THEORETICAL ESTIMATES OF MINIMUM SHOCK METAMORPHIC LEVEL FOR LUNAR CRATER PRIMARY EJECTA AS A FUNCTION OF EJECTA RANGE AND IMPACT ANGLE,
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What shock levels must primary ejecta from lunar impact craters have been subjected to in order to have been ballistically transported a given distance on the lunar surface? The answer to this question would provide a quantitative basis for using diagnostic metamorphic features present in lunar minerals and characteristic of a certain shock level to determine if the lunar material could have been transported ballistically a certain distance on the lunar surface. Elaboration of a method outlined by Dence (1) can provide approximate bounds on this question. Dence's method in brief is: first, relate the ejecta range and assumed impact angle to its ejection velocity from the cratering flow field; then, estimate or bound the relationship (which can be very complex) between ejection velocity and the initial shock induced material particle velocity; and finally, relate particle velocity to peak shock pressure by the appropriate form of the equation of state for the crater target material.

Figure 1 provides the results of preliminary calculations based on the ballistic transport equation of Oberbeck et al. (2), a first-order theoretical estimate of the relation between particle velocity and ejection velocity for an idealized cratering flow field, and an equation of state for a lunar material developed by Ahrens and O'Keefe (3). The chain of data and models used for these calculations requires further refinement to evaluate the effects on the calculated shock levels of the uncertainties in the data and of the simplifications present in the models, but they should be a useful first approximation if the limitations and assumptions of the method are kept in mind.

In order to find the ejection velocity, assume a perfect void and no ejecta interactions during the ballistic trajectories. Then the impacting angle of ejecta is equal to its ejection angle and the ejection velocity may be back calculated from its range and assumed impacting angle by the following equation for ballistic trajectories over a spherical body from Oberbeck et al. (2) :

$$v_e^2 = r_m g_m \left[\sin 2\theta_e / 2\tan(r_e/2r_m) + \sin^2\theta_e \right]^{-1}$$

where v_e is the ejection velocity of the ejecta, r_m is the mean radius of the moon (1738 km), g_m is the lunar gravitational acceleration (1.162×10^{-3} km/sec^2), θ_e is the ejection angle measured from the surface normal, and r_e is the range of the ejecta.

Once the ejection velocity has been calculated for a given range and angle, an estimate must be specified for the relation between the particle velocity imparted by the initial outgoing shock wave that resulted from the crater producing impact and the ejection velocity of the material at the ground surface. For the purposes of this work, the maximum ejection velocity possible for a particle which was given a certain shock imparted particle velocity must be estimated. In the crater forming process, the outgoing shock wave leaves behind an initially radial particle velocity field. As rarefactions from the free surface interact with material in the cratering region the particle velocities are modified in direction and magnitude and become more upwardly directed as they are accelerated toward the free surface by the fan of rarefaction waves. If possible shock reflections and other interactions from material layers below the crater region are ignored, the maximum particle velocity at the free surface should be approximately less than or equal to twice the initial shock imparted particle velocity. Further analysis may be able to lower

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EJECTA SHOCK LEVELS

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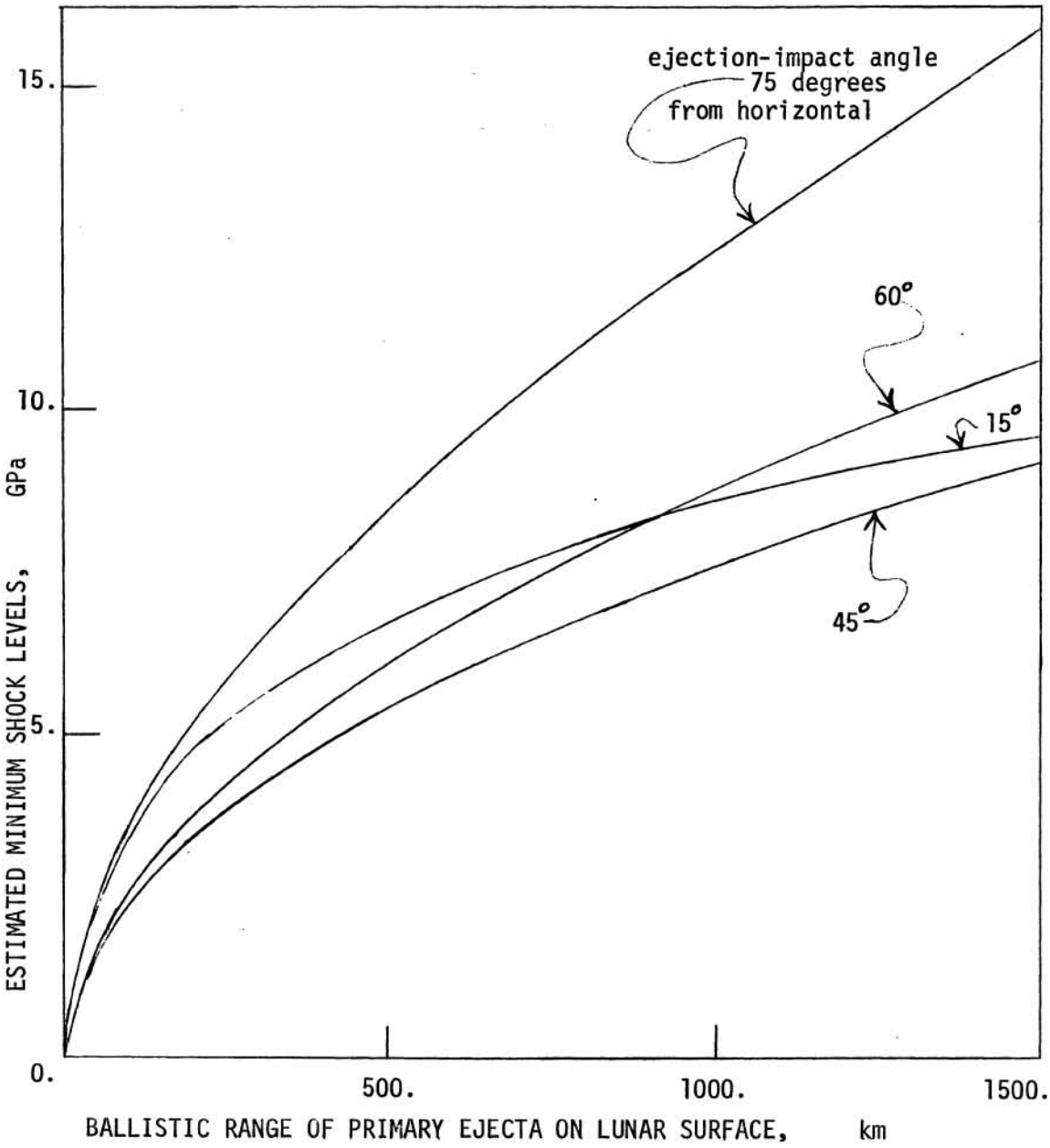

Figure 1. Estimated shock levels that primary ejecta from lunar impact craters must have been subjected to in order to have been ballistically transported to a given range on the lunar surface as a function of ejection angle (degrees from horizontal) .

this bound for some cases, perhaps as a function of the ejection angle. For the ideal case of a planar shock impacting parallel to a free surface, the free surface particle velocity after the shock reflection is exactly twice the material particle velocity due to the shock before interactions with the free surface occur.

The last step is to find the peak pressure given the shock induced parti-

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cle velocity. The equation of state for a material can be expressed in the form of a relation between the peak shock pressure and the material particle velocity imparted by a shock wave with that pressure. The equation of state derived by Ahrens and O'Keefe (3) for a lunar material, the low-pressure phase assemblage of gabbroic anorthosite, is used in the calculations presented here. Thereby, the minimum shock pressure experienced by this material if it is to be ejected at a given ejection velocity can be estimated.

This is a first attempt to estimate the minimum shock level that ejecta must have experienced in order to have been ballistically transported a given distance on the lunar surface. Ejecta interactions are not considered, the cratering flow field is idealized, and only one lunar material equation of state is considered. We are making further refinements of these shock pressure estimates by giving more detailed consideration to the phenomenology discussed here. In particular, even for the idealized case of a homogeneous target half-space with no gravity effects, the relation of ejection velocity to initial particle velocity for material in the cratering flow field needs to be better understood and quantified. Theoretical continuum mechanics computer calculations of the impact cratering process such as those of Thomsen et al. (4) can and should be analyzed to provide this quantitative understanding. Further work of this type might possibly raise the minimum pressures shown in Figure 1. The result should be a more confident prediction of the minimum shock pressure levels ejecta needs to have experienced in order to have been ballistically transported a given distance on the lunar surface, and also, thereby, a better tool for helping to distinguish between local and non-local origins for material examined at different lunar locations.

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