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Multiscale structural and lithologic controls in the development of stream potholes on granite bedrock rivers

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ABSTRACT

Jointing, veins, dikes, and fracture patterns influence the genesis of potholes in bedrock rivers. We use measures of surface rock strength (Schmidt hammer readings, joint orientation, and spacing) and subsurface rock properties (ultrasound velocity) to analyze the spatial relationship between joints and potholes in three rivers of the Spanish Central System: the Tietar, Manzanares, and Alberche rivers. At each site, we measured the dimensions of between 45 and 77 potholes; at least 50 randomly located Schmidt hammer rebound values, as well as Schmidt hammer values in a 15 × 15 cm grid around each pothole; and ultrasonic *p*-wave velocities measured in a 15 × 15 cm grid around a subset of 12 of the potholes. Results support our hypotheses that most potholes correlate with joints (89% of potholes are related to joint sets), potholes exhibit preferred orientations associated with dominant joints, and pothole genesis correlates more strongly with variations in substrate resistance than with hydraulics. We classify potholes by morphology and present a genetic sequence for specific morphologies in relation to substrate characteristics.

1. Introduction

Stream potholes are erosive morphologies usually linked to fluvial processes such as abrasion or hydraulic erosion. Potholes develop in diverse types of substrate, from soft material like clays to resistant bedrock such as granites. Potholes also characterize bedrock fluvial channels with differing levels of incision (Elston, 1917; Alexander, 1932; Lorenc and Saavedra, 1980; Jennings, 1983; Kale and Shingade, 1987; Sato and Hayami, 1987; Wohl, 1993; Hancock et al., 1998; Springer et al., 2006). Several external processes have been described as responsible for pothole genesis, including glacier abrasion (Gilbert, 1906); mechanical abrasion by means of grinders (moulin theory; Charpentier, 1841); depression forms eroded by subglacial meltwater (glaciofluvial theory; Ljunger, 1930); and hydraulic erosion (eddy theory; Alexander, 1932), among others. Whipple et al. (2000) noted that 'large, often coalescing potholes characterize the lee side of obstructions, protuberances, and knickpoints'. These authors noted that potholes are related to the position and geometric configuration of the channel, although pothole shape is also related to the 'formative mechanisms and internal hydraulics' (Kale and Shingade, 1987; Springer et al., 2005, 2006).

Lithology plays an important role in bedrock river erosion from larger scales such as valley geometry and the formation of straths to smaller scales such as the development of sculpted forms (Selby, 1980; Hancock et al., 1998; Richardson and Carling, 2005; Springer et al., 2006; Wohl, 2008). Potholes can form from relatively minor depressions associated with rock heterogeneities that result from weathering or abrasion by boulder impacts (Lorenc et al., 1994; Wang et al., 2009). Joints can be a particularly important form of heterogeneity with respect to pothole initiation and development and can also facilitate block quarrying (Elston, 1917; Ängeby, 1951; Dubinski and Wohl, 2013). Whipple et al. (2000) highlighted potential interactions between quarrying and potholes: quarrying from zones of more locally jointed rock creates the rough bed and bank topography required to initiate flow separation and vortex formation, which in turn drive abrasion that can lead to potholes; but quarrying can also remove blocks before potholes have sufficient time to form. Springer et al. (2006) demonstrated a strong correlation between potholes and jointing and suggested that joints might create a limit for the depth reached by potholes. Thus, jointing appears to be one of, if not the most important, controls on the occurrence of potholes. This indicates the need to know more about how the presence of joints, particularly the density and three-dimensional configuration, affects potholes.

The erosive mechanisms acting in bedrock rivers are relevant for understanding the beginning of sculpted forms in bedrock rivers, although more in-depth understanding is needed of the processes that result in well-developed potholes. Plucking, abrasion, and cavitation can all contribute to pothole formation (Miller, 1991; Wohl et al., 1994; Hancock et al., 1998; Sklar and Dietrich, 1998; Dubinski and Wohl, 2013). Whipple et al. (2000) established the first-order scaling

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of forces involved in fluvial plucking and abrasion and related the relative contributions of saltating and suspended sediment grains to abrasion. These authors also described the conditions under which cavitation can occur and contribute to bedrock erosion, as well as the interaction between plucking and abrasion processes in long-term bedrock channel incision.

In this research, we focus on the relationship between potholes and (i) hydraulics (main and secondary flow, vorticity, and flow separation, e.g., Hancock et al., 1998; Whipple et al., 2000; Springer and Wohl, 2002); and (ii) structural and substrate characteristics, particularly the massive character of the bedrock (Hancock et al., 1998; Springer et al., 2006; Wohl, 2008) or the presence of joints. Schmidt hammer rebound values and ultrasound velocity techniques were used to detect rock weakness related to jointing.

The Schmidt hammer measures the rebound value of a spring-loaded mass exerted against materials with a consistent force. Although the Schmidt hammer was developed primarily to measure the hardness of concrete, it has been used extensively in geomorphic research (see Goudie, 2006, and Viles et al., 2011, for reviews), starting with De Puy's (1965) studies of rock weathering. The rebound value depends on the elastic properties of the surface where the hammer impacts and is considered extremely sensitive, not only to discontinuities in a rock (Selby, 1980) but also to weaker bedrock.

The *p*-wave ultrasound velocity, otherwise known as ultrasound pulse velocity (UPV), depends on the elastic properties of the rock as well; and *t* is directly related to surface strength (*Rn*) as measured by the Schmidt hammer (Fort et al., 2013). As for the Schmidt hammer, UPV was developed as a nondestructive tool for concrete evaluation during the mid-1940s (Bungey et al., 2006). The UPV is measured between two transducers applied to the surface of the rock. Consequently, UPV reflects material properties for the surface and the first few centimeters below the surface of the area between which transducers are applied. While the Schmidt hammer rebound number reflects surface properties only for the point where the hammer impacts, UPV is influenced by a larger mass of rock and will be affected by material properties and by larger discontinuities crossing the path of ultrasound pulses. Ultrasound velocity depends on material density and is largely dependent on porosity and other discontinuities within materials. Therefore, ultrasound velocity is a good indicator of “quality” or state of decay of a material and has been used extensively as a nondestructive technique for the evaluation of density, porosity, and elastic properties of materials (e.g., Prikryl et al., 2007; Fort et al., 2010, 2011, 2013). Although limited, some references are made to the combined use of UPV and Schmidt hammer values for an overall determination of rock strength (Kahraman, 2001; Vasconcelos et al., 2007; Sharma et al., 2011; Fort et al., 2013).

Our objective is to study the relationship between the presence of potholes and substrate characteristics (rock strength, jointing, and weakness zones) in granite bedrock rivers located within intramountain basins. Accordingly, we performed ultrasonic analyses on the bedrock surrounding potholes for three rivers chosen for different structures (fractures, joints, veins, and dikes), lithologies (granite and granodiorite), and drainage areas. The Tietar, Alberche, and Manzanares rivers are located within the Spanish Central System in the center of the Iberian Peninsula.

A secondary objective is to examine the pattern, evolution, and genesis of potholes, particularly as these characteristics could reflect substrate conditions rather than hydraulic environment. We hypothesize that most potholes initially develop in relation to jointing (*H1*), as indicated by past work (Whipple et al., 2000; Springer et al., 2006; Wang et al., 2009). Testing this hypothesis requires systematic analysis of all the joint sets affecting the bedrock. Related to *H1*, we evaluate whether all joints with a surface expression influence pothole development, or whether potholes only form in association with dominant joints and thus exhibit preferred orientations (*H2*). Data supporting *H1* and *H2* would indicate that pothole genesis correlates more strongly with substrate characteristics (*H3*) than with primary or local flow direction. If *H3* is true, we should be able to detect these preferred erosional trends with ultrasonic analysis and relate them to zones of weakness that may have no surface expression, such as nonhomogeneous granite with an anisotropic behavior. Finally, this study classifies and presents a genetic sequence for specific pothole morphologies that are clearly related to substrate characteristics.

2. Materials and methods

We characterized the field sites using macro- and microscale analyses. Macroscale analyses were based on three digital elevation maps (DEMs) with a pixel size of 50 × 50 m obtained from the website www.ign.es/pnoa. Morpholineaments, veins, and dikes were interpreted as linear structures; and the orientation of these features was compared to the orientation of the drainage network. All of the structural information for each of the three drainages is represented in rose diagrams. Regional joint patterns, as well as some large-scale dikes, could be inferred from DEM analysis over areas of many square kilometers.

Microscale analyses involved systematic field measurements at three sites. We chose one site each along the Tietar, Alberche, and Manzanares rivers. Each site was on the order of 50–100 m long and 30–40 m wide and included numerous potholes and joints. Orientation of joints and pothole (planview) main axes were measured with a compass, with at least 50 measurements at each site. Primary and secondary flow directions were also inferred from local- and reach-scale bedrock morphology at every pothole. Primary flow direction was downstream in the channel, whereas secondary flow direction was identified based on local obstructions and evidence of flow separation (Fig. 1).

Rock strength values (*R*) in outcrops were obtained using a Schmidt hammer. We doubled the sample size suggested by Selby (1980) and measured at least 50 rebound values per site. Strong rocks ($R > 50$), like granite, may require a larger sample: Niedzielski et al. (2009) recommended 30 measurements per site. In addition to random measurements, Schmidt hammer readings in a grid were taken around the potholes in order to develop a map of relative rock strength around the pothole. The grid size varied for each pothole so as to be large enough to surround the whole weathering form. The mesh for these grids was 15 cm in all cases.

The CNS Electronics PUNDIT portable test equipment was used for measuring the time-of-flight of ultrasonic *p*-waves in (micro)s (accuracy ± 0.1 (micro)s). The system included 54 kHz transducers with a round, 50-mm-diameter contact surface. Transducers were fixed into a wooden frame so that the distance between the centers of the transducers was kept constant at 15 cm in order to make velocity calculations straightforward. A fine layer of plasticine-like clay was used to improve the sonic continuity between the rock and the transducers. Measurements were taken using the indirect mode of transmission (i.e., both sensors are placed parallel on the same surface, as described by Alvarez de Buergo and González (1994). This method is often used in building material testing when only one surface of the assessed element is accessible and sensors cannot be opposed, analogous to the rock surfaces where the potholes are found. Although pulse velocity determined by the indirect method is slightly different than that using the direct method, this difference can be neglected when making ultrasound pulse velocity maps, as velocity is only assessed relative to the overall distribution.

A rectangular grid was set up around each selected pothole. The absolute magnitude of these grids varied in each case, but was sufficient to cover the pothole and the immediate vicinity. Measurements were taken at 15-cm intervals. Velocity of ultrasonic *p*-waves was calculated from time-of-flight measurements, and values were represented in Vp maps using a natural neighbor interpolation method: i.e., a method based on finding the closest subset of input samples to a query point and applying weights to the samples based on proportionate areas in order to interpolate a value (Sibson, 1981).