THE USE OF BASIN EJECTA TO DETERMINE LUNAR CRUSTAL STRUCTURE AND COMPOSITION: CURRENT MODELS AND LGO CONTRIBUTIONS.

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Our knowledge of the composition and structure of the lunar crust has important ramifications for understanding the origin, crustal formation, and geologic evolution of the Moon. Although the Apollo samples provided us with a wealth of information on lunar compositions, we still do not understand completely how those samples relate to global rock types and when and where they were distributed in the crust. Fortunately, the Moon has obliged us in one respect towards this end by providing for our inspection over 40 large impact craters, i.e., multi-ring basins [1]. Through the use of basins as natural drill holes into the crust, we are able, in principle, to determine the chemical and petrological composition of the crustal target.

Although this technique is applicable in theory, numerous difficulties and uncertainties attend its application in practice. The purpose of this paper is to review some of these difficulties and to assess the probable uncertainties of using basins as probes of the lunar crust. Also, we will examine current understanding in this field derived from Apollo sample data, orbital chemical data, and Earth-based spectroscopy, and we will estimate the contributions and improvements to our understanding that are likely to be provided by data from the Lunar Geoscience Observer (LGO) mission [2].

Problems in using basins as drill holes. A long-standing controversy in the field of basin research involves the shape and dimensions of the original cavity of excavation [e.g., 1, 3-5]. This problem is critical to the use of basins as crustal probes; some estimates of the original size and shape of the excavated cavity must be made prior to any inference of crustal composition and/or layering. Most excavation models fall into two broad categories: proportional-growth models [e.g., 3, 5, 6], in which basins are simply larger versions of smaller craters, and nonproportional-growth models [e.g., 1, 4, 7], in which the size and shape of the excavated cavity are fundamentally different from those of smaller craters. Quantitative proportional-growth models are now available [6], but no quantitative model of nonproportional-growth excavation has yet been developed. This controversy is not likely to be resolved in the near future; investigators using basins to probe the crust must choose at the outset some type of semi-quantitative excavation model to estimate ejecta volumes and probable depths of ejecta derivation.

An equally important controversy in basin studies is related to the nature of the ejecta blanket itself. During Apollo planning, it was widely believed that deposits extending continuously from the basin rim were primary ejecta from the basin cavity, hence the name "ejecta blanket" and selection of the Fra Mauro (Apollo 14) landing site [1]. Later experimental and theoretical study [8-10] suggested that the impact of basin ejecta on the lunar surface excavated the preexisting local terrain and that this local material is mixed with primary ejecta in basin deposits. These results suggested that near Fra Mauro (the edge of Imbrium continuous deposits), primary Imbrium ejecta constitute only 15%-20% of the total mass of the deposit; near the rim of the apparent crater (Apennines at Imbrium), the Oberbeck et al. model predicts that roughly half of the material is primary ejecta [9]. Recently Schultz and Gault [11] have investigated the effects of deposition of clouds of comminuted debris during ejecta emplacement, instead of the single-body impactors assumed by Oberbeck et al. [8, 10]; they found that primary ejecta constitute greater than 90% of the deposit near basin rims and up to 80% at Fra Mauro ranges [11]. Thus, near-rim basin deposits consist of at least 50% to greater than 90% primary ejecta.

A final problem in using basins to probe the crust is the nature of the ejecta stratigraphy (if they are indeed stratified). Studies of ejecta from simple craters indicate that materials from the deepest horizons of a crater target tend to concentrate nearest the crater rim (the "overturned flap") [12]. On the basis of this analogy, near-rim basin ejecta would be dominated by ejecta from the deepest parts of the crustal target, possibly leading to an incorrect assessment of the target's composition. However, detailed study of the deposits of the Ries crater [13] suggests that for large-scale impact events, ejecta tend to be well-mixed averages of all stratigraphic horizons in the crustal target and that they include (unfortunately) the local material incorporated into basin continuous deposits, as noted.

Current use of basins as crustal probes. In the past several years, we have attempted to use basin ejecta to understand lunar crustal structure and composition [3, 14-17]. We have been well aware of the problems discussed above that are associated with this usage but we have felt that the potential insights into crustal structure given us by basins greatly outweigh the model uncertainties. For basin excavation, we have relied on the proportional-growth model for two main reasons: (1) evidence from terrestrial impact craters [5, 13] and lunar photogeology [15, 18] suggest that this model is valid for basins, and (2) this model permits some quantitative modeling of ejecta volumes and derivation depths [6, 15, 17]. To put it another way, nothing in the lunar data suggests that proportional growth for basins is not valid. For determining the local vs. primary ejecta content of basin deposits, we have used only the clearly mappable deposits that are one-half to one apparent basin radius from the basin rim, and we have assumed that these deposits are mostly primary basin ejecta. The observation that near-rim basin deposits tend to be compositionally different from the average interbasin deposits on the Moon [16, 17] suggests that this assumption is reasonable to a first order. Of course, this means that we have inevitably included some local material [cf. 9, 11] in our estimate of basin ejecta composition, and in this sense our results are model dependent. We have assumed that basin ejecta are well mixed, in accordance with the Ries data [13], and also that a given sector of basin deposits is representative of the basin deposits as a whole. (No lunar basin has complete orbital chemical coverage of all of its deposits.)

Spudis, P.D. and Hawke, B.R.

Based on these assumptions, studies of lunar basin deposits indicate the following: (1) the lunar crust is both laterally and vertically heterogeneous [14, 16, 17]; (2) roughly the upper half of the crust consists of "anorthositic gabbro" (Al_2O_3 26%-28%), while the lower half is grossly "noritic" (Al_2O_3 20%) [17]; (3) rocks of the Mg-suite [19] make up a minor fraction of upper crustal rock types [16, 17]; (4) the polymict lunar rock types "LKFM basalt" and "VHA basalt" may represent impact melts formed during basin impacts [17, 20]; and (5) the average alumina content of the bulk crust (Al_2O_3 25%) suggests that most of the crust formed during a global "magma ocean" stage [e.g., 19], rather than by "serial magmatism" [e.g., 21]. Such tentative results address basic problems, but, based on so many uncertainties, but how valid are they? More importantly, how much better will we be able to do with LGO data?

LGO data and lunar crustal problems. Because the Apollo 15 and 16 missions flew in near-equatorial orbits, only about 19% of the lunar surface and only 11 lunar basins are covered by at least some chemical data [14, 17]. Spectroscopic measurements are limited to the lunar nearside. Data from the LGO mission will greatly augment this meager information. First, of the 40 basins randomly distributed over the Moon, at least half display recognizable (preserved) deposits [1]. Thus, we will at least double our statistical sample of basins. Second, global coverage will allow petrologic and chemical measurement of all the deposits of a given basin; moreover, the chemical data will be nearly complete for major and trace elements, as opposed to the minimal data we currently have for some basins (e.g., for Orientale, we know only the Th, Fe, and Ti contents of the northern one-quarter of basin deposits). Third, nonchemical data from LGO (gravimetric, topographic, imaging) will permit better assessment of lunar crustal-thickness variations and models of basin formation [2].

Some of the basic problems of basin formation can also be addressed with LGO data. By examining certain large craters in detail at high resolution, we may find evidence to resolve both the proportional-growth controversy and the local mixing ratio problem. That such an approach is potentially useful is well demonstrated by a recent study of the crater Copernicus that used Earth-based spectroscopy; results indicate both adherence to and divergence from the Oberbeck et al. local mixing model [22]. High-resolution gravimetric and topographic data from LGO will permit refined estimates of the excavated volume of large craters and basins, an important referent in the proportional-growth controversy. Images from LGO will permit examination of basins currently poorly covered by Lunar Orbiter pictures, and such images could lead to recognition of additional prebasin topography [15, 18].

The larger quantity and better quality of LGO data as compared with the current dataset will probably allow a definitive resolution of one of the most important lunar problems, i.e., the origin of the crust. Current estimates of the total plagioclase inventory in the crust (equivalent thickness of plagioclase 20 km; [17, 23]) is at the high end of the permissible range of values for some "serial magmatism" models (10-20 km; [24]). The greater quantity and precision of data available from LGO should permit the resolution of this question [2]. The mechanism of lunar crustal formation has important ramifications for general models of terrestrial planet evolution [19].

We believe that the LGO mission will provide not only good science for its own sake, but also results of great significance for planetary exploration in general. The sooner this mission flies, the better.

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