LUNAR FLOOR-FRACTURED CRATERS: MAGMA VOLUMES, EMPLACEMENT MECHANISMS, SEQUENCES OF DEFORMATION AND VOLATILE EVOLUTION.

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Introduction: Floor-fractured craters (FFCs) are a distinctive class of lunar features, currently interpreted to be the result of magmatic intrusions into the breccia lenses beneath impact craters [1-8]. Shallow sub-horizontal sill and laccolith intrusions form on Earth when upward-propagating dikes encounter an interface where either there is an increase in rigidity, i.e., shear modulus [9-16] or there is a change from brittle to non-brittle rheology [17, 18]. The latter condition could hold at the base of the breccia lens beneath an impact crater, and the former might characterize the base of a solidified impact melt sheet on an impact crater floor.

New magma ascent models: Previous detailed treatments of the formation of FFCs by the intrusion of sills or laccoliths beneath impact craters [5-8] assumed that dikes approaching the lunar surface propagated from magma reservoirs in the lower crust or upper mantle that were large enough that the source pressure remained nearly constant during the FFC formation event. Recent work [19, 20] implies that most lunar mare volcanism was fed from dikes that formed slowly (decades to centuries) at the tops of diapirically-rising partial melt zones when these diapires reached rheologic boundaries dictated by their sizes and ascent rates. The dikes pinched off from their sources when a critical stress distribution around their boundaries was reached, and migrated upward rapidly (in about one day) as isolated magma-filled cracks to enter the crust - see Figure 1.

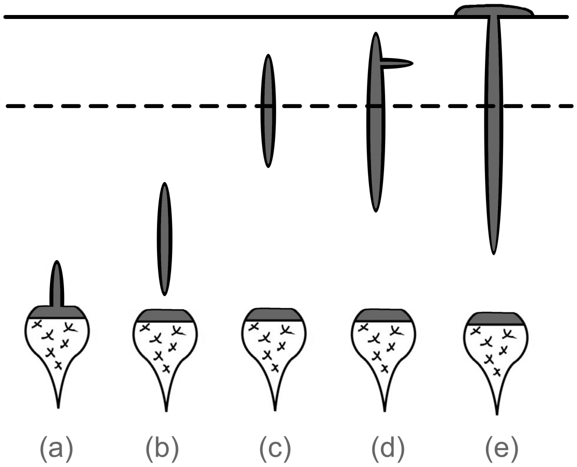

Figure 1: Stages in the formation of dikes growing from partial melt zones, rising through the mantle, and intruding the crust, as both dikes and sills, and feeding eruptions.

Each rising dike approached equilibrium with its upper part in the crust and its lower part in the mantle. If the dike had a great enough vertical extent, its upper tip would have broken through the surface to feed an eruption [(e) in Fig. 1]. A dike not quite reaching the surface but encountering the substrate of an impact crater naturally created a sill or laccolith intrusion resulting in an FFC as it reached equilibrium [(d) in Fig. 1]. Calculations by [19] show that the total magma volumes in dikes capable of approaching to within about 5 km of the nearside surface were ~50 km^3; dikes capable of just reaching the nearside surface would have had volumes of up to ~100 km^3; dikes erupting on the nearside surface would have had volumes of several hundred km^3; and dikes capable of penetrating the thicker farside crust and erupting on the lunar farside must have had volumes of more than 1000 km^3.

Intrusion implications: The lateral injection of magma to form sills and laccoliths beneath FFCs on the Moon has been modeled by [5-8] and is not treated again here. We focus on the equilibrium configuration of the residual dike and the sill/laccolith after intrusion has taken place. A large enough pressure must exist in the dike at the sill entrance to support the weight of the overlying crust. Because the dike magma is denser than the crust and therefore negatively buoyant, this requirement in turn dictates the vertical extent of the part of the dike remaining in the mantle. The situation is complicated by the presence of volatiles in lunar magmas: CO produced by both exsolution and smelting; sulfur species released as a function of pressure at depth; and H_2O release mainly at pressures less than 2 MPa. These volatile release patterns are now well-enough understood [21-30] that we can evaluate the bulk density of the magma, and the effect that this has on its buoyancy. The total volume of magma remaining in the dike can therefore be determined for a dike forming an intrusion of a given thickness at a given depth below the surface of an impact crater as a function of the total magma volatile content. Total volatile contents range from several hundred to ~3400 ppm, and the Table below shows the total residual magma volume that must be present in dikes that fed sills injected 5 km beneath the surface for 4 intrusion thicknesses and 3 total volatile contents. Similar volumes are found for the same range of sill thicknesses and volatile contents for intrusions at other depths ranging up to 10 km, as implied by gravity data [8].

Comparison of the volumes that must be present in residual dikes given in the Table below with the volumes predicted by [19] for dikes leaving the mantle summarized above shows that:

(a) on the lunar nearside, the range of dike volumes consistent with nearside eruptions is also consistent with the volumes needed to form FFCs;

(b) on the lunar farside, the magma volumes needed to ensure FFC formation are so large that the same dikes would also commonly have generated surface eruptions. Since surface eruptions, and FFCs, are rare on the farside [5] we conclude that the volumes of magma in dikes leaving source regions deep in the lunar mantle were generally less than ~1000 km^3, and [19] show this implies that the vertical extents of partial melt zones in the mantle were generally less than ~30 km.

Post-formation evolution: The durations of the dike rise and sill/laccolith injection events are short, of order hours, and so movement of gas bubbles nucleating in the rising magma is negligible. The gas bubble population can therefore be found immediately after the intrusions have occurred and we can follow the subsequent upward migration of gas bubbles and the downward migration of the cooling fronts extending into the intrusion from its upper and lower contacts with the crustal host rocks. Very thin (100s meters) sills solidify in months with negligible gas bubble migration and the consequent volume decrease causes subsidence compensating for ~ 15% of the initial intrusion uplift. Thick (1-2 km) sills and laccoliths cool over decades permitting extensive gas migration and the formation of gas pockets and magmatic foams at the tops of the intrusions. For a 2 km thick intrusion this process can cause up to ~30 m of additional uplift following the original intrusion uplift, followed eventually by ~60 m of subsidence. The consequence surface deformation could create fractures through which magmatic foams could erupt explosively to form local volcanic deposits like those in, e.g., Alphonsus.

Conclusions: Formation of FFCs by sill and laccolith intrusions beneath impact craters is quantitatively consistent with our understanding of the way in which the varying thickness of the lunar crust combines with the volumes of magma generated episodically in mantle partial melt zones to ensure that lunar volcanic eruptions and shallow intrusions are concentrated on the thinner crust of the lunar nearside. The implication is that that the vertical extents of partial melt zones in the mantle were generally less than ~30 km.

References: [1] Brennan, W.J. (1975) *Moon*, *12*, 449–461. [2] Schultz, P.H. (1976) *Moon*, *15*, 241–273. [3] Wichman, R.W. and Schultz, P.H. (1995) *JGR*, *100*, 21,209–21,218. [4] Wichman, R.W. and Schultz, P.H. (1996) *Icarus*, *122*, 193–199. [5] Jozwiak, L.M. et al. (2012) *JGR*, *117*, E11005. [6] Thorey, C. and Michaut, C. (2014) *JGR*, *119*, 286–312. [7] Jozwiak, L. et al. (2015) *Icarus*, *248*, 424–447. [8] Jozwiak, L.M. et al. (2017) *Icarus*, *283*, 224–231. [9] Menand, T. (2008) *EPSL*, *267*, 93–99. [10] Menand, T. (2011) *Tectonophysics*, *500*, 11–19. [11] Gudmundsson, A. (2011) *Tectonophysics*, *500*, 50–64. [12] Maccaferri, F. et al. (2011) *JVGR*, *208*, 39–50. [13] Thomson, K. (2007) *Bull. Volcanol.*, 70, 183–201. [14] Abdelmalak M.M. et al. (2012) *EPSL*, *359-360*, 93-105. [15] Le Corvec, N. et al. (2013) *JGR*, *118*, 968–984. [16] Mathieu, L. et al. (2013) *EPSL*, *271*, 1-13. [17] Schofield, N. et al. (2010) *Geology*, *38*, 63–66. [18] Schofield, N.J. et al. (2012) *J. Geol. Soc. Lond.*, *169*, 127–141. [19] Wilson, L. and Head, J.W. (2017) *Icarus*, *283*, 146-175. [20] Head, J.W. and Wilson, L. (2017) *Icarus*, *283*, 176-223. [21] Sato, M. (1976) *Proc. Lunar Sci. Conf. 7*, 1323–1344. [22] Sato, M. (1979) *Proc. Lunar Sci. Conf. 10*, 311–325. [23] Fogel, R. and Rutherford, M. (1995) *GCA*, *59*, 201–215. [24] Nicholis, M.G. and Rutherford, M.J. (2006) *LPS XXXVII*, Abstract #2061. [25] Nicholis, M. G. and Rutherford, M. J. (2009) *GCA*, *73*, 5905–5917. [26] Rutherford, M.J. and Papale, P. (2009) *Geology*, *37*, 219–222. [27] Hauri, E.H. et al. (2011) *Science*, *333*, 213-215.[28] Wetzel, D.T. et al. (2013) *Proc. Nat. Acad. Sci.*, *110*, 8010-8013. [29] Wetzel, D.T. et al. (2015) *Nature Geosci*, *8*, 755–758. [30] Yoshioka, T. et al. (2015) *Amer. Min.*, *100*, 1641-1644.

Table. Volumes *V* of magma needed to form sills or laccoliths of thickness *S* at 5 km depth below the lunar surface on the nearside and farside. The subscript is the total magma volatile content in ppm by mass.

Nearside

S /km	V_{1000} /km^3	V_{2000} /km^3	V_{3400} /km^3
0.1	256	180	104
0.5	268	188	109
1	283	200	115
2	316	213	129

Farside

S /km	V_{1000} /km^3	V_{2000} /km^3	V_{3400} /km^3
0.1	2964	2292	1541
0.5	3041	2352	1582
1	3139	2429	1634
2	3342	2586	1741