

Soft sediment deformation in dry pyroclastic deposits at Ubehebe Crater, Death Valley, California

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ABSTRACT

Soft sediment deformation structures are common in fine-grained pyroclastic deposits and are often taken, along with other characteristics, to indicate that deposits were emplaced in a wet and cohesive state. At Ubehebe Crater (Death Valley, California, USA), deposits were emplaced by multiple explosions, both directly from pyroclastic surges and by rapid remobilization of fresh, fine-ash-rich deposits off steep slopes as local granular flows. With the exception of the soft sediment deformation structures themselves, there is no evidence of wet deposition. We conclude that deformation was a result of destabilization of fresh, fine-grained deposits with elevated pore-gas pressure and dry cohesive forces. Soft sediment deformation alone is not sufficient to determine whether parent pyroclastic surges contained liquid water and caused wet deposition of strata.

INTRODUCTION

Soft sediment deformation structures are common in fine-grained pyroclastic deposits. Deposits of dilute pyroclastic currents (pyroclastic surges) are among the most common hosts of such deformation (Douillet et al., 2015). Structures that indicate plastic deformation of a deposit are often taken as evidence that it was damp and cohesive. This and other criteria (poor sorting, deposition against vertical surfaces, steep-sided dune forms, accretionary lapilli, mud lumps, and vesiculated tuffs; Lorenz, 1974; Fisher and Schmincke, 1984) are used to support interpretations of emplacement by cool (<100 °C), “wet” pyroclastic surges involving water droplets (e.g., Heiken, 1971; Dellino et al., 1990; Cole, 1991; Sohn, 1996). This implies incomplete vaporization of water at the location of phreatomagmatic explosion, direct ejection of groundwater or surface water, and/or sufficient cooling during surge transport to allow condensation of steam. These are all valid scenarios and have different implications for eruption mechanisms and hazards, so it is important to test the criteria for interpreting wet versus dry pyroclastic surge processes (note that *wet* and *dry* do not refer to the explosion mechanisms, only to the resultant pyroclastic currents).

We revisited Ubehebe Crater (Death Valley, California, USA), one of the first sites where soft

sediment deformation was described in pyroclastic surge deposits. All other evidence points to dry deposition. We argue that freshly deposited, fine-ash-rich layers were soft because of elevated pore-gas pressure due to rapid deposition from surges and to local granular flows caused by remobilization of surge deposits off of steep slopes. The abundant fine ash in the deposits contributed cohesion through dry intergranular forces rather than moisture.

UBEHEBE CRATER DEPOSITS

Ubehebe Crater formed during the last phase of phreatomagmatic explosive activity at an ~2100-yr-old cluster of craters in Death Valley (Fig. 1; Fierstein and Hildreth, 2017; Champion et al., 2018). Its deposits extend at least 5 km from the crater, and they have diverse characteristics that change with distance and with topography. Within ~200–300 m from the crater edge, deposits include massive, framework- to coarse ash-supported beds, typically decimeters thick, of dense basalt and country rock lapilli and blocks. These are separated by laminated and cross-laminated ash and lapilli-ash horizons, which become the dominant facies with increasing distance, and which, especially in medial areas up to ~1.5 km from the crater, contain dune forms (Crowe and Fisher, 1973). This lateral change may record a decrease in the

importance of ballistic relative to density current (pyroclastic surge) transport and deposition processes (Breard et al., 2015).

Outcrops in reestablished pre-eruptive drainages reveal channel facies that include massive, poorly sorted, matrix-supported ash and lapilli-ash beds. These are typically ~0.1–1 m thick, with flat tops except very close to the channel margins, where they slightly drape the slope and pinch out over 1–3 m laterally, or they simply abut very steep slopes. The beds have ponded geometry; the slight draping of many examples is inferred to be partly an artifact of deflation/compaction of deposits that had flat, horizontal tops immediately upon emplacement and that were up to twice as thick as they are now.

Several locations are particularly instructive about the origins of these massive beds; here, we highlight two sites ~800 m north of the crater (Fig. 2A). Site U20–38 is on a flat, gently sloping surface. Ubehebe deposits there consist of laminated and cross-laminated, fine- to medium-ash deposits and some continuous layers of coarse ash and fine lapilli. The coarser layers are overlain by ash laminae and cross-laminae that fine upward and are capped by several millimeters to 1 cm of fine ash. These coarse-to-fine sequences, or bedding subsets, are interpreted to record the passage of individual pyroclastic surge pulses, with fine ash recording the final waning of a pulse and/or fallout afterward (e.g., Dellino et al., 2008, 2020). We consider the U20–38 section to have been deposited by pyroclastic surges that traveled directly from the crater (primary surge deposits).

Site U20–45 is only ~50 m away from U20–38, at the bottom of a gully and at the foot of a rugged hill (Fig. 2). It has the same detailed stratigraphy, although slightly coarser, but with added massive, ash-rich, poorly sorted beds. Individual surge bedding subsets can be correlated between the two sites (Fig. 2A), and the

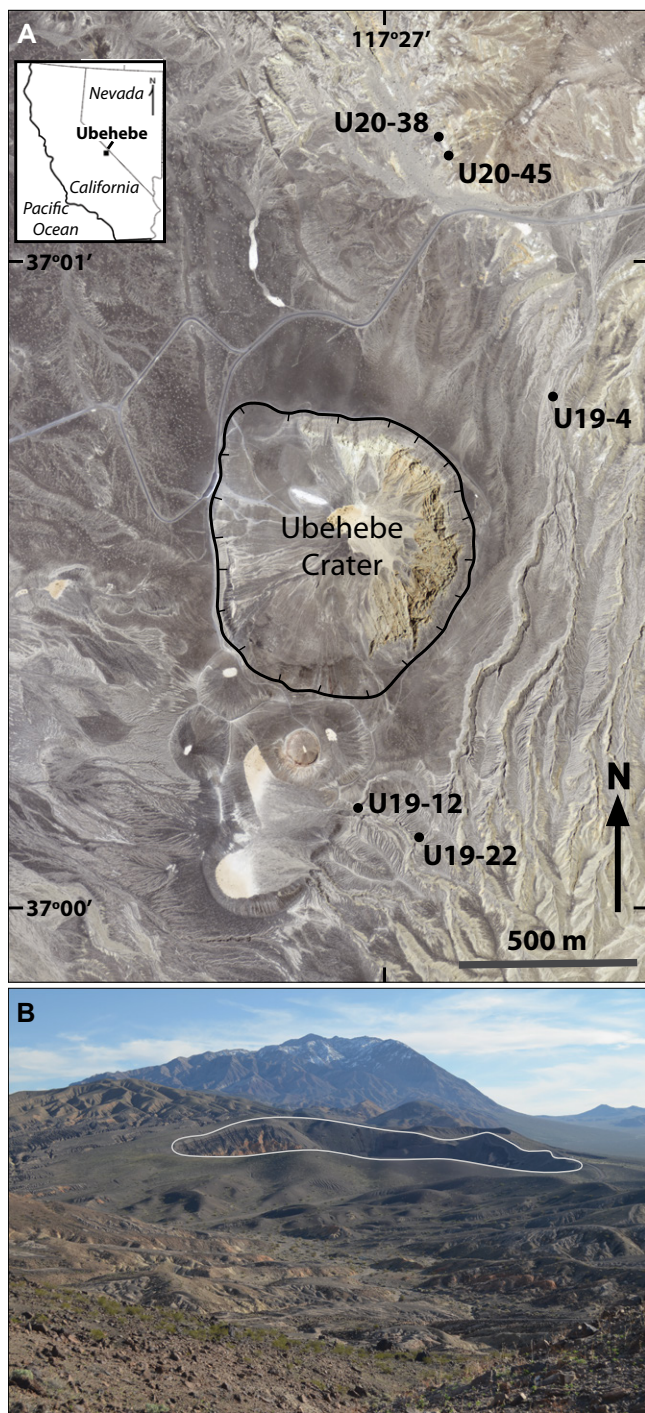


Figure 1. (A) Aerial photo of Ubehebe volcanic center (Death Valley, California, USA), highlighting Ubehebe Crater itself and sites in the text. (B) Ubehebe Crater viewed from the north; crater rim is outlined in gray.

thickness of laminated and cross-laminated (primary surge) deposits at both sites is ~1 m. The massive beds at U20-45 contribute an additional 1.8 m, which decreases gradually away from the hillside, halving over a distance of ~15 m. Thus, the massive beds have the form of small fans at the foot of the hill that are interbedded with inferred primary surge horizons.

Similar characteristics of massive, poorly sorted beds in the Ubehebe section at other locations indicate that most were emplaced by remobilization of rapidly sedimenting, or rapidly sedimented, surge deposits on the steep hillsides

(small-scale cousins of surge-derived pyroclastic flows documented elsewhere; Druitt et al., 2002). These remobilized materials formed dry granular flows that mixed up the individual strata from the depositing or freshly deposited surge beds. The resulting deposits are typically composed of 50–80 wt% fine ash (<0.25 mm) but contain a few percent of grains >1 mm, with occasional coarse lapilli and lithic blocks. This granulometry is consistent with nearby primary (stratified) deposits. In some cases, there is a fine ash layer between a primary surge bedding subset and the overlying massive bed. In oth-

ers, this is absent, indicating that emplacement of massive beds at the site may have occurred so soon after emplacement of primary surge pulses that fine ash had not yet accumulated. Some massive beds are capped with a layer recording settling of fine ash, either elutriated from the granular flows or in suspension from a surge pulse incompletely sedimented when the massive bed was emplaced. The granular flows were not remobilized by rain runoff; there is no evidence for erosion between beds (Fierstein and Hildreth, 2017), and it would seem fortuitous for rain-driven runoff to repeat itself multiple times between surges.

Most features that would indicate wet deposition are absent. Observations at more than 100 pits and outcrops have yielded no accretionary lapilli, mud lumps, or depositionally vesiculated tuff. All cross-stratification is low-angle, with most lee and stoss laminae dipping between 5° and 22°. Only within ~400 m east of the crater did we see primary deposits draped (covering topography but thinning on highs) on gully-wall slopes of up to ~40°. These deposits included coarse lapilli beds, which could not have been cohesive due to moisture. Instead, we attribute the in situ preservation of proximal deposits on steep slopes to the rapid accumulation of ejecta and burial of the topography during repeated explosions, rather than to wet deposition. We do note that in distal areas, where the very fine-grained Ubehebe deposits are ~1 dm thick, vesicles occur locally in the uppermost 1–2 cm, but these are of pedogenic origin rather than an original deposit feature (vesicular A-horizons; Valentine and Harrington, 2006).

SOFT SEDIMENT DEFORMATION STRUCTURES

We focused on two scales of soft sediment deformation: (1) impact sags associated with individual clasts or clusters of clasts (Figs. 3A and 3B), and (2) bed-scale contortion without an associated impactor. Impact sags in the Ubehebe deposits are associated with proximal lapilli-and-block beds and with laminated and cross-laminated horizons; some of these penetrate into underlying massive beds, but coarse lapilli and blocks hosted within the massive beds normally do not have sags. In many proximal locations around Ubehebe, blocks fell in clusters or formed beds that extend for several meters or more laterally, forming breccia lenses and layers and producing complex load and sag structures in underlying strata (Fig. 3B).

Smaller-scale sags involve individual clasts 2–5 mm in size that caused indentations in the top of fine ash layers; in many cases, clasts penetrated 1–2 cm into the fine ash (Fig. 3A) with only vague trails of grains showing that they came from above. Such features are consistent with the ash being dry and “fluffy” due to trapped gas (pore pressure), rather than being

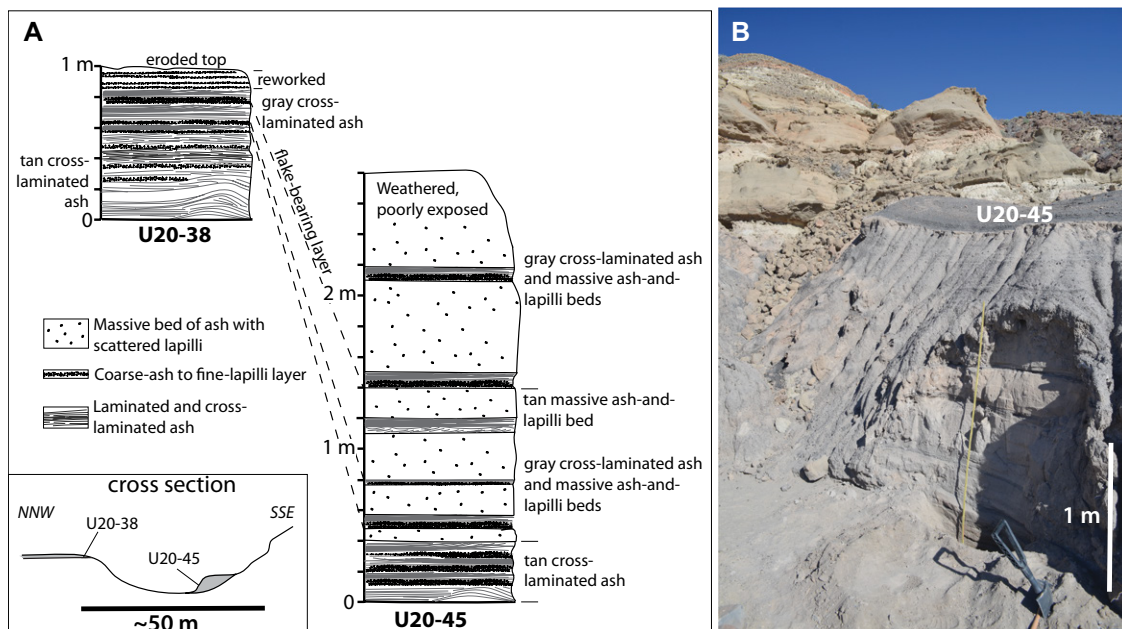


Figure 2. (A) Stratigraphic columns for sites U20-38 and U20-45 in Ubehebe volcanic center (37.0198°N, 117.4478°W and 37.0193°N, 117.4475°W, respectively; Fig. 1A). Dashed lines indicate correlations of bedding subsets (flake-bearing layer refers to the coarse basal portion of a bedding subset that contains conspicuous flake-shaped juvenile lapilli, along with denser lapilli). Inset: Approximate topographic relations (gray represents Ubehebe deposits). (B) Photo of site U20-45 (partially excavated) illustrating the relationship of deposits to the nearby hillside.

damp and cohesive, which would have resisted such small impactors.

Contorted bedding nearly always involves the massive, poorly sorted beds we interpret

to be remobilized, surge-derived granular flow deposits. Such features involve folds and thrust faults (displacements of centimeters), and some involve strata immediately overlying the

deformed massive bed. At one excellent example (Fig. 3C), the upper portion of a massive unit is deformed into a complex set of folds that involve overlying primary surge bedding

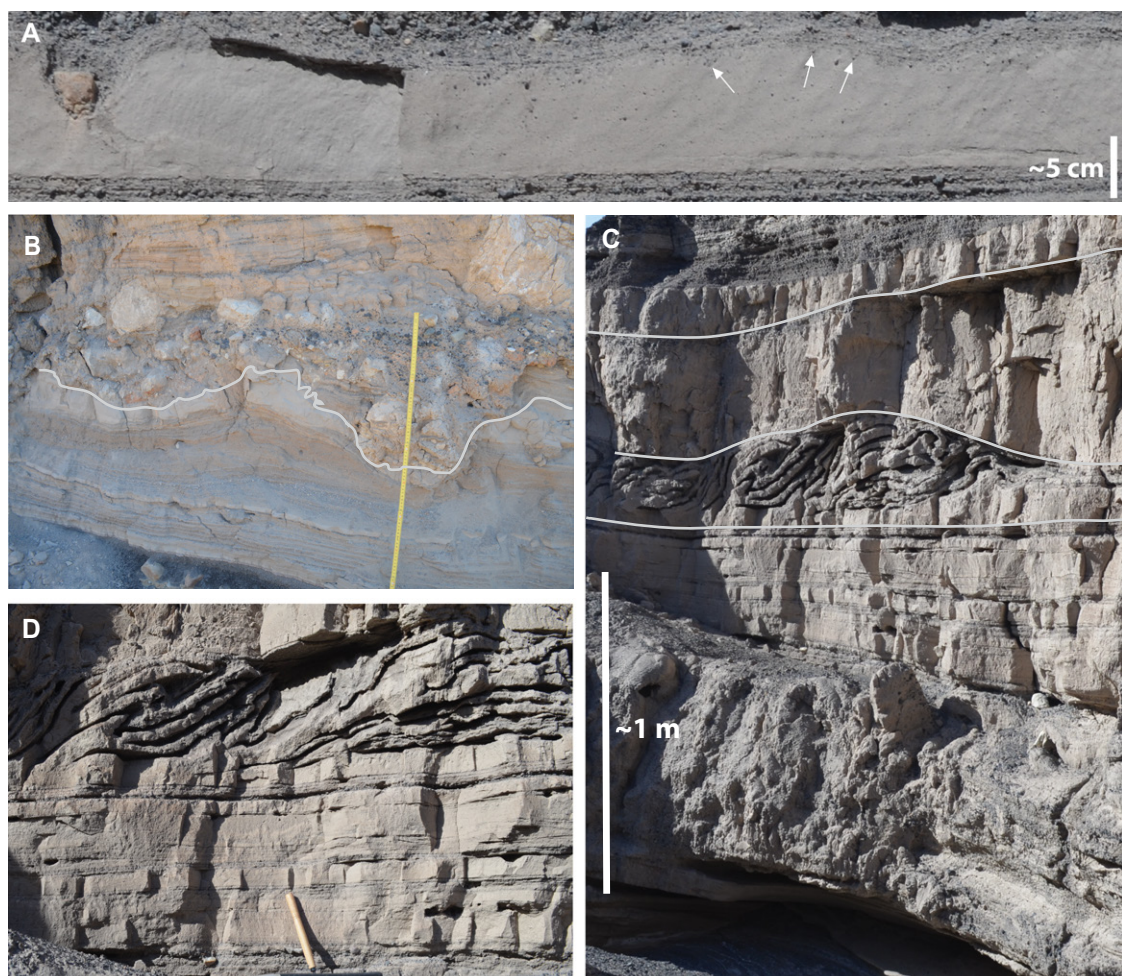


Figure 3. (A) Ash layer overlain by thin coarse-ash/fine-lapilli layer, showing sag due to an individual coarse lithic lapillus (left side of photo), and smaller impact structures involving fine lapilli related to overlying strata (site U19-12, 37.0193°N, 117.4502°W; Fig. 1A). Arrows point to examples of the latter. (B) Complex load/sag structures beneath a cluster of lithic blocks (site U19-4, 37.0127°N, 117.4441°W; Fig. 1A; gray line denotes top of a massive bed). Scale = 80 cm. (C) Contorted horizon among interbedded massive and laminated units (site U19-22, 37.0020°N, 117.4484°W; Fig. 1A). Lower gray line is the base of deformed massive bed; upper two lines are the base and relatively flat top of the overlying massive bed. Dark areas in folded portion are shadows where coarser layers have eroded out. (D) Close view showing that the structure dips toward the plane of the outcrop. Tool handle is ~20 cm long.

subsets. Coarser layers in the latter have partly eroded out, visually enhancing the structure. The exposure is in the wall of a gully that drains from right to left. The fold axes appear to be mostly tilted upward to the right, or upstream with respect to the modern drainage, but the folded bedding planes also dip steeply toward the outcrop face (Fig. 3D). This is consistent with the structure having been produced at least in part by movement downward and parallel to the paleoslope of the gully wall, rather than (or in addition to) the gully axis. The upper portion of the massive bed crept downhill after its original emplacement, carrying and crumpling the overlying surge bedding subsets as the mass neared the channel axis. A subsequent massive bed overlies the deformed layers; it simply filled in around the deformation structure and has a flat top across it (Fig. 3C).

DISCUSSION

Soft sediment deformation structures at Ubehebe have been recognized by others. Crowe and Fisher (1973) briefly described contorted bedding and possible origins due to overriding surges, seismicity, and creep. Douillet et al. (2015) cataloged examples from Ubehebe in their survey of soft sediment deformation in several pyroclastic surge deposits around the world, finding several types of structures, including flames, folds, thrust faults, curls, pull-aparts, potatoids, and impact sags. They attributed some structures to impact and some to density contrasts between rapidly emplaced beds causing Rayleigh-Taylor instabilities, with denser layers sinking into less-dense layers and vice versa, sometimes accompanied by shear of overriding pyroclastic surges to produce bent flames and vortex structures. They inferred that deformation was, at least in part, facilitated by liquefaction of water-saturated deposits. Folded structures (e.g., Figs. 3C and 3D) were interpreted to have formed during slumping of “wet sediment” (Douillet et al., 2015).

We suggest that the soft sediment deformation at Ubehebe actually occurred under dry conditions, as indicated by all other characteristics of the deposits. Pore-gas pressure in the low-permeability, fine-grained deposits facilitated deformation (see also Douillet et al., 2015). Emplacement of bedding subsets by individual explosions in rapid succession produced conditions where impacts of large clasts and clusters of clasts easily deformed fresh deposits that were still soft (fluid-like) due to pore pressure. In this case, “large clast” is relative; for fine-ash layers, 2–5 mm clasts qualified as large and produced tiny sags.

Massive, poorly sorted beds host the most complicated soft sediment deformation structures. The surge-derived granular flows that deposited these beds developed pore-gas pressures during initiation and flow (Roche et al.,

2010), which imparted fluid-like behavior such that they ponded in topographic lows. Pore-pressure diffusion time scales (t_d) can be estimated by $t_d \approx 1.6(h^2/\alpha)$, where h is the initial bed thickness, and α is the pressure diffusion coefficient (0.1–0.01 m²/s, using values determined by experiments on ignimbrite materials with similar fine ash contents to the massive beds; Druitt et al., 2007; Roche et al., 2016). Time scales to initiate diffusion-induced pore-pressure decline (deflation) throughout the full precompaction thickness of individual beds ~0.1–2 m thick would be seconds to ~10 min, with deflation continuing for some time afterward. During deflation, a given bed would compact from the bottom up, with the upper part still expanded (Druitt et al., 2007). Any destabilizing event during the deflation process could trigger deformation. This may explain why deformation such that as in Figures 3C and 3D, and in some examples shown by Douillet et al. (2015), is commonly rooted in the upper portions of massive, poorly sorted beds, while overlying strata were caught up in the deformation. Within those overlying strata, surge bedding subsets formed alternating weak (coarse-grained) and cohesive (fine-grained) layers. As in scaled tectonics laboratory experiments using dry granular materials, the former acted as glide planes, while the latter folded, combining with small-scale thrust faults to produce the final structure (Abdelmalak et al., 2016).

Expanded, massive beds would have had significantly lower bulk densities than any overlying coarser material, even though their constituents are similar; this configuration would promote deformation and mixing by Rayleigh-Taylor instability, and any shearing due to overriding currents or continued motion of the upper part of a bed would contribute to that deformation and mixing. The fact that material from a given horizon retained some of its integrity while folding, sinking, rising, and/or shearing might have been partly due to the dry cohesive forces of very fine ash, but it also might simply indicate that motion stopped before mixing was complete.

CONCLUSION

While Ubehebe Crater deposits exhibit a range of soft sediment deformation structures, no other evidence supports a significant presence of liquid water, indicating that the parent pyroclastic surges were dry. Instead, pore-gas pressure played a key role in promoting deformation, while dry intergranular forces in the abundant fine ash contributed a degree of cohesiveness. Caution should be used when interpreting soft sediment deformation structures to indicate deposition from cool, wet pyroclastic surges; multiple lines of evidence must be used to make such a determination. Abdelmalak et al. (2016) measured cohesion between 100 and

600 Pa for dry mixtures of silica powder and glass spheres (10–20 μ m and <50 μ m, respectively). Tests are needed to determine whether ash would have similar values, but dry aggregation of ash grains is well known (James et al., 2002). Our work also points to potential benefits of studying deformation in dry, fine-grained pyroclastic deposits under various pore-pressure conditions. Because elevated pore pressure in a deposit is transient, quantifying the required pressures could allow estimation of time intervals between emplacement events.

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REFERENCES CITED

- Abdelmalak, M.M., Bulois, C., Mourgues, R., Galland, O., Legland, J.-B., and Gruber, C., 2016, Description of new dry granular materials of variable cohesion and friction coefficient: Implications for laboratory modeling of the brittle crust: *Tectonophysics*, v. 684, p. 39–51, <https://doi.org/10.1016/j.tecto.2016.03.003>.
- Breard, E.C.P., Lube, G., Cronin, S.J., and Valentine, G.A., 2015, Transport and deposition processes of the hydrothermal blast of the 6 August 2012 Te Maari eruption: Mt. Tongariro: *Bulletin of Volcanology*, v. 77, p. 100, <https://doi.org/10.1007/s00445-015-0980-5>.
- Champion, D.E., Cyr, A., Fierstein, J., and Hildreth, W., 2018, Monogenetic origin of Ubehebe Crater maar volcano, Death Valley, California: Paleomagnetic and stratigraphic evidence: *Journal of Volcanology and Geothermal Research*, v. 354, p. 67–73, <https://doi.org/10.1016/j.jvolgeores.2017.12.018>.
- Cole, P.D., 1991, Migration direction of sand-wave structures in pyroclastic-surge deposits: Implications for depositional processes: *Geology*, v. 19, p. 1108–1111, [https://doi.org/10.1130/0091-7613\(1991\)019<1108:MDO SWS>2.3.CO;2](https://doi.org/10.1130/0091-7613(1991)019<1108:MDO SWS>2.3.CO;2).
- Crowe, B.M., and Fisher, R.V., 1973, Sedimentary structures in base-surge deposits with special reference to cross-bedding, Ubehebe Craters, Death Valley, California: *Geological Society of America Bulletin*, v. 84, p. 663–682, [https://doi.org/10.1130/0016-7606\(1973\)84<663:SSIBDW>2.0.CO;2](https://doi.org/10.1130/0016-7606(1973)84<663:SSIBDW>2.0.CO;2).
- Dellino, P., Frazzetta, G., and La Volpe, L., 1990, Wet surge deposits at La Fossa di Vulcano: Depositional and eruptive mechanisms: *Journal of Volcanology and Geothermal Research*, v. 43, p. 215–233, [https://doi.org/10.1016/0377-0273\(90\)90053-I](https://doi.org/10.1016/0377-0273(90)90053-I).
- Dellino, P., Mele, D., Sulpizio, R., La Volpe, L., and Braia, G., 2008, A method for the calculation of the impact parameters of dilute pyroclastic density currents based on deposit particle characteristics: *Journal of Geophysical Research*, v. 113, B07206, <https://doi.org/10.1029/2007JB005365>.
- Dellino, P., Dioguardi, F., Doronzo, D.M., and Mele, D., 2020, A discriminatory diagram of massive versus stratified deposits based on sedimentation and bedload transport rates: *Experimental*

- investigation and application to pyroclastic density currents: *Sedimentology*, v. 67, p. 2013–2039, <https://doi.org/10.1111/sed.12693>.
- Douillet, G.A., Taisne, B., Tsang-Hin-Sun, È., Müller, S.K., Kueppers, U., and Dingwell, D.B., 2015, Syn-eruptive, soft-sediment deformation of deposits from dilute pyroclastic density current: Triggers from granular shear, dynamic pore pressure, ballistic impacts and shock waves: *Solid Earth*, v. 6, p. 553–572, <https://doi.org/10.5194/se-6-553-2015>.
- Druitt, T.H., Calder, E.S., Cole, P.D., Hoblitt, R.P., Loughlin, S.C., Norton, G.E., Ritchie, L.J., Sparks, R.S.J., and Voight, B., 2002, Small-volume, highly mobile pyroclastic flows formed by rapid sedimentation from pyroclastic surges at Soufrière Hills Volcano, Montserrat: An important volcanic hazard, *in* Druitt, T.H., and Kokellar, B.P., eds., *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995–1999: Geological Society [London] Memoir* 21, p. 263–279, <https://doi.org/10.1144/GSL.MEM.2002.021.01.12>.
- Druitt, T.H., Avar, G., Bruni, G., Lettieri, P., and Maez, F., 2007, Gas retention in fine-grained pyroclastic flow materials at high temperatures: *Bulletin of Volcanology*, v. 69, p. 881–901, <https://doi.org/10.1007/s00445-007-0116-7>.
- Fierstein, J., and Hildreth, W., 2017, Eruptive history of the Ubehebe Crater cluster, Death Valley, California: *Journal of Volcanology and Geothermal Research*, v. 335, p. 128–146, <https://doi.org/10.1016/j.jvolgeores.2017.02.010>.
- Fisher, R.V., and Schmincke, H.-U., 1984, *Pyroclastic Rocks*: Heidelberg, Springer-Verlag, 471 p., <https://doi.org/10.1007/978-3-642-74864-6>.
- Heiken, G.H., 1971, Tuff rings: Examples from the Fort Rock–Christmas Lake Valley basin, south-central Oregon: *Journal of Geophysical Research*, v. 76, p. 5615–5626, <https://doi.org/10.1029/JB076i023p05615>.
- James, M.R., Gilbert, J.S., and Lane, S.J., 2002, Experimental investigation of volcanic particle aggregation in the absence of a liquid phase: *Journal of Geophysical Research: Solid Earth*, v. 107, B9, <https://doi.org/10.1029/2001JB000950>.
- Lorenz, V., 1974, Vesiculated tuffs and associated features: *Sedimentology*, v. 21, p. 273–291, <https://doi.org/10.1111/j.1365-3091.1974.tb02059.x>.
- Roche, O., Montserrat, S., Niño, Y., and Tamburrino, A., 2010, Pore fluid pressure and internal kinetics of gravitational laboratory air-particle flows: Insights into the emplacement dynamics of pyroclastic flows: *Journal of Geophysical Research*, v. 115, B09206, <https://doi.org/10.1029/2009JB007133>.
- Roche, O., Buesch, D.C., and Valentine, G.A., 2016, Slow-moving and far-travelled dense pyroclastic flows during the Peach Spring super-eruption: *Nature Communications*, v. 7, p. 10890, <https://doi.org/10.1038/ncomms10890>.
- Sohn, Y.K., 1996, Hydrovolcanic processes forming basaltic tuff rings and cones on Cheju Island, Korea: *Geological Society of America Bulletin*, v. 108, p. 1199–1211, [https://doi.org/10.1130/0016-7606\(1996\)108<1199:HPFBTR>2.3.CO;2](https://doi.org/10.1130/0016-7606(1996)108<1199:HPFBTR>2.3.CO;2).
- Valentine, G.A., and Harrington, C.D., 2006, Clast size controls and longevity of Pleistocene desert pavements at Lathrop Wells and Red Cone volcanoes, southern Nevada: *Geology*, v. 34, p. 533–536, <https://doi.org/10.1130/G22481.1>.

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