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Subsurface structure of water–gas escape features revealed by ground-penetrating radar and electrical resistivity tomography, Glen Canyon National Recreation Area, Lake Powell delta, Utah, USA

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ABSTRACT

Data gathered by electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) were used to produce a three-dimensional image of subsurface soft-sediment deformation structures developed on the modern Lake Powell delta at Hite, Utah. ERT and GPR lines were run orthogonal across the crater. ERT resolved a low-resistivity layer up to 2 m thick in the area near the vents within the crater. This low-resistivity layer thins toward the margins representing clays ejected from the vents. Below and adjacent to this layer is a high-resistivity layer that reflects delta top and pro-delta sands. The deepest zone recognized in the ERT profiles consists of a low-resistivity layer, clay deposits that accumulated during the maximum lake high stand. This clay zone is connected to the vent within the crater by a conduit that changes diameter vertically. GPR profiles recognized the presence of collapse features restricted to the proximity of the vent. The geometry of the model is consistent with those proposed for marine pockmarks that can be generated seismically or aseismically with the exception of subaerial exposure after the dome stage development.

1. Introduction

Soft-sediment deformation structures found in the rock record are commonly used to infer the proximity to greater than 5.5 magnitude earthquakes (Sims, 1973; Seilacher, 1984; Allen, 1986; Galli, 2000; Manga and Brodsky, 2006; Moretti, 2000; Reicherter et al., 2009; Loope et al., 2013; Hilbert-Wolf and Roberts, 2015) and are used to make inferences concerning ancient earthquake spatial and temporal distributions (Moretti, 2000; McLaughlin and Brett, 2004; Migowski et al., 2004; Hilbert-Wolf et al., 2009; El Taki and Pratt, 2012). However, recent studies have shown that the production of certain types of soft-sediment deformation structures is not uniquely linked to seismic events (Holzer and Clark, 1993; Greb and Archer, 2007; Pringle et al., 2007). In deltaic settings, seismically induced and aseismic soft-sediment deformation structures are recognized (Postma, 1984; Clague et al., 1992; Stewart et al., 2002; Porebski and Steel, 2003; Owen and Moretti, 2008; García-Tortosa et al., 2011; Oliveira et al., 2011).

Depositional settings with fluid-saturated layers, such as rivers in flood with channels elevated above the floodplain, can expel water vertically, producing soft-sediment deformation structures (Holzer and Clark, 1993; Guhman and Pederson, 1993). In addition, gas and fluid over-pressuring often leads to secondary deformation of consolidated and unconsolidated sediment into a diverse suite of sedimentary structures including domes, pockmarks, and mud volcanoes that have been mainly reported from the marine setting (Hovland and Judd, 1988; Yuan et al., 1992; Cole et al., 2000; Dimitrov, 2002; Dimitrov and Woodside, 2003; Cartwright et al., 2007; Judd and Hovland, 2007; Barry et al., 2012). The origin of marine domes, pockmarks, and mud volcanoes is complex and may or may not be seismically generated (Hovland and Judd, 1988; Judd and Hovland, 2007).

Less commonly, however, the underlying conduit geometries have been documented, and the models are simplistic and only for seismically generated structures (Obermeier, 1996; Loope et al., 2013; Quigley et al., 2013). The Lake Powell, Glen Canyon National Recreation Area soft-sediment deformation structures are of particular interest because the product is aseismic in origin and the result is combination of methane gas and over-pressured artesian water migration. The Lake Powell soft-sediment deformation structures display more complex surficial geometries, craters, and mud volcanoes and are exposed making them amenable to examination (Livingston et al., 2014; 2015). The combination of electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) methods employed in this study of Lake Powell craters, provides accurate, continuous, three-dimensional images of subsurface sediment geometries.

This paper documents the subsurface structure of aseismically generated craters, with identifiable vents on the exposed delta surface by

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employing shallow geophysical techniques: ERT and GPR. The crater structures are then compared to aseismically and seismically generated pockmarks from marine settings and a more accurate model of subsurface fluid/gas flow for the formation of the Lake Powell craters is presented.

2. Geological setting

The damming of the Colorado River at Page, Arizona, in 1963 created Lake Powell (Figs. 1, 2). The lake first reached full pool depth in 1980, and as a result, a delta immediately formed in the lower reaches of Colorado River (Figs. 1, 3). The large sediment load of the Colorado River and the narrowness of its canyon resulted in the rapid progradation of the delta. Seasonal droughts reduced inflow from 2000 to 2005 and again from 2011 to 2014 resulting in a drop in lake level of more than 0 m. The Colorado River channel responded to the rapid base level drop by incising into the delta and revealing a 60 km length of delta sediments along the exposed channel banks (Pratson et al., 2008). Lake level rose from 2006 through 2010 drowning the delta top at Hite, UT (see GoogleEarth.com historical images; Fig. 3; Netoff et al., 2010).

The development and evolution of modern, soft-sediment deformation structures, for example, exposed domes, pockmarks, and mud

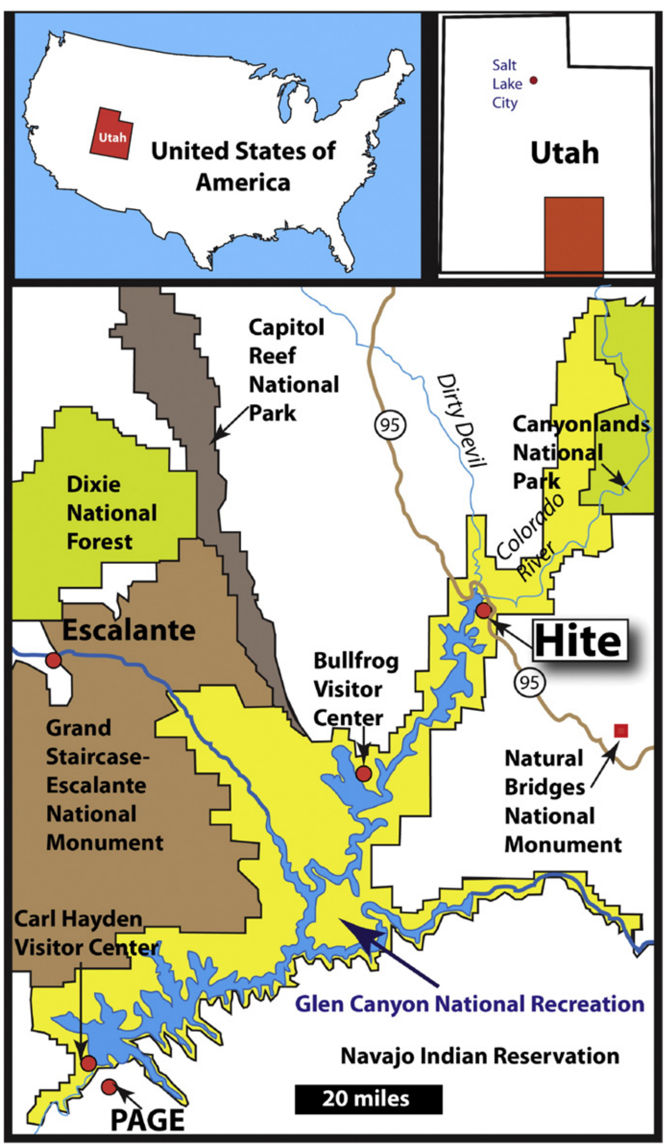

Fig. 1. Locality map of the study area on Lake Powell near Hite, Utah.

volcanoes (Fig. 4) on the Lake Powell delta sediments in Glen Canyon National Recreation Area was first reported in Netoff et al. (2010). Netoff et al. (2010) examined earthquake epicenter distribution in the Lake Powell, Utah, vicinity (Figs. 1, 2) and demonstrated that earthquakes of greater than 5.5 magnitude, the magnitude at which liquefaction takes place, did not occur locally. This absence of significant seismic shaking indicates that this spectrum of Lake Powell delta soft-sediment deformation structures must be attributable to an aseismic origin.

In addition, Netoff et al. (2010) inferred the aseismic mechanism to be the over-pressured water from the underlying artesian system combined with gas methanogensis in the modern Lake Powell sediment. Pore-water pressure was generated from the delta muds overlying and sealing the water-saturated, westward shallow-dipping Cedar Mesa Sandstone creating a confined aquifer setting (Anderson et al., 2000). Methane gas pressure was produced from methanogenic bacterial breakdown of organics in sediment in the lacustrine sediments (Netoff et al., 2010; Livingston et al., 2014, 2015). As a consequence of methane gas and pore-water pressure coupled with declining lake levels from 2000 through 2005 reducing overlying pressure, scores of meter-to-decameter diameter mud domes formed by deflection of the montmorillonite-rich clay upward eventually breaching the dropping lake surface (see Fig. 10 in Netoff et al., 2010). After this initial subaerial exposure of the domes because of dropping lake levels and entrenchment by the Colorado River, many of these domes ruptured and remained active for months expelling water and gas subareally, indicating an extended period of reducing water and gas pressure (Netoff et al., 2010). Subaerial exposure transformed some of the more actively spewing structures into crater-like structures. The crater-like features are typically 0.5 to ~20 m in diameter and 0.1–2.0 m deep (Livingston et al., 2014; 2015) with concentric normal faults exhibited on the desiccating crater flanks. Less vigorous venting of water and gas produces low-sloping mud volcanoes (Livingston et al., 2014, 2015). Generation of the craters in some instances caused development of resurgent mud volcanoes in the crater floor (Livingston et al., 2014, 2015) and/or the development of small-scale, shallow-sourced gas vents (Miller et al., 2015). More recent flooding of the exposed delta surface from 2006 through 2011 followed by a subsequent drop in water levels 1) recharged the aquifer, 2) caused observed fluid flow out of the pits in September 2012, and 3) modified the craters, particularly the margins closest to the Colorado River, probably during the falling lake level stage and subjected the surface structures to subaerial erosion processes (James Kirkland personal communication, August 2013).

3. Geophysical methods

3.1. Electrical resistivity tomography

Electrical resistivity tomography (ERT) is used to measure the electrical properties of the ground in three dimensions and has been successfully utilized in numerous situations to image subsurface structures and stratigraphy without excavation. Electrical current induced into the subsurface follows high-conductivity (low-resistivity) pathways, rendering this method ideal for mapping preferential flow paths in groundwater investigations and for identifying high-conductivity stratigraphic layers such as clay.

Clay and water content are two major contributors to low-resistivity signals in modern depositional environments such as the Colorado River Delta at Hite, Utah. Robinson and Coruh (1988) report resistivity ranges for clay-rich sediments of 1–100 Ωm, compared to sands that vary from 1 to 1000 Ωm. The saturation state of the subsurface impacts overall resistivity. Archie's law indicates the bulk resistivity decreases as the saturation state increases (Archie, 1942). This law is defined as follows:

$$\rho_{arc} = a\varphi^{-m}s^{-n}\rho_w \quad (1)$$