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Research paper

Gas bubble cavities in deltaic muds, Lake Powell delta, Glen Canyon National Recreation Area, Hite, Utah

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ABSTRACT

Cavities produced by migrating gas, mainly methane, emanating from the near subsurface are a rarely reported sedimentary structure from either modern or ancient clastic sediments. The delta of the Colorado River in Lake Powell, Glen Canyon National Recreation Area provides an excellent recently accessible locality for examining soft sediment deformation structures generated by escaping gases and fluids. Sub-meter-scale to tens-of-meter-scale structures, including craters, salses, and sand and mud volcanoes are present on the modern Lake Powell delta. Abundant sub-centimeter-scale cavities are found in excavations through crater sediments and exposed along cut-bank exposures of the Colorado River. In cross section the cavities are subvertical, irregular-to sigmoidal-to lenticular-shaped, 1–3 mm short axes, up to ~3.0 cm long axes, and ~1 cm intermediate axes. Cavities are developed in cm-scale, laminated silty clay and clay graded beds. The tops of the cavities are wider than their bases.

The cavities observed in the Lake Powell delta are interpreted as mode 1 fractures and probably represent a clastic morphologic analog to 'molar-tooth' carbonate structures. The characteristics of the cavities, and the geometries and deformation of the surrounding delta-mud host, are consistent with bubbles and fracturing generated by gas migration experiments and theoretical calculations but vary because of inherent heterogeneity of the sediments. Fractures developed as gas migrated into pre-existing cavities causing overpressure in cavities and leading to subvertical mode 1 fracture propagation. Recent sudden decompression related to rapid lake level drops of Lake Powell may have enhanced the release of gas, primarily bacterially produced, leading to the development of these soft sediment deformation structures.

1. Introduction

Gas generation and migration have played a historically important role in the understanding of clastic sedimentary structure genesis, particularly morphologies akin to raindrop impressions (Buckland, 1842; Twenhofel, 1921). Subsequent investigations into the origin of near circular sedimentary features have supported the similar nature of gas- and raindrop-produced structures in mainly siliciclastic sediments (Maxson, 1940; Cloud, 1960; Moussa, 1974; Rindsberg, 2005). The features interpreted as gas structures have two potential origins, gas-escape and/or gas bubble generation due to biogenic gas build-up (Maxson, 1940; Cloud, 1960; Rindsberg, 2005; Eriksson et al., 2007; Noffke, 2009, 2010; Simpson et al., 2013).

Recent methane gas production studies from the pore-scale to the macroscale have elucidated sources and migration pathways of methane (Bangs et al., 2010; Boudreau, 2012; Tsunogai et al., 2012; Hilbert-Wolf et al., 2016). For example, in the marine setting, macro-scale structures, 10's to 100 m in diameter such as pockmarks, domes, and mud volcanoes vent methane from sources at meter to kilometer or greater depth (Hasiotis et al., 1996; Dimitrov and Woodside, 2003; Boudreau et al., 2005; Barry et al., 2010; Cathles et al., 2010; Boudreau, 2012). Theoretical and experimental studies of methane gas generation and migration at mm-scale in particularly fine-grained sediment have produced ellipsoidal–shaped bubbles that originate and grow by fracture migration (Boudreau et al., 2005; Frey et al., 2009; Boudreau, 2012; Katsman et al., 2013; Katsman, 2015).

Ellipsoidal cavities resembling those produced in theoretical and experimental studies have seldom been recognized in naturally occurring settings (Garcia-Gil, 2003; Jianua et al., 2004; Hilbert-Wolf et al., 2016). This paper describes and interprets small ellipsoidal cavities

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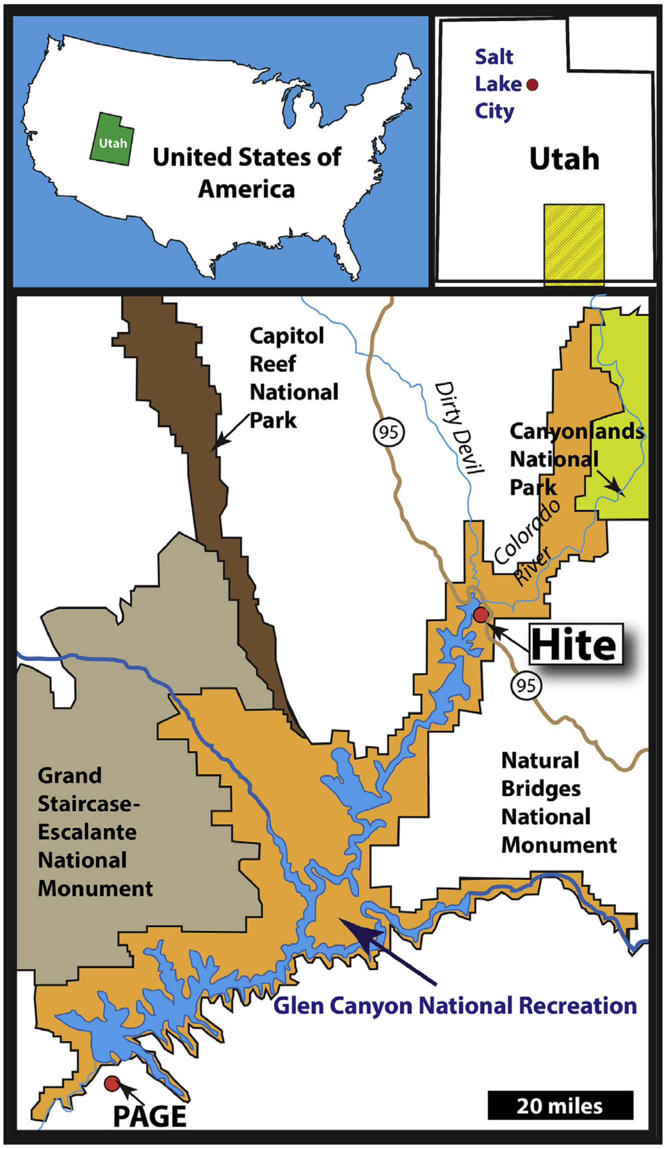

Fig. 1. Locality map of the study area on Lake Powell near Hite, Utah.

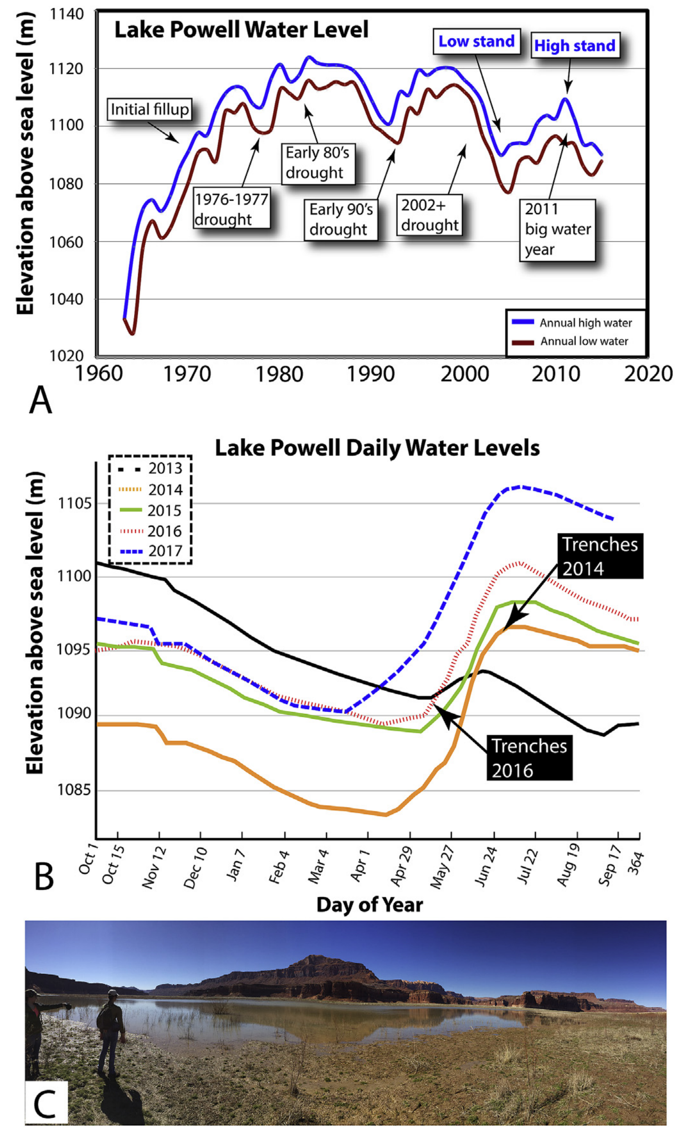

Fig. 2. Lake Powell historical water levels. (A) Hydrograph of lake levels of since inception. (B) water levels from 2013 to 2017. Lake levels at the time of pit excavation are indicated. (C) Lake Powell shoreline at Hite in March, 2015.

preserved in deltaic muds in Lake Powell, Glen Canyon National Recreation Area near Hite, Utah and observed during the 2015 and 2016 field seasons (Figs. 1–3). The cavities are morphologically similar to mode 1 fracture cavities (bubbles) generated in experimental and theoretical studies of migrating gas (Boudreau et al., 2005; Frey et al., 2009; Boudreau, 2012; Katsman et al., 2013; Katsman, 2015). The Lake Powell cavities are associated with distinctive meter-scale gas- and fluid-vent expulsion structures (Netoff et al., 2010; Livingston et al., 2015; Sherrod et al., 2016), which supports an interpretation that the cavities were produced by gas generation and escape processes.

2. Geological setting

Completion of the Glen Canyon Dam at Page, Arizona in 1963 created Lake Powell on the Colorado River (Figs. 1 and 2). A rapidly prograding delta formed at the lower reaches of Cataract Canyon (Fig. 3) around 1980 when Lake Powell first attained full pool depth (Fig. 2). Extended droughts reduced inflow from 2000 to 2005 and again from 2011 to 2014 and resulted in a significant drop in lake water level of almost 40 m (Fig. 2A). During these low-water level periods, the Colorado River channel incised into the delta-top sediment as base level dropped (Fig. 3; Pratson et al., 2008). Water level fluctuates significantly during the year with lows in April to early May followed by annual high levels in mid-July (Fig. 2B; see graphs.water-data.com/lakepowell/).

Pore-water over pressure was generated in the westward dipping Cedar Mesa Sandstone confined aquifer when low permeability pro-delta muds sealed the porous sandstone compounded by the hydrostatic pressure of the lake water column (Netoff et al., 2010). The drop in hydrostatic pressure, related to a 20-year low in lake level starting in 2002 permitted water from the aquifer and shallow methanogenic gas from the recent muds to escape and produce at least 100 pockmark features, each up to 10s of meters in diameter (Netoff et al., 2010; their Fig. 10; Sherrod et al., 2016)). No reports of extensive degassing were found in any studies conducted before Netoff et al. (2010).

The shallow methanogenic gas release probably orginated from the recently accumulated organic-rich bed that is identifiable in trenches and ground penetrating radar profiles (Fig. 4; Sherrod et al., 2016). Gas chromatograph analysis of samples from active vents documented the presence of methane, atmospheric air and carbon dioxide components; the percentage of each gas component varied per vent site and through time (Malenda et al., 2017). $\delta^{13}C$ methane vs δD methane isotopic analysis identified the source as bacterial degradation of organics