SEISMICALLY INDUCED MODIFICATION OF LUNAR SURFACE FEATURES;

The formation of large lunar basins produced not only large volumes of secondary ejecta but also enormous seismic waves (Schultz and Gault, 1974). Remnants of such seismic catastrophes include the grooved and hilly terrains antipodal to the largest and most recent basins, subdued and furrowed walls of craters beyond 10⁵ km from the basin center, probably some of the light plains units, and perhaps the concentration of farside maria in the Apollo Ingenii region. Copernicus-size craters also should generate seismic waves that may have a significant effect on both the appearance of its ejecta facies and the degradation of small (<1 km) pre-existing surface features.

Magnitudes of impact-generated ground movement can be extrapolated from the Apollo Passive Seismometer data. Latham et al. (1972) suggest the following scaling relation between impact energy and ground motion amplitude for distances less than 200 km from the impact: \( A = \left( \frac{2}{K} \right)^{2B} \frac{E}{P r^2} \) where \( A = \) peak-to-peak amplitude, \( K = \) constant, \( E = \) kinetic energy of impact, \( r = \) distance from impact. The exponent \( 2B \) allows for differences in the coupling between the impact energy and the generated seismicity. Coupling is poor for small cratering events in which most of the seismic energy is scattered near the source; it becomes more efficient for larger impacts, which penetrate the regolith and, for the mare, reach a competent substratum. Values of \( 2B \) less than 2 represent a coupling efficiency independent of impact energy, and a value of 1.2 was adopted by Latham et al. (1972) for small (<100m) impacts. Figure 1 illustrates the effect of varying \( 2B \) on the predicted ground motion for different size craters scaled to a distance of four times the crater radius from the impact point (beyond the continuous ejecta blanket). These calculations are based on the observed peak-to-peak ground motion amplitude of 75 nm generated by the Apollo 13 SIV-B impact at the Apollo 12 seismic station (Latham et al., 1970). Approximate ground accelerations are calculated on the assumption that displacements will occur with a frequency of 1 Hz, as indicated by the SIV-B impacts. Direct extrapolation for \( 2B = 1.2 \) produces enormous movements from impacts producing craters larger than 1 km in diameter. Figure 1 also includes three simple models that incorporate a change in \( 2B \) dependent on the size of the impact. Models II and III allow for a gradual decrease in the coupling constant as the impact penetrates below the surface scattering zone; Model II also includes an increase in this constant for craters larger than 50 km as the impact extends deeper into the lunar crust. Model I uses a very conservative approximation but still indicates large displacements and accelerations for craters larger than 1 km. Models I, II, and III suggest ground movements of 2 m, 5 m, and 45 m, respectively, for Copernicus (incipient diameter = 70 km) at a distance of 140 km.

Figure 2 shows the arrival times of secondary ejecta and seismic waves from a Copernicus-size event. Arrival times of ejecta include effects of a finite time of crater formation, distance from the crater center at the time of ejection, and the velocity of ejection dependent on the stage of crater formation. Although the initial arrival of the seismic wave train group appreciably precedes any ejecta, the Apollo seismic record shows that the
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Fig. 1 Ground displacements and accelerations due to impact-generated seismic waves at a distance 2.0 D from crater center. Dashed lines are for different values of the seismic coupling exponent, 28; solid lines, for different models incorporating changes in 28 at different crater diameters.

Duration of intense shaking is on the order of 10^1 minutes owing to extensive wave scattering. Consequently, most of the secondary ejecta and their tertiary ejecta should experience severe and continual jostling. Moreover, secondary ejecta may account for as much as 50% of the original impact energy, and their arrival also will generate significant seismism, adding considerably to the apparent duration and intensity of the primary event. For example, Fig. 1 indicates that a 2 km-diameter secondary crater could produce, by itself, local ground movement between 0.3m to 1m.

These results suggest that the deposition process of ejecta could be altered significantly by violent surface oscillations. In particular, the subdued nature of pristine secondary craters can be attributed, at least in part, to sustained ground movement induced by the primary and adjacent secondary impacts that would mobilize newly arrived tertiary ejecta. Additionally,
the continuous ejecta blanket surrounding the primary crater may experience creep-type movement. Pre-existing features also should experience important seismic modifications from the formation of a Copernicus-size impact. Incompetent wall debris within partly degraded 0.5km-diameter craters on the maria should be transferred to the floor, transfiguring a concave profile to a flat-floored profile with well-defined walls. Such lateral mass transfer will be encouraged by the typically large horizontal ground movement, at least a factor of 5 greater than the vertical movement (Latham et al., 1972). Small craters in relatively incompetent material, e.g., some of the highland plains, more likely will degrade to subdued funnel-shaped, dimple-floor, and mounded-floor craters. Larger craters in either terrains are degraded and rejuvenated zonally: the incompetent ejecta blanket being smoothed by seismically induced creep and compaction, the walls being rejuvenated by scree-type movement. Smoothing of ejecta blankets probably is enhanced by the well-known amplification of seismic waves within incompetent material overlying a competent substrate.

Consequently it is proposed that the degradation of lunar surface features is not only by secular meteroid erosion and deposition but also by catastrophic moonquakes generated by large impacts. Such degradation could alter significantly estimates of surface ages determined by crater statistics.