THE SIGNIFICANCE OF THE GEOMETRIES OF LINEAR GRABEN FOR THE WIDTHS OF SHALLOW DIKE INTRUSIONS ON THE MOON. Jennifer A. Petrycki[1], Lionel Wilson[1,2] and James W. Head[2]. [1]Planetary Science Research Group, Environmental Science Department, Lancaster University, Lancaster LA1 4YQ, U.K. [2]Geological Sciences Department, Brown University, Providence RI 02912, U.S.A.

Summary: We show that there are statistically significant differences between the widths and depths of lunar graben that do and do not have volcanic features associated with them. Graben associated with volcanic features are deeper and narrower. The differences in horizontal crustal displacement implied by the differences in depth suggest that within several km of the surface the dikes feeding eruption deposits were typically ~50 m to ~100 m wide. These widths suggest dikes rising mainly from shallow depths in the mantle through a crust progressively invaded by intrusions.

Background: There has been much discussion about the extent to which the lateral variations in both density structure and overall thickness of the lunar crust influence the ability of dikes to penetrate from the mantle to the near-surface (to form intrusions) or to the surface (to form lava flows or pyroclastic mantling deposits). All eruptive vents on the Moon must, of course, be underlain by a feeder dike, and all of the above-mentioned analyses of crustal density structure and stress state imply that the stalling of dikes at various depths within the lunar crust should be common. Various analyses have stressed the importance of the interplay between crustal thickness and depth of partial melting zones in the mantle in cases where magma buoyancy is a major factor [1,2,3] and also of the lateral and vertical variation of crustal density [4,5] in relation to magma density. Doubtless all of these factors are important.

We have previously argued that there are limitations on the minimum volumes of batches of magma that can rise buoyantly through the lunar lithosphere to erupt or intrude at shallow depth [6]. Some of our models of this process were based on an early treatment by Weertman [7] of magma rise under buoyancy forces that, as pointed out by Lister [8,9,10], did not fully account for the pressure distribution in a magma which is both holding open a dike and propagating vertically. However, the observational constraints posed by the estimated volumes of mare lava flows [11] (150 km^3 to 1000 km^3) and lava ponds [12] (35 to 8800 km^3) and of dike intrusions [13] (10^3 km^3) are still valid.

Unfortunately, no existing theoretical models of the dynamics of magma flow in dikes treats the case where the magma motion is driven by both buoyancy and an excess pressure in the magma source zone. Yet clearly it is very unlikely that all lunar magmas erupted or formed shallow intrusions as a result of buoyancy effects alone. We have therefore stressed the utility of models that describe the final geometry of intruded dikes after magma motion has ceased, which are easier to formulate, and have already described how a model originally developed to study giant dike swarms on Mars [14,15] can be applied to the Moon [16]. That study found that the two main controls on dike width were the crustal stress field and the depth of magma accumulation. It implied that, for a wide range of magma densities, crustal density structures, crustal tensional stress fields, and depths of magma accumulation below the crust-mantle boundary prior to its rise, the widths of dikes that reached or approached the surface could be in the range ~35 to ~450 m. We now attempt to obtain some more direct indication of the properties of shallow dike intrusions.

Results and Analysis: To pursue this aim we have analysed the distributions and morphologies of lunar linear graben (rilles) that either do or do not show evidence of volcanic features in close spatial association. We have already described the compilation of the data base [17,18] and now present the results of a statistical analysis of the spatial variations of the properties of the two kinds of rilles. First we divided the rilles by lunar region, identifying 14 regions with relative high concentrations of rilles. We then evaluated the mean value of the length, width and depth of the rilles with and without associated volcanic features in each region, together with the standard deviation of each parameter.

Next a t-test and a non-parametric Mann-Whitney test was performed on the data for each region to assess whether or not there was any significant difference between a given parameter measured on rilles with or without associated volcanics. Only 4 examples of significant differences at the 5% level and 4 examples of significant differences at the 10% level were found among the 42 tests performed. This result was largely the consequence of the relatively small numbers of rilles in a given category in a given area (in many cases less than 10, sometimes only 2 or 3). It was decided, therefore, to ignore possible regional variations (though we shall look at these later) and to combine all of the data. The overall results of performing the statistical tests were then strikingly different and are illustrated in Table 1. There is still no significant difference between the lengths of the two types of rilles, but both their depths and widths are seen to be very significantly different, with the chances of this being untrue lying at the 0.05% and 1.6 x 10^{-5}% levels, respectively.

Assuming that rilles with associated volcanics are underlain by dikes and those without such features are not, the mean difference between the depths of the two classes of rilles can be used as an indicator of the typical widths of the dikes. Graben boundary faults probably dip at angles averaging about θ = 55 degrees, which means that a depth D corresponds to a total lateral extension E given by E = (2 D) / tan θ = 1.4 D. Thus D = 132 m for rilles with associated volcanics (see Table 1) implies E = 184.8 m and D = 97 m for rilles without volcanics implies E = 135.8 m. The difference between these extensions should correspond to the average horizontal space occupied by dikes, 49 m. We note that the recognition of minor volcanic features on the lunar surface is not trivial, and we have tended to be conservative in deciding whether such features are present. Any accidental inclusion of graben without volcanic features in the group with such features will reduce the inferred mean depth, and will result in the above calculation underestimating the dike width. The extreme difference between the depths of the two classes of rilles occurs in the region bounded by latitudes 8.0 degrees South to 11.25 degrees North and longitudes 22.5 to 57.0 degrees West, where there are six rilles with associated volcanics having a mean depth of 227 m and 6 rilles without volcanics having a mean depth of 155 m. The 72 m difference would imply a mean dike width of 101 m, double the global average. Given the large standard deviations associated with all of these measurements, we suggest likely dike widths in the range 50-100 m. This width range is significantly less, by a factor of order 2, than implied by our earlier work [3] as a result of the use of a more detailed model of lunar crustal density structure.

Conclusions: What are the implications of these new dike width estimates for the density and stress structure of the lunar crust and for the geometry and depth of origin of dikes? Scott and Wilson [16] presented predicted dike widths as a function of ranges of values of magma density, crustal density, crustal stress and depth of magma accumulation prior to ascent. When we compare our inferred dike widths with the modelling results, we find that dikes with widths in the range 50-100 m correspond best to magmas with densities not much more than 200 kg m^{-3} greater than that of the crust, rising from depths no more than 20-30 km below the base of the crust, and doing so under conditions where the crust was subject to a tensional deviatoric stress no more than about 20 MPa. These stress conditions are not at variance with what is expected from thermal models [19,20]. Also the magma-crust density differences we find support the contention by Head and Wilson [3] that the ability of dikes carrying dense magmas to penetrate to shallow depths on the Moon was mainly facilitated by the progressive invasion and consequent upward densification of the crust over time.

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Table 1: Data on lengths, widths and depths for lunar graben with and without associated volcanic features.

Graben With Volcanics			Graben Without Volcanics			Is difference significant?
Parameter	Value	s.d.	Parameter	Value	s.d.	
Number of graben	73		Number of graben	175		
Length in km	72.0	76.6	Length in km	75.1	63.1	No
Width in km	1.23	0.64	Width in km	1.83	0.84	Yes, at 1.6 x 10^{-5}% level
Depth in m	132	81	Depth in m	97	73	Yes, at 0.05% level