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Introduction: Rima Hyginus is one of the more complex of the basically linear graben structures on the Moon. Linear graben can be formed by purely tectonic extensional forces [1, 2], but the presence (Fig. 1) of numerous collapse pits, two more caldera-like depressions, and a dark mantling deposit [3] directly associated with the Hyginus rille are strong evidence of a volcanic connection. Since all volcanic eruptions are fed by dikes, the presence of volcanic features associated with numerous linear graben [4-7] is evidence that these graben at least are underlain by dikes [8-10]. The morphology of the Hyginus rille and its depressions and pyroclastic deposits make it possible to infer much about the geometry and emplacement conditions of its associated dike.

Morphological data: Measurements were made on Lunar Orbiter images, especially Orbiter V frame 95M which has a scale of 197 m/mm and a solar elevation of 18.4°. The lateral extent of the main rille is ~100 km. The average width of the least-disturbed linear sections of the rille is ~1990 m and its depth is ~130 m. The 15 collapse craters associated with the rille average ~2360 m in diameter and the typical depth is ~490 m, making the total volume ~10.7 km^3. The larger, near-circular caldera-like depression has a diameter of ~7880 m, a depth of ~656 m and a volume of 32 km^3. The smaller, elongate caldera measures ~5910 by ~2956 m, has a depth of ~492 m and a volume of 6.7 km^3. Albedo variations in the vicinity of the rille suggest the presence of an associated deposit; the lack of a well-defined boundary suggests that this consists of pyroclastic material rather than lavas. The maximum range of the pyroclasts is 29.5 km (measured from the center of Hyginus crater) to the ESE and 22.5 km to the SW, with a typical range of 14 to 15 km.

Dike geometry: If a graben is caused by the near-surface intrusion of a dike, there will be a relationship between the dike geometry and the graben geometry. This may be influenced by the pre-existing state of stress in the lithosphere [11]. However, based on field evidence, [12] found that the ratio of the width of a graben to the depth to the top of the causative dike would be in the range ~3 to 4, implying that the depth to the Hyginus dike top D is of order 1990/~3.5 = ~580 ± ~80 m. The same field evidence implies that the ratio of the dike width W to amount of vertical subsidence S of the graben floor is 1.0 to 1.5, so we estimate W = ~1.25 × 130 m = ~163 ± ~32 m. The lateral extent of the rille is ~100 km, so the underlying dike must extend for at least this far laterally. The vertical extent of the dike is less easy to estimate, but it is reasonable to assume that the magma source is in the upper mantle. A depth of 100 km is adopted, based on the recognition [13] that many erupted lunar lavas are inferred on geochemical grounds to have come from at least this depth. The dike magma volume is then at least (100 km × 100 km × 0.151 km =) ~1.5 × 10^{12} m^3 and assuming a magma density of ~3000 kg m^{-3}, the magma mass is ~4.5 × 10^{15} kg.

Syn-intrusion activity: It is likely that the upper surface of a dike approaching the surface will be curved convex upward, with the center of the dike top approaching the surface first. Even if the bulk of the magma does not reach the surface but remains as the intrusion, it is possible that some connection between volcanic products and the surface may be made through the fractures that form to allow the graben floor to subside. If so, then what will be released is largely gas. This is because all propagating dikes have a low pressure cavity at any propagating tip, in this case mainly the upper tip, as a result of the system maximizing the pressure gradient driving magma flow [14, 15]. Volatiles exsolve into the cavity, and beneath the pure gas region will be a zone occupied by magmatic foam. The interface between the foam and the gas will be characterized by the pressure at which the gas volume fraction is so large, ~0.85, that the foam is unstable [16]. In the lunar case, where the dominant magma volatile is CO formed by a smelting reaction [17, 18], the pressure at the base of the foam will be that at which smelting takes place, ~40 MPa [19]; production of 500 to 2000 ppm of CO leads to a gas cavity pressure of ~ 0.1 to 0.5 MPa.

Gas escaping from the pure-CO gas cavity into the vacuum at the surface will not transport any magma, but may entrain regolith clasts. Depending on the mass loading, the gas and entrained clasts will accelerate to speeds of 1 to 2 km/s and form an enormously widespread and vanishingly thin deposit that would probably not be detectable. However, if any of the underlying magmatic foam is able to reach the surface through the dike boundary faults, the ranges of the pyroclastic magma droplets from the disrupted foam will depend on the size distribution of the droplets. If all of the droplets are smaller than ~1 mm, the mixture of gas and droplets will have speeds of ~100 to 125 m/s and will form pyroclastic deposits out to ranges of ~6 to 10 km. However, if a significant fraction of the pyroclastic droplets are larger than ~1 mm they will decouple quickly from the gas stream forming a more localized deposit. This will allow the expanding gas to reach a greater velocity, allowing greater dispersal of the remaining smaller droplets out to ranges of order 30 to 40 km. These predicted ranges are consistent with the extents of what we interpret to be the pyroclastic deposits.

Post-intrusion evolution: We have inferred above that the width of the dike underlying the Hyginus rille is ~160 m. It is inevitable that convection cells will develop in the magma in the dike immediately after the intrusion process ceases. The convection within the foam layer will rapidly (on a time scale of minutes to tens of minutes given the low viscosity of lunar magmas) concentrate all of the gas in the foam into the overlying cavity. This process will raise the pressure in the trapped gas to ~10 MPa, high enough to cause fractures in the overlying rocks and allow subsidence of these rocks into the gas cavity space as gas escapes. The total volume of gas, allowing for the gas pressure and the likely gas mass (~500 to 2000 ppm of the mass of magma in the dike), is 20 to 30 km^3. Above, we found the volumes of the collapse pits along the Hyginus rille to be 10 to 11 km^3 and the total volumes of the two caldera-like depressions to be ~39 km^3. Given the uncertainties in the measurements and in the theoretical assumptions this amounts to an excellent match.

Conclusions: There is a close (better than a factor of 2) match between (a) the measured volumes of the collapse pits and caldera-like depressions along the Hyginus rille and (b) the predicted volumes of space made available in the sub-surface by gas escape and minor eruptive activity from an intruded dike. Furthermore the extent of what we interpret as pyroclastic deposits around the rille are consistent with what would be expected during minor volcanic activity from the intruded magma. These results strongly support the idea that all of the major structural features of the Hyginus rille are the direct consequence of a shallow dike intrusion.

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Figure 1. Image of Rima Hyginus. Image width~190 km.