Anatomy of a Mud Volcano on the Colorado River Delta, Lake Powell, Hite, Utah

UNDERWOOD, Abigail C.[1], WIZEVICH, Michael C.[1], SIMPSON, Edward[2], REICHARD-FLYNN, Willow R.[2], ILSEMANN, Lara[2], and KEEBLER, Abby[3]

[1] Department of Geological Sciences, Central Connecticut State University, 1615 Stanley St., New Britain, CT 06050; [2] Department of Physical Sciences, Kutztown University, 425 Boehm, Kutztown, PA, 19530; [3] Earth and Space Sciences, West Chester University, Westchester, PA 19383

Abstract

Recent drop in Lake Powell water levels has exposed features such as mud lakes (salsas), small craters, and sediment volcanoes on the Colorado River delta near Hite, Utah. These features developed by the escape of shallow-produced, bacterially generated methane gas (CH_4) and pressurized fluids. Characterizing the internal features of sediment volcanoes helps to distinguish methane-generated volcanoes from seismic-generated volcanoes. A mud volcano situated on the heavily mudcracked sediments of the Colorado River delta was trenched in order to study the internal structures and sample for grain size and organic matter content analyses. The cone exhibits a near-circular shape of ~2 m dia. with a 25 cm dia. and 7 cm deep crater located near the center. The cone, up to 12 cm tall, is comprised of 8 thin beds of fine silt (mean = 6.0-6.5 phi), each 1-1.5 cm thick. The beds are graded, contain parallel and ripple cross laminations, soft sediment deformation (SSD) and scour marks. Below the strata of the cone, large downward tapering sediment-filled fissures extend ~6 inches into the lower deltaic sediments. These features, interpreted as mudcracks, are distinguished from conduits by their "V" shape, and laminated fill, similar in grain size and appearance to the strata present in the cone. Directly beneath the crater of the cone is a 10-cm wide conduit, likely arising from the mud ejecting source, that is filled with non-laminated sediment (5.5 phi) slightly coarser than the surrounding delta sediment (6.5 phi). The organic matter of the sediment from the conduit is similar to that of the delta muds, mudcracks fillings, and cone laminae, all ~1.5-2.0%. The mudcracks that extend into the deltaic sediment beneath the cone clearly existed before the volcano and the laminated sediment within them indicates their fill came from mud volcano eruptions. Although the large mudcracks indicate exposure of the delta surface before development of the mud volcano, the cone's external symmetry and internal features of SSD, scours, graded bedding, and cross ripple laminations indicate the volcano was deposited subaqueously in a very low-energy environment. The consistent thickness of the cone and mudcrack strata suggest cyclical eruptions of similar volume of sediment from the main vent.

Introduction

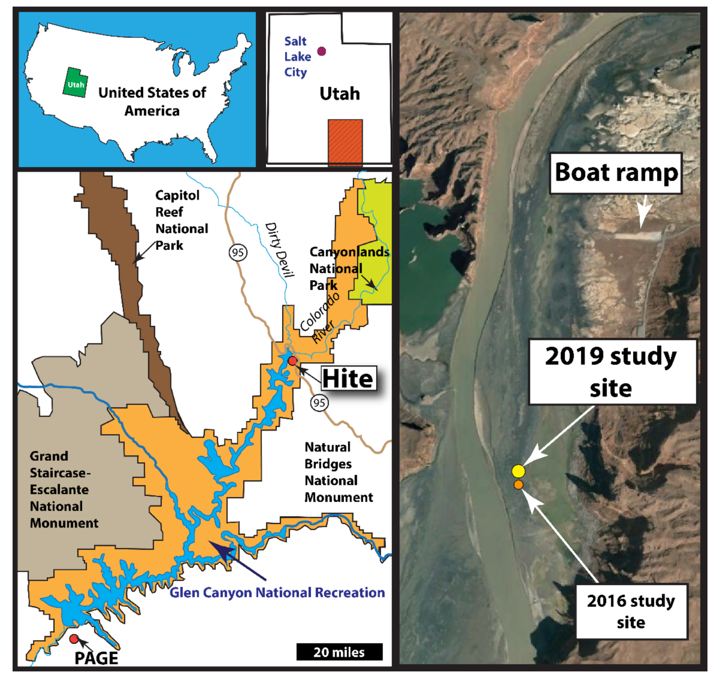

Figure 1. Map of the 2016 and 2019 study area on Lake Powell near Hite, Utah. Air photograph from March, 2016 Google Earth. Stranded boat ramp is 270m in length.

Seismic-generated sedimentary volcanoes have been documented and studied all around the world. These features contain complex internal stratigraphies and are typically used in paleoseismic reconstruction. The structure and formation of seismically generated sedimentary volcanoes is reasonably well understood, however, limited studies have been completed on sedimentary volcanoes generated from a non-seismic origin. Other geological processes reported for the generation of sedimentary volcanoes include local artesian conditions, river flooding, and the escape of trapped methane gas. Strict criteria has been previously developed characterizing the features within seismic generated sedimentary volcanoes, yet defining characteristics specific to non-seismic sedimentary volcanoes are not as well understood. This research contributes to the understanding of non-seismic generated volcanoes by reporting the internal features of a trenched mud volcano exposed on the Colorado River delta during low water levels, in Lake Powell, Hite, Utah (Fig. 1). Formed by the expulsion of trapped bacterially generated methane gas (CH_4), the features of the volcano can be used to aid in differentiating seismic from non-seismic generated volcanoes.

Acknowledgements

We thank Jim Kirkland, Utah Geological Survey, for pointing us in the direction of the project. This research was funded by an AAUP-CSU Research Grant to MW and a Kutztown University Research Committee Grant to ES.

Geologic Setting

In 1963, the Glen Canyon dam was constructed in Page, Arizona. Subsequently, Lake Powell and Colorado River delta formed near Hite, Utah. Significant droughts over the past two decades have decreased the water levels by as much as 40 meters (Fig. 2). Rapid base level drop caused the Colorado River to incise into the delta sediments and exposed a number of soft-sediment deformation structures, including mud lakes (salsas), small craters, and sediment volcanoes. Below the deltaic sediments the Cedar Mesa sandstone acts as a confined aquifer sealed by Lake Powell muds (Netoff et al., 2010). As hydrostatic pressure decreased due to the lake level decline, locally derived and generated methane gas increased fluid and gas pressure in the aquifer. This led to the expulsion of CH_4, CO_2, air, and over-pressured water from the aquifer and the formation of the mud volcano on the delta (Fig. 3).

No active faults are present in the immediate vicinity of Hite, Utah (Netoff et al., 2010). The closest earthquake to the site occurred in the San Rafael Swell in 1988, shaking with a magnitude of 5.3. Furthermore, according to the USGS database, no earthquakes with a magnitude greater than 4.5 have occurred close to Lake Powell in the past 15 years.

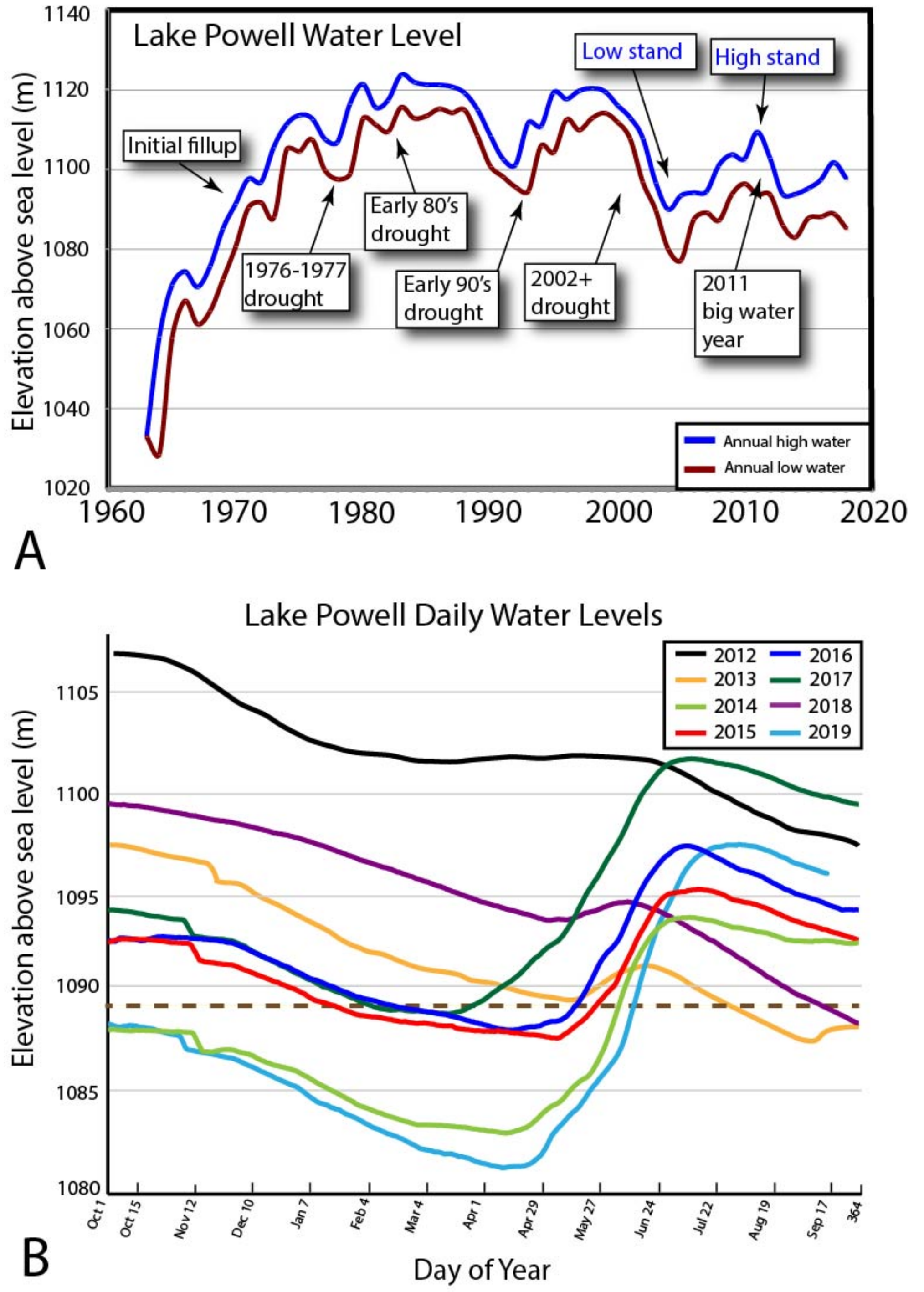

Figure 2. A) Graph of Lake Powell water levels from 1963 (inception) to 2019. B) Lake Powell daily water levels of the past 7 years. Dashed line indicates the elevation of the excavated mud volcano. Data from lakepowell.water-data.com.

Methods

The mud volcano was trenched and samples were taken from the cone, laminated fissures, lower deltaic sediment, lower sand layer, and the conduit of the volcano. A Malvern Mastersizer 3000 was used to determine sediment grain size for the samples (Fig. 4). The instrument obtains grain sizes between 0.01 and 2000 microns via laser diffraction. Two subsamples were analyzed from each sediment samples to ensure accuracy, all samples were dispersed in Calgon for 24 hours before analysis. Standard loss on ignition tests were performed to determine the organic matter content of each sample (Table 1). Photos of the trench walls of volcano were analyzed and interpreted; line-drawing overlays outline significant internal features (Figs. 5, 6 & 7). Results were compared to those from another Lake Powell mud volcano studied in 2016 (Simpson, E.L., unpublished data).

Description

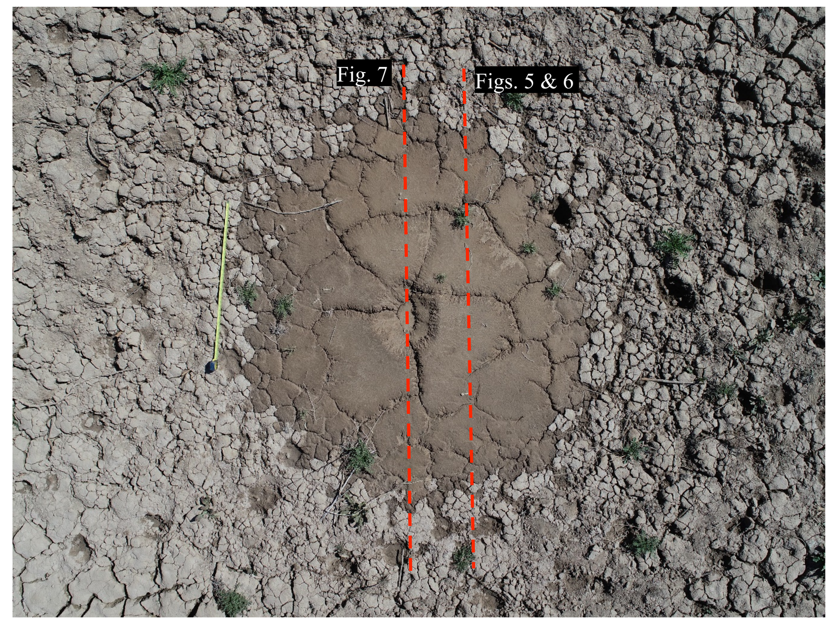

Figure 3. Field photograph taken with a drone showing the external symmetry of the feature. Tape measure is 1 meter for scale. Red dashed lines represent trench lines.

The mud volcano is situated on heavily mudcracked sediments of the Colorado River delta, and consists of a nearly circular-shaped cone with a diameter of ~2m (Fig. 3). The cone extends up to 12 cm above the deltaic sediment. The cone's centrally located crater is 25 cm in diameter and 7 cm deep. The crater is mostly filled in with sediment, but a 20 by 10 cm elliptical depression likely represents the vent.

Sample Name	Organic Matter Content
SV-1	1.80%
SV-2	1.79%
SV-3	1.81%
SV-4	2.03%
SV-5	1.97%
SV-6	1.08%
SV-7	1.54%
SV-8	1.64%

Table 1. Organic content of each sediment sample determined by loss on ignition test.

The internal stratigraphy of the cone flanks revealed in the trench consists of up to 8 normally graded couplets that vary in thickness from 1-2 cm (Fig. 5). The couplets are characterized by parallel-laminated fine sands with sharp, often erosional, bases overlain by parallel-laminated silts. The laminations are thicker, and best defined near the periphery of the volcano. The couplets contain ripple cross laminations, soft sediment deformation (SSD), and scour marks (Fig. 6). The mean grain size of the cone strata is 6.0 – 6.5 phi (fine silt), similar to the deltaic sediment, ~6.5 phi (Fig. 4).

Below the strata of the cone, downward tapering, "V" shaped, sediment-filled fissures extend for ~15 cm into the lower deltaic sediments (Figs. 5, 6, 7). The sediment fill is laminated with a similar appearance and grain size (Fig. 4) to the laminations within the cone. The conduit , stretching 10 cm across, is filled in with non-laminated sediments, differing from the surrounding fissures (Fig. 7). The sediment within the conduit is slightly coarser than the deltaic sediments, with an average grain size of 5.5 phi. A laterally continuous, heavily deformed sand layer, 5 cm thick, exists beneath the fissures within the deltaic sediments (Fig. 5 & 7). The sand layer has an average grain size of 4.4 phi.

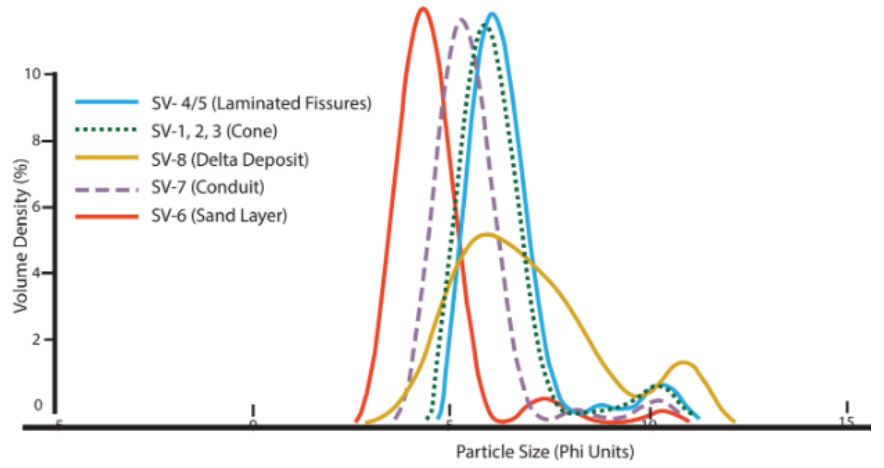

Figure 4. Grain size distribution of the laminated fissures, cone sediments, delta deposit sediments, lower sand layer, and the conduit.

Internal Structures

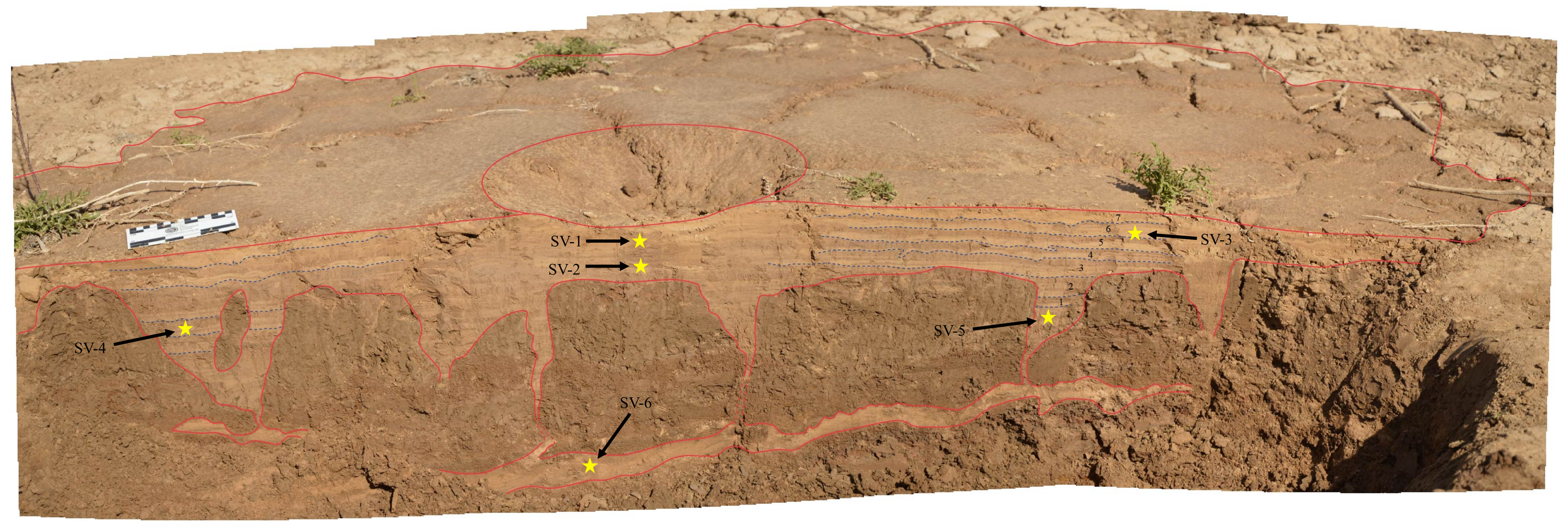

Figure 5. Photomosaic of the trenched mud volcano including interpretations of internal stratigraphy. Strata are labeled 1-8 and are more defined to the left and right of the crater than directly below it. Stars represent sampling locations.

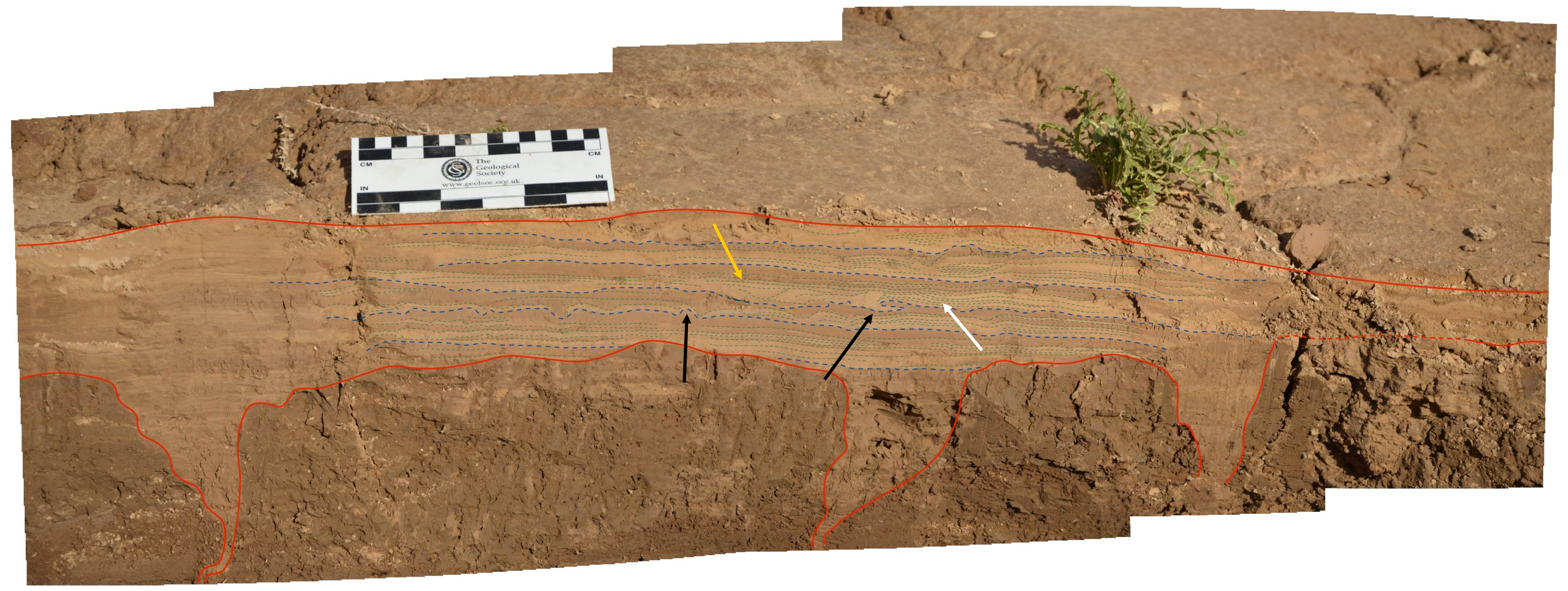

Figure 6. Up-close photomosaic of trenched mud volcano including interpretations of internal features. Dashed blue lines delineate the cones strata and the green dashed lines outline internal features such as scour marks, ripple cross laminations, and scour marks. Yellow arrow points to a scour mark, black arrows point to SSD, and white arrow points to ripple cross laminations

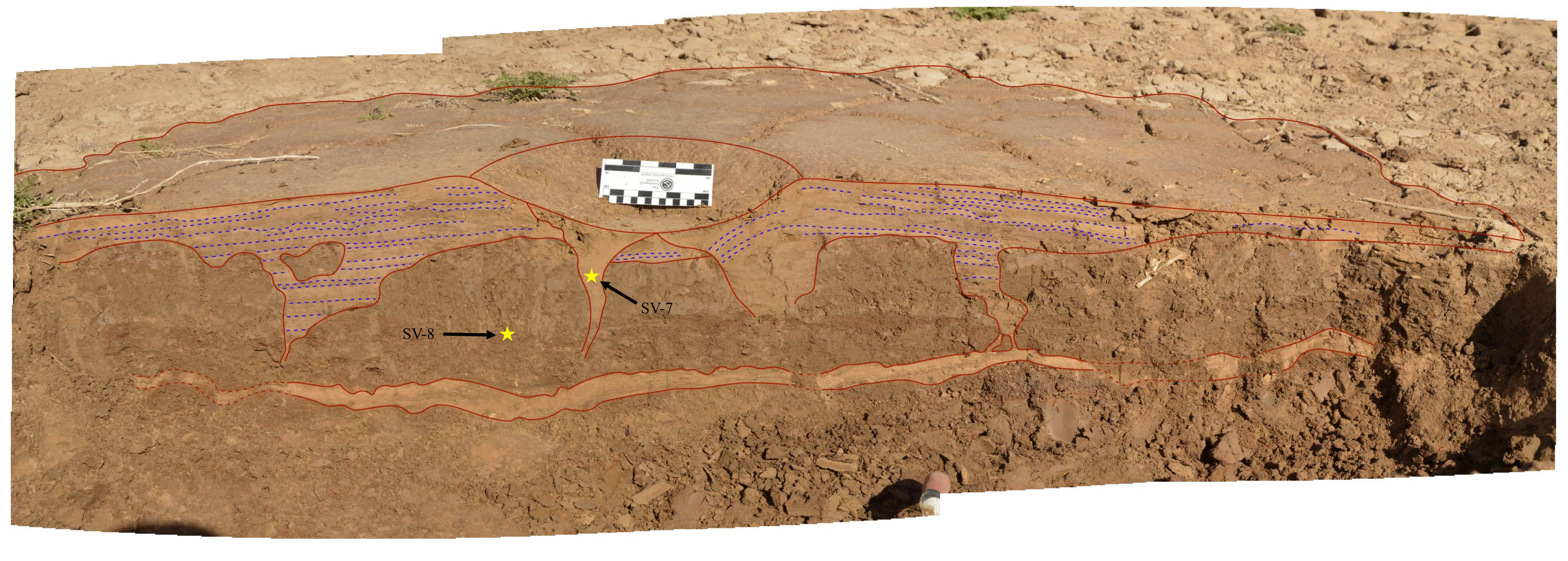

Figure 7. Photomosaic of mud volcano further trenched with interpretations of the revealed conduit system. Stars represent more sampling locations.

Analysis

The cone of the volcano likely formed as a result of cyclical eruptions from the main vent, resulting in the graded sets of laminations comprising the cone. After each eruption, sediment settles through the still water column, depositing the coarser sediments first, followed by finer sediment. Scoured base and ripple cross lamination indicate down-the-cone subaqueous flow of some of the coarser sediment. SSD also supports subaqueous deposition. The circular shape and fine grain size of the cone shows that the water must have essentially been still. After each eruption, sediment back-filled the feeder conduit and sealed the main eruption vent. The methane driving these eruptions became trapped, and gas pressure slowly rose until it eventually reached a threshold and another eruption occurred, depositing sediment as graded laminations. Relatively low organic content of the conduit and cone sediment (Table 1) suggests that the volcano effluent was not likely the source of the methane gas.

2016 Volcano

Another Lake Powell sedimentary volcano was trenched in 2016, which was about the same size and had similar cone stratification as the volcano in this study (Figs. 3, 6, 8, 9). However, the elliptical external shape, sediment grain size and the feeder conduit system, are significantly different (Figs. 3, 4, 7, 8, 10, 11). The 2016 volcano was composed of coarser sandy sediment, while the one trenched this year, is mostly composed of fine silt (Figs. 4 & 11). Although both volcanoes erupted subaqueously, the coarser grain size of the 2016 cone can be explained by current flow winnowing away finer sediments, supported by the current-parallel elliptical cone shape. The dikes in the conduit systems in the 2016 volcano comprise a complex geometry of irregular walls and contained muds in the lower parts and void space above. Despite these differences, they likely ejected a similar volume of sediment, represented by similar size and internal stratigraphy consisting of 8 distinct strata (Figs. 5 & 9)

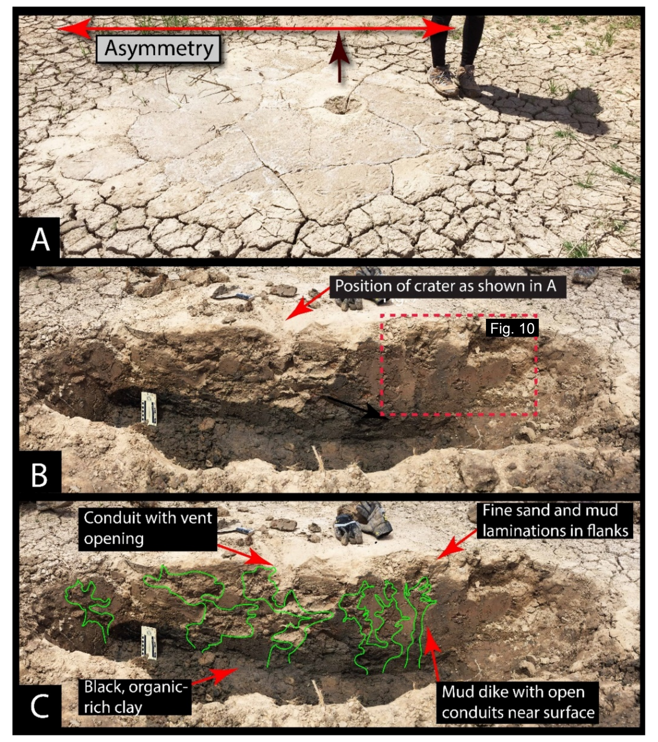

Figure 8. Photographs of the 2016 volcano. (A) Geometric expression of the cone and vent before excavation. (B and C) Trench excavation of the sand volcano. Features are outlined and labeled in C. Box in B shows position of Figure 10 to the right.

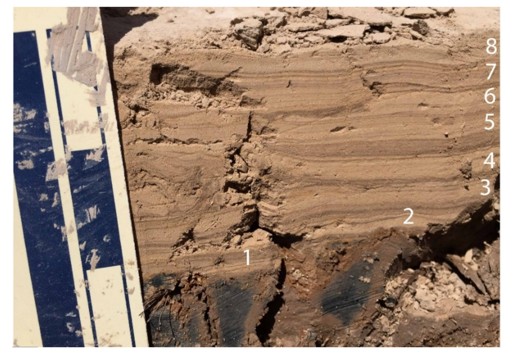

Figure 9. Field photograph of trench wall showing internal cone stratigraphy of 2016 volcano. Strata consist of graded beds numbered 1-8. Open conduits cut the cone strata.

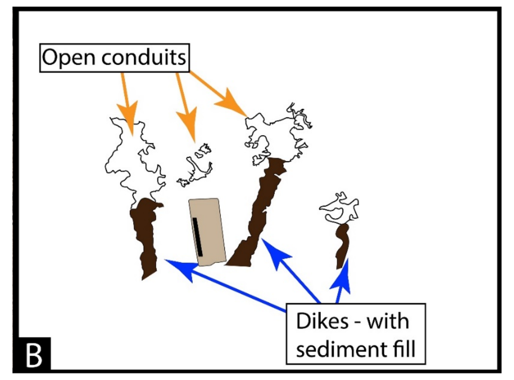

Figure 10. Interpretation of trench wall conduit system outlined in a dashed red box in figure 9B.

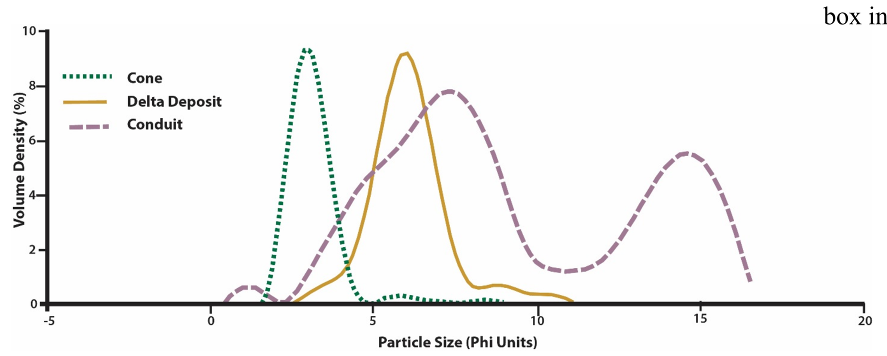

Figure 11. Grain size distribution of the cone, dike and host sediment.

Discussion

Differentiating seismic-generated sedimentary volcanoes from non-seismic generated sedimentary volcanoes can be determined using strict criteria. In reports of seismic generated volcanoes, the internal stratigraphy consists of either one layer, or multiple stacked layers (Rodríguez-Pascua et al., 2015), and is thus not a useful criterion. Dikes of seismically generated sedimentary volcanoes have been described to widen downwards or have parallel walls, and appear approximately linear in plan view (Obermeier, 1996). Additionally, the sediment within seismic generated volcanoes dike systems fines upwards (Obermeier, 1996). The Lake Powell sedimentary volcano exhibits complex dike feeder systems that do not widen downwards, have parallel walls, and are not linear in plan view. The sediment fine of conduit fills within the Lake Powell volcanoes varies for each different volcano, but does not fine upwards. The internal structure and sediment fill of the volcano feeder systems are potential distinguishing criteria, but needs further investigation.

References

Obermeier, S.F., 1996. Using liquefaction-induced features for paleoseismic analysis: an overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. Engineering Geology 44, 1-76.

Netoff, D., Baldwin, C.T., Dohrenwend, J., 2010. Non-seismic origin of fluid/gas escape structures and lateral spreads on the recently exposed Hite delta, Lake Powell, Utah – Preliminary findings. In: Carney, S.M., Tabet, D.E., Johnson, C.L., (Eds.), Geology of South-Central Utah: Utah Geological Association Publication 39, 61-92.

Rodríguez-Pascua, M.A., Silva, P.G., Pérez-López, R., Giner-Robles, J.R., Martín-González, F., Del Moral, B., 2015. Polygenic sand volcanoes: On the features of liquefaction processes generated by a single event (2012 Emilia Romagna 5.9 M_W earthquake, Italy). Quaternary International 357, 329-335.