B.P., giving a maximum possible span of 4,000 years for the duration of large meanders. The duration was probably less than this, for the large stream had time merely to cut through the shallow loess and to make slight excavations in the underlying gravel; although its meanders greatly extended themselves in the lateral sense, they failed to migrate downvalley to any appreciable extent. The spread of loess on the valley floor does not seem stratified; if it were proved to be stratified, it would seem referable to deposition by a braided stream, as it extends wholly across the valley floor in a belt much wider than the large meander belt of Black Earth Creek. In that event, the span available for the initiation and development of large meanders would be reduced below the possible 4,000 years.

The date of 10,000 years B.P. for the base of the flood plain depends on gross determination of pollen in sediment samples taken on line 2 (fig. 15), where part of the fill of the old pool remains. Determinations were made through the courtesy of Dr. Estella B. Leopold of the U.S. Geological Survey Paleontology Laboratory, Denver, Colo. Although the sediment in the old pool is almost barren of pollen and thus fails to provide adequate material for dating, the sandy layer at the base of the present flood plain (USGS paleobotany loc. D1559–A, D1559–B) seems to relate to Zone III of Jelgersma's pollen sequence for east-central Wisconsin (Jelgersma, 1962). The top of Jelgersma's Zone I (nonarboreal pollen) is fixed by radiocarbon dating at 12,000±350 years B.P. Next comes Zone II (*Picea*), then Zone III (Mixed *Picea* and *Pinus*), followed in turn by Zone IV (*Quercetum mixtum* and birch) with its top at 9,300±350 years B.P. Zone III would seem to bracket an interval of about 11,000–10,000 years B.P. These dates are thought to give lower and upper limits for the deposition of the base of the present flood plain, which unconformably truncates the fill in the pool of a large meander, and thus to locate the conversion to the small meanders of the present day.

Gross determinations of pollen have been made, also through the courtesy of Dr. Estella B. Leopold, for two samples from the valley of Mounds Creek (USGS poleobotany loc. D1558–A, D1558–B). The samples were taken from the lowermost part of the fill which overlies the gravel on the Elvers profile (fig. 18). They contain mostly spruce pollen with some pine near the base of the section and mostly spruce pollen at the base, immediately above the gravel. Both are tentatively assigned to Jelgersma's Zone II (*Picea*). As noted above, the beginning of this zone is fixed at 12,000±350 years B.P. The date confirms the interpretation of the gravel in the Mounds Creek valley as a sludge train of congelifractate provided by weathering in a periglacial climate near the ice front at the glacial maximum. If conversion from braiding to meandering on Black Earth Creek coincided with the cessation of sludging in the valley of Mounds Creek and if the base of the flood plain of Black Earth Creek is dated to 11,000 years B.P., then the large meanders acquire a maximum duration of only 1,000 years.

The approximate date of 12,000 years B.P., however, resembles the opening date of the Two Creeks Interstade. It is entirely possible that the large meanders of Black Earth Creek were abandoned during this interval and that a gap of time separates their abandonment from the deposition of dated material at base of the flood plain (table 2). On this view, the existing flood plain accumulated after Two Creeks time.

On the assumption that the movement of colluvium into Mill Creek valley was contemporaneous with the delivery of gravel into the valley of Mounds Creek and that the first channeling of the gravel of Mounds Creek at Elvers coincided with the appearance of large meanders on Black Earth Creek, a further minor hypothesis becomes possible—namely, that loess was able to accumulate in Black Earth valley because the stream flowing at the time of loess fall was a small one. Reasoning of this kind depends on some such correlation as that presented in table 2, which must remain tentative until further dates are forthcoming—that is, for the deposits at Mill Creek.

The dating assigned to the oldest channels beneath these Wisconsin streams (see table 4), however, is comparable to that established by Daniels, Rubin, and Simonson (1963) in a paper that was published after the present text had been drafted. These three writers find

TABLE 2.—*Possible correlation of events on Black Earth Creek, Mounds Creek, and Mill Creek, Wis.*

Event	Black Earth Creek	Mounds Creek	Mill Creek	Time correlation
7	Present slight downcutting; epicyclic(?), independent of control by Wisconsin River?		Cut terrace formed?	----------
6	Base of present flood plain	----------	----------	11,000–10,000 years B.P.
5	Large meanders abandoned		Intermediate channel filled	Two Creeks Interstade
4c 4b 4a	Large meanders cut through low terrace Low terrace formed (episode of stability?) Large meanders formed and incised through high terrace		Intermediate channel cut	Identical with Zone Ic
3	Stream shrinkage and loess fall			----------
2b	Wisconsin high terrace and correlatives		Colluvium fed into valley	Johnstown ice stand, 14,000 years B.P. approximate
2a	Outwash train accumulating	Sludge-train formed		
1	Valleys excavated in bedrock		Largest channel cut in bedrock	----------

for the Thompson Creek watershed, Iowa, that alluviation began some time before 14,300 years B.P., and that the oldest member of the formation studied may be related to climatic changes associated with the retreat of Cary ice. Although they state that alluviation was apparently continuous from before 14,300 B.P. to some time before 2,000 B.P., the several members of the De Forest Formation are described as separated by disconformities, and these disconformities are ascribed to erosion. The evidence adduced by Daniels, Rubin, and Simonson thus lends general support to the view here advanced, that the last major episode of infilling—that is, the episode when many streams lost contact with bedrock—was associated with end-glacial climatic changes. Their observations are especially important to the present thesis, as relating to valleys that appear to represent type 5a in figure 4 of Dury (1964)—that is, valleys that are too greatly eroded to preserve valley meanders, and where the trace of the present stream channel is merely irregular.

The Mission River of south Texas represents that group of manifestly underfit streams which possess drowned valley meanders in their coastal reaches. Streams of this type are common on the south Texas coast, just as manifestly underfit streams are well displayed farther inland; despite the claims of Stricklin (1961) that the Brazos River is not underfit, his own diagrams (figs. 3, 4) show the familiar combination of stream meanders with valley meanders. The Brazos system, containing an alluvial sequence dated with reference to the fall of Pearlette Ash Member of the Sappa Formation in Kansan or early Yarmouth time, incidentally extends the list of streams known to have long histories of ingrowth.

The adjacent Woodsboro and Rockport (Texas) quadrangles (1: 62,500) clearly show the relation of meandering valleys to tidewater. Drowned valley meanders occur at the mouth of the Aransas River at the west end of Copano Bay, on the border of Refugio and Aransas Counties; others lie at the east end of the bay, where the county line runs inland along Copano Creek. A third and larger train has been cut by the Mission River (fig. 35).

Each side of Mission Bay is a valley-meander scar that rises 10–25 feet above sea level; this level is but slightly affected diurnally by a mean tidal range of less than 0.5 foot. Scars similar to those on the flanks of the Bay run inland up the valley, uniting in series of blunt cusps and enclosing a valley floor where the present levees, possibly with the aid of artesian water, create pools and swamps. The history of development of the Mission River, is, in general terms, easy to read. The scars of valley meanders, now partly drowned and truncated by low receding cliffs of 10–20 feet at the seaward end, relate to a time when the river was distinctly larger than it is now and when sea level stood below its present mark. Drowning seems to have promoted infilling about as far upstream as Refugio, 11 miles from where the Mission debouches from its embanked channel onto the flats at the head of Mission Bay.

Alternate cutting and filling on the lower Mississippi are known to correspond to the alternation of glacial and interglacial conditions (Fisk and McFarlan, 1955). Whatever effects may have been produced in and near the delta by crustal warping, the south Texas coast seems to have remained crustally stable during the last deglaciation; so that the drowning of its valley mouths is referable to glacioeustatic recovery of sea level. Radiocarbon dates from nearby sites indicate rates and extent of drowning without, however, preventing some uncertainty about the date of recovery from low glacial levels to a level near the present; dating, discussion, or both, appear in Shepard and Suess (1956), Deevey, Gralenski, and Hoffren (1959), and Bray and Burke (1960). There is fair agreement that sea level stood about 200 feet below the present mark at 12,000 years B.P., and 120 feet below at 10,000 B.P. But whereas Shepard and Suess would defer completion of recovery until about 2,000 B.P. or even later, Godwin, Suggate, and Willis (1958) regard it as sensibly completed by about 5,000 years B.P. This earlier date agrees with the schema presented by Fairbridge (1961) which is broadly accepted here. (See also McFarlan, 1961; Broecker, 1961.)

Until more is known of the sedimentary fill of the Mission River valley or comparable neighboring valleys, the record of drowning and abandonment of large meanders will remain imprecise. Information already available shows that the cutting of the lowermost drowned bends dates from not earlier than the last glacial maximum, whereas their inundation and filling are deglacial. Thus, the evolution of the Mission River since the last glacial maximum in no way contradicts the histories of better known streams. Occurring far beyond the extreme limit of land ice and indeed beyond the limit of permafrost at last glacial maximum, the Mission River will subsequently buttress the general hypothesis that changes in temperature and precipitation are primarily responsible for underfitness.

Southern England lay south of the ice front at the last (=Wisconsin) glacial maximum. For this reason, its rivers, which became underfit at end glacial or in deglacial times, require explanation by some climatic hypothesis. Detailed studies of fossil pollen in this region not only serve to confirm that reduction to underfitness postdates the last glacial maximum but also to

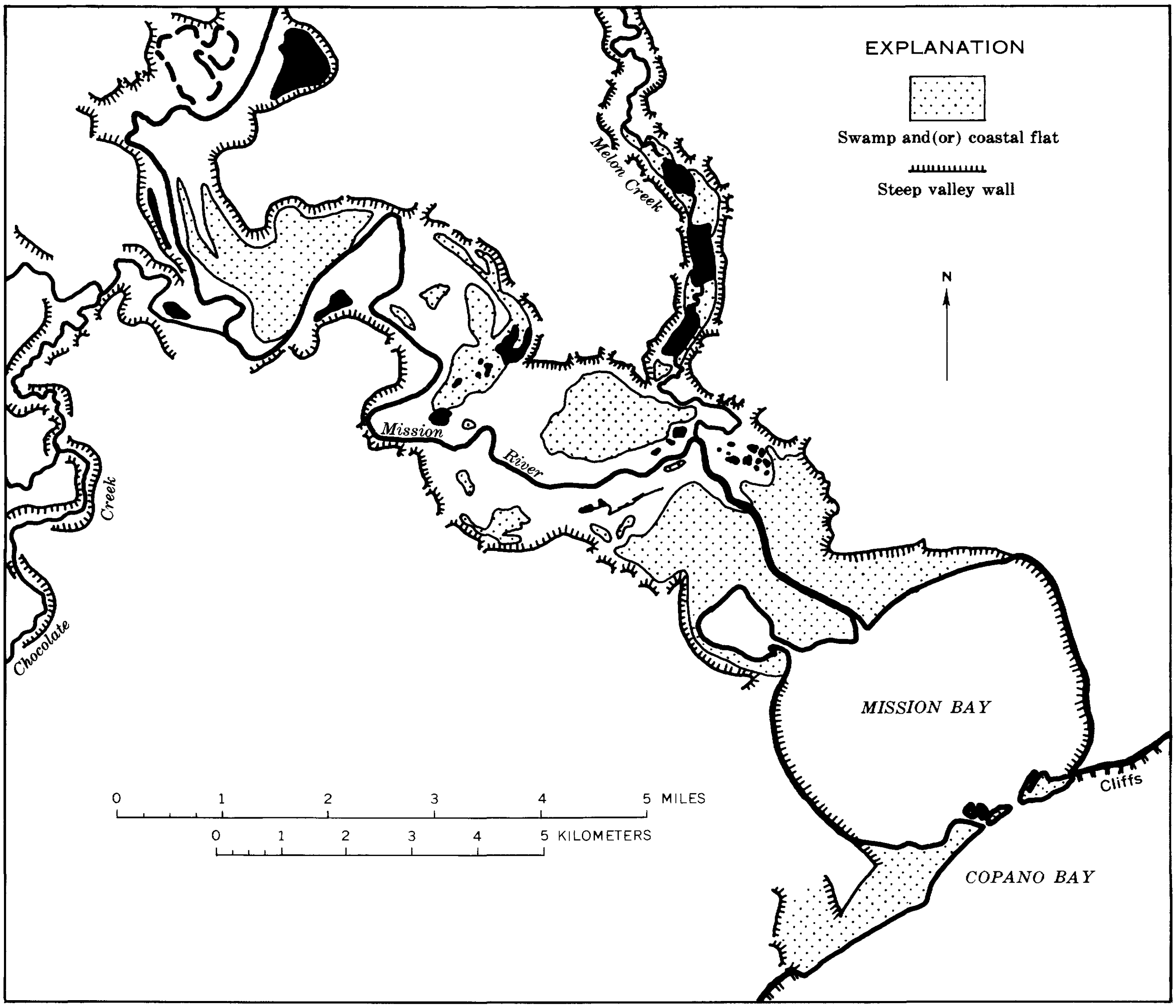

FIGURE 35.—Morphologic sketch map of part of Mission River, Refugio County, Tex.

show that channeling and filling went on long after the date of 10,000–11,000 years B.P. obtained for the base of the present flood plain on Black Earth Creek.

The peaty flood plain of the English River Kennet constitutes the top of a composite valley fill. Both the large channel that contains the fill and its first infilling predate the Atlantic phase (Zone VII), when partial reclearance took place (Dury, 1958). Slight reexcavation may have affected the Zone V fill of the Dorn Valley, for part of the alluvial silt and clay of the topmost layer descends below the sandy base of the present flood plain. Not two channels, but three, may occur here (fig. 36).

The Nazeing site lies in the valley of the Lea at Nazeing, Essex, close to the northern outskirts of London, England, and 7 miles downstream from the confluence of the River Rib. Standing about 80 feet above sea level, the present surface of the flood plain at Nazeing is well below the mark of a proglacial lake which during the Penultimate Glacial (= Illinoian) remained for some time at about 230 feet above sea level (Clayton and Brown, 1958). A gravel fill in the valley bottom relates not to the Penultimate but to the last (= Wisconsin) glacial, when the nearest ice front lay far to the north of the Lea basin. At this time the lower reaches of the Lea were controlled by a sea level lower than the present, and gravel moved into the valley in response to thawing-and-freezing. Within the gravel occurs the Arctic Bed, with its content of dwarf willows, arctic plants, and remains of *Elephas primigenius* and

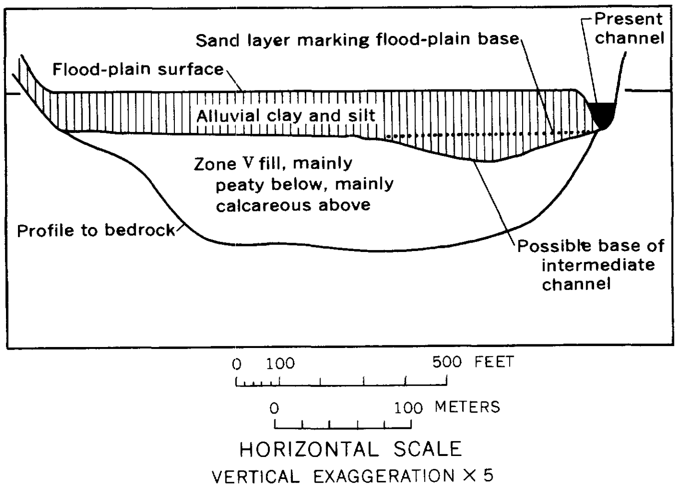

FIGURE 36.—Profile section showing possible interpretation of the sedimentary sequence on the River Dorn, Oxfordshire, England. View is downstream.

Rhinoceros tichorhinus (Warren and others, 1912; Warren, 1916; Reid, 1949).

A complex sequence of channeling, filling, and vegetational change at Nazeing has been disentangled by Allison, Godwin, and Warren (1952), who identify the changing character and the floral and faunal content of deposits both within the channels and upon the adjacent valley floor. The earliest of three channels postdates the gravel of the valley fill, wherein the Arctic Bed supplies a radiocarbon date of 28,000±1,500 years B.P. (Godwin and Willis, 1960). The second channel contains near the base a sediment that is referred to pollen Zone III (Younger Dryas), whereas the cutting of the third channel took place in Zone VI (Transitional) and filling was completed in Zone VII (Atlantic).[5]

The relation of the channels to one another, to the valley fill of gravel, and to valley-floor deposits is diagrammatically shown in figure 37; figure 37, drawn by the present writer, relies on the text of Allison, Godwin, and Warren and incorporates features recorded in their cross sections. Channels are numbered for convenience of reference in the present text. Allison, Godwin, and Warren refrain from dating the cutting of channel 1 except to place it later than the deposition of the Arctic Bed and the immediately succeeding valley fill and earlier than channel 2. The fill of channel 1 consists of gravel at the bottom but mainly black organic peaty muds with some sand throughout the remainder. Pollen and faunal remains in the muds resemble the content of the Arctic Bed, indicating tundra of either the grass-sedge or the park type.

Above the fill of channel 1 is found the calcareous nekron mud of a lake (lake marl in the diagram), still with fauna of the cold type and with an old land surface at the top. The lacustrine stage was succeeded by the cutting of channel 2, during which much of the nekron mud was cleared away. Infill of channel 2, above bottom gravel, begins with organic mud and continues with detritus mud, with contents indicating Zones III and IV (Younger Dryas and pre-Boreal). While infilling was taking place, closed birch woodland replaced the herbaceous vegetation of the surrounding countryside. Shallowing of channel 2 promoted the

[5] Zonal numbering used in this and following sections accords with the general schema of table 4.

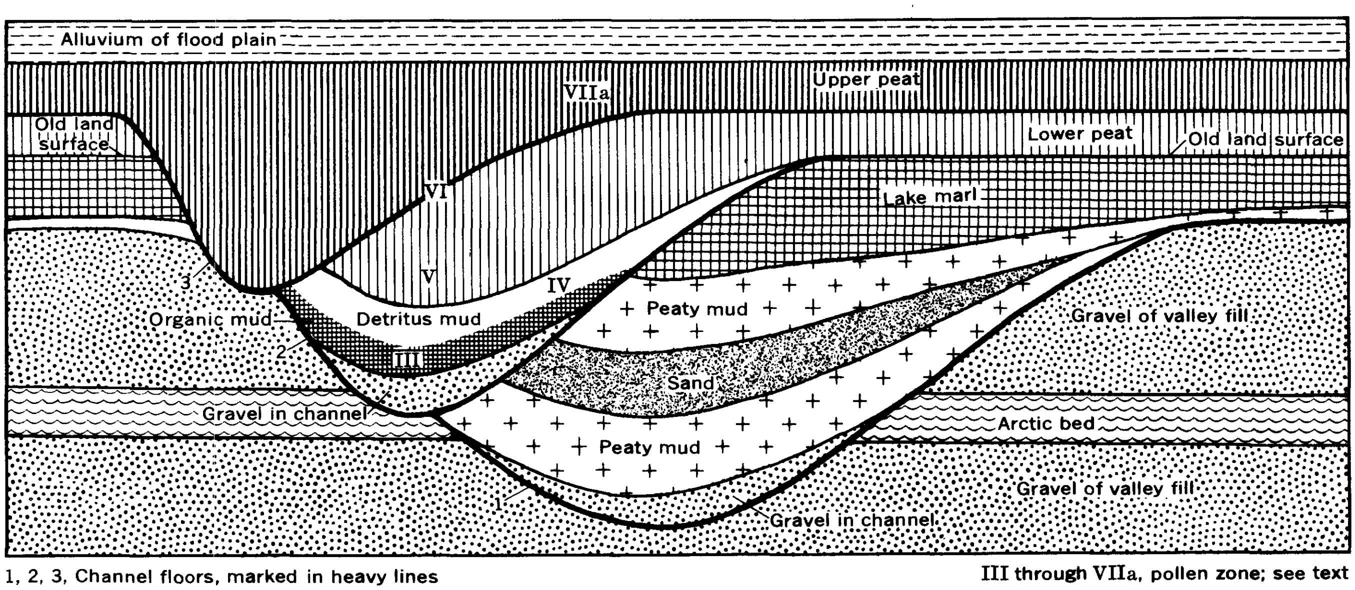

FIGURE 37.—Diagrammatic interpretation of the sedimentary sequence on the River Lea at Nazeing, Essex, England.

growth of sedge peat or reed peat in an ameliorating climate that saw the spread of pine and the arrival and extension of hazel. Peat continued to form through Zone V (Boreal), but eventually the channel and the valley floor almost dried out.

Environmental changes set in during Zone VI (Transitional), causing waterlogging of the valley floor and the renewed erosion which produced channel 3, and brought a mixed-oak forest with hazel to the region. Fen peat grew on the valley bottom and in channel 3 until undated erosion of forest soils in the headwaters supplied clay which forms the existing flood plain and seals in the organic muds and the peats.

Allison, Godwin, and Warren (1952) point out that the record suggests some element of cyclic repetition in physiographic history and thus indicates also a corresponding—and causal—alteration of climate. There could accordingly have been additional cutting and filling to that proved by the available findings. In particular, nothing in the Nazeing record proves the occurrence of the park tundra which may be supposed to have established itself during the Bölling phase, (Ib), or the woodland, which elsewhere is widely indicated for the Allerød (II).

Channel 3, cut at the end of a period of relative dryness and warmth and associable with the change from birch-pine-hazel forest to mixed-oak forest, can scarcely be referred to anything but the onset of the Atlantic phase. Channel 2 predates much if not all of Zone III sediment and postdates the lake marl. A distinct possibility seems to be that the lake and its ultimate drying-out belong in the Allerød, in which event the cutting of channel 2 could be linked with the increasing rigor of climate at the end of the mild Allerød fluctuation. Similarly, the cutting of channel 1 might belong near the base of Zone Ic in the Older Dryas phase and between the preceding Bölling and the following Allerød. The correlation of the whole sequence on these assumptions is schematized by the present writer in table 4, which implies that the cutting of channels 1 and 2 was induced by increasing cold and wetness whereas that of channel 3 was due to increased wetness in conditions of rising temperature.

A general difficulty arises from the indubitably low temperatures—low, that is, compared with those of today—which existed when channels 1 and 2 were cut. Quite apart from possible gaps in the floral record, low temperatures tend to make that record imprecise by comparison with the needs of the present discussion. However, the Nazeing record of channeling spans an interval not shorter than that bracketed by Zones I through VI. Dates listed in table 4 indicate a minimum span of 4,500 years for this interval, the length of which in terms of climatic phases and floral zones is not affected by any revisions to absolute dating which may prove necessary in future.

The Broads are shallow lakes in the valleys of the East Anglian Rivers Bure, Yare, and Waveney. The three rivers unite near Yarmouth in Breydon Water, an estuary enclosed on the seaward side by a massive spit. Spasmodic growth and erosion of the spit, slight changes in sea level, slight crustal warping, and levee building by the rivers combine to make the record of sedimentation a complex one. In a first study, Jennings (1952) regards the Broads as natural lakes surviving amid the backswamps of naturally embanked streams but also notes certain discrepant evidence that was used by Jennings and Lambert (1953) and later amplified and reinvestigated by Lambert and others (1960) in accounts which reveal that the Broads originated as medieval turf pits. The revised origin does not, however, affect the chronology established by Jennings for the channels beneath the Broadland rivers (Jennings, 1952, 1955).

These channels closely resemble those identified by the present writer beneath manifestly underfit streams. Indeed, the Bure, Yare, and Waveney are all manifestly underfit, so that the presence of large meandering channels beneath their flood plains is in no way surprising. As the chief concern of Jennings and Lambert was to study the Broads as water bodies and to explain the peaty basins which contain them, their lines of cross profile do not everywhere run completely across the valley bottoms nor lie at the inflections of valley bends where the widths of filled channels are most fittingly determined. However, the block diagram drawn by Jennings for the Bure valley (Jennings, 1952, fig. 31) clearly displays the asymmetry of a filled channel at two valley bends and the near-symmetry at one inflection of the valley.

The block diagram is here redrawn as figure 38, in which the excavations of turf pits flanking the stream have been arbitrarily restored. Zonal numbers inserted in the diagram agree with Jenning's classification into climatic phases but not with his scheme of forest zones; they have been revised to accord with the sequence employed here.

The *Phragmites* peat at the base of the section on the fore-edge of the block is Boreal, with a very high ratio of nonarboreal to tree pollen in its lowermost part, suggesting that it may have begun to form at the very beginning of Zone V. That part of the trench which it occupies is therefore earlier than Boreal in age; when the trench was cut, the Bure was controlled by a sea level perhaps as much as 70 feet below the present (Jennings, 1952, p. 49). The Boreal-Atlantic transition occurred before deposition of the peat was completed, and a slight marine incursion during the Atlantic phase brought estuarine mud some way up the valley. This mud appears immediately above the basal peat on the fore-edge of figure 38; farther upstream, beyond reach of estuarine sedimentation, nekron muds continued to accumulate as they had done previously. (See central and rear profiles, fig. 38.) Part of the fill of brushwood peat belongs to Zone VII (Atlantic phase), but its deposition continued into the succeeding Zone VIII (sub-Boreal). Infilling was interrupted during the Sub-Atlantic by channeling, after which renewed deposition of clay occurred. The final part of the record, which includes a fresh establishment of *Phragmites* peat across the top of the fill, is greatly obscured by the effect of peat cutting.

Although the profiles on the Bure do not reveal channeling during the Transitional or Atlantic phases, they do not conflict with the possibility of channeling at this time in other valleys; for events in the Broadland were certainly then affected by rising sea level that may either have obscured the record of any channeling which took place or have prevented cutting altogether in that downstream reach of the stream for which the record is the most detailed. In outline, then, the sequence of cutting and filling is:

1. Channeling dated earlier than Boreal;
2. Filling by *Phragmites* peat, beginning early in Zone V and continuing into Zone VI, interrupted in lower valley by

2a. Incursion of estuarine clay (Zone VII);

3. Channeling? (partly or wholly offset by effects of transgression?);
4. Bulky accumulation of brushwood peat (Zone VIII);
5. Renewed channeling in Zone IX, followed by a second and farther reaching incursion of estuarine clay;
6. Spread of *Phragmites* peat across the valley bottoms, with levee formation alongside the channels.

As in the Lea valley at Nazeing, the largest, deepest and oldest channels are older than Boreal. If the deepest channel under the Bure correlates with channel 2 at the Nazeing site, and if, as suggested above, the equivalent of Nazeing channel 2 is obscured in, or missing from, the Bure sequence, then the Zone IX channel of the Bure brings the combined record to four successive filled-and-cut channels. The Bure profiles are especially useful in demonstrating minor channeling as late as Zone IX, when it can be referred to a change in climate toward increased cold and wetness.

Sparks and Lambert (1961) record a fill on Willow Brook, Northamptonshire, England, that they describe as not occupying a deep buried channel. However, Willow Brook in the reach described is manifestly underfit (Sparks and Lambert, 1961, fig. 1; Ordnance Survey of Great Britain, 1:25,000, Sheet TL/09), and the explored profile is entirely similar to many of those described by the present writer for sites elsewhere. (See fig. 39.) The fill beneath Willow Brook begins either at the very end of Zone III or early in Zone IV, continuing with Zone IV and Zone V deposits, displaying the results of disturbance and erosion in Zones VI and VII, and recommencing with sedimentation in Zones VIII and IX. The general import of this sequence resembles that of the previously described sites with satisfactory closeness, although it suggests that details of the basal parts of some other fills may have been undetected. On Willow Brook, infilling of a large channel began about 10,000 years B.P. and was interrupted by partial reexcavation at about the time of the hypsithermal maximum.

The 1,300 square miles of Fenland in eastern England constitute a region of drained swamp separated from the coastal inlet of the Wash by a low broad compound baymouth bar of littoral and estuarine silt (Skertchly, 1877; fig. 40). The history of artificial drainage is very long, going back at least to the 3d century, although the principal works date from the 17th century or later (Dugdale, 1662; Wheeler, 1868; Miller and Skertchly, 1878; Darby, 1940a,b). The trace of extinct natural waterways remains visible on the ground and even more clearly so on aerial photographs (Fowler, 1932, 1933, 1934a,b). Their principal type is the roddon, a low bank of clay-silt which stands a little higher than the surrounding peat. Godwin (1938) rejects Fowler's original view that the peat alongside the roddons has been lowered by shrinkage and also denies the efficacy of compaction and wastage, maintaining instead that the roddons are natural levees.

In their lower reaches, as Godwin shows, the roddons result in part from estuarine sedimentation, much of their total bulk having accumulated in Romano-British times—roughly speaking, in the first eight centuries. The natural channels that the roddons border are, however, underlain in places by two earlier and large channels, dating, respectively, from the Neolithic division of prehistory and from some pre-Boreal part of the deglacial climatic sequence (Godwin, 1940; Godwin, 1956, fig. 8; Godwin and Clifford, 1939, fig. 34; fig. 41 herewith).

Although channeling may not equate at all simply with the record of floral change, it seems to correspond sufficiently well to the established sequence of deglacial events and to specific happenings elsewhere. Godwin and Willis (1960) show by radiocarbon dates that track-

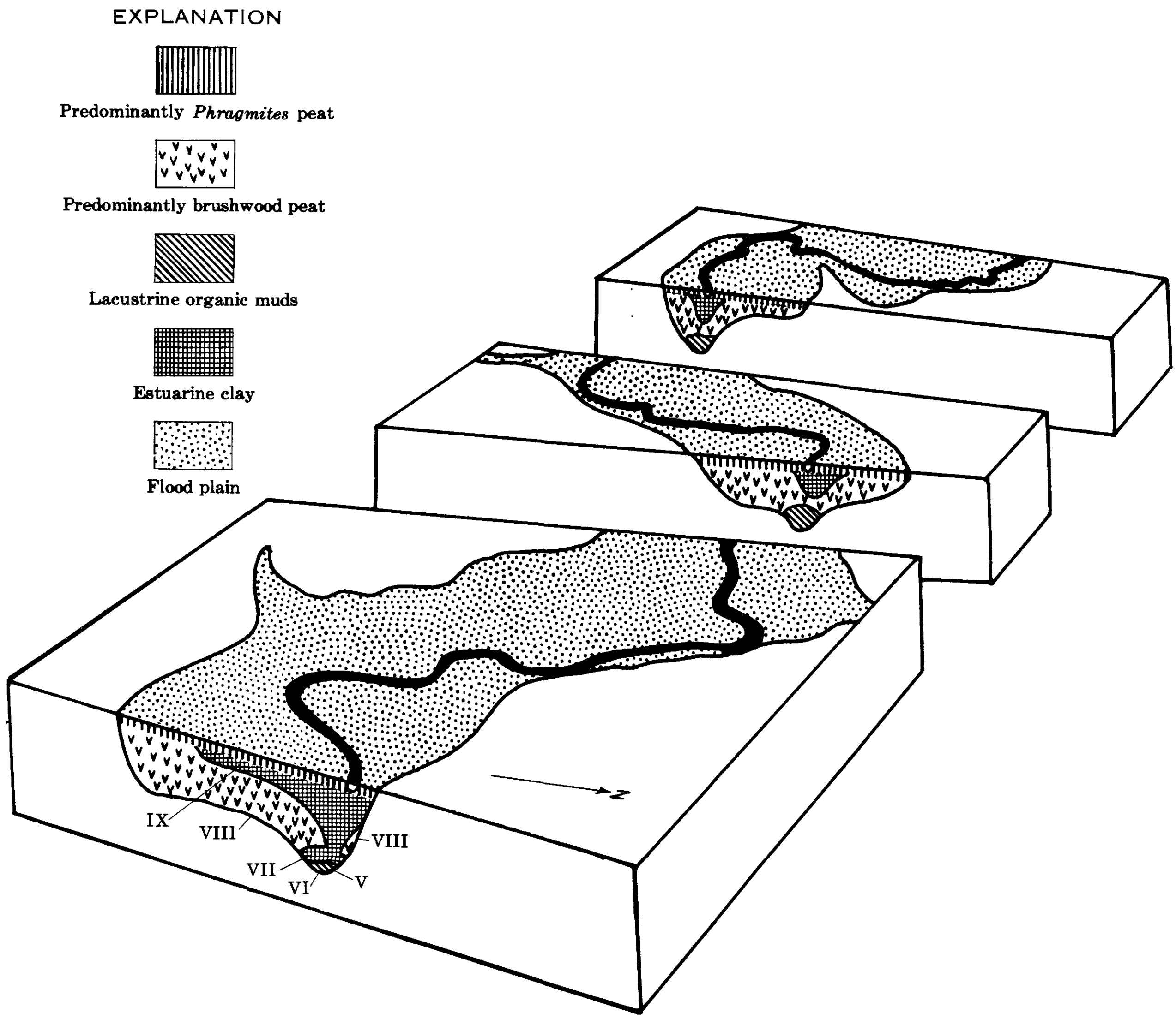

FIGURE 38.—Block diagrams of the filled channel beneath the River Bure, Norfolk, England. Redrawn from Jennings (1952) with excavations restored. Zonal numbers from Jennings (1955) to accord with Firbas (1949).

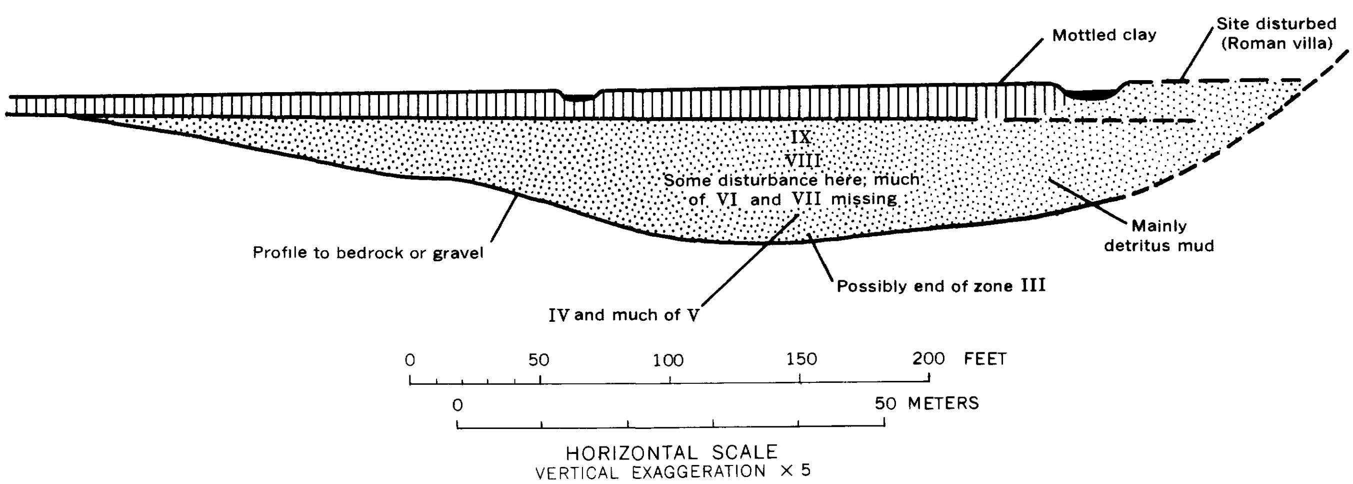

FIGURE 39.—Profile section across the valley floor of Willow Brook, Apethorpe, Northamptonshire, England. Redrawn and zones renumbered from Sparks and Lambert (1961). View is downstream.

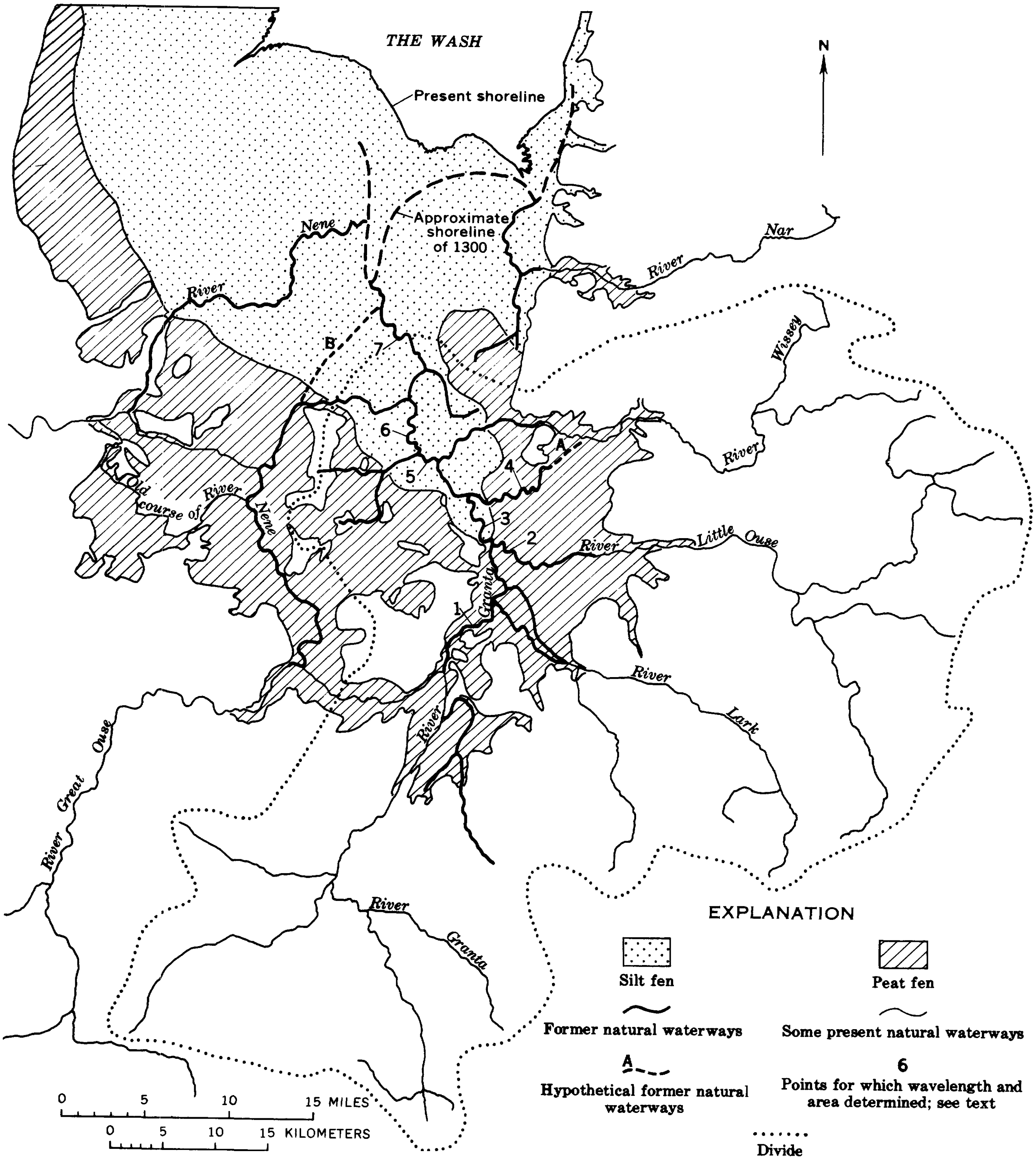

FIGURE 40.—Map of the Fenland of eastern England with reconstructed early drainage pattern. After Fowler (1932, 1933, 1934a, b).

ways were laid across the increasingly moist and growing bogs of Somerset, on the other side of England, at times which indicate increased wetness underfoot for late Zone VII (Atlantic) and for about the beginning of Zone IX (sub-Atlantic). For the Fenlands, Godwin and Clifford observe that peat growth was controlled to some extent by profile drainage, which may have worsened during episodes of drying climate. However,

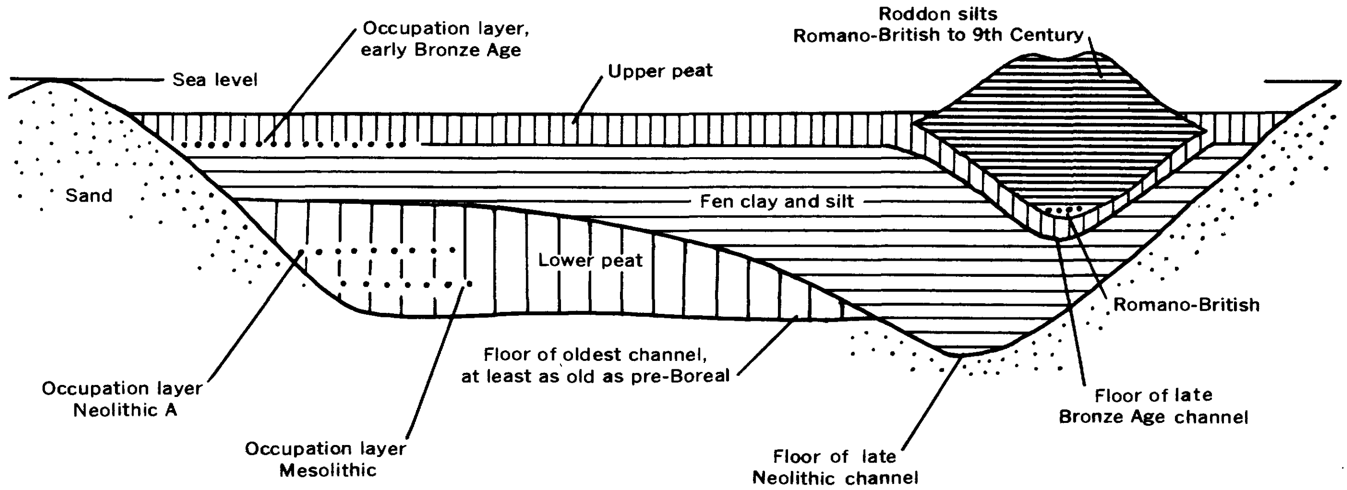

FIGURE 41.—Profile section of channels, sediments, and archeological correlation in the Fenland of eastern England. Redrawn from Godwin and Clifford (1939). View is dowstream.

a reasonable outline of the alternation of channeling and filling in the Fenland seems to be:

1. Largest channel, cut at least as early as Zone IV (pre-Boreal);
2. Infilling;
3. Second channel, intermediate both in age and size, cut in Zone VII (Atlantic);
4. Infilling;
5. Third channel, cut in Zone IX (sub-Atlantic), with levees which now form roddons completed in historic times;
6. Shrinkage of streams in third channel.

Roddon building need not have ceased entirely when shrinkage began.

The channels with which the roddons are associated describe large meanders that are distinctly larger than the meanders of existing streams, area for area of drainage, but distinctly smaller than the valley meanders on reaches upstream from the Fenland. In figure 42, wavelengths for roddons are plotted against drainage area for the River Granta, the largely extinct stream now called indifferently the Cam or Granta in its upper reaches and largely superseded in the Fenland by artificial waterways (fig. 40). As shown in the diagram, the meander wavelengths for roddons on the reconstructed Granta plot consistently against drainage area at about one-third of the extrapolated values for valley meanders on the Nene and the Great Ouse.

Certain difficulties arise from the former cross connections between the Great Ouse and the Nene and between the Great Ouse and the Granta that, being uncertainly known, make uncertain the former drainage areas of downstream reaches. But the eastward channel between Great Ouse and Granta, just within the limits of the fens, and the west-east reach linking the Nene to the Granta may not be earlier than medieval. (See Darby, 1940b.) Points plotted in figure 42 for the reconstructed Granta suggest that the wavelengths in question relate to a stream extending itself across the Fenland swamp independently of the Ouse.

Because the old course is marked by roddons, the extension appears to belong to Zone IX. (See fig. 41.) The 3:1 ratio of wavelength between the extended and the present streams means that bankfull discharge on the restored Granta was less, area for area of drainage, than the earlier discharge responsible for the 9:1

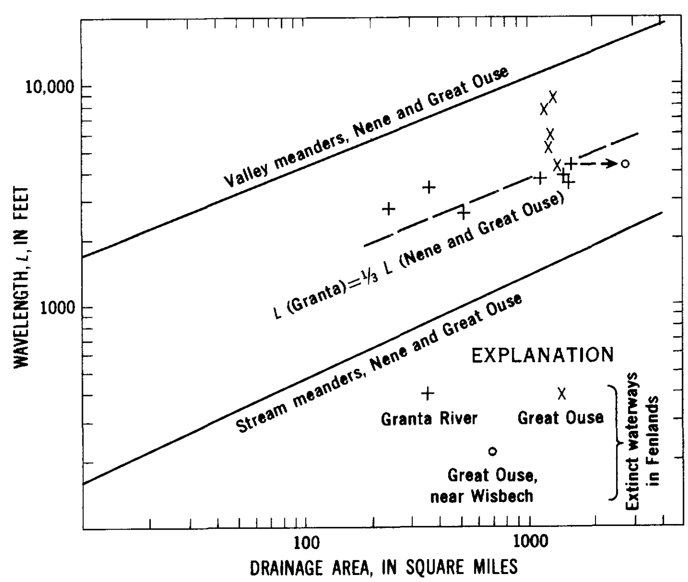

FIGURE 42.—Graph showing relation of wavelength to drainage of the Fenland and adjacent areas, England. Values for the Nene and the Great Ouse from Dury (1958); determinations for the Granta according to reconstructed course in figure 41; for discussion of the former course of the Great Ouse in its lower reaches, see text.

ratio on the landward reaches of the Great Ouse and the Nene. It would perhaps be stretching the evidence to claim that the apparent progressive downstream reduction of wavelength on the large meanders of the restored Great Ouse corresponds to a progressive reduction in bankfull discharge per unit area as the stream lengthened its established channel across the swamp; but the observations are at least enough to show that the points plotted for the Granta belong to that river rather than to the Ouse, which, greatly changed by artificial means, is now the main waterway of the region.

No problem arises with the point plotted for location 4 in figure 40 if the Wissey is taken at the relevant time to have taken the course marked by the broken line A. The hypothetical early course, B, for the lower Nene, on the other hand, makes uncertain the placing in figure 42 of the lowermost downstream point for the Ouse; the addition of the Nene drainage would shift the point to the position indicated in figure 42 by an open circle. Uncertainties aside, the wavelength ratio between the roddon systems and present streams accords with evidence from dimensions of channels: channels cut during Zone IX are distinctly smaller, both in width and in wavelength, than those referred to Zone IV or earlier.

Although fixes on the scales of time, stratigraphy, and floral succession remained few, the reduction of streams to underfitness could be regarded as an abrupt single happening. More specifically, the last reduction to underfitness could be placed at the end of the last glacial without prejudice to partial clearance—for instance, in Zone VII. The foregoing summaries of successive channeling and sedimentation require a more complex view. Nevertheless, simply because successive channels are preserved at more than one site, the younger and smaller being contained in the older and larger, the principal shrinkage below the size of stream appropriate to valley meanders is still to be put as early deglacial. If, after their first deglacial reduction, streams generally had regained their former volumes, former channels could scarcely have survived renewed erosion. In this sense, that reduction which caused certain rivers to lose contact with bedrock is the most significant of all. But because ice persisted north of the Great Lakes region long after other districts were far into deglacial time, the first main reduction was not everywhere simultaneous. Flint and Rubin (1955) give 6,000 years B.P. for the time when the receding ice front reached Cochrane. Southern England, the Great Plains, and the Cordilleran country in the Southwest were by that time closely approaching their hypsithermal maximum. Whereas the large channel beneath Black Earth Creek was abandoned before 10,000 years B.P. and that beneath the Dorn was infilled by 8,000 years B.P., parts of the Great Lakes shores were still drowned at these times. Therefore, the initiation of their valley meanders postdates the main reduction of streams in more genial climates. If long-distance correlation is possible, then the main channeling and main reductions of streams in the Lake Border country correspond to minor channeling and minor filling—for example, in southern England.

The alternative view that climatic belts moved across country as the ice front receded, giving similar but not synchronous changes in different regions, runs counter to much recent work. Broad synchrony throughout midlatitudes seems to characterize certain events, at least; one such event is the hypsithermal maximum, even though various authors place it at various positions in the range Zone VI through Zone VIII. The fact that the country near Cochrane still experienced an ice-marginal climate as late as 6,000 years B.P. involves a truncation rather than a deferment or compression of the local climatic sequence.

The upper part of table 4 summarizes and correlates the foregoing observations on the abandonment of large channels in southern England and Wisconsin. As noted in table 4, the principal known episodes of channeling in the Driftless Area predate the Two Creeks Interstade and the Valders ice advance, whereas most of the dated large channels in southern England seem to have remained clear as late as the Pre-Boreal. To some extent the evidence here, provided by the absence of deposits earlier than those of Zone IV, is negative; but the Zone IV fill of the bedrock channel beneath the Dorn and consistent reports of channeling before Zone IV throughout the Fenland, when viewed together, suggest that erosion was indeed marked in Zone III. Results obtained by West (1961) suggest a possible reason for the difference between the two regions; West uses floral evidence to show that a continental climate maintained itself in Wisconsin close to the Valders ice, whereas New England experienced a maritime climate. If the south of England, like New England, still had a maritime climate at the relevant period, then vigorous channeling may have been possible there in Zone III, when it was inhibited by drier conditions in the Driftless Area.

So far as they go, the records for the Kennet and the Bure agree with the more complex record from the Fenland. Slight marine transgression during Zone VII affected the Bure, which cannot therefore be expected to show channeling at this time; otherwise, with the aid of the early pollen reported from the base of this large channel, the revised sequence for the Bure (Jennings, 1952, 1955) accords with that for the other rivers. Correlations with the Lea at Nazeing are less easy, especially since the inference that channeling and filling were cyclic rules out the influence of evulsion or other shifts of channel. In some reaches, the present River Lea is given in the natural state to anastomosis, which is perhaps a response to the deep infilling of its lower valley caused by the deglacial rise of sea level. But the inference of cyclic change combines with the fact that the Lea is manifestly underfit at flood-plain level in some reaches to point to widely operating causes rather than local accidents as responsible for the proven record. Future studies must be relied on to resolve the apparent conflict between the Nazeing sequence and the indications from the Bure, Kennet, Dorn, Willow Brook Rivers and the Fenland rivers that their last time of complete channel clearance was Zone III.

EVIDENCE FROM ARID AND SEMIARID REGIONS

Channels in humid regions, many diminishing progressively in size with increasing lateness of origin, demand comparison with successive cuttings and fillings in drier country and with the histories of pluvial lakes. Literature about cut and fill in the Great Plains and in the Cordilleran country embodies opposing views on the mechanisms involved: some authors claim that accelerated erosion results from increasing wetness; others consider it a response to increasing dryness. Caliche formation, in particular, can be taken in either of the two ways. Debate on causes is all the keener because the sequence of cut and fill appears sensibly identical throughout a very large area (for data, references, and discussion, see Leopold and Snyder, 1951; Miller and Leopold, 1952; Leopold and Miller, 1954, 1956; Schumm and Hadley, 1957; Albritton, 1958; Miller, 1958; Hadley, 1960; Schumm, 1961; Martin, Schoenwetter, and Arms, 1961).

In one respect it is immaterial to the present argument whether aridity or humidity causes erosion to accelerate. Once conceded, shifts or climate link themselves to changes in the erosional or depositional tendency of streams either directly, as by altering the discharge occurring at any given point on the frequency scale, or indirectly, through the medium of vegetation cover. In a sense, also, redistribution of rainfall in time (see Leopold, 1951a, b) does not affect the present discussion, even though it can involve shifts in weather which do not appear in the average values defining climate. Whatever the mechanisms, certain regional trends of erosion of deposition result from external causes, either climatic or meteorologic. They are thus similar in kind, although not necessarily in direction, to those of humid regions. The progressively diminishing cuts of the West and Southwest broadly resemble those described above for rivers in humid climates, lending general support to the hypothesis that underfit streams owe their condition primarily to climatic change.

Grave difficulties are foreseeable, however, if the question of parallel or opposite sequences of cut and fill, respectively, in moist and in dry regions is altogether overlooked. With increased cutting in moist regions ascribed to increased discharge, and that in turn to increased precipitation, 4 items produce 2 contrasted pairs of combinations (table 3). If channeling is everywhere a response to increased wetness, and if simultaneous increases affect climates of both kinds, then the records of cut and fill should be parallel. They should also be parallel if moist regions become increasingly humid while dry regions become increasingly arid and if increasing aridity in dry regions causes accelerated erosion. In this event, however, intermediate areas should be unaffected—a logical inference at variance with the facts of distribution of underfit streams. If increasing humidity affected moist and dry regions at the same time but caused infilling in dry climates, then channeling in humid regions should be on the time scale where filling appears for arid regions. If humidity increased in moist regions while aridity increased in dry regions, and if increased wetness promoted channeling in whatever climate, then the two kinds of sequence would again be out of phase. In these last two instances, evidence of a highly ambivalent kind should be available from areas intermediate in location between distinctly moist and distinctly dry regions.

TABLE 3.—*Possible interrelation of channeling in dry and humid regions*

		Channeling in dry regions caused by—	
		Increased wetness	Increased dryness
Direction of change, to or from pluviality or aridity	Same for dry and humid regions	Humid regions and dry regions alike become more humid	
		Channeling synchronous in dry and in humid regions	Channeling not synchronous
	Opposite, respectively, for dry and humid regions	Humid regions become more humid; dry regions become drier	
		Channeling not synchronous	Channeling synchronous in dry and in humid regions

In the broad view, many streams in dry parts of the United States resemble streams in humid parts in being manifestly underfit (Dury, 1964). One well-investigated instance of manifest underfitness in the arid Levant is described by Voûte (1955); that author notes deeply incised valley meanders on the Orontes River, that cut through bedrock to well below the level of the present streambed and include a large channel which in characteristic manner is asymmertical in cross profile at valley bends, being deepest at the outsides of curves. The valley fill of the Orontes rises above present flood-plain level, to which it descends in terraces. The present river, winding in alluvium, is manifestly underfit, with a wavelength ratio between valley and stream channel—measured on Voûte's figure 3—of 3.7 : 1. The former alluvium which constitutes the fill and the terraces is coarser than the present alluvium, suggesting that regimen has changed. Although not wishing altogether to exclude tectonic movement, Voûte regards climatic change as the preponderant cause of change in regimen.

Neither the condition of the Orontes nor the widespread occurrence of underfit streams in the dry parts of the United States accord with the concept of opposed stream behavior in arid and in humid regions, respectively. As streams in humid midlatitude regions are commonly underfit at the present time, the concept would require existing streams in arid regions to be delivering unusually large volumes of water; this they fail to do. In the longish term, dry and moist regions have experienced similar effects—namely, the effects of marked desiccation. Furthermore, the principles of interrelationship between bankfull discharge and downstream slope require slope to decrease (or, at the least, to tend to decrease) as bankfull discharge increases. Accelerated erosion should correspond to increased discharge and increased wetness.

At this point a caution becomes necessary. Erosion in upland areas can obviously correspond to deposition in low areas, so that deposition alternating in time with erosion need not always mean quite the same as filling and channeling. Langford-Smith's observations (1960) on the Murrumbidgee River, Australia, usefully illustrate the relevant topographic context. Dealing with sedimentation on the riverine plains of the Murrumbidgee, he associates it with greater-than-present discharge that occurred in former times. As for the Southwest United States, climatic fluctuations are admitted as the causes of change in stream habit, but various workers take the direction and effect of change in different ways. Butler (1950) and van Dijk (1959) conclude that sedimentation along the Murrumbidgee corresponded to arid phases, whereas channeling occurred during humid phases. Langford-Smith, by contrast, maintains that sedimentation by prior streams, flowing in channels larger than those of existing rivers, resulted from increased discharge at a time when headwater streams deepened their valleys in the uplands and supplied increased quantities of sediment to the plains. To associate accelerated erosion in the uplands with accelerated deposition on the plains and to associate both with increased discharge seems to the present writer entirely reasonable. The instance of the Murrumbidgee points to the need for precise use of the term "deposition": if it connotes valley filling, then it is the antonym of channeling; but if it means sedimentation at the junction of mountain and plain, then it is the essential complement of erosion (=channeling) in the uplands.

The references cited above show that the deposition which alternated with erosion in the dry parts of the United States took place mainly in valley bottoms and not at mountain feet. Scattered radiocarbon dates place in the range 7,000–11,000 years B.P. an interval of filling that lies at the beginning of the best-studied sequence but is later than the major period of cutting responsible for the largest channels of all (Martin, Schoenwetter, and Arms, 1961). That is to say, the well-authenticated succession of deposits and the channels which they occupy, dating stratigraphically upward from the Ucross gravel and its correlatives, correspond in time to the lesser fills and channels of English rivers (table 4). The main reduction to underfitness of streams in the dry Southwest is to be sought not in this division of time, but earlier.

Although it is not yet possible to equate in detail the cut-and-fill sequence of the Southwest with that of southern England, two sets of events promise to supply fixes in both sequences—those associated with the hypsithermal maximum, and those associated with the Two Creeks (= Allerød) fluctuation. The hypsithermal maximum of temperature is widely reported not only in midlatitudes but also far beyond. Flint and Brandtner (1961) present evidence for impressive correspondence among northwest Europe, lower Austria, the Great Lakes–St. Lawrence region, the Great Basin, and Bogotá, Colombia, all of which attained their highest deglacial temperatures in about 5,000 years B.P. Gill (1955) suggests 6,000–4,000 years B.P. for the thermal maximum in Australia, and Hough (1953) detects evidence in a Pacific Ocean core for similar effects in the same bracket. Livingstone (1957) concludes that Umiat, Alaska, experienced a temperature increase at about this time. (See table 4.) In northwest Europe, for which the hypsithermal maximum is usually taken to coincide with Zone VII, increased warmth coincided with increased wetness.

Martin, Schoenwetter, and Arms (1961) use palynologic, biogeographic, and geologic evidence to demonstrate heavy summer rainfall, rather than overall drought, for the period of extensive erosion in the

Southwest United States during middle postglacial time—that is, for a bracket which includes the hypsithermal maximum. They also cite work by Murray (1951) and Butzer (1958) to the effect that increased temperature in this interval was associated with increased precipitation in the arid Near East, and they call on Selling's work (1948) for data on the precipitation increase in New Zealand and Hawaii at the same time. Whatever the niceties of change in seasonal regimen, the hypsithermal maximum seems to have been a time not only of increased temperature but also of increased precipitation, with rising precipitation well documented for widely separated regions, both dry and moist. Just as in humid northwest Europe, so in the dry West and Southwest of the United States it was a time of accelerated erosion and channeling.

The record of rising and falling levels in pluvial lakes is somewhat coarser than that of channeling and filling in river valleys; it is also longer and earlier, in part extending back from about 10,000 years B.P., whereas the channel records date mainly from 12,000 B.P. onward. The overlap, although short, is most useful.

If rather short-term fluctations be envisaged for lake level, then difficulties in separating full pluvials and interpluvials from minor shifts are easy to imagine. Similar difficulties, of course, arise with the subdivision of glacials into stadials and interstadials. Further complications ensue from attempts to equate glacials directly with pluvials. (For discussions, see Charlesworth, 1957, and Flint, 1957. For correlations, see Gromow and others, 1960; Termier and Termier, 1960; and Fairbridge, 1961. For recasting of stadials within the Wisconsin glacial, see Frye and Willman, 1960.) Nevertheless, data from the Great Basin and from certain other regions provide the means to associate one long pluvial with prolonged glaciation and to relate rapid changes in lake level with rapid climatic and glacial fluctuations in and near the Two Creeks Interstade.

Broecker and Orr (1958), and Broecker, Ewing, and Heezen (1960) infer a broad maximum of lake level in the Great Basin between 24,000 and 14,000 years B.P., a succeeding minimum, a sharp maximum about 11,500 years B.P., and near desiccation by about 9,000 years B.P. Correlation of the last two maximums, respectively, with Zone Ic and Zone III (see Curray, 1961) requires a slight displacement of dates in table 4 but does no violence to the association with the Two Creeks recession of the minimum between the two sharp maximums. The first long high stand agrees sufficiently well in date with the findings of Ruhe and Scholtes (1956) that forest dominated Iowa between 24,000 and 11,000 years B.P., under a cold moist glacial climate with cool moist intraglacial interludes. Reduced temperatures and increased humdity characterized the Midwest simultaneously with the Great Basin, but this long high stand occurred during the maximum cold of Wisconsin glaciation (see Flint and Brandter, 1961; Andersen and others, 1960; van der Hammen and Gonzalez, 1960), including that point on the time scale where glacially controlled sea level was at its lowest (Curray, 1961; table 4.) The very high, brief, and late stands of Lake Lahontan, occurring when deglacial rise of sea level was well advanced, seem referable to increased pluviation rather than to increased cold. Each admittedly coincided with a cold fluctuation, but nothing more was involved than temporary reversals of the temperature graph; the cold of full maximum glaciation failed to reestablish itself in Zone Ic.

Flint and Gale (1958) find records of two successive deep-water bodies in the basin of Searles Lake, California. Each lake implies pluvial climate, with its molluscan fossils indicating reduced temperatures. Each was followed by deposition of evaporites and, at least, by near desiccation, in climates similar to the present. Radiocarbon dates show the first pluvial as well established by 46,000 years B.P., and as beginning to wane by 32,000 years B.P. The second pluvial spans the interval 23,000–10,000 years B.P., being thus contemporary with the classical Wisconsin Glaciation, with the long pluvial specified for Lake Lahontan, and with the dominance of cold moist climate in the Midwest. The deglacial minimum stand of Searles Lake falls at the hypsithermal maximum, squarely correlative to Zone VII of the general schema (table 4).

Hunt, Varnes, and Thomas (1953), discussing the Lake Utah remnant of Lake Bonneville, state that mean annual evaporation at the north end of the present lake is at least three times as great as rainfall; they infer a very different precipitation and evaporation ratio for Lake Bonneville times. Changing speed of soil formation, as demonstrated in palaeosols, records changes in the humidity of the environment; and facies changes in sediments indicate former prevalence of northerly or northwesterly winds, by contrast to the southwesterly prevalence of today. Lakes existed during the Tertiary but disappeared or greatly shrank at the beginning of the Quaternary. When they later reappeared, they fluctuated in level with alternation of semiarid and humid climates, giving at least four lacustrine episodes prior to the desiccation of Lake Bonneville. The Lake Bonneville episode included two maximums during the Wisconsin Glacial, for which volume of sedimentation indicates erosion more rapid than that now in progress.

Eardley and Gvodetsky (1960) conclude that a 650-foot core taken near Saltair in the deposits of the Great

Salt Lake records sedimentation from somewhere in the Aftonian Interglaciation until 11,000 years B.P., when the lake withdrew from the Saltair site. Using the Pearlette Ash Member of the Sappa Formation as a marker for early Kansan deposits, they distinguish five strong pluvials, the first beginning in Kansan times, and the whole series correlative with the record of cyclic cutting and filling in the valley of the lower Mississippi. As their figure 2 shows, however, the succession of pluvials does not correspond exactly with the succession of glacials. They extend the pluvial which begin during the Kansan Glaciation through two-thirds of the succeeding Yarmouth Interglaciation, making the uppermost one-third of the Yarmouth succession relate to arid climate, with pluvial conditions reestablishing themselves during the Illinoian Glaciation, and arid conditions returning during the Sangamon Interglaciation. Then come pluvial, arid, pluvial, arid, pluvial, arid, and pluvial, giving a total since Kansan times inclusive of six pluvials, four of them belonging to the last glacial.

Frye and Leonard (1957), interpreting the ecology of the Great Plains region during the Pliocene and Pleistocene, infer replacement of semiarid by increasingly humid conditions at the beginning of the Pleistocene and a culmination of humidity in Kansan times. Thus far their findings resemble those of Eardley and Gvodetsky, but the evidence of great soil groups, offset to the west by about 100 miles during the Sangamon Interglaciation, indicates humidity greater than that of the present day instead of the aridity shown for Saltair. This point will be taken up below. According to Frye and Leonard, the Great Plains, since the peak humidity of the Kansan, have been subject to a pulsating and irregular trend of progressive desiccation, eventually producing a present-day climate approaching in dryness and rigor that of the late Tertiary.

SOME PROBLEMS OF GENERAL CORRELATION

In their several ways, the Great Basin, the dry Southwest, the Great Plains, the Midwest, and the East all exhibit signs of desiccation—greatly reduced levels in some enclosed lakes, complete drying out of others, reduced volume of sedimentation, vegetational change, abandonment of large river channels, and manifest underfitness of streams. But the incomplete correspondence of pluvials with glacials, the great fluctuation of pluviality within the time range of the Wisconsin Glaciation, the conflicting evidence of conditions in the Sangamonian, and the contrast between increased summer rain in the Southwest in Zone VII with the simultaneous fall of Searles Lake all suggest lack of correspondence between changes in temperature and changes in precipitation.

As commonly used in studies of enclosed lakes, the term "pluvial" connotes not increased precipitation but rise in lake level. In its implication that changes in precipitation are solely responsible for changes in level, the term is unfortunate. Similarly, phases intermediate between pluvials are arid only in the sense that, during them, lake level is reduced. Reduction in level can be due not only to reduced precipitation but to increased temperature. If the low stand of Searles Lake during Zone VII is ascribed wholly to increased temperature, it ceases to conflict with the widespread evidence of increased pluviality elsewhere. In this way, an actual increase in precipitation during hypsithermal maximum could be accommodated in the record for the Searles Lake drainage area, a record which is comparable with that reconstructed by Martin, Schoenwetter, and Arms (1961) for the Southwest. But as the lake itself was lowered by the postulated increase in warmth, it should follow that inflowing streams were also reduced in their lower reaches. For this reason, their record of cutting and filling should differ as between lower reaches and headwaters, supposing the headwaters to have been affected by increased precipitation and discharge.

The brief high stands of Lake Lahontan in Zones Ic and III have already been ascribed to increased pluviality rather than to reduced temperatures. Their occurrence and their cause are much less discordant with the record of erosion in the dry Southwest than is apparent from the generalized successions marked in table 4. As table 4 shows, erosive episodes in the Southwest correspond broadly with intervals of increased humidity; whereas depositional episodes coincide, again somewhat roughly, with intervals of increased aridity. The end of the chief pluvial associated with Wisconsin Glaciation and the end of the accompanying erosion are set at about 10,000 years B.P., extending beyond the Two Creeks interval, which was a time of low stand in the Lahontan Basin. But the studies of the Rampart Cave deposits by Martin, Sabels, and Shutler (1961) indicate an arid maximum which, bracketing 11,350 years B.P., lies between a cool moist interval of 35,000–12,000 years B.P. and a slight climatic reversal which probably relates to Zone III. For the Grand Canyon country, then, the climatic and vegetational changes in the known record are in phase with, and similar in direction to, those associated with the last high stands of Lahontan. Increasing dryness in Zone II times appears distinctly; a reversal toward moistness, coolness, or both during Zone III times, rather obscurely. The weak development of Zone III conditions recalls the evidence from Wisconsin that channeling and the development of valley meanders were vigorous in Zone Ic but can have been slight or absent in Zone III.

Infilling of some of the largest channels in southern England during Zone V is referable to increasing dryness. As the floristic record demonstrates, this was a time of increasing cold, which necessarily reduced evapotranspiration. It follows, therefore, that the reduction of precipitation was great enough not merely to compensate for the influence on runoff of reduced temperatures but actually to promote stream shrinkage.

Sea-level changes provide a scale of comparison for sequences of cutting and filling or of pluviality and desiccation. But just as pluviality can involve changes in temperature rather than in precipitation, and possibly changes in temperature great enough to offset changes in precipitation, so sea level is not controlled by temperature alone. Fairbridge (1961) convincingly urges that eustatic events should be assumed for every geologic period, regardless of climatic events, and presents massive evidence for overriding controls of eustasy that supersede both climatic and local tectonic influences. However, his detailed analysis for the last 15,000 years gives a very close correlation between minor oscillations of sea level on the one hand and climatic events on the other, with every recorded glacial advance during the last 5,000 years matched by eustatic lowering.

The conclusion of Fairbridge that each of the younger cool phases corresponds to a drought in the arid West of the United States but to pluvial events in humid midlatitudes emphasizes the principle that pluviality can be either in or out or phase with trends of temperature change. Once again, however, the term "pluvial" connotes net effects of climatic shift. If the additional supply of surface water in midlatitudes in these cool phases were due to temperature decrease, it may even have coincided with decrease in precipitation, provided that reduced evapotranspiration more than compensated for the latter.

The younger cool phases here in question set in during a span of time which produced minor episodes of cutting and filling. The known record of minor change in stream behavior may well be no more than partial; probable minor changes of sea level under control of temperature (Fairbridge, 1961; table 4) suggest comparison with the climatic and vegetational changes signalised by von Post for deglacial time. (For references and discussion, see Conway, 1948.) Reservations seem to be necessary about the likelihood of strict parallelism in the respective erosional-depositional sequences of humid and arid regions, within the scope of minor fluctuations, especially as the evidence of cut-and-fill is much coarser than the record of slight irregularities in sea level. Above a certain limit, however, parallelism and synchrony seem to apply. The evidence for widespread pluviality, rise of temperature, and accelerated erosion at the hypsithermal maximum means that the relevant happenings lay beyond the critical limit for nonparallelism and lack of synchrony. The last abandonment of the largest stream channels and of valley meanders lies still higher above this limit, for it constituted events of greater magnitude than the partial reexcavation of channels in Zone VII.

Minor irregularities apart, the graph of sea level for the last 20,000 years records, among other things, the replacement of full-glacial conditions by full-interglacial conditions. The Zone Ic rise of Lake Lahontan roughly matches a reversal of the rising trend in sea level, whereas the renewed pluviality of Zone III corresponds to another, but less marked, inflection of the sea-level graph. The major conversion from glacial to deglacial sea levels and from pluvial to nonpluvial climates was by no means steady. Although corresponding to the main change of streams to underfitness, the conversion permits the hypothesis that the dates of last abandonment of large channels and of valley meanders differed, for example, between the Driftless Area of Wisconsin and southern England. The dates offered for the main conversion to underfitness of streams distant from the still-receding ice fronts accord less well with the claim of an abrupt change of climate about 11,000 years ago (Broecker and others, 1960) than with the modifications proposed by Curray (1961, and references therein).

SUMMARY

1. Field investigation in both England and the United States, supplemented by information from miscellaneous sources, demonstrates large meandering channels beneath the flood plains of underfit streams.

2. These large channels are taken as the beds of former streams that cut valley meanders.

3. The infilling is ascribed to stream shrinkage rather than to aggradation in the usual sense.

4. Cutting of large channels and of valley meanders may be dated in terms of initiation, duration, or abandonment. Initiation has ranged from early Pleistocene (=Early, Nebraskan, Günz Glacial) in some areas to perhaps as late as 2,000 years B.P. in parts of the Lake Borders. Duration of cutting has ranged accordingly. Measurement of duration by interval between initiation and abandonment does not, however, imply continuous cutting. The evidence shows alternate cutting and filling—certainly associated in some valleys with alternate meandering and braiding—on the

part of former streams prior to the last reduction to underfitness. There is ample room for onsets of the underfit condition earlier than the last.

5. Channeling and downcutting—in humid regions, generally, and in upland parts of arid regions—are associable with increased wetness. This can have been due to increased precipitation, reduced temperature, or both.

6. Pollen analysis and radiocarbon analysis supply approximate dates for the abandonment of some large channels and their associated valley meanders. The dates appear to concentrate themselves either near the end of Zone Ic (Older Dryas and Allerød boundary; beginning of the Two Creeks Interstade), or in Zones III and IV (recession of Valders ice, change to Boreal phase), except in certain areas that were still covered by land ice or by lake water at the relevant times.

7. Simultaneous decrease in temperature and increase in precipitation are inferred for Zones Ic and III; the opposite effects for Zone II. Simultaneous increase in temperature and in precipitation are inferred for Zone VII in both arid and humid regions, with increase in precipitation more than sufficient to offset the increase in temperature except perhaps in some parts of some really dry areas. Infilling of some of the largest channels in southern England during Zone V was due to increasing dryness which, occurring at a time of reduced temperature, is referable to a distinct decrease of precipitation.

8. From the orders of magnitude represented by the last full use of valley meanders and the last complete scouring of large channels to bedrock, down to and including the orders of magnitude represented by partial reclearing of large channels in zone VII, the sequences of cut and fill appear mainly parallel and synchronous, respectively, in arid and in humid regions.

9. Lesser fluctuations betwen erosion and filling, however, need not have been parallel and synchronous, according to whether or not changes of temperature and precipitation were in or out of phase and according to which type of change acted the more powerfully on discharge in particular climates.

10. Quantitative implications of the conclusions here reached will be stated and discussed in a succeeding professional paper.

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