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ORIGINAL ARTICLES.

I.—THE DEVELOPMENT OF RIVER MEANDERS.

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THE paper by Dr. Callaway, "On a Cause of River Curves," in the GEOLOGICAL MAGAZINE for October, 1902, suggests comment for two reasons: first, because the cause that he brings forward seems of doubtful application; second, because the habitual entrance of branch streams at a certain part of the curves of main streams is satisfactorily explained by controls which seem to be of surer and more powerful application than the control which he advocates.

In ascribing to a tributary the power to make a main stream bend in a definite manner towards the tributary, and thus determine the habitual entrance of tributaries on the convex side of the main stream's curves, Dr. Callaway argues that the detritus brought by the tributary will be deposited on the further side of the main stream and somewhat below the tributary's mouth. Various examples known to me of the deposits formed by side streams in the channels of main streams do not bear out this conclusion: the detritus is not deposited on the further side of the main stream, but as a delta at the mouth of the tributary or a little below it; and the main stream does not bend toward, but away from the tributary. The Rhine, the Colorado, and many other rivers that might be instanced, show abundant examples of this kind. Moreover, the assumption of an initially straight main river, as stated by Dr. Callaway, involves an extreme improbability. Rivers cannot be habitually straight in their initial stage, and the bends with which they begin are as a rule spontaneously exaggerated in their later development. The processes by which the initial bends are developed into meanders, and by which the meanders are persistently maintained when once developed—entirely independently of the action of tributaries,—are too important to be omitted from the problem in hand: above all, they should not be replaced by a doubtful or at most a weak process.

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The most important process in the development of river meanders is the displacement of the line of fastest current by inertia from mid-channel toward the outside of every curve. As a result erosion tends to take place on the outside and deposition on the inside of the curve. This process is self-perpetuating. However slight the initial bends, they will be increased; and as the valley floor is broadened the curves will be developed into systematic meanders of increasing radius and breadth, as in Fig. 1. The only conditions under which the river course will tend to straighten itself are: strong tilting in the direction of river flow, and downward erosion upon a weak stratum between two resistant strata in an inclined structure. Both these conditions are only temporary; for as grade is reached in either case and the valley floor is widened, the residual departures from a perfectly rectilinear course will be exaggerated again, and in advanced maturity the river must always be curved. The smaller the stream, the greater the effect of accidental causes, such as falling sods and trees, tributary deltas, etc., in forming new bends. The larger the river, the greater the effect of inertia in exaggerating pre-existent bends and in overcoming local or accidental irregularities.

FIG. 1.

FIG. 2.

A river not only tends to increase its meanders; it also tends to push the whole meander system down the valley. This is because the line of fastest current, displaced toward the outside of each curve, enters the succeeding curve (or stretch between two curves) near the down-valley bank, which is therefore worn away, while the opposite up-valley bank is built out. As a result, Fig. 1 should be modified by a persistent down-valley migration of every bend, as in Fig. 2. Cut-offs occur now and then, here and there, but the shortened course at a cut-off is not straight, and its faint curves are

soon systematically exaggerated into meanders again. Abundant verification can be given of this scheme of development, by observing the behaviour of actual rivers, or more simply by studying the new edition (1900-1901) of the preliminary maps published by the Mississippi River Commission at St. Louis, Missouri, on which the river channels as determined by surveys in 1893-5 are over-printed in red upon the results of surveys in 1881-3, printed in black.

FIG. 3.

FIG. 4.

Any river that we now see meandering in an open alluvial plain must have been meandering a long time. Its individual meander curves must have already advanced down the valley over considerable distances; and it is, I believe, chiefly for this reason that tributaries are taken in where the main stream bends toward them. To make this clear, let a number of tributaries be added at random to the latest river course, drawn in Fig. 2. Four of them are shown in Fig. 3: one enters the river at a convex bend, the other three at or near concave bends. Now let the normal changes of the meanders continue still farther, as in the dotted lines of Fig. 4. In the first of these changes, tributary D is taken in by the convex curve next above the concave curve that it entered before. In the second change, the mouth of the tributary B is similarly transferred to a convex curve. In the third change, the same fate overtakes tributary A. During all these changes, tributary C has been only a little shortened; it still enters on a convex curve. When this curve comes to move down the valley the tributary will prolong its course, but will continue to enter the main stream on the up-valley side of a curve, until it is captured by the approach of the next following curve. It therefore appears natural enough that tributaries should usually

enter the main river meandering freely on a flood plain where its curves turn toward them.

The simplest conditions under which a tributary should be led to enter its master at an abnormal point are found in the occurrence of a cut-off, as in Fig. 4; but this special case would soon be brought under the rule, either by the development of a new meander which will usually grow towards the tributary in the neighbourhood of the cut-off,¹ or by the approach of the next up-valley meander.

A second group of examples would include rivers that follow relatively narrow meandering valleys, like those of the lower Wye, the lower Seine, the lower Moselle, or the north branch of the Susquehanna. Here the same rule may be expected to apply to the entrance of the tributaries, and that for two reasons. In the first place, because such rivers have, it may be said with much confidence, incised their meandering valleys from a meandering course that they formerly possessed on the upland in which the valleys are incised, when that upland was a lowland of erosion. On such a lowland the rivers must have reached a late stage of their cycle of development, and in a late stage they must have been meandering freely. While the uplift was going on and afterwards, the meanders would have been incised beneath the uplifted lowland; but the entrance of the tributaries has not been thereby significantly altered from whatever orderly arrangement they had gained during the former lowland stage of erosion.

In the second place, if by chance any abnormally entering tributary existed when uplift and incision began, the normal processes of widening the meander belt and of shifting the meanders down-valley, which must accompany incision, would sooner or later bring about a normal entrance in the same manner as on an alluvial flood plain, shown on Fig. 3, but at a lower rate than there obtains. An excellent instance of this kind is known in the lower Seine, where the Ste. Austreberte has been taken in at Duclair, not far below Rouen, precisely as illustrated in Fig. 3.

Another instance of the same kind occurs on the Marne not far east of Paris (see "The Seine, the Meuse, and the Moselle," *Nat. Geogr. Mag.*, 1896, vii, 191). The Moselle exhibits at least one illustration of the entrance from the south-east of a small tributary, the Veldenzer Bach, on a concave stretch a short distance up-stream from Berncastel; but this is demonstrably the result of a cut-off, as shown in Fig. 4 (*ibid.*, pl. xxii, opp. p. 193).

These normal, effective, and fully verified habits of change in the course of a meandering river seem to account very fully for the rule that tributaries usually enter where the river curves toward them; a rule that Mr. Callaway shows to obtain for various rivers in many parts of the world, and that is supported by certain additional examples that I have recently inspected.

¹ The changes following the occurrence of a cut-off, as illustrated on the maps of the Mississippi, show that the growth of a new meander towards the cut-off and abandoned meander, but a little further down-valley, is not unusual.