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Fast evolving conduits in clay-bonded sandstone: Characterization, erosion processes and significance for the origin of sandstone landforms

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ABSTRACT

In Strelec Quarry, the Czech Republic, an underground conduit network > 300 m long with a volume of ~10^4 m^3 and a catchment of 7 km^2 developed over 5 years by groundwater flow in Cretaceous marine quartz sandstone. Similar landforms at natural exposures (conduits, slot canyons, undercuts) are stabilized by case hardening and have stopped evolving. The quarry offers a unique opportunity to study conduit evolution in sandstone at local to regional scales, from the initial stage to maturity, and to characterize the erosion processes which may form natural landforms prior to stabilization. A new technique was developed to distinguish erodible and non-erodible sandstone surfaces. Based on measurements of relative erodibility, drilling resistance, ambient and water-saturated tensile strength (TS) at natural and quarry exposures three distinct kinds of surfaces were found. 1) Erodible sandstone exposed at ~60% of surfaces in quarry. This sandstone loses as much as 99% of TS when saturated. 2) Sub-vertical fracture surfaces that are non-erodible already prior to exposure at ground surface and which keep considerable TS if saturated. 3) Case hardened surfaces that start to form after exposure. In favorable conditions they became non-erodible and reach the full TS in just 6 years. An increase in the hydraulic gradient from ~0.005 to > 0.02 triggered conduit evolution, based on long-term monitoring of water table in 18 wells and inflows to the quarry. Rapidly evolving major conduits are characterized by a channel gradient of ~0.01, a flow velocity ~40 cm/s and sediment concentration ~10 g/l. Flow in openings with a discharge 1 ml/s and hydraulic gradient > 0.05 exceeds the erosion threshold and initiates piping. In the first phase of conduit evolution, fast concentrated flow mobilizes erodible sandstone between sets of parallel fractures in the shallow phreatic zone. In the second phase the conduit opening mainly expands vertically upward into the vadose zone by mass wasting of undercut sandstone slabs. Mass wasting is responsible for > 90% of mobilized sandstone. Sides of the mature conduits are protected by non-erodible fracture surfaces.

Natural landforms were probably formed very rapidly by overland flow, piping and possibly fluidization during or at the end of the glacial periods when sandstone was not yet protected by case hardening.

1. Introduction

The weathering and erosion of sandstone result in the formation of interesting morphology features in many areas including the Colorado Plateau (United States) and the Bohemian Cretaceous Basin (Czech Republic, Germany) (Howard and Kochel, 1988; Härtel et al., 2007). Several researchers have investigated the role of erosion by subsurface flow in the evolution of sandstone landscapes (e.g. Laity and Malin, 1985; Howard and Kochel, 1988; Lamb et al., 2006). Analysis has included erosion mechanisms in cohesionless sand (Howard and McLane, 1988; Lobkovsky et al., 2004) as well as cohesive sand in recent fluvial deposits (Fox et al., 2006; Chu-Agor et al., 2008, 2009). However, there remains a limited understanding of mechanism of erosion by subsurface flow in fractured sandstone at the field scale.

To better understand the potential role of erosion by subsurface flow in clay-bonded quartz sandstone research has been undertaken in the Strelec Quarry, Czech Republic (Fig. 1). In the quarry quartz sandstone has been mined since 1941 for the glass industry. Many fresh sandstone faces in the quarry are weak enough to be eroded by running water and rain and the sandstone was even mined for decades by spraying a jet of pressurized water. The same sandstone however has to be mined by explosives when dry, and it has formed stable (up to 40 m high) vertical mining faces prior to present safety regulations. The significant decrease in the strength of the wet

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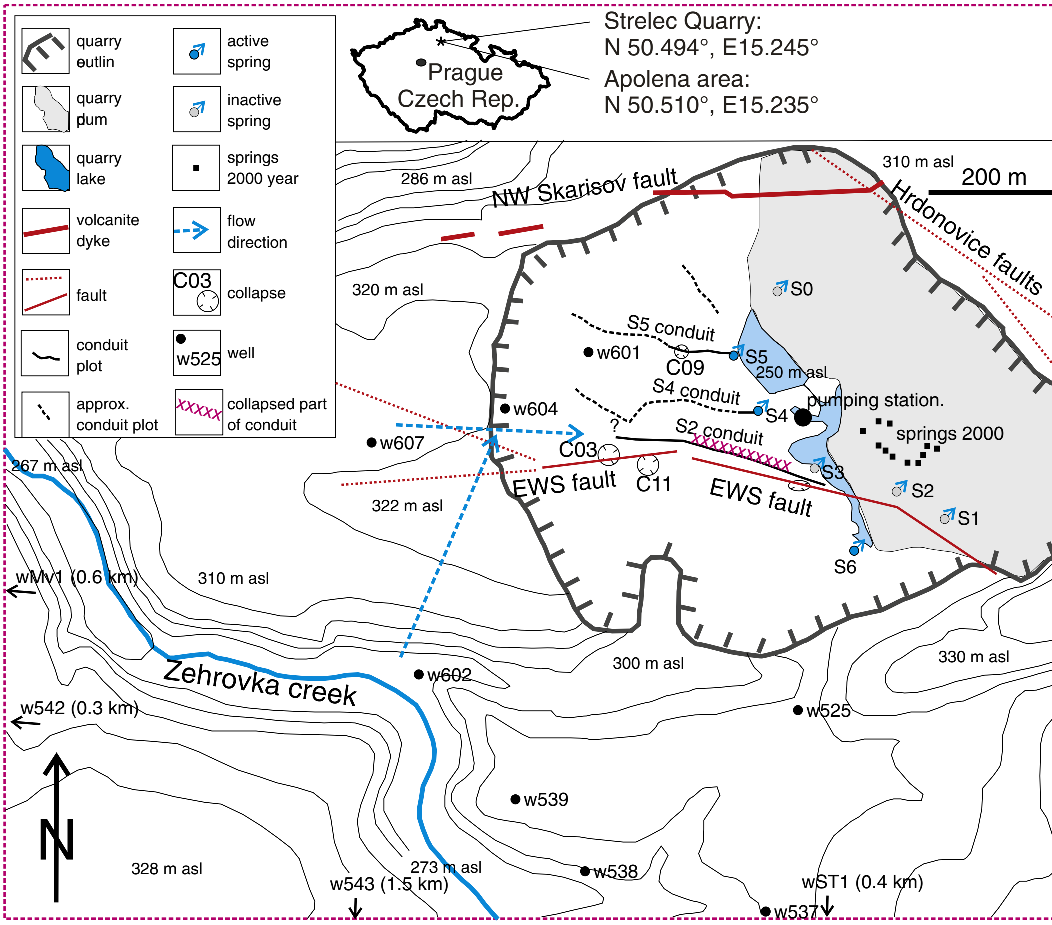

Fig. 1. Map of quarry and close surroundings. Approximate conduit outlines are based on negative Bouger anomalies from detail geophysical prospection (Barta in Nadrchal and Smutek, 2008).

sandstone compared to its dry state is known as wetting weakening (Lin et al., 2005). Outside of the quarry natural sandstone vertical cliffs, slot canyons and towers that are tens of meters high show no evidence of recent erosion due to a thin but firm case hardening (Conca and Rossman, 1982). Some landform features at natural sandstone exposures have similar appearances to those found in the quarry.

To facilitate mining, accumulated groundwater is pumped from the open pit. Since 1985, mine inflows have resulted in a 20 m drawdown of the regional water table. This lowered water table initiated the fast evolution of conduits at recently developed quarry faces (Fig. 1; Břízová et al., 1993; Nadrchal and Smutek, 2008). Initially groundwater enters the quarry from new quarry faces along numerous fractures with flow rates of a few l/s and less. Within several months to a few years conduits, with flow rates as great as 70 l/s, developed along some of the fractures. Discharge locations from the conduits are designated as springs and flows in the conduits are open channel streams that flow along the largely sandy bottoms of the conduits. The conduits are few cm to 2 m wide and one half to several meters high. The largest conduit formed between 2000 and 2006 (Fig. 1). This conduit was up to 17 m high and has an explored length of 300 m from the quarry face (Nadrchal and Smutek, 2008). In 2003, 2006, and 2011 parts of the conduit roof collapsed forming collapse structures up to 25 m in diameter.

Strelec Quarry offers a unique possibility to study conduit evolution in sandstone at various scales from local to regional and from the initial stages to maturity. Conduit evolution at the regional scale can be elucidated from long-term regular monitoring of inflows into the quarry and water table logging in 18 wells spread over the area of 14 km^2 (Nadrchal and Smutek, 2008). Data obtained from monitoring can be combined with a field study of the conduits exposed in the quarry (conduits at initial stage of evolution as well as fully evolved). Critical parameters such as sandstone strength, erodibility, character of the binding agent, groundwater discharge and flow velocity, hydraulic gradient, sediment flux, etc. (e.g. Sherard and Decker, 1977; Howard and McLane, 1988; Dunne, 1990; Chu-Agor et al., 2009; Hanson et al., 2011) can be measured directly inside the quarry conduits and at taken samples. These parameters were estimated or roughly inferred in previous field studies (e.g. Wray, 2009). Finally the sandstone from the quarry (not yet affected by weathering or case hardening) can be used for physical modeling (e.g. Chu-Agor et al., 2008) of erosion processes.

Four modes of sediment mobilization may occur in Strelec Quarry (Budhu and Gobin, 1996; Hanson and Cook, 2004; Lobkovsky et al., 2004; Fox et al., 2006; Chu-Agor et al., 2009):

1) Piping (tunnel scour), is mechanically similar to fluvial erosion where erosion is the result of an effective shear stress applied by concentrated flow to the margins of macropores (Eq. (1)). Flow velocity is a critical parameter, which controls the maximum diameter of transported sedimentary particles (Dietrich, 1982). Eroding stress is proportional to the square of the average flow velocity (Dunne, 1990). As demonstrated by Howard and McLane (1988), seepage force (force proportional to hydraulic gradient in pore space; e.g. Chu-Agor et al., 2008) is not an important contributor to entrainment of particles in the case of concentrated flow. Piping is often caused by dispersion of clay particles (Sherard and Decker, 1977; Dunne, 1990). Sodium adsorption ratio (SAR) is used most commonly as indicator of soil dispersivity.