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The multi-ring basin problem

Ever since their recognition, multi-ring basins have fascinated and vexed scientists attempting to reconstruct the geological history of the Moon. As the other terrestrial planets were photographed at high resolution, it became apparent that basins are an important element in the early development of all planetary crusts. This importance spurred research into the basin-forming process and yielded a plethora of models and concepts regarding basin origin and evolution. In this chapter, I outline the general problem areas of basin formation and describe the approach taken by my own work on lunar basins.

1.1 Multi-ring basins and their significance

Multi-ring basins are large impact craters. The exact size at which impact features cease to be "craters" and become "basins" is not clear; traditionally, craters on the Moon larger than about 300 km have been called basins (Hartmann and Wood, 1971; Wilhelms, 1987). Basins are defined here as naturally occurring, large, complex impact craters that initially possessed multiple-ring morphology. This definition purposely excludes simulated, multi-ring structures that result from explosion-crater experiments on the Earth and whose mechanics of formation differ from impact events (e.g., Roddy, 1977), although important insights into the mechanics of ring formation may be gained from these studies. The qualification that basins *initially* possessed multiple rings is in recognition of the fact that many older, degraded basins display only one or two rings, even though their diameters of hundreds of kilometers indicate that they had multiple rings when they originally formed.

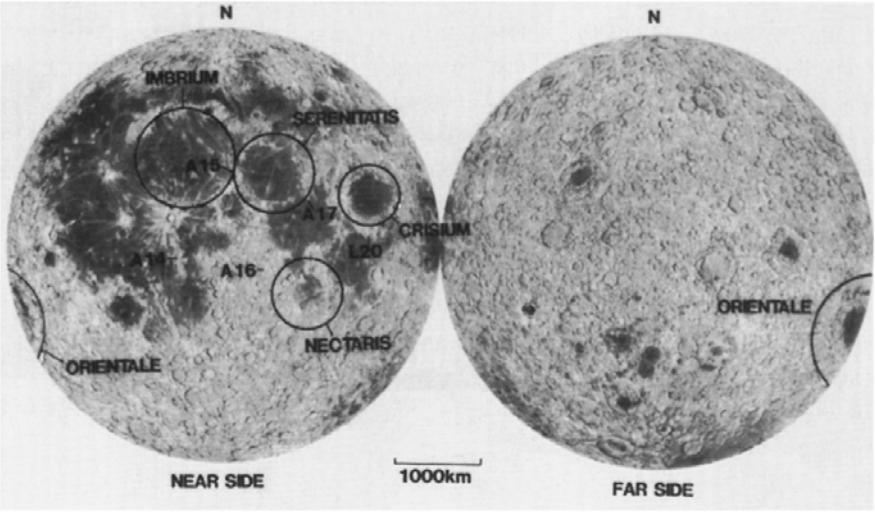
The distinction should also be made in the case of lunar basins between the terms *basin* and *mare*. Basin refers to the circular structure produced by the collision of a large planetesimal (asteroid) with the Moon; such features may be subsequently flooded by volcanic materials, but many are only partly filled or are not filled at all. The term mare is used to refer to any dark, plains-forming material and may or may not be contained exclusively in a basin. Thus, Mare Imbrium refers to only the low-albedo plains that mostly fill the Imbrium basin.

Basins are ubiquitous on the terrestrial planets and typically occur within the most ancient, heavily cratered terrain on the Moon, Mars, Earth, Mercury, and some of the icy satellites of Jupiter and Saturn. Multi-ring basins formed in the earliest stages of terrestrial planet evolution and exerted important influence on the subsequent geological history of these bodies. Moreover, the extensive structural effects on planetary lithospheres produced by a basin impact may alter the spatial distribution of ongoing geological processes, in particular, the timing and distribution of volcanism. Basin sites frequently act as loci for the eruption of volcanic materials and this relation was responsible for the confusion between the terms basin and mare in some early studies. The crustal unloading resulting from a basin impact may have far-reaching consequences, as long-term rebound and crustal adjustment can alter the location of subsequent planetary volcanism and tectonism.

A basin-forming impact extensively redistributes vast amounts of crustal materials, thereby changing the regional chemistry and petrology of planetary crusts. Samples returned by spacecraft missions are typically collected from surficial deposits. On the Moon, and possibly samples returned from Mars in the future, some of these samples may be related to basin deposits. Thus, it behooves us to understand better the many effects of basin formation on the planetary surface compositions and the emplacement of ejecta.

Among terrestrial planets, the Moon is a particularly suitable object for the study of multi-ring basin problems. As a relatively primitive body in the geological sense, many of the Moon's earliest features are well preserved. In addition, the Moon has been extensively photographed, both from the Earth and from spacecraft, at a variety of viewing geometries and lighting conditions. These photographs permit clear

Figure 1.1 Index map of the Moon (Lambert equal-area projection), showing the location of five multi-ring basins whose geology is analyzed in detail in Chapters 3–7 of this book.



delineation of morphologic features associated with basin deposits and structures. Remote-sensing techniques furnish geochemical, mineralogical, and geophysical data for lunar basins which allow us to infer the regional chemistry and petrology of basin ejecta deposits, local variations in crustal thickness, and basin topographic and gravimetric properties. Finally, the American Apollo and Soviet Luna missions obtained samples of basin deposits and much detailed work on these samples has revealed the chemical and petrologic properties of the lunar crust and has provided tantalizing clues to the impact process.

A detailed study of multi-ring basins synthesizing all of this information has never been attempted. I have studied five basins on the Moon (Figure 1.1), collating multiple and diverse sets of data. My objective is to integrate these data into a coherent geological model for basin formation and evolution that not only sheds light on processes involved in lunar basin evolution, but also produces constraints on the general problem of multi-ring basin formation on all of the terrestrial planets.

1.2 Overview of the lunar multi-ring basin controversy

Although intensively studied, the problems surrounding the formation and evolution of multi-ring basins have been responsible for much debate, but little consensus. The controversy over basins largely revolves around questions of the size and shape of the crater of excavation and the origin of multiple rings. By way of acquainting the reader with the debate over these issues, I here review both the history of basin studies and some of the key questions associated with their genesis.

1.2.1 Recognition of multi-ring basins

When Galileo first studied the Moon through the telescope in 1609, he saw that large, overlapping craters make up the lunar highlands; he also sketched the arcuate mountain ranges on the Moon. Galileo and subsequent workers recognized that the mountains bordering the circular maria are similar to crater rims, a key link towards understanding that basins are merely large craters and have the same origin. Later workers mapped the Moon's surface in increasing detail, usually with the aim of advocating some mechanism of crater formation, typically, as a result of volcanism. Few scientists proposed that impact was an important process in crater genesis, but Gruithuisen (1829) and especially Proctor (1873) championed the impact origin of craters on the Moon.

The first study to advocate an impact origin for lunar basins was the classic paper of Grove Karl Gilbert (1893), who was at the time Chief Geologist of the U.S. Geological Survey. Although Gilbert was primarily concerned with the origin of lunar craters, he was the first to recognize the extensive pattern of "sculpture" surrounding the Imbrium region of the Moon and hypothesized that this was produced by a flow of "pasty" debris that proceeded outward in radial directions from the Imbrium "collision" area, a surprisingly modern view (see review by Oberbeck,

1975). To buttress his conclusions that lunar craters formed by impact, Gilbert studied Meteor crater, Arizona (Gilbert, 1896), ironically concluding that this feature resulted from a volcanic steam explosion! (For a detailed and fascinating history of the study of Meteor crater and the development of impact theory, see Hoyt, 1987).

Historiographical myth has it that Gilbert's ideas on the Moon were ignored because he chose to publish his work in the *Bulletin* of the Philosophical Society of Washington, a journal rarely consulted by today's lunar scientists. In fact, Gilbert was one of the most eminent men of science in the nineteenth century and his opinions regarding the origin of lunar craters were bound to attract notice (see Hoyt, 1987, pp. 65–67). The reluctance of Gilbert's scientific peers to embrace impact as an important process largely resulted from the lack of a clear example of an impact crater on the Earth; surely a process of such importance should be detectable somewhere! Thus, the few that did think about the Moon preferred to interpret its surface largely in terms of processes (such as volcanism) that made holes and that were well displayed and (allegedly) well understood on the Earth. In this intellectual milieu, Gilbert's work on the Moon was forgotten. A contributory factor to this relative obscurity was his own reluctant pronouncement on the volcanic origin of Meteor crater. Gilbert's vision of the geology of the Moon had to await the space age to be read and appreciated.

Astronomers of the early twentieth century tended to favor volcanic origins for the surface features of the Moon (see Hoyt, 1987). Few geologists thought much about either the Moon or the process of impact, but two landmark papers are noteworthy. Boon and Albritton (1936) suggested that meteorite impact was responsible for the origin of a variety of terrestrial features known as "cryptovolcanic structures". The recognition of a class of impact craters with diameters of tens of kilometers on the Earth permitted detailed investigation of the chemical and physical processes at work in very energetic impacts. Also, an important contribution by Dietz (1946) outlined a new geological sketch of the Moon similar to that of Gilbert (1893), involving impact origins for craters as well as the "maria" (i.e., basins); like Gilbert, Dietz believed that the dark mare plains filling the Imbrium depression were generated during the basin-forming impact and he considered volcanism on the Moon to be possible, but of minor significance.

Two important twentieth century works by Baldwin (1949, 1963) extended the discussion of impact basins to include all of the circular maria on the near side of the Moon. Baldwin (1949) presented a model for the geology of the Moon that was nearly completely accurate, concluding that most craters formed very early in the lunar history by impact of asteroidal objects and that the dark maria are flows of basaltic lava, unrelated genetically to the basins that contain them. In this and his subsequent work, Baldwin (1949, 1963) used the term "circular maria" to refer to basins because the basins on the near side of the Moon are nearly always completely filled by mare basalt. This terminology produced confusion in the minds of many workers (e.g., Urey, 1952), who conflated the topographic features produced by impact (basin) and the unrelated, subsequent fill by volcanic lava flows (maria).

In the course of mapping the geology of the Moon, Shoemaker and Hackman (1962) clearly marshaled the evidence that the basins formed substantially before the surface flows of basaltic maria; they also developed a simple and practical stratigraphic system for the Moon based on the use of ejecta deposits of basins as marker beds. This system permitted the relative ages for basins and other surface features to be delineated. As systematic mapping of the geology of the Moon continued, many new basins were discovered and new appreciation emerged for the control by basins of the basic structural framework of the lunar surface (e.g., Stuart-Alexander and Howard, 1970).

In the same years that Shoemaker and Hackman were developing the rationale for the geological mapping of the Moon, a project at the Lunar and Planetary Laboratory at the University of Arizona was to lead to a new dimension in basin studies. By projecting transparencies of Earth-based telescopic photographs of the Moon onto a blank sphere, William K. Hartmann produced a series of geometrically rectified views of the lunar basins. This led to the recognition that the basins were surrounded by a series of multiple, concentric *rings*. During systematic study of the near side of the Moon, Hartmann identified multiple rings associated with all of the mare basins (Hartmann and Kuiper, 1962; for a personal and excellent reminiscence on these discoveries, see Hartmann, 1981).

The systematic pre-Apollo geological mapping program of the U.S. Geological Survey, summarized in Wilhelms (1970) and in Stuart-Alexander and Howard (1970), surveyed the entire Moon, demonstrated the prevalence of basins in its early evolution, and documented the profound influence of basins on regional geological patterns. Continued study of basins led to debate concerning the particulars of their formation. The debate focused mainly on two different, but closely related questions: (1) What were the dimensions of the original crater of excavation for these large impact features? and (2) How do multiple rings form? The next sections summarize these controversies.

1.2.2 The problem of the original crater of excavation

It was recognized early that although basins are very large impact craters, the profound differences in morphology between basins and smaller craters must be a reflection of fundamentally different processes at work during and after the impact event. A major problem of basin geology is the identification of the original crater of the basin or *transient cavity* (Table 1.1). This identification is required for understanding the mechanics of basin formation, crustal volume displacement, lunar sample provenance, and the origin of *mascons* (anomalous concentrations of mass in the lunar surface).

One of the earliest hypotheses for the size of the original craters of basins resulted from studies of the mechanics of formation of smaller impact craters, both natural and experimental. These studies suggested that the initial crater for lunar basins was a feature much smaller than the currently expressed *topographic rim*

Table 1.1 *Concepts and models for the excavation of multi-ring basins*

Models	
Group A	Group B
Basins are scaled-up versions of smaller impact craters (proportional growth)	Basins form by fundamentally different cratering mechanisms (non-proportional growth)
Proponents	
Gault, 1974 Croft, 1980, 1981a, 1985 Grieve *et al.*, 1981 Schultz *et al.*, 1981 Spudis, 1986 Spudis *et al.*, 1984, 1988b, 1989	Baldwin 1974, 1981 Hodges and Wilhelms, 1978 Murray, 1980 Wilhelms, 1984, 1987 Schultz and Gault, 1986
Arguments	
For	
(1) Predicts excavated depths and volumes that agree with sample and geophysical data (2) Does not invoke hypothetical and untestable mechanisms	(1) Predicts shallow excavation cavities, in agreement with sample data (2) Explains basin inner rings by either strength differences or oscillatory uplift and collapse
Against	
(1) Experimental evidence indicates that flow fields might change with increasing crater size (2) Does not explain basin rings; these must form during modification stage	(1) Some mechanism changes cratering process above a certain size limit (*deus ex machina*) (2) Does not explain basin *outer* rings

Source: Adapted from Pike and Spudis (1987)

(Figure 1.2; Gault, 1974; Dence, 1976, 1977a; Schultz, 1976a). A tradition established early in basin studies was the association of one of the observed rings with the *excavation cavity*, the feature from which material is ejected during the formation of the basin. Most of the studies mentioned above equated one of the innermost rings with the boundary of excavation during basin formation. In contrast, Schultz (1979) suggests that for some lunar basins, particularly the older ones, post-impact structural modification has completely obliterated any morphologic evidence for the original crater rim, but the boundary of the transient cavity still lies well within the current basin rim.

The depth to which these small cavities excavated is controversial; the use of terrestrial analogs (Dence *et al.*, 1974; Dence, 1976) initially suggested deep excavation, with depth–diameter ratios approaching those of simple craters (approximately 1:3). Croft (1980, 1981a) suggested that the use of a simple cratering flow model

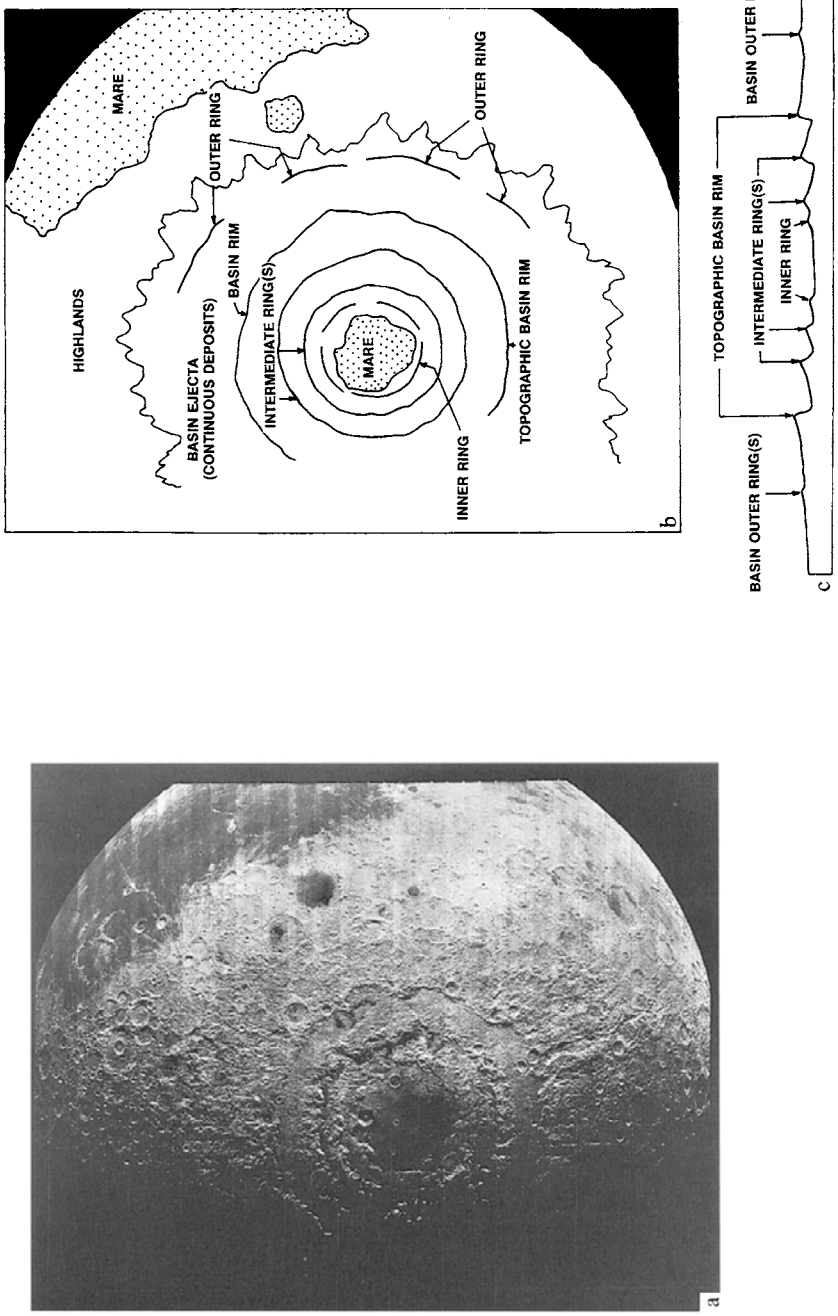


Figure 1.2 Photograph (a), sketch map (b), and hypothetical cross section (c) of a typical multi-ring basin on the Moon (Orientale), showing specific features discussed in this book. For more details on the Orientale basin, see Chapter 3.

may better approximate the effective excavation depth for small cavity basin formation. The "Z-model" of Maxwell (1977) attempts to explain cratering phenomena by analysis of hydrodynamic flow of particles during the crater excavation phase. In this model, particles follow flow streamlines radiating from a point source within the transient cavity. In Z-model results, effective excavation by the crater is from depths shallower than that of the transient cavity (Maxwell, 1977; Croft, 1981a). For basin-sized impacts, the Z-model suggests a depth–diameter ratio of the excavation cavity of about 1:10, a significant reduction of Dence's 1:3 estimate.

Many workers have relied on morphologic and stratigraphic relations seen in lunar photographs to estimate the location of the original crater. Most of these studies suggest that a ring within the main rim of the basin, usually at some intermediate position (Figure 1.2), best approximates the location of the transient cavity of the basin (Head, 1974a; Moore *et al.*, 1974; McCauley, 1977; Scott *et al.*, 1977). In this view, the innermost rings of basins represent central uplifts, analogous to central peaks seen in smaller craters, and the outer rings form in response to structural adjustment of the crust to an initially smaller crater. The estimates of the depths of these transient cavity structures vary widely, ranging from very deep, implied by the simple crater geometry assumed by Moore *et al.* (1974), to relatively shallow, resulting from the increasing dominance of substrate strength, which allegedly would reduce excavation depth by substantial amounts (Head *et al.*, 1975).

Other workers, studying the same photographs, interpret the main topographic rim of the basin (Figure 1.2) as the boundary of excavation (Baldwin, 1974, 1981; Wilhelms *et al.*, 1977; Hodges and Wilhelms, 1978; Murray, 1980). In this view, basins are simply the scaled-up equivalents of the rims of smaller lunar craters, which these authors believe represent the original cavity of excavation, enlarged little by slumping. Opinions differ, however, as to the nature of the cratering process. Baldwin and Murray believe that basins are true analogs to smaller craters, whereas Wilhelms and co-workers advocated a "nested crater" model which contends that basin interior rings are the result of strength-dependent layering in the lunar crust. In this view, basin rings are analogous to sub-kilometer-sized concentric craters formed in the maria, where unconsolidated debris overlies coherent basaltic bedrock (Quaide and Oberbeck, 1968). In both of these models, the depths to which basin impacts may excavate is an order of magnitude greater than estimates from models that identify the transient cavity rim with one of the inner basin rings. Finally and most recently, Pike and Spudis (1987) specifically repudiate the concept that *any* of the currently expressed rings *must* represent the original crater of the basin, noting that such an equivalence merely is assumed and is not required to model or understand the formation of basins.

1.2.3 The origin of basin rings

Understanding the origin of basin rings is dependent in part upon the identification of the original crater rim. In general, those workers favoring a small excavation

crater favor structural origins for ring systems; those favoring large initial craters believe that physical properties of the lunar crust, either during or after the impact, are responsible for rings (Table 1.2). These two modes of origin are not entirely mutually exclusive and some models incorporate features of both.

The concept of a *megaterrace*, a large concentric slump feature around a small excavated crater, was one of the first ideas to be advanced for the origin of basin rings (Hartmann and Kuiper, 1962; Mackin, 1969; Gault, 1974; Dence, 1976, 1977a; Head, 1974a, 1977a; McCauley, 1977; Melosh and McKinnon, 1978). All of the above workers agree on this origin for the main topographic rim of basins (Figure 1.2); both Gault and Dence visualize all of the basin outer rings as being produced by this mechanism around a small, simple transient cavity. Those authors equating an intermediate ring (Figure 1.2) with the basin cavity suggest a dual mechanism whereby the main rim is a megaterrace, but the inner rings are rebound features, analogous to central peaks seen in smaller craters (Head, 1974a; McCauley, 1977; Scott *et al.*, 1977). The megaterrace hypothesis is based in part on analogous slumping evident in smaller lunar craters (see Chapter 2). This slumping in basin-forming events cannot be scaled up from complex craters directly; it requires that the lunar crust respond as if it consisted of coherent blocks during the modification stage of basin formation.

A completely different approach to ring genesis is taken by Baldwin (1974, 1981) and Murray (1980). They argue that an impact large enough to produce a basin would "fluidize" the lunar crust in the target region and that wave-like phenomena would produce rings like the ripples in a pond after a stone had been dropped into it. The use of the term "fluidization" is used here in the rheological sense that lunar crustal materials behave in a fluid manner (Melosh, 1979); this use does not imply any volatile content within crustal materials on the Moon. Van Dorn (1968) and Baldwin (1974) suggest that lunar "tsunamis" produced by the impact of a basin-forming projectile would freeze in place after impact excavation, producing basin rings. Murray (1980) envisions an oscillatory mechanism whereby "fluidized" lunar crust would produce ring systems by continuous overthrust of ripples until the crust had solidified into a multi-ring plan.

Yet another mechanism for ring production requires target strength to be the dominant factor in ring formation. An example of such a mechanism is the nested crater model advocated by Wilhelms *et al.* (1977) and Hodges and Wilhelms (1978). In this model, basin interior rings reflect the presence of global layering in the lunar crust, each layer having different strengths. Basin rings represent the boundary of excavation of a series of nested craters into deeper crustal levels; the basin topographic rim marks the boundary of excavation. Melosh and McKinnon (1978), McKinnon (1981), and Melosh (1989), while favoring a dominantly structural origin for basin rings, suggest that rings can form only under conditions in which the planetary lithosphere (rigid outer layer) is of such a thickness as to permit structural failure. Thus, this model also falls into the "target strength" category of ring-forming mechanisms (Table 1.2).

Table 1.2 *Concepts and models for basin ring origin*

Models		
Group A	Group B	Group C
Impact-driven wave mechanism; dominantly surficial	Deep-seated structures, modification phase; "megaterraces"	Target strength or thickness differences; syn- or post-impact
Proponents		
Baldwin, 1974, 1981 Murray, 1980 Pike, 1983 Van Dorn, 1968 Chadderton *et al.*, 1969	Hartmann and Wood, 1971 Head, 1974a, 1977a Howard *et al.*, 1974 Mackin, 1969 McCauley, 1968	Melosh and McKinnon, 1978 Hodges and Wilhelms, 1978 McKinnon, 1981 Melosh, 1989
Grieve *et al.*, 1981 Croft, 1981b Pike and Spudis, 1987		
Arguments		
For		
(1) Evidence for oscillatory uplift at terrestrial impact craters (2) Potentially explains $\sqrt{2}\,D$ ring spacing	(1) Geologic evidence for structure associated with rings (2) Gravity-driven collapse observed at complex craters	(1) Evidence for strength-related excavation at Ries crater (2) Lithospheric thickness an overlooked variable
Against		
(1) Physical plausibility uncertain (2) Evidence for deep structures associated with basin rings	(1) Does not explain $\sqrt{2}\,D$ spacing or outer rings (2) Cannot be responsible for inner rings unless excavation cavity	(1) Does not explain $\sqrt{2}$ spacing or outer rings (2) Strength differences probably negligible at basin scales

Source: Adapted from Pike and Spudis (1987)

There is no general agreement on a model for the origin of lunar basin rings and one's preference of mechanism primarily depends upon which model one accepts for the location of the rim of the basin transient cavity.

1.2.4 Basin ejecta and deposit emplacement

As large impact craters, basins distribute enormous volumes of *ejecta* widely over the lunar surface. Study of this material has produced intense controversy over its provenance and mechanism of emplacement. Whether or not basin ejecta were