How to make a meandering river

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Despite the ubiquity of meandering rivers in nature, only recently have appropriate experimental conditions been produced to replicate a stably meandering stream in the laboratory, as described in a recent issue of PNAS (1). Meandering channels occur in a wide variety of sedimentary environments, including on deep sea fans formed by turbidity currents (2), as relict meanders on Mars (3) (Fig. 1), and as channels formed by flowing alkenes on Titan.

The mechanics of formation of meanders is reasonably well understood (4). When flow enters a channel bed, a helical secondary current is set up that increases flow velocity and channel depth along the outer bank in proportion to bed curvature, which encourages bank erosion. The secondary current has an intrinsic downstream scale related to flow velocity and depth; this results in gradual increase in bend amplitude and propagation of the meandering pattern upstream and downstream. Linear theory of flow in bends (5) has permitted construction of simulation models that replicate many aspects of meandering behavior, including meander cutoffs, creation of oxbow lakes, and patterns of floodplain sedimentation (6, 7). Interaction of the bend-induced flow and bed topography with superimposed alternate bar bedforms complicates the flow and bed topography in wider meandering channels (8, 9). These complications have been incorporated into increasingly detailed models of stream meander evolution (10).

In settings where rivers are not laterally confined by resistant valley walls either the planform generally displays sinuous meandering of a single channel or the river splits into multiply interconnected braided channels. Both empirical studies and theory have helped to define the conditions that control channel pattern (11–15). For a stream of a given flow discharge, steep channel gradients and large ratios of channel width to flow depth are associated with braiding, with the converse for meandering. The occurrence of braiding has been related to the natural tendency for sediment transport to produce multiple depositional bars in sufficiently wide channels, which tends to split the flow as the bars grow (13, 15). If stream banks are composed of loose gravel or sand of the same size range that is transported on the channel bed, channels tend to be wide, shallow, and braided. Narrow, deep channels favoring a meandering pattern require appreciable bank strength. This typically occurs where streams carry a high relative quantity of silt and clay which is easy to transport but is difficult to re-erode once deposited on stream banks. In terrestrial meanders vegetation helps both to encourage deposition of silt and clay by retarding near-bank flows and to add additional cohesion by means of root strength (16–18). Vegetation also inhibits bank erosion through flow retardation. The difficulty of replicating the effects of vegetation on bank sedimentation and stability has been an important reason that laboratory meandering has been difficult to achieve. Recently, however, the use of seed sprouts has permitted scaling the effects of vegetation in experimental channels and has encouraged channel meandering (1, 19, 20).

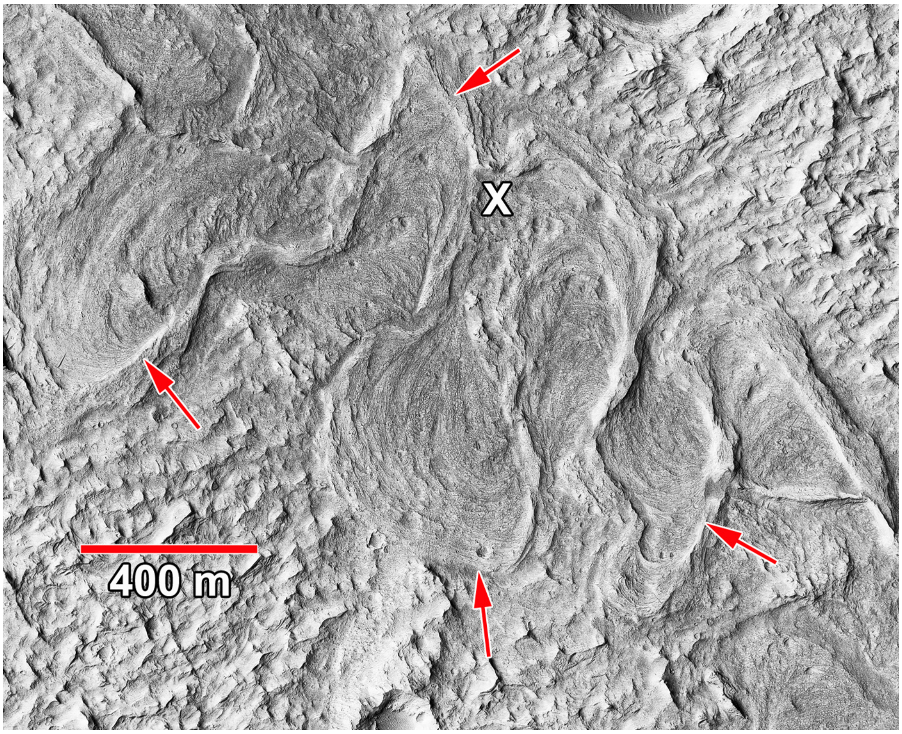

Fig. 1. Fossil highly sinuous meandering channel and floodplain on Mars. Red arrows point to representative locations along channel. The channel bed is now a ridge (in inverted relief) because wind erosion has removed finer sediment from the floodplain and surrounding terrain. The low curvilinear ridges interior of the main sinuous ridge are remnants of the meander loops as they grew through bank erosion along the outside of bends. A cutoff may have occurred shortly before flow ceased above location "X," resulting in abandonment of the loop lying below. Rough terrain at upper right and lower left is due to wind scour. Image is a portion of NASA HiRISE image PSP_006683_1740.

Past studies have focused on the role of channel width and bank cohesion in producing a meandering pattern. The flume experiments of Braudrick et al. (1) described in this issue of PNAS have identified an ample supply of fine sediment in transport as additional requirement for stable meandering in gravel-bed streams. During initial stages of meandering as the bends enlarge and translate downstream a depressed region of the bed (a chute) is typically left behind between the bed sediment deposited on the bend interior (the point bar) and the edge of the adjacent floodplain. In situations where little fine sediment is in transport the chute can carry an increasing portion of the flow as the main channel meander bend enlarges, eventually leading to a cutoff. Such chute cutoffs have been an important factor

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limiting the sinuosity achievable in laboratory meanders and likewise serve to limit the amplitude of meanders in natural gravel channels with meager budgets of fine sediment. In the flume study reported here (1) transport of silt and clay in natural channels is scaled to smaller laboratory channels by the use of low-density, sand-sized plastic particles that are carried in suspension. The bed sediment transported along the bed was coarse sand that scales as gravel in natural channels. The low-density plastic particles accumulated on the inner, upstream side of meander bends and blocked the upstream edge of the chutes, preventing appreciable diversion of flow through the chute, thus allowing the meanders to enlarge to amplitudes and to an overall sinuosity greater than had been achieved in previous laboratory studies. Some fine sediment also accumulated on the downstream end of chutes, further blocking them. The deposition of the fine sediment was enhanced by the flow retardation resulting from the presence of the alfalfa sprouts that developed on emergent portions of the sediment deposited on the inside of bends.

Deposition of fine sediment by overbank flood flows has long been considered as a requirement for development of cohesive banks and a meandering pattern. A surprising result of the flume experiments is that steady high flows that only slightly submerge channel margins deposit enough fine sediment to produce a stable meandering pattern with occasional cutoffs.

The use of seed sprouts has permitted scaling the effects of vegetation in experimental channels.

Although a stable meandering pattern with repeated cutoffs was created by the flume experiments, the ≈1.2 observed sinuosity is considerably less than the value of ≈3 reached in highly sinuous natural channels. Braudrick et al. (1) attribute the restricted sinuosity to the relatively rapid bank erosion in comparison to scaled values in natural channels. They suggest that reducing bank erosion rates through greater vegetation density would allow more complete infilling of chutes, allowing a more sinuous channel to develop. However, the time required to complete the experiment might become excessive.

Developing experimental procedures to permit stable, high-sinuosity meandering in scaled laboratory experiment will be a challenge for future work, but the payoff would be large in terms of understanding the critical factors responsible for meander development and to address practical issues of meandering river maintenance and restoration. Challenges also remain with regard to understanding the mechanisms and environments creating meandering channels in subsea and extraterrestrial environments. For example, the ancient, highly sinuous channels with cutoffs found on Mars (Fig. 1) are enigmatic, because vegetation apparently played no role in providing bank cohesion and fine sediment deposition. Bank cohesion resulting in narrow channels might have been afforded by a large quantity of silt and clay in transport, by ice under permafrost conditions (perhaps analogous to highly sinuous rivers in northern Alaska and Siberia), or by chemical cementation of floodplain deposits (hardpans).

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