TENTATIVE SPECULATIONS ON LUNAR SAMPLE TRANSPORT, M.G. Austin, Physics International Co., San Leandro, CA 94577 and B. Ray Hawke, Hawaii Institute of Geophysics, Honolulu, HI 96822

A major challenge in lunar geology is the determination of the provenance of many of the samples from the Apollo and Luna landing sites. We speculate on a possible relationship between peak shock pressure and ejection velocity, and hence range, to develop a model to help set constraints on the source of these samples. For material to have originated at a given source and to have been transported in ballistic flight from that source to a particular landing site, it may have been subjected to certain minimum levels of shock pressure. Estimates of the minimum shock pressure can be obtained by making reasonable assumptions concerning ejection angles and calculating the range of ejection velocities necessary to transport material from the impact structure to the site. These ejection velocities can then be converted into minimum shock pressure estimates as described below. Material which does not exhibit shock metamorphic effects characteristic of pressures greater than the minimum predicted levels might not be ejecta from the impact structure.

In an impact event on the lunar surface, the outgoing shock wave due to the impact first accelerates a particle in the cratering flow field to a particle velocity u_p corresponding to the peak shock pressure (Fig. 1). The fan of rarefactions trailing immediately behind the outgoing shock wave then decelerates the particle to its cratering flow field radial velocity u_c (u_f is the sum of the effects due to the rarefactions behind the outgoing shock). More slowly over the remainder of the ejection process, continuous rarefactions from the free surface accelerate the particle toward the free surface by a velocity increment u_r to give the particle its final velocity u_e. Theoretical considerations suggest a bounds $u_e \lesssim 2u_p \pm (1)$. Peak particle velocity is related to shock pressure by the appropriate form of the equation of state for lunar gabbroic anorthosite (2). Ejection velocity and angle correspond to a range on the lunar surface by an appropriate ballistic equation (3). The resulting relationship is that to be transported a given range and at a given angle, a sample may have seen a certain minimum shock level. The bounds above is given credence by analysis of a small-scale impact calculation (4), but in some cases where volatiles are abundant the bounds must be looser (5). However, in the absence of volatiles the bounds may be tighter for most of the flow field. Estimates based on the above reasoning are shown in Figure 2.

The proposed shock model has several major limitations and the following points should be stressed:

(1) No constraints are placed on the maximum shock pressures to which material from a given impact structure were subjected. Hence, samples which exhibit higher grades of shock metamorphism than those predicted from the minimum pressure estimates must still be considered as candidates for primary ejecta from a given source.

(2) The model presented here in no way suggests the existence of uniform concentric ejecta zones which exhibit increasing shock damage at greater distance from the primary impact structure. Both experimental (6) and terrestrial cratering studies (7) have demonstrated that a variety of shock classes can be found at any radial distance from the present structure (8). However, we do maintain that at a given radial distance, primary ejecta must have been subjected to at least certain minimum shock pressures.

(3) The technique is useful only for constraining the origin of material at large distances from the proposed impact structure. Only rather low ejection velocities are required to transport material short distances from the parent crater and result in low minimum pressure estimates ($\ll$10 GPa).

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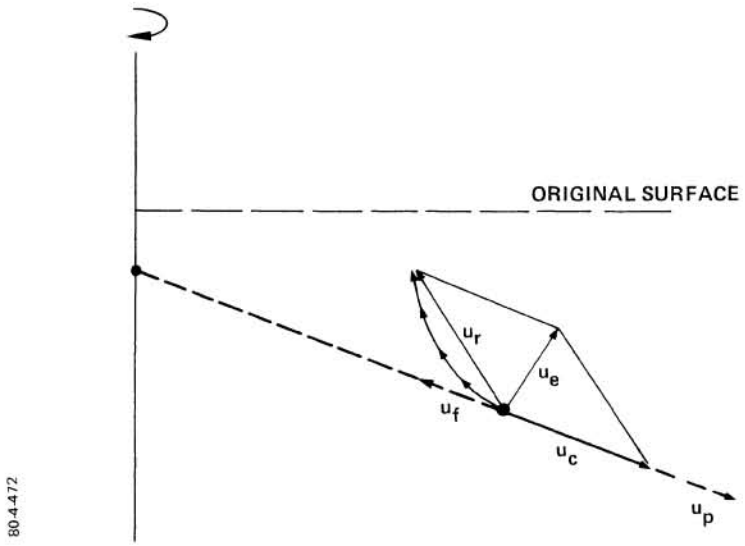

Fig. 1. Schematic diagram of velocities associated with an ejected particle. Proceeding outward from the center of the cratering flow field which is located beneath the original target surface, the outgoing shock wave due to the impact first accelerates the particle to a particle velocity u_p corresponding to the peak shock pressure. Rarefactions add vectorially to give the ejection velocity u_e.

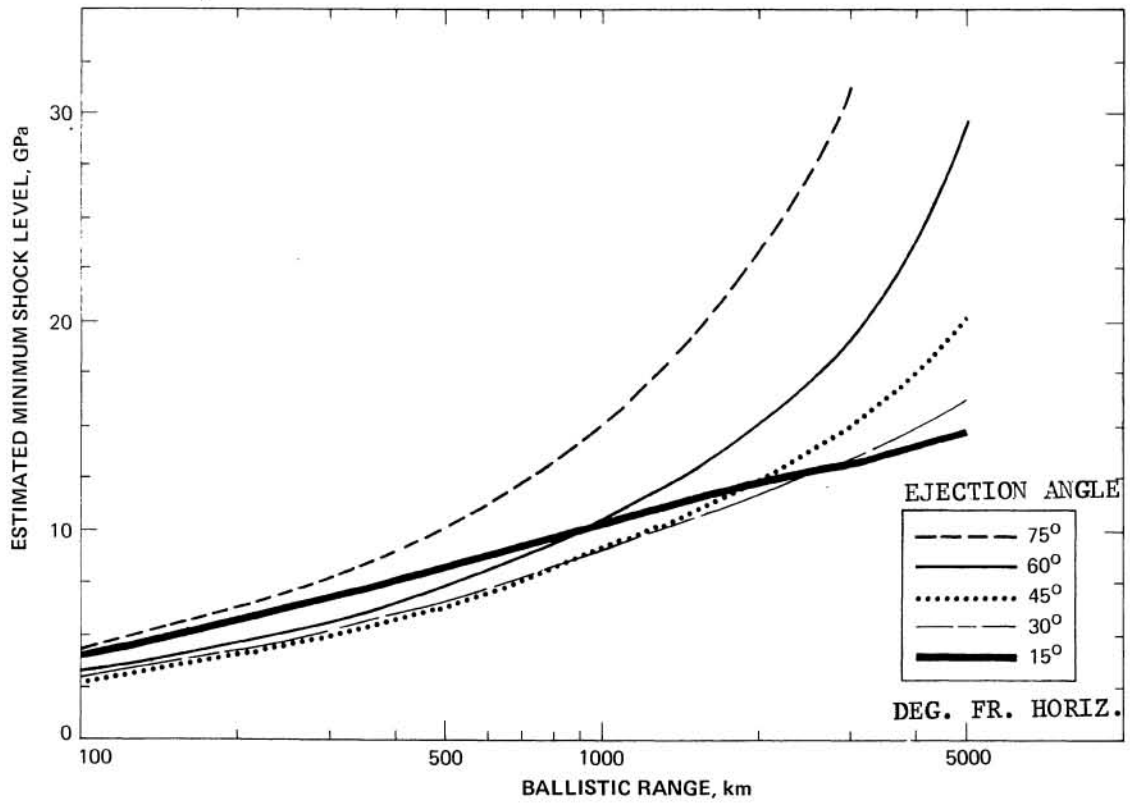

Fig. 2. Estimated minimum shock levels that primary ejecta from lunar impact craters or basins must have been subjected to in order to have been ballisti-

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Fig. 2 caption, continued. cally transported to a given range on the lunar surface as a function of ejection angle (equal to the ejecta reimpact angle) measured in degrees from horizontal.

The scarcity of definitive shock features at these low pressures make determinations of shock metamorphic grade quite difficult.

(4) The assumption that the ejecta travels from the primary crater or basin to a particular landing site in ballistic flight may not be valid in every instance. While many workers agree that the final distribution of ejecta around lunar craters predominantly reflects ballistic emplacement (9), others emphasize the role of surface flows. While the model presented here assumes ballistic transport, the minimum shock pressure estimates remain valid even if the ejecta was emplaced by surface flow subsequent to ballistic flight. It is very energy efficient to transport material by ballistic processes. If material is transported a portion of the distamce from the impact site to the point of final deposition by surface flow, high initial ejection velocities (and hence shock pressures) are required

In order to apply these ideas to basin ejecta at selected Apollo landing sites, minimum shock pressure estimates were made for material transported from Imbrium and Orientale basins to various Apollo landing sites these estimates are presented in Table 1 for a range of ejection angles. For the more likely ejection angles (15°-30°), Imbrium ejecta at the Apollo 14 site must have experienced minimum shock pressures of 9.2-10.4 GPa. Minimum shock estimates for Imbrium material at the Apollo 16 site are only slightly higher (10.4 and 11.4 GPa for ejection angles of 30° and 15°, respectively). It should be noted that these values are considerably less than previous estimates. Still, if it can be demonstrated that a given Apollo 14 or 16 sample has not been subjected to the required shock pressures, it might be considered a poor candidate for Imbrium primary ejecta.

It has been suggested that Orientale basin was an important source of the material in the Apollo 16 region. Estimates of minimum shock pressures for Orientale ejecta at the Apollo 16 site range from 13.4 GPa to 19.9 GPa. Apollo 16 material which does not have shock features compatible with this pressure range is possibly not related to the Orientale impact event.

Ejection angle (degrees from horizontal)	Imbrium to Apollo 14 (1000 km)	Imbrium to Apollo 17 (1105 km)	Imbrium to Apollo 16 (1410 km)	Orientale to Apollo 14: (2165 km)	Orientale to Apollo 16 (3128 km)
15	10.4 GPa	10.7 GPa	11.4 GPa	12.4 GPa	13.4 GPa
30	9.2 GPa	9.6 GPa	10.4 GPa	12.1 GPa	13.6 GPa
45	9.2 GPa	9.7 GPa	10.8 GPa	12.9 GPa	15.3 GPa
60	10.6 GPa	11.2 GPa	12.7 GPa	15.9 GPa	19.9 GPa

Table 1. Minimum shock pressure estimates for material transported from Imbrium and Orientale basins to various Apollo sites (average ejecta ranges were used: one-half transient cavity radius from center of each impact structure to each Apollo site).

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