PROCEEDINGS OF THE TWENTY-EIGHTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

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SIZE OF PERCHED LAVA PONDS AS A PRODUCT OF VOLUMETRIC FLUX

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Research Advisors: Jeffrey A. Karson, Richard W. Hazlett, Eric B. Grosfils

INTRODUCTION

Perched lava ponds form during basaltic volcanic eruptions and occur when a channelized lava flow enters a region of flatter topography, after which the lava spreads radially and stalls due to increased cooling (Wilson and Parfitt, 1993). For a series of flows at Mauna Ulu Crater, Kilauea Volcano, Hawaii, Wilson and Parfitt (1993) find that both travel distance of radially spreading lava and pond diameters are strongly dependent on volumetric flux, which, in a channel of uniform width, is defined as

$$V_c = U_c D_c W_c \quad (1)$$

where W_c is width, U_c is flow velocity, and D_c is flow depth. Furthermore, in a situation in which U_c and D_c are both treated as constant due to unchanging channel width, velocity can be approximated as

$$U_c = D_c^2 \rho g \sin \alpha / K\mu \quad (2)$$

where μ is viscosity, ρ is flow density, g is gravitational acceleration, α represents the angle of the slope, and K is a constant dependent on the cross-sectional geometry of a flow, defined as $3(1+2(D/W))^2$ by Wilson and Parfitt (1993). Field measurements of channel width and depth can thus be used to estimate volumetric flux via this model.

A series of perched lava ponds is present in the flows originating from the 1975-1984 Krafla Fires fissure eruption in Iceland, which broke out across the crest and on the flanks of the Pleistocene Leirhnjukur hyaloclastite cone in northeastern Iceland (Brandsdottir and Einarsson, 1979; Hauksson, 1981; Hjartardottir et al., 2012). The Krafla ponds have not been studied extensively and are of particular interest due to their extent and freshness, which make them of potentially great use in studies of the role of volumetric flux in lava pond formation.

For this project, the system of fissures at Leirhnjukur was mapped in relation to these ponds, and following fieldwork at Krafla, perched lava pond development was modeled via small-scale analogue ponds at Syracuse University, New York. Further studies were undertaken at Amboy Crater, a Pleistocene scoria cone in San Bernardino County, California, in order to examine a feature hypothesized to be a very large-scale perched pond. The overall purpose was to determine whether pond size can be directly tied to volumetric flux, using data from both the Krafla and Amboy lava flows as well as data from the Syracuse pours.

KRAFLA LAVA PONDS

At Leirhnjukur, a radial pattern of vents at the summit may mark the initial upwelling and outbreak of the 1975 eruptions (Fig. 1). The other fissures, which run north-south, show *en echelon* offset; a series of fissures travels south from the Krafla cone itself, and approximately 400 m south of the cone, a parallel system of vents appears offset roughly 100 m to the east. This system continues south, passing Leirhnjukur, and the directional flow of the lava indicates that most of the lava was erupted from fissures in this region. The area immediately around Leirhnjukur is marked by several perched lava ponds (Fig. 1); the largest of these ponds (Pond 5 in Fig. 1) lies immediately south of Leirhnjukur, in a flat area nestled between a line of vents associated with an older eruption to the west and mountains of pre-eruption tuff to the east. Field evidence suggests that the lava in this pond originated from fissures to the immediate east, and the close proximity of the pond to these fissures indicates that ponding occurred almost immediately after the lava was emplaced. Pond 3 in Figure 1, meanwhile, is situated to the immediate west of Leirhnjukur and to the north of the large pond, in the immediate area of the vents flanking Leirhnjukur. Unlike the large pond, it appears to have received inflow from both the spatter vents immediately to its east and from a channel to the south. The lava in this channel poured down a slope estimated conservatively to be about 15˚, before reaching an essentially flat area into which lava from nearby vents was already pouring.

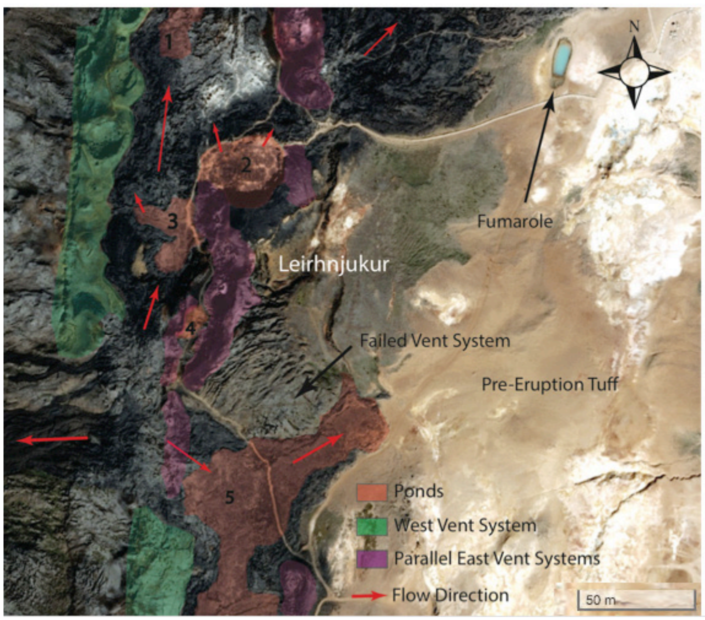


Figure 1. Location of ponds and vents in the Krafla lava flows. Image taken from ja.is.

The pond that is most applicable to this study is Pond 2 in Figure 1. Notably, it has levees 2.5 m in height, far exceeding those seen at the other ponds in the region. The pond appears to have been exclusively fed by a channel approximately 1 m in width at the southwest corner of the pond, for there is no evidence of eruptive vents. The center of the pond does contain several features interpreted to either be hornitos or pieces of the levees, having broken off and been "suspended" in the center of the pond, a feature previously documented in lakes at Halemaumau and Kilauea Iki at Kilauea, Hawaii (Hazlett, 2014). Outflow from this pond appears to have been sporadic, for sheets of lava and a small network of pyroducts, both of which suggest intermittent overflow, overlie the levees. Supporting this hypothesis, there is a'a in the path of this outflow, slightly to the north; pahoehoe can transition to a'a when previously-stored lava is suddenly remobilized and forms clots (Peterson and Tilling, 1980), and Patrick and Orr (2012) find that rapidly moving a'a flows can develop with the sudden release of bodies of lava accumulated in perched ponds.

The pond itself is elliptical and has diameters of 100 ft. (30.48 m) on the East-West axis and 75 ft. (22.86 m) on the North-South Axis, yielding an approximate area of 547.24 m^2. The channel feeding into this pond has an approximate width of 1 m and an approximate depth of 0.3 m, although the depth was difficult to measure. Harris et al. (2000), in their treatment of lava effusion rates at Krafla, use a lava density of 2600 kg m^{-3}; they also estimate a viscosity of approximately 100 Pa s for the dike-fed eruption at Krafla. Given that the lava in the channel moved down a slope of approximately 5˚, the average velocity through this channel would be

$$U_c = ((0.3\ m^2)^2 * (2600\ kg\ m^{-3}) * 9.8\ m\ s^{-2} * 0.087) / 7.68 * (10^2\ Pa\ s) = 0.259\ m\ s^{-2}.$$

Using this value then gives us V = 0.3 * 1.0 * 0.259 = 0.078 $m^3\ s^{-1}$. Though a depth of 0.3 m is estimated, it could plausibly have varied between 0.1 and 0.5 m; the velocity thus ranges from 0.05 and 0.46 m s^{-1}, while the volumetric flux varies from 0.0051 and 0.23 $m^3\ s^{-1}$ (Fig. 2a). If the viscosity is increased to 1000 Pa s, U ranges from 0.005 to 0.046 m s^{-1}, with V varying from 0.0005 to 0.023 $m^3\ s^{-1}$ (Fig 2a); if it is decreased instead to 10 Pa s, U ranges from 0.51 to 4.62 m s^{-1}, with V varying from 0.05 to 2.31 $m^3\ s^{-1}$ (Fig. 2b).

These ranges stand in contrast with Wilson and Parfitt's results from their case study at Mauna Ulu crater; they find that a pond approximately 70-80 m in diameter is associated with a flux of 12.6-16.0 $m^3\ s^{-1}$. They note that this pond was short-lived, which may explain why such a large flux was needed to create a pond of that diameter in such a short time. In contrast, Harris et al. (2000) find that the time-averaged bulk eruption flux of Krafla during the 1950-1995 period was 0.86 $m^3\ s^{-1}$, which is more in line with our estimates.

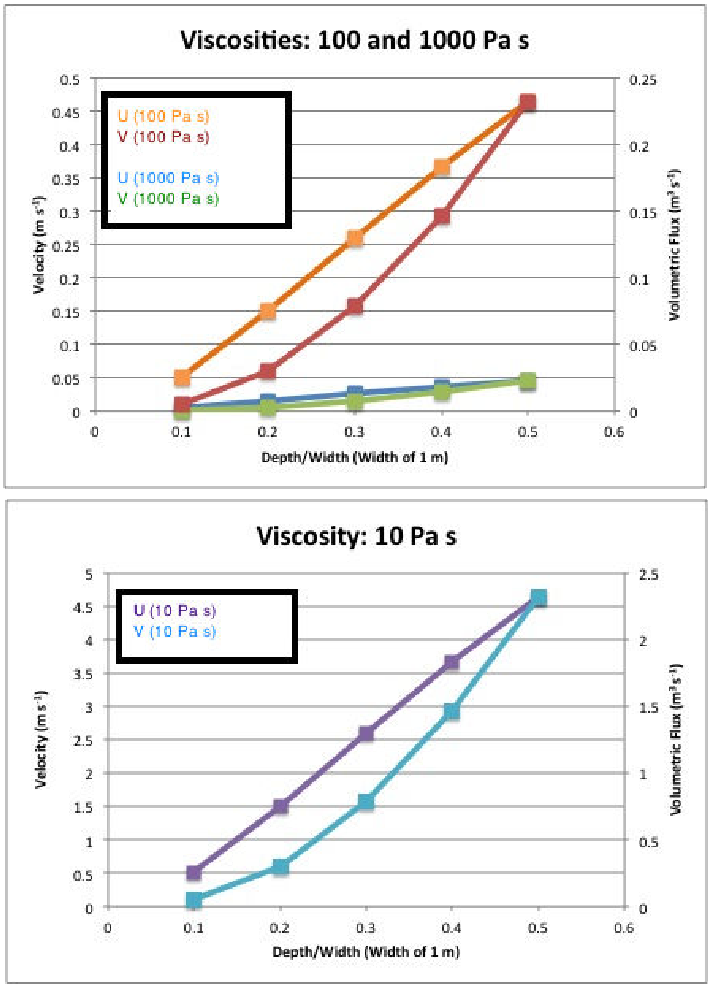


Figure 2. Variation of U and V with D/W ratio at μ = 100 Pa s and 1000 Pa s (2a) and μ = 10 Pa s (2b), for Krafla.

Pond 2 is characterized by the formation of levees at a distance from the initial inflow at which the slope steepens. This occurrence is counterintuitive, for the rate of flow would be expected to increase at such locations. It appears, however, that levee development was advanced enough by an early stage that lava was unable to spread as broad sheets or form channels, and instead was only able to exit via pyroducts or during brief periods of overflow. If the flux is indeed as low as modeled, the pond may have indeed been long-lived, consistent with the degree of leveeing observed here.

COMPARISON TO AMBOY CRATER, CALIFORNIA

Another volcanic terrain hypothesized to have perched lava ponds is the series of lava flows surrounding Amboy Crater, a scoria cone located approximately 75 miles east of Barstow, CA. It is estimated to be 79 ka and rises over a 70 km^2 field of highly vesicular Pahoehoe emplaced over an alluvial plain (Phillips et al., 2003; Byrnes et al., 2006). The flows are associated with the Mojave Neovolcanic Province and are characteristic of the small-scale basaltic volcanism that occurred in Southern California from the Miocene onward (Allison et al., 2013); they are hummocky and devoid of pyroducts, with few distinct channels (Byrnes et al., 2006). There is some difficulty in comparing the Amboy volcanic field to the Krafla lava flows, in that the former is both less fresh and more heavily eroded than the latter. Additionally, much of the flow is at least partially covered by sand, much of it from the catastrophic flooding associated with the drainage of Lake Manix (Hazlett, pers. comm., 2014).

A feature consisting of impounded lava is located approximately 1.5 km west of Amboy Crater itself (Fig. 3a); it may either be a perched pond or inflated lava situated over an active vent. Eye-shaped and having diameters 600 m (on its NE-SW axis) and 300 m (on its NW-SE) axis, it is surrounded by a ridge, inside which the lava slopes gently downward towards the center (Fig. 3b). It has almost certainly undergone collapse, given the breakage of lava observed in the rim, but it is unclear from where precisely the lava originated, for directional flow of lava has essentially been erased by erosion. There is a feature in its northeastern corner that resembles a broken secondary vent, while two depressions along this same axis that are now filled with sand may also represent former vents (Fig. 3b).

On the other hand, it is plausible that the feature was indeed fed by a channel to the northeast, given the morphology of that area, and that the ridge represents self-impounded levee development akin to that observed at Krafla (Fig. 3b). Following this assumption, the channel can be approximated as being 50 m wide and 2 m deep in order to estimate volumetric flux, although depth was very difficult do determine due to the condition of the lava. Values akin to those at Krafla were employed as proxies, with an angle of 0.1˚ being assumed due to the terrain's flatness.

While using a viscosity of 100 Pa s and density 2600 kg m^{-3}, 10.45 is obtained as the constant for K, yielding U and V values of 0.165 m s^{-1} and 16.5 m^3

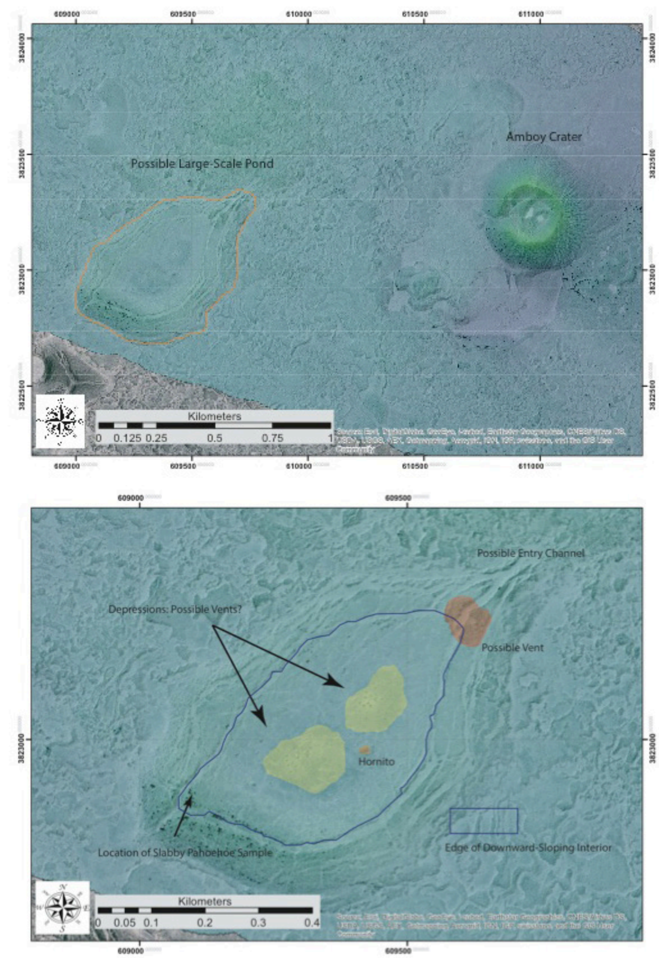


Figure 3. Possible pond: location in relation to Amboy crater (3a), closeup showing possible vents (3b).

s^{-1}, respectively. The depth might plausibly be varied between 1.0 and 3.0 m, which yields U = 0.13-1.06 m s^{-1} and V = 6.85-159.53 m^3 s^{-1} (Fig. 4a). If viscosity changes to 10 Pa s, it instead yields U = 1.37-10.63 m s^{-1} and V = 68.52-1595.3 m^3 s^{-1} (Fig. 4b); changing it to 1000 Pa s yields U = 0.0137-0.106 m s^{-1} and V = 0.685-15.95 m^3 s^{-1} (Fig. 4c).

Volumetric flux is very sensitive to channel depth, and there is also a great deal of uncertainty given that the exact viscosity is not known. The values obtained at μ = 10 Pa s are probably unrealistically large, even for a pond of this size, suggesting that the lava was somewhat more viscous than this. If the channel depth and viscosity are indeed 2 m and 100 Pa s, respectively, then the volumetric flux is on the scale of that observed by Wilson and Parfitt (1992) for their Hawaiian ponds; given the size of this pond, that result would suggest that it was very long-lived and slow-filling.

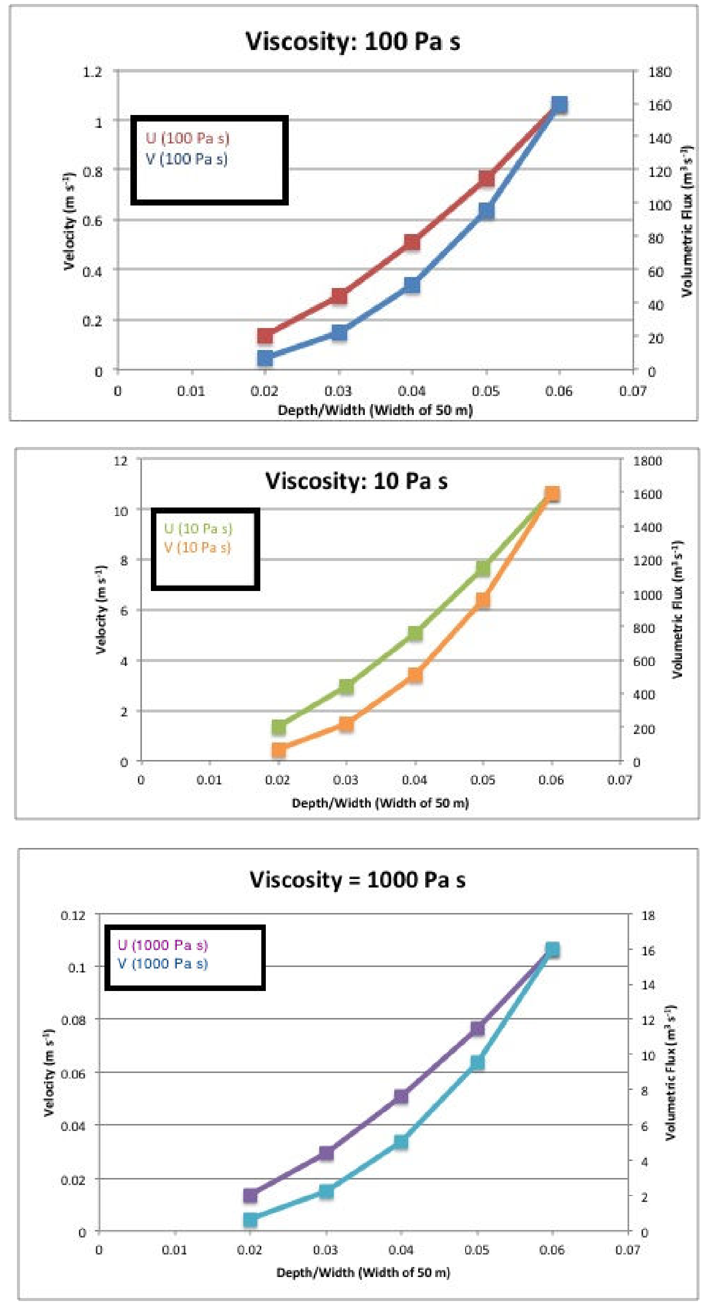


Figure 4. Variation of U and V with D/W ratio at μ = 100 Pa s (4a), 10 Pa s (4b), and 1000 Pa s (4c), for Amboy.

ANALOGUE WORK AT SYRACUSE UNIVERSITY

Perched lava pond development was modeled via the Syracuse University Lava Project, which employs a furnace large enough to melt significant quantities of basalt and generate small flows. Basalt obtained from the Precambrian Keweenawan Rift in northern Wisconsin was melted and poured onto a sand terrain. Lava poured down a metal chute 30 cm in width, onto a slope of 5˚, and the pours were filmed using both conventional video and Forward-Looking Infrared (FLIR) footage.

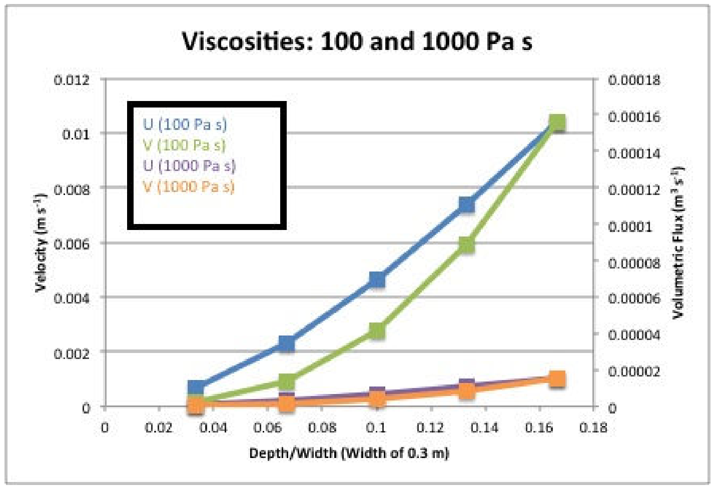
Since the amount of lava present in the furnace was orders of magnitude smaller than that emitted by either Krafla or Amboy, the system was heavily scaled down. The ratio of depth to width is constrained well at approximately 3 cm to 30 cm, or 0.1, which is close to the ratios inferred for Krafla and Amboy. Due to the small volume of lava, however, the model is affected by rapid cooling, and it is also essentially degassed due to having been recycled so many times.

Two pours were undertaken, with the size of the resultant pond being essentially the same in each case. The first pour was underlain by an elliptical pit of diameters 0.3 and 0.5 m; the lava immediately flowed into this pit and spread radially, cooling rapidly and forming a pond approximately 30 cm in diameter, with outflow occurring in a breakout zone of no more than 10 cm in width. Replacing this pit with three small pits of 15 cm diameter did not change the diameter of the pond significantly. The form of the ponds, however, was heavily influenced by pre-existing topography, as observed at Krafla: in this second pond, some lava was able to pour around the cooling lava, since less of it was arrested by a large depression.

The D/W ratio yields 4.32 for the constant K, and given this value and the slope of 5˚, viscosity and density are fixed at 100 Pa s and 2600 kg m^{-3}, respectively, to obtain U = 0.000651-0.0104 m s^{-1} and V = 0.00000195-0.000156 m^3 s^{-1} (Fig. 5a). Since the channel depth is fairly well constrained at 0.03 m, the most likely values for U and V are 0.00463 m s^{-1} and 0.0000416 m^3 s^{-1}, respectively (Fig. 5a). The lava actually flowed at approximately 0.1 m s^{-1}, and it is likely that the viscosity was in fact somewhat lower; a value of 10 Pa s produces U = 0.006-0.104 m s^{-1} and V = 0.0000195-0.00156 m^3 s^{-1}, with U=0.046 m s^{-1} corresponding to the channel depth (Fig. 5b). These data still yield velocities that are far too slow, which suggests that the scale of the flow, and possibly the altered properties of the basalt, make this setup difficult to compare to Krafla and Amboy.

CONCLUSION

Data from the Krafla and Amboy lava fields support the notion that the overall size of a pond is strongly



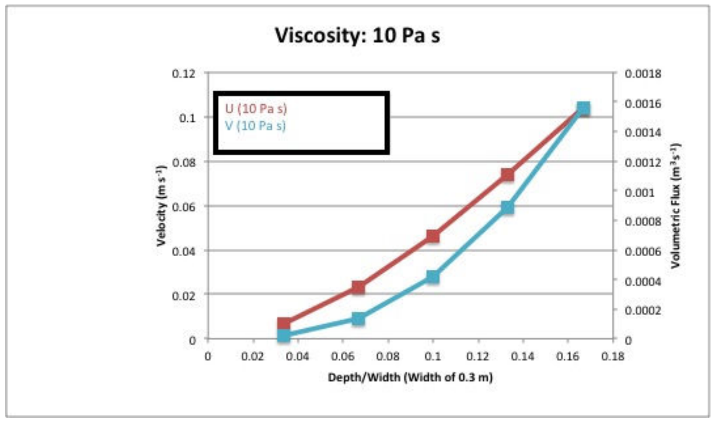


Figure 5. Variation of U and V with D/W ratio at μ = 100 and 1000 Pa s (5a) and μ = 10 Pa s (5b), for Syracuse.

dependent on volumetric flux; longer-lived ponds may, however, typically be associated with lower fluxes, which complicates this relationship. More definite viscosity data are needed for the Amboy flows, as is further research into whether the feature considered is a perched pond at all.

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