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Possible hydraulic significance of two kinds of potholes: Examples from the paleo–Potomac River

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ABSTRACT

Potholes preserved along abandoned sections of bedrock-bounded rivers should provide significant paleohydraulic data if the conditions for pothole formation are understood. In a prototype study, we recognize two kinds of potholes along the paleo–Potomac River near Great Falls, Virginia. Vertical potholes, drilled into the strath floor, are circular in plan and are interpreted to form at sites of small stream depths and high flow velocity. Lateral potholes, noncircular with overhanging roofs, are found on flanks of rock obstacles. They are interpreted to be eroded by sediment-laden vortical flow near the air-water interface. The vortices circulate water in the horizontal plane, and begin to form near the free surface in flow separation zones downstream of the obstacles. The geometry of flow separation zones and thus the location of the lateral potholes are scaled by flow Reynolds number. Therefore, lateral potholes could be used to reconstruct paleoflow depths and velocities if parts of the channel bed adjacent to the flow obstruction are preserved.

INTRODUCTION

Potholes, erosional features carved into the beds or sides of degrading bedrock river channels, preserve information on the hydraulic regime of vanished river systems. This paper presents morphological evidence for distinguishing vertical potholes from the newly recognized lateral potholes, which are the focus of this study, and discusses their possible origin and significance. The studied potholes are located on the Virginia side of Great Falls on the Potomac River, where it plunges abruptly from an open valley through the 15 m cataract of Great Falls into the narrow Mather Gorge. The pre-gorge river channel downstream from Great Falls, developed on quartzite and schist of the upper Proterozoic Wissahickon Formation (Fisher, 1970), is preserved as a bedrock strath (see Tormey, 1980; Reed, 1981) that shows a few metres of relief (Fig. 1). Although the rock strath has been flooded at least five times since 1936, such floods are brief events and have caused negligible bedrock erosion on the strath (centimetre-size crustose lichens, inside and outside of the potholes, survived the Hurricane Agnes flood of 1972).

MORPHOLOGIC TYPES OF POTHOLES

Vertical potholes (site 1, Fig. 1; see also Reed et al., 1980) drilled into the rock floor are nearly circular, vertical ($\pm\sim20°$) cylinders, typically a few decimetres across, with depths comparable to their widths, and have complete circumferences except where subsequently breached. The original rims of the potholes are water worn but well-defined. The bases of vertical potholes, where visible, have conical rises or even compartments (see also Alexander, 1932).

The newly recognized lateral potholes are located on the sides of rock prominences, have incomplete circumferences, and are commonly found in groups strung out on the outcrop in the downstream direction. They are not circular in plan view; many are alcovelike with overhanging roofs (Fig. 2) and superfically may resemble tafoni (Twidale, 1982). The floors of lateral potholes either have well-defined basins or are smooth, shallow concavities resembling automobile bucket seats (Fig. 3). The walls of lateral potholes show bas relief of a few millimetres that correspond to centimetres-thick mica- vs. quartz-rich layers. Because the layers are polished and unweathered, the relief records a process of pothole enlargement that was sensitive to material properties at millimetre to centimetre scales.

PROFILES OF LATERAL POTHOLES

Profiles of selected lateral potholes were measured using a string marked at 10 cm intervals. Orthogonal horizontal distances to the backwall, Y, were taken at the marked points. Vertical profiles, Z, were measured by hanging the weighted string from the highest point of the pothole and are shown (Fig. 4) normalized by the total vertical dimension Z_o. Horizontal profiles or plan views (Fig. 5) were obtained by placing the string left-right across the pothole opening at mid-height ($Z/Z_o = 1/2$). Duplicate measurements agree to ±3 cm. Despite the different sizes of the potholes, the normalized upper thirds of the vertical profiles are similar.

PALEO-GEOMORPHIC SETTINGS OF THE LATERAL POTHOLES

The lateral potholes described here are assigned to the pregorge Potomac River stream regime for the following reason. About 1 km upstream from Great Falls and immediately downstream from a water-intake dam for the Delacaria Reservoir, the strath of the Potomac is a kilometre-wide, flat, bedrock river bottom, studded with rock islands 1 to 3 m in relief. This section of the river floor is not yet affected by the cataracts of Great Falls and is between 142 and 146 ft above sea level. This elevation, together with that of the rock strath between Great Falls and Plummer Island about 10 km farther downstream, allow estimation of the longitudinal gradient of the paleo–Potomac River. This gradient is consistently $\sim$0.06% (0.6 m/km or 3 ft/mi) and is adopted as that of the strath-forming paleo-Potomac for the intermediate area of Figure 1 (see also Reed, 1981). The elevations of the lateral potholes described here are between 140 and 142 ft., consistent with their formation on the rock islands of the pregorge strath.

LATERAL POTHOLES IN MODERN RIVERS

Lateral potholes are found in modern rivers. A lateral pothole, complete with conical basin, is actively forming on a rock island in the middle of Mather Gorge (Site 5, Fig. 1). This pothole is totally submerged only during high discharge, so its upper part is exposed to spray and wave action for large parts of a normal year.

Lateral potholes have developed on seasonally submerged rock islands, each a few

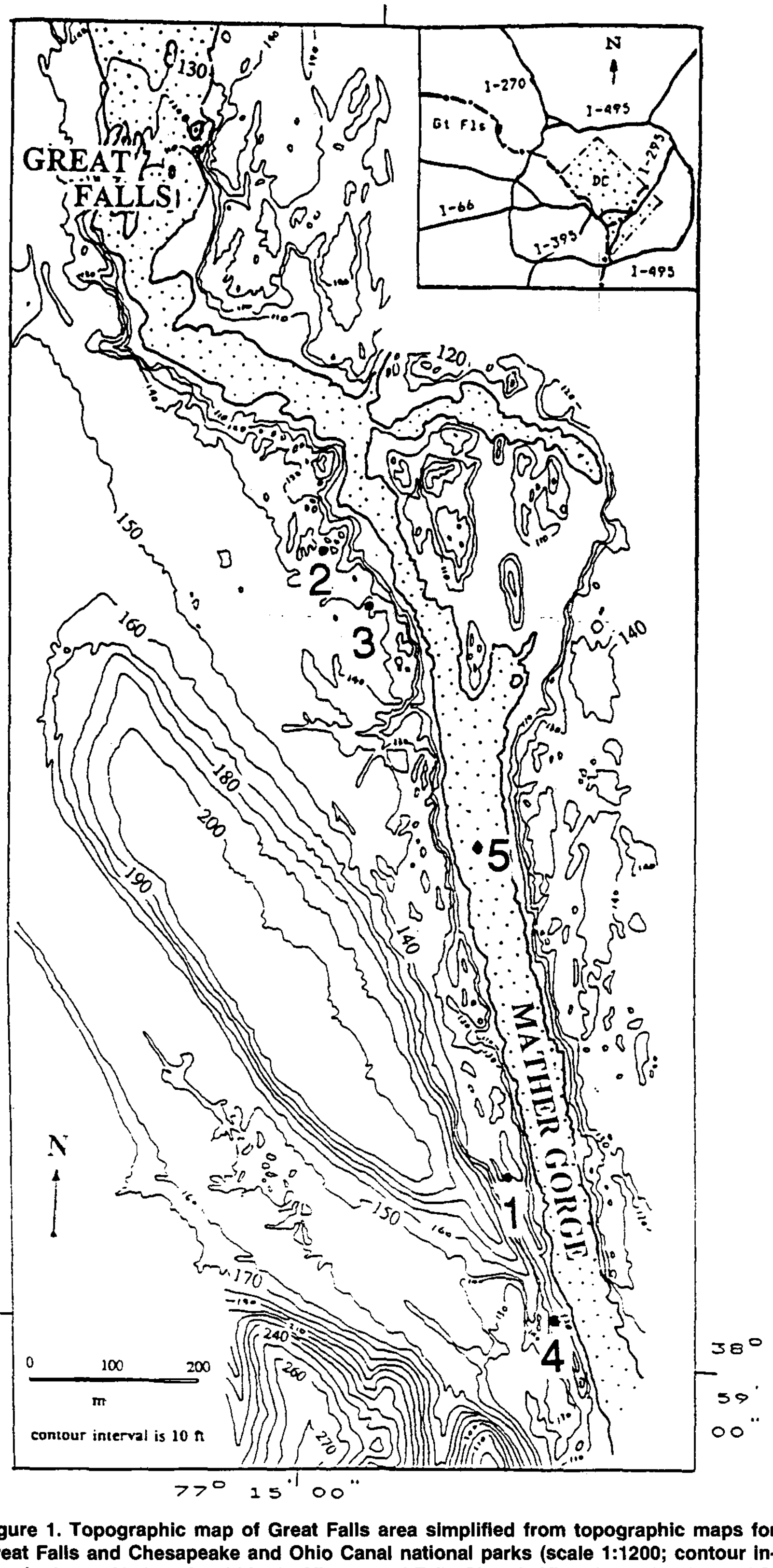

Figure 1. Topographic map of Great Falls area simplified from topographic maps for Great Falls and Chesapeake and Ohio Canal national parks (scale 1:1200; contour interval 2 ft or 5 ft). Area is within the Vienna and Falls Church, Virginia, 7-1/2 minute U.S. Geological Survey quadrangle sheets). Stippled area is Potomoc River. Contours for 110 and 120 ft are incomplete; those below 110 ft are omitted. All closed contours enclose higher areas. Sites 1–5 are discussed in text. Inset shows location (solid rectangle marked "Gt Fls") relative to major highways of Metropolitan Washington area; dash-dot lines mark Potomac and Anacostia rivers; Potomac River separates Virginia from Maryland. DC is District of Columbia.

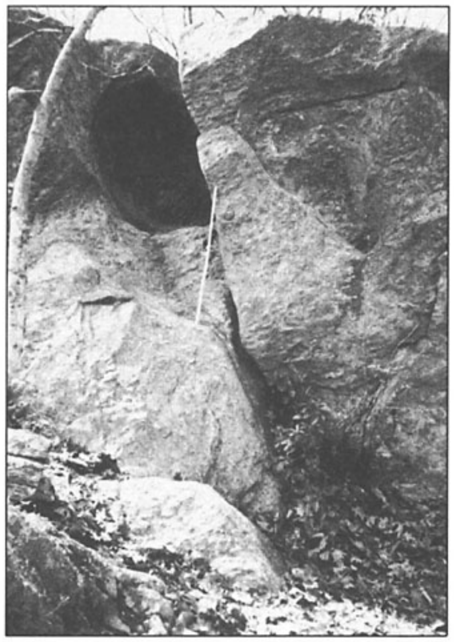

Figure 2. Lateral potholes 2 (left) and 3 (right). Third pothole of cluster of three is just to left of area shown. Prow of rock is ~4 m upstream (to right) from pothole 3. Stick is 1 m long. Site 3 of Figure 1.

metres high, in the Rappahannock River at Bank's Ford upstream from Fredericksburg, Virginia, and, in great abundance, on the Snowy River at McKillops Bridge (between Bonang and Suggan Buggan), in Victoria, Australia (see below). They also occur on the Susquehanna River at Conewago Falls and near Holtwood Dam in Pennsylvania. Other potholes that may be of this type are described in the literature (e.g., Sugden and John, 1976; Spitznas, 1950; Ives, 1948; Bernard, 1971; and Putzer, 1971).

ORIGIN AND HYDRAULIC SIGNIFICANCE OF LATERAL POTHOLES

Lateral potholes are not merely breached vertical potholes (Thompson, 1990), because, first, their rounded, water-worn descending edges and lips are integral parts of and continuous with the concave space and the conical basins (Fig. 3). Second, they occur on the flanks of rock prominences. If they were remnants of vertical potholes, then significant bedrock removal must have occurred without reshaping their interior. For example, if lateral pothole 5 (Fig. 5), the only one measured that can be fitted to the equation of a circle, was originally a complete circle, it would have a diameter of 5.4 m, but only about 1/5 to 1/6 of the circle would be preserved. Further, if pothole 5 was formerly a large vertical pothole, it would have interfered with other adjacent lateral potholes developed at the same level.

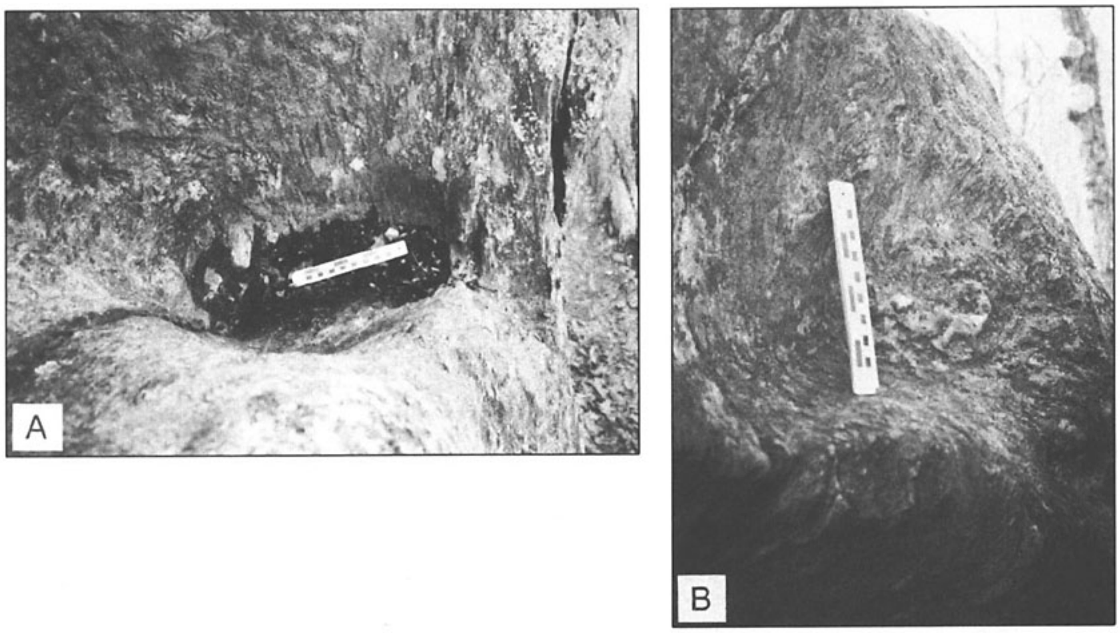

Figure 3. A: Downward view of conical basin and lip of lateral pothole 3; notice smooth, water-worn surface on both sides of descending rib (bottom of photo; down is to right). Small part of lip has been destroyed. B: Smooth, flat bottom and broad, water-worn rim of small bucket-seat lateral pothole above pothole 3, visible at recess in skyline between potholes 2 and 3 in Figure 2. Scale is in centimetres and inches.

Third, compound lateral potholes are common. One type consists of linked small basins that resemble paternoster lakes; others have smaller lateral potholes nested within the larger one. These cannot be breached vertical potholes.

To define the hydraulic significance of potholes in bedrock rivers, we need to document their three-dimensional geographic location in a bedrock channel, identify the hydraulic conditions under which they formed, and associate these conditions with their location. Our working hypothesis is that both types of potholes are eroded primarily by vortices having vertical to steeply inclined axes of rotation. These vortices are generated near the free surface by rock prominences where horizontal shear stresses are the largest (Yalin, 1992, p. 47). Vertical potholes form where the mixing lengths of the vortices exceed water depth (Yalin, 1992, p. 53). This limits the occurrence of vertical potholes to shallow water; this is consistent with Thompson's (1990) observation that vertical potholes on the Susquehanna River are concentrated near nickpoints (sites where the gradient steepens, velocity increases, and flow depths decrease). Both types of potholes should be most common downstream of rock obstacles, including channel islands.

Lateral potholes are commonly found in chains that begin a few metres downstream from the prow of a rock island in zones of flow separation where the vortices can circulate without being dispersed by downstream flow. The first pothole forms where the vortices, shed from the head of the island, are constrained against the rock surface by the downstream flow. Thus, the distance between where flow separation begins and the first pothole should depend on the geometry of the separation zone, which is scaled by Reynolds number. On the Snowy

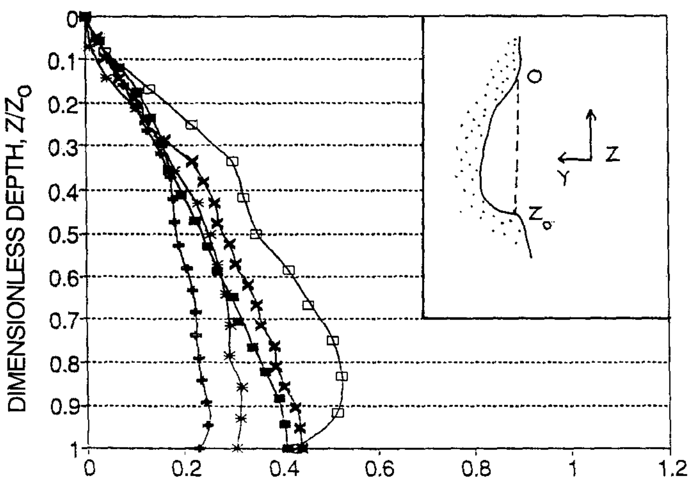

Figure 4. Vertical profiles of five lateral potholes, plotting Y/Z_o against Z/Z_o. Pothole 1 (solid squares) is at site 2 of Figure 1; potholes 2 (crosses) and 3 (asterisks) are at site 3 of Figure 1. Potholes 4 (open squares) and 5 (Xs) are at site 4 of Figure 1; pothole 4 is a few metres north (upstream) of 5. Dimensions of potholes, not including conical basins: 1—Z_o = 170 cm; 2—Z_o = 190 cm; 3—Z_o = 140 cm; 4—Z_o = 120 cm; 5—Z_o = 210 cm. Data points from field measurements.

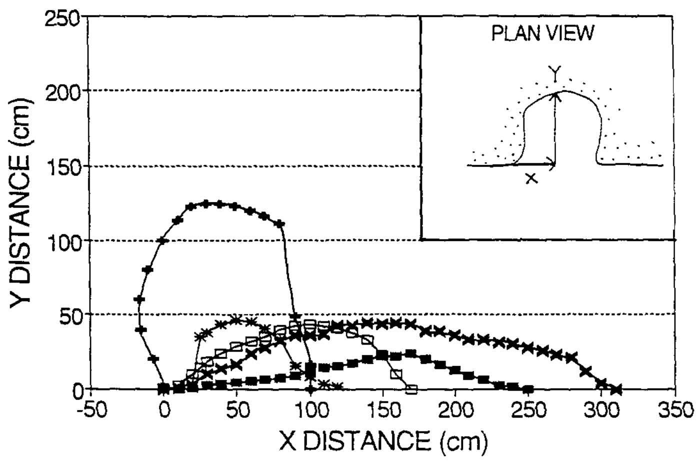

Figure 5. Horizontal profiles (plan view) of same potholes as in Figure 4; profiles were taken at vertical midsections. Symbols as in Figure 4. Pothole 5 can be fitted as arc of large circle having radius of 2.7 m. Nominal paleocurrent direction was from right (north) to left (south), except for 1, for which the direction is uncertain.

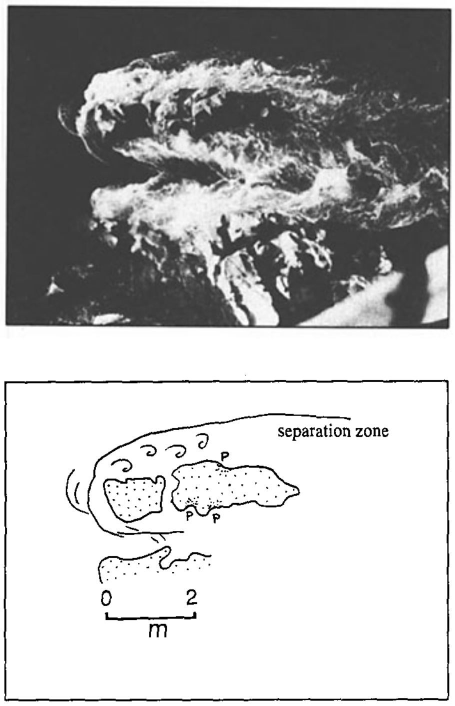

Figure 6. A: Vertical view of rock island at McKillops Bridge over Snowy River, Australia. B: Sketch showing hydraulic features relevant to formation of lateral potholes. Flow separation zone forms around bedrock island (stipple pattern). P indicates potholes. Distance between onset of flow separation and first pothole is ~2 m.

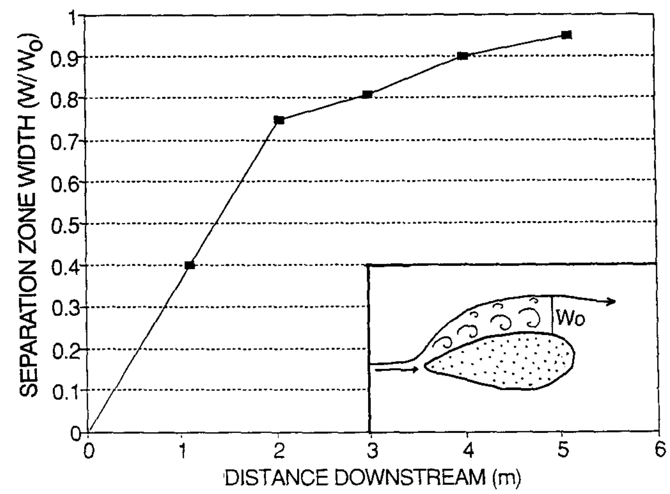

Figure 7. Diagram of geometry of flow separation zone shown in Figure 6B. Dimensionless width of flow separation zone (*W*/*W*o) is plotted against downstream distance. Potholes are located where flow separation zone width stabilizes and vortices generated upstream are constrained against bedrock island.

River, Australia, this distance is ~2 m (Fig. 6). The pothole forms where the width of the separation zone begins to stabilize and the velocity of flow outside of the shear layer constrains the vortex against the rock outcrop (Fig. 7). Research on the scaling of flow separation (e.g., Best and Roy, 1991) indicates that the geometry of the separation zone and thus the site of the first pothole would move downstream with decreasing Reynold's number. Although flow vortices may impinge upon the bedrock surface at different flow levels, only flows with significant suspended sediment loads that occur relatively frequently (e.g., bankfull flows) will result in significant pothole formation. Once initiated, a lateral pothole may perpetuate itself by promoting vortex flow.

In addition to vorticity, other processes add to the erosion of shallow conical basins (bucket-seat–like floors may be produced by rollerlike vortices having nearly horizontal axes). Examination of pothole surfaces indicates that the process of erosion must be sensitive to material properties at centimetre-to-millimetre scale, therefore, pounding of large stones that could not be entrapped in open cavities may be excluded. Abrasion by suspended sediment is probably the most important erosional process, but vortex-induced cavitation may also be important (Barnes, 1956; see also Kato, 1985; Robinson and Blake, 1992). The uppermost parts of modern lateral potholes are subaerial during low water; therefore, spray- and wave-induced weathering and erosion, in addition to turbulent scour, could be significant in their formation. Our hypothesis of lateral pothole formation requires that they be formed near the free water surface and therefore they may be useful paleo-depth indicators. Certainly, their similar normalized profiles (Fig. 4) indicate that upper parts of lateral potholes were formed by comparable processes.

The idea of vortical sculpturing of potholes and Reynolds number scaling of pothole location should be testable by experimental flume studies (e.g., Best and Roy, 1991). Such studies, coupled with field measurements of current velocity, vorticity, and their relation to channel geometry at places where lateral potholes are developing, eventually could be used to develop pothole paleo-flow equations. Potholes represent unique visual evidence of the two-dimensional distribution of turbulence that can be related to depth, Reynolds number, and hence velocity in bedrock-bounded rivers.

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