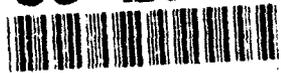


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| Public reporting burden: gathering and maintaining collection of information Davis Highway, Suite 1204 | |  | | Use, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, reviewing comments received, and revising the reports. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Blvd., Washington, DC 20540. | |
| 1. AGENCY USE ONLY | | DATE Aug 93 | | 3. REPORT TYPE AND DATES COVERED THESIS/DISSERTATION | |
| 4. TITLE AND SUBTITLE Search for Lunar Water Ice in Cometary Impact Craters | | | | 5. FUNDING NUMBERS  | |
| 6. AUTHOR(S) Steve S. Brandt | | | | | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AFIT Student Attending: Univ of Texas at Austin | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/CI/CIA- 93-138 | |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) DEPARTMENT OF THE AIR FORCE AFIT/CI 2950 P STREET WRIGHT-PATTERSON AFB OH 45433-7765 | | | | 10. SPONSORING / MONITORING AGENCY REPORT NUMBER | |
| 11. SUPPLEMENTARY NOTES | | | | | |
| 12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release IAW 190-1 Distribution Unlimited MICHAEL M. BRICKER, SMSgt, USAF Chief Administration | | | | 12b. DISTRIBUTION CODE | |
| 13. ABSTRACT (Maximum 200 words) <div style="text-align: center;">  <p>DTIC ELECTRIC OCT 06 1993</p> <p>S A D</p> </div> <div style="text-align: right;"> <p>93-23199</p>  <p>0488</p> </div> | | | | | |
| 14. SUBJECT TERMS | | | | 15. NUMBER OF PAGES 58 | |
| | | | | 16. PRICE CODE | |
| 17. SECURITY CLASSIFICATION OF REPORT | | 18. SECURITY CLASSIFICATION OF THIS PAGE | | 19. SECURITY CLASSIFICATION OF ABSTRACT | |
| | | | | 20. LIMITATION OF ABSTRACT | |

SEARCH FOR LUNAR WATER ICE IN
COMETARY IMPACT CRATERS

by

STEVEN SCOTT BRANDT, B.S.

THESIS

Presented to the Faculty of the Graduated School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

of the Degree of

MASTER OF ARTS

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THE UNIVERSITY OF TEXAS AT AUSTIN

August, 1993

ABSTRACT

SEARCH FOR LUNAR WATER ICE IN COMETARY IMPACT CRATERS

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STEVEN SCOTT BRANDT, B.S.

SUPERVISOR: AUSTIN GLEESON

The search for water on the moon began with the introduction of the idea of polar cold traps as a region where large deposits of water could be stored. James Arnold (1979) presented this hypothesis after reviewing many methods by which water was delivered to the moon. The principle method is cometary impacts. Carl Sagan and Christopher Chyba (1990) further stated that enough water was delivered to the earth by comets to account for the volume of the terrestrial ocean. We investigate the possibility that large amounts of water are deposited in the floors of cometary impact craters. The impact of a 1-2 km comet brings over 10^{15} g of water to the lunar surface. If 1% of the mass survives the impact to be trapped in the crater and 1% of that is retained over the 3-4 billion years required for it to be present today, there will still be 10^{10} g of H_2O per impact. With the impact of a few hundred comets, up to 10^{12} g of H_2O is trapped in lunar craters.

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I. INTRODUCTION

In this paper we present a study of the question of the existence of water-ice on the moon. By developing an option for the survivability of water-ice which has not yet been studied to date, we contend that there are regions of the moon in which reasonable quantities of water-ice can be harvested. The debate over the moon's water-ice content has grown over the past fifteen years or so with the presentation of many theories concerning whether or not water-ice is present on the moon or if it is a completely dry body as the Apollo lunar program suggested. The purpose of our study is an investigation of the mechanism of cometary impacts as the means by which water was delivered and retained in the lunar environment. Investigations into the development of the moon as the earth's only orbiting satellite show that the moon during its cooling phase became a dry planetary satellite. Thus, during the past 4.5 billion years of our history, water had to be brought to the moon for it to have any water or ice now. This occurred during the period of heavy bombardment of the inner solar system comprised of the bodies inside the orbit of Mars. Extensive cometary and asteroidal impacts occurred in this period from ~4.5 to ~3.8 Gigayears ago (Chyba, 1987). The cometary flux during this period has been determined from the lunar crater record which is very well defined today. Most assumptions concerning the percentage of the projectiles which were

cometary is 10% (Chyba, 1987). Best estimates, which I will use, show that during this period from 10^{16} to 10^{17} grams of water were delivered to the moon (Arnold, 1979). The methods by which this water is retained on the moon will be addressed here.

In the development of this paper, we present first the problem description followed by why there is a debate over this issue. In Chapter II, the history and various sides of the debate will be discussed. The difference between the actual amount of water-ice on the moon and the amount of hydrogen on the moon will also be explained. In Chapter III we will develop the basics of impact mechanics which is central to the understanding of our proposal. In Chapter IV I review the description of cometary impacts on the moon presented by John D. O'Keefe and Thomas J. Ahrens (1982). In Chapters V and VI we develop the new analysis in this work by examining the processes which occur at the impact interface between the impactor and the impact surface. This along with the process of crater excavation and, finally, the shape and depth of the steady state crater all lead to the final conclusions in Chapter VII of whether or not water ice could survive in the depths of the crater floor. We will conclude by suggesting the next step which should be taken in the pursuit of the best test of our theory on water-ice on the moon without actually searching for it on the lunar surface.

II. PROBLEM DEFINITION AND BACKGROUND

As prologia to this study of crater retention of lunar water-ice, we must explain the different views in the current debate on the existence and amount of water on the moon. In our work we develop a theory based on the collision of a cometary impactor into the lunar surface, from which some of the ice, which comprises a large part of the cometary material, survives the impact and remains buried within the depths of the crater floor. For our study, although there are many good studies of surface impact dynamics, several of the reactions which take place upon impact are difficult to articulate at the present time due to the difference of the lunar environment, (i.e. low gravity, no atmosphere). We will address these issues as completely as possible.

Why is this topic important? The discovery of an ample amount of water or ice on the moon would provide a basic element which would make the moon a place which could serve as a launch platform if we ever intend to continue the exploration of space beyond the earth and moon. The availability of water in the lunar environment has many advantages for the survivability of man there for long periods of time. Furthermore and equally important, one of our primary fuels for space travel today is liquid hydrogen, and the mining of water or even only hydrogen and oxygen separately from the moon can provide an excellent gas station for space travel to the outer planets. Because of a low

lunar gravity and resultant escape velocity, performing a manned mission to Mars would be much easier and efficient if we could leave from a lunar base than an earth base. This is an exciting possibility and defines why this issue must be resolved. Hans Mark and Harlan Smith of the University of Texas at Austin are among the first to address this issue, "Because of the low lunar gravity this scheme [travelling from the moon to Mars] would take less energy by a factor of thirty or more than would transporting the equivalent amount of fuel from Earth" (1991). This idea motivates research to understand all the possible areas and mechanisms by which water can be deposited and retained on the moon.

The beginning of the entire argument was presented in 1961 by K. Watson, B.C. Murray, and H. Brown. This group suggested that ice and other volatiles exist; trapped in permanently shadowed regions near the lunar poles. No notice was taken until eighteen years later when James R. Arnold (1979) revisited this theory presenting a complete analysis on how water was deposited on the moon, and more importantly, whether any still remains. This article spurred the multi-faceted debate which is still unresolved today.

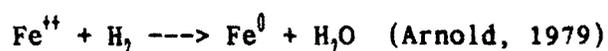
Arnold states four potential sources of lunar water,

- (1) Solar wind reduction of Fe in the regolith
- (2) H₂O containing asteroids
- (3) Cometary impact
- (4) (the least certain) the degassing of the interior (1979).

and implies that we should find water on the moon.

The acceptance of this view was not widespread due to the samples which were collected by the Apollo astronauts. All their samples proved to be extremely dry. Arnold argued that these samples were collected from shallow surface depths and that the moon has areas in the high latitudes which have not been exposed to sunlight for a very long time. It is in these cold traps where, "surface temperatures were stated to be lower than 120 K, in fact low enough to retain solid H₂O for billions of years" (Arnold, 1979). This concept of polar cold traps is the most widely accepted theory of how substantial deposits of water can remain on the moon over long periods.

To determine how much water-ice can be retained on the moon we need to know quite accurately how much water ever got there. The four methods of deposition described by Arnold begins with the reduction of Fe by the solar wind. This method of hydrogen trapping results from the hydrogen-rich solar wind hitting the Fe⁺⁺ in the silicates of the lunar soil. The following reaction produces water,



Arnold continues and states that if all the H₂O produced by this reaction were retained, the fraction of weight would be 0.13% of the weight of the agglutinates on the lunar soil (1979).

This is not considered an efficient method of water deposition and retention. The water created by this method is very near the surface of the moon and may be 'gardened' to a depth of three meters at most by asteroid and comet impacts which mix the lunar soil (Arnold, 1979).

Shallow deposition of water is not an effective reservoir for large water deposits. Feldman and Reedy (1991) discuss the first substantial problem with finding lunar water,

The portions of the moon explored to date are extremely dry because the moon formed very depleted in volatiles and because lunar gravity is not sufficient to prevent the escaped of volatiles over geological times.

This problem is the limiting factor for the retention of water from cometary impacts.

The development of the argument of solar wind deposition along with the small amount of water which may be delivered by H₂O containing asteroids lead to what L.A. Haskin (1988) describes as hydrogen in mature lunar soils. Mature lunar soil is simply the surface regolith soil which is known to contain small fractions of hydrogen, on the order of 10-50 micrograms of H per gram of lunar soil, deposited by the solar wind as describe by Arnold. Haskin studies just how much hydrogen remains in mature lunar soils,

The upper two meters of the lunar regolith thus contains approximately 8×10^9 tonnes of H, 1.5×10^{10} tonnes of C, and 8×10^9 tonnes of N. These amounts do not rival those on earth, but are nonetheless substantial. Converted to water this amount of H would form a Lunar Great Lake some 70 km wide and 100 m deep. On the moon they [these elements] have to be mined (1988).

Furthermore, he states that mining such elements is "not complex as technologies go" (Haskin, 1988). These estimates of Haskin's come from the best data from lunar samples. The most optimistic estimate is 100 $\mu\text{g/g}$ (Heiken et. al., 1991).

Generally, the method of cometary impacts proposed by Arnold and others is thought to be the most abundant supply mechanism of water to the moon. Comets are mostly ice, and, as stated in Chapter I, during the period of heavy bombardment described by Chyba (1987, 1990) and Sagan (1990) a substantial number of comets impacted the Earth which translates to the fact that a substantial number of comets impacted the moon. The result is large volumes of ice had to be distributed somewhere. This is not largely debated because of the clear impact record of thousands of large impact craters on the moon, but the trapping mechanisms and the moon's ability to retain the water over geological times is debated greatly. As stated, Arnold and many others have subscribed to the notion of polar cold traps, regions of permanently shadowed basin near the lunar poles. As recently as March 1993, articles continue to be published holding onto the idea of polar lakes. The most difficult part of this hypothesis is that the water must have a method to concentrate itself at the poles. Bruce Cordell (1993) writes in this article,

Comets appear to be the most likely source of lunar polar waters. A comet can deliver as much water in one impact as lunar outgassing or meteors in billions of years. A comet impact is rapid and produces an appreciable but temporary atmosphere around the Moon which then might condense at the poles.

This demonstrates the importance of understanding the cometary impact process. Arnold's other methods become unimportant if some percentage, even a small one, of water survives each significant cometary impact.

We believe that there is another process which is more effective than simply allowing the water to migrate to the poles and to store it there, gardened into the surface to depths only of 2-3 meters.

Three different groups have identified the issue which we will address in this work, but none seek a solution. O'Keefe and Ahrens (1982) in their analysis of comet impacts into a lunar-like surface in a lunar-like environment only address the issue in passing. They published a complete analysis of the impact process which we use as a starting point for our work. The issue for us is what happens at the interface of the projectile and the impact surface. Furthermore, we propose the mechanism of water retention through the burial of projectile debris and vapor by the back-filling of the crater over the longer time scales of the cratering process. They clearly and succinctly state the problem,

The icy projectile is vaporized in virtually all the flows considered. The growth and chemistry of volatiles in planetary regoliths are a problem which has not been addressed in this study (1982).

This process of the growth and retention of volatiles in the crater floors will be studied here as a source of water. Secondly, Roush and Lucey (1986) touch briefly on this aspect of the search for water on the moon. Their work entails the search for water by telescopic observations of the Reiner Gamma Formation. They discuss the chemical process of cometary impacts.

Comets are known to contain large amounts of H₂O, and Arnold (1979) discusses the possible occurrence of cometary impacts as a source of H₂O on the lunar surface. The specific nature of the impact of an icy body into a silicate target is poorly constrained at the present. It is undetermined whether the kinetics of reactions that produce minerals with structural OH- or bound water are appropriate to form such minerals from ice and dry igneous rock during an ice silicate impact event (1988).

This work here extends the question posed by O'Keefe's group deeper into the processes at the impact interface. Feldman and Reedy (1991) explain that during an impact event the vapor cloud may be driven deep within the lunar regolith. Then the vapor is trapped in pores and cracks within the crater floor. In addition, they state that this water vapor, while hot, may react to form hydrated minerals. This method is extremely important as the sites of cometary impacts are numerous, and, due to burial and slow diffusion times, the water could remain for extremely long times.

This discussion briefly reviews the background research which has been accomplished in the last few years. The idea of finding polar lakes or large ice deposits near the poles is not the only source of water on the moon. Reactive elements like H and O can come in many forms. The production of water from this is quite easy which would be used for astronaut survival. More importantly, we need to have an understanding of the ability of the moon to provide usable resources beyond the life support for astronauts. This may drive the chances of ever having another astronaut on the moon. The following analysis leads to questions which could only be resolved completely if we return to

the moon and confirm or defy the many hypotheses concerning water on the moon.

III. IMPACT THEORY

Crater Development

The largest projectiles which now enter the Earth/Moon system are either entire asteroids or comets. These are up to a few kilometers in diameter with some tens of kilometers across. Many that impact today are much smaller than one kilometer. The history of these events is what is important in this study, and in general the same size comets impacted the moon billions of years ago during the period of heavy bombardment. To understand the effect of the impact of such a object on the lunar surface we must understand a single hypervelocity (>3 km/sec) impact and the consequences it produces (Heiken, et. al., 1991). The impacts make impressive land forms and are characteristic of the lunar surface. The important factor is the long term geological consequence which impacts leave on the moon.

Impact physics is well understood today except that we deal here with very high velocities which cannot be attained in the laboratory. Thus, we must take the best simulations of impacts and infer from the physical parameters of the impact surface and projectile material the physical processes which occur over a certain time scale. This defines the importance of understanding the impact process before proceeding further with this work.

We deal here explicitly with simple craters which are defined as

bowl-shaped or slightly flat-floored craters with diameters of 5-25 km. These type of craters are the most advantageous in their ability to trap water deep within the floor depths. This is because these craters form from lower impact velocities which promote the survival and deposition of some of the cometary material. Figure 1 below is a cross section of a simple crater (Heiken, 1991).

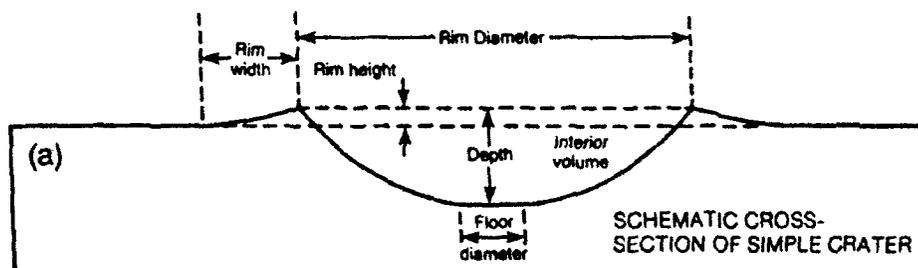


Figure 1
Cross-Section of Simple Crater

From the extensive studies of lunar impact craters it is possible to represent different characteristics of these craters by an equation of the form

$$y = aD^b \quad (\text{III-1})$$

where y is a given crater characteristic (e.g. depth, rim height), D is the crater diameter, and a and b are constants (Heiken, 1991). Table 1 shows these constants for various simple crater dimensions (Heiken, et al., 1991).

Morphometric relations for fresh lunar impact craters (see Fig. 4.2).

| Crater Characteristic | D, km* | N | Exponent (b) | Coefficient (a) | Source |
|---------------------------|--------|-----|--------------|-----------------|---------------------|
| <i>Simple Craterforms</i> | | | | | |
| Depth | <15 | 171 | 1.010 | 0.196 | <i>Pike (1974b)</i> |
| Rim height | <15 | 124 | 1.014 | 0.036 | <i>Pike (1977)</i> |
| Rim width | <15 | 117 | 1.011 | 0.257 | <i>Pike (1977)</i> |
| Floor diameter | <20 | 38 | 1.765 | 0.031 | <i>Pike (1977)</i> |
| Interior volume | <13 | 47 | 3.00 | 0.040 | <i>Croft (1978)</i> |

Table 1
Crater Dimension Relation Values

The primary objective now is to develop an understanding of the growth, excavation, and filling of a crater over time scales on the order of one minute, long compared to the initial impact time scales. The work of H.J. Melosh (1989) in his book, *Impact Cratering*, and of O'Keefe and Ahrens, who have been mentioned earlier, form the basis for the discussion of this complex phenomena. We limit our discussion to impact in a lunar environment, but many of the processes are independent of the environment.

The process, of course, begins with the hypervelocity projectile incident on the lunar surface. Upon impact we enter the contact and compression stage. With a vertical impact, which is the only type addressed here, the displacement of impact material begins immediately. The impact surface is compressed, and the material is accelerated velocities which are a large fraction of the impact velocity (Melosh, 1989). At this point, the projectile is decelerated as these changes

in velocities are mediated by shock waves between the compressed and uncompressed materials. The shock waves propagate both into the impact surface and back into the projectile. Pressures grow quickly into the hundreds of GPa, which exceeds the yield strength of both target and projectile (Melosh, 1989). Both materials may either melt or vaporize upon unloading from such pressures.

The projectile as it travels into the impact surface begins to distort in shape. The shock wave, hemispherical in shape, propagates into the target. A rarefaction wave develops, and the interference of the two cause the evacuation and ejection process. The propagation of these waves in the target surface is shown on the next page in Figure 2 (Heiken, 1991). The figure shows the evacuated zone which is ejected target material and the displaced zone which is the compressed and shock heated target material. The transient cavity will be explained later in detail.

As the projectile continues into the surface, the shock wave propagating into the projectile reaches its rear surface. At this point the impactor-target interface, or the original surface, has been pushed approximately one-half a projectile diameter deep (Melosh, 1989). The projectile is becoming extremely distorted and slowed to a fraction of its impact speed. When the shock wave has traversed the length of the projectile, the rarefaction wave is produced, and it propagates back into the target. This wave unloads the projectile, which may cause melting or vaporization, but the impact material completely lines the crater cavity. Due to the unloading the ejection

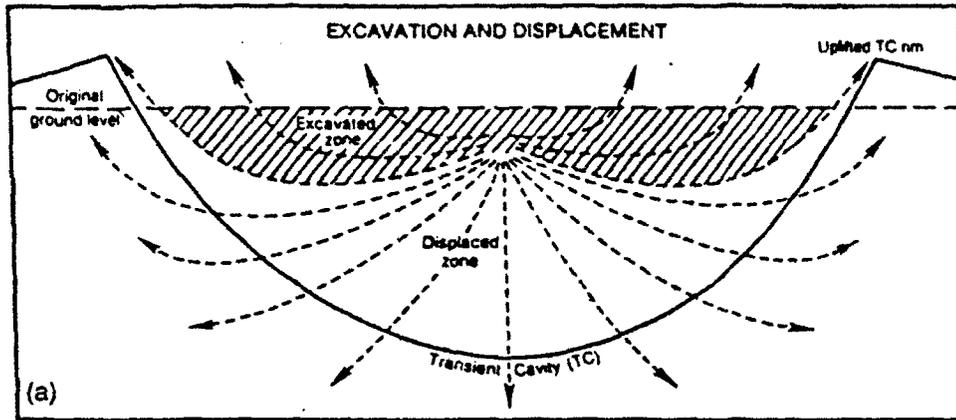


Figure 2
Shock Wave Radiation and Transient Crater Position

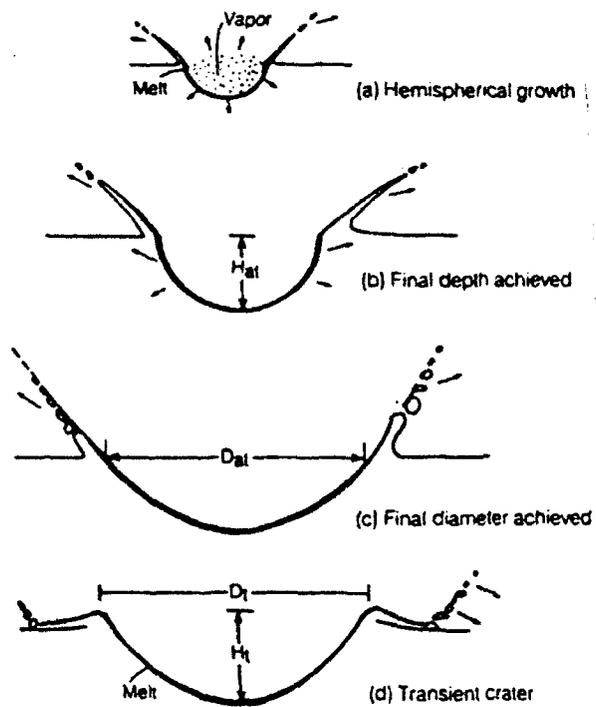


Figure 3
Crater Stage Growth

of material begins. The radial growth of the cavity proceeds, and the upward lifting of the rim begins. (See Figure 2 previous at lifted TC rim.) The projectile vapors and any remaining material are expanding into the crater cavities (Melosh, 1989). The depth of the crater is determined before the crater has completely formed. This is the result of the shock waves' ability to propagate more easily into the sides of the crater than into the hard rock directly down in the crater. Figure 3 on the previous page demonstrates this process clearly (Melosh, 1989). The figure depicts how the depth growth ceases while the radial growth into the walls continues to provide a wider diameter than depth. The relation between these two dimensions will be explained further.

The time scales of these occurrences are dependent on the size of the projectile, velocity of impact, the physical properties of the lunar surface, and the gravitational acceleration slightly. The time of maximum depth growth is dependent on the depth of the crater. The problem is that it is difficult to compute this depth theoretically. The development of the crater on this time scale is depicted in Figure 4 below (Melosh, 1989).

The value L is the comet diameter and τ is the time for the projectile to travel its own radius, $L/2v_i$. This value, τ , is in the range of 0.1 to 1 second. The figure shows that during the contact and compression stage the depth grows linearly with time. During the excavation stage, depth increases as a power n of time, where $n \sim 0.4$ in many experiments. During the final time period after T_d the depth is

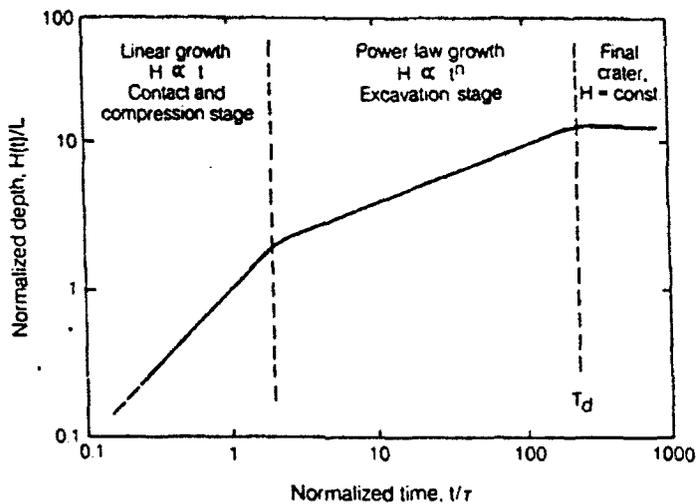


Figure 4
Crater Growth vs. Time

constant as the diameter continues to expand. This period, T_d , is constrained by the gravity at the impact site by the equation,

$$T_d \approx (2H_{at}/g)^{1/2} \quad (\text{III-2})$$

where g is the acceleration due to gravity (Melosh, 1989). Since we are looking at the moon this time is larger on the moon than on earth

$$H_{at} \approx \langle u \rangle^2 / 2g \quad (\text{III-3})$$

by a factor of the square root of six. We define H_{st} in (III-3) where

u is the mean impact velocity which is difficult to know accurately (Melosh, 1989). The time development of the completed crater is defined as

$$T_f = (D_{st}/g)^{1/2} \quad (\text{III-4})$$

which is the time after back-filling and modification occurs. D_{st} and H_{st} are defined in Figure 3.

Except for collapse and back-filling, the complete formation of the crater dimensions occurs during the excavation stage. Before this collapse, we have the final crater which we call the transient crater. (See Figures 1 and 3.) The dimensions of this transient crater is given in ratios of height, H_t , and diameter, D_t , typically and standard values for H_t/D_t is on the order of one-fourth to one-third (Melosh, 1989). In the development of the crater there are many processes. There is the excavation of some material, material compressed into the crater floor, and material shock heated to either vaporization or melting conditions. For a typical cratering process Figure 5 below shows the different stages. Notice the excavation depth is only about one-third the transient crater depth (Melosh, 1989). This fraction of the depth of excavation compared to the transient crater depth is very important since the depth to which the impact is felt is much deeper than the final depth which is seen when a crater is studied. This is shown further in Figure 6 (Heiken, 1991) in a detailed cross section of the simple crater. The importance of this concept is that the mixing which occurs in the region below the excavation region and the

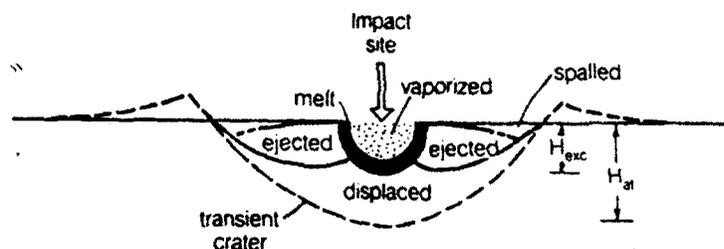


Figure 5
Crater Excavation, Vaporization and Displacement

region below the Transient Crater line are the primary areas where vapor and melt from the projectile can be trapped. This is the region in which O'Keefe and Ahrens do not attempt to explain what happens in an impact event. This is where we examine the reactions further.

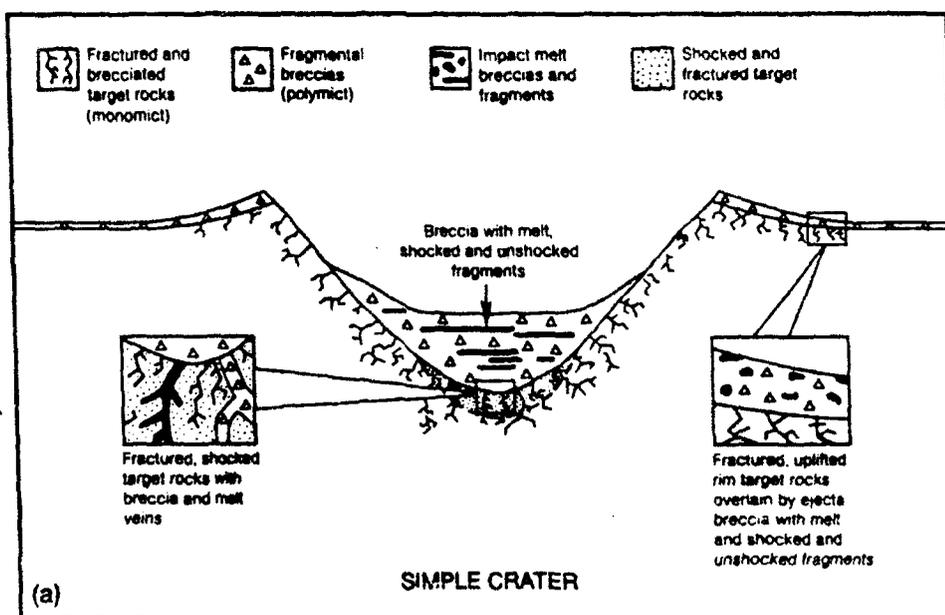


Figure 6
Crater Breccia Lens and Impact Melt

Melt and Vapor Volume

Due to the high impact velocities, determining the amount of vapor and melt created in an impact event is very difficult. For an iron impactor on a lunar-like surface, gabbroic anorthosite, at 45 km/sec the target vaporized by the projectile to a depth of about 2.5 projectile diameters and melts target material to a depth of about 5 diameters below the original surface (Melosh 1989). For the impact of a water based projectile like a comet, O'Keefe and Ahrens (1982) discovered that it is very similar to the iron impactor for the amount of melt and vaporization. The result of their work allows the simplification of the melt and vapor volume to the following relations. These apply if the amount of melt and vaporization is several times larger than the projectile mass.

$$\frac{\text{Mass of Melt}}{\text{Mass of Proj.}} = 0.14 \frac{v^2}{\epsilon_m} \text{ for } v \geq 12 \text{ km/sec} \quad (\text{III-5})$$

$$\frac{\text{Mass of Vapor}}{\text{Mass of Proj.}} = 0.4 \frac{v^2}{\epsilon_v} \text{ for } v \geq 35 \text{ km/sec} \quad (\text{III-6})$$

where ϵ_m and ϵ_v are the specific internal energy of melting and vaporization of the target (Melosh, 1989). The mass of the material melted or vaporized is determined in the high pressure phase of the shock wave expansion which occurs early in the process. This mass is

independent of material strength, but the final size of the crater is dependent on gravity.

The size of the melt zone is very important, but we address first what happens in this zone to describe the melt development. To determine the depth of the melt we must be able to identify what melt looks like in crater. According to Heiken, et al. (1991), there are three criteria of which must be present to label the find as part of the melt region.

The first is chemical composition. Melts are simply mixtures of preexisting target rocks. This mixed composition creates unique characteristics which cannot be created by a conventional heating process. The second is the nature of the rocks and mineral inclusions which produce effects on the melt. Basically, the impact melt bodies pick up numerous inclusions of target rocks or mineral deposits. They either cool rapidly or slowly which creates two distinct glass structures in the melt. Both can be identified quite easily giving a positive identification as part of the melt region. The final criteria is the most significant in relation to this work. This is the retention of projectile remnants in the impact melt. Simply, as we have stated, during the impact process the projectile experiences sufficient shock pressures to virtually melt and vaporize all the projectile. However, part of the this melted material will be deposited in the melt zone. This also provides an identification method for determining what kind of projectile created the crater (Heiken, et. al., 1991). This is vital in the search for water in

lunar craters because we first must know if a comet impacted there if we are to examine it further for more remnants. But more importantly, this states that through the impact process remnants of the projectile can be deposited in the crater melt zone.

Melosh indicates that the size of this melt zone is dependent on the size of the crater. For small crater sizes which we are addressing, an amount equivalent to approximately one-tenth of the displaced material by mass will consist of melted mass. As the crater grows the melted mass will equal the amount of mass displaced from the impact surface to produce the crater (1989). This melt region lines the floor of the crater as the crater develops and then is buried under the breccia lens. This burial process will be examined next.

Breccia Depth

The back-filling of the crater is the final stage of the cratering process. This occurs on a time scale which is long compared to the impact time scale. An understanding of this process is essential to our model of water capture. The variation in this time scale is quite large because of the varying crater dimensions. For simple craters on earth the time from impact to completion is on the order of ten seconds where for a large complex crater (300 km in diameter) times are over 60 seconds (Melosh, 1989). We use equation (III-4) which defines this time. For a 20 km diameter crater on the moon because of lower gravity, this time, which is scaled by an order

of 0.5, is about 60 seconds. The vast majority of this time is spent in the back-filling or modification stage which is slower on the moon. This stage is the modification of the transient crater which is defined as the crater shape at the end of the excavation stage. The crater would possess a depth of deepest penetration of the impactor. See Figure 1 presented previously. The process of modification is the development of a pool or lens of broken rock, shocked debris, and impact melt which has rolled back into the transient crater. From terrestrial craters studied and through some experiments, the maximum depth of the breccia lens or pool is about one-half the rim-to-floor depth of the transient crater (Melosh, 1989). This lens develops as the impactor continues to drive down the center of the crater floor, while along the walls great shear stress is felt in the melt and breccia there which causes extensive mixing. As the upward flow stops at the end of the excavation stage, the mixed and shocked breccia may now flow back down the steep sides of the crater to completely cover the transient crater floor. This crater floor contains melt which is covered by the slumping breccia which results in a large trapped melt pocket. We contend that is the best place to find the trapped remnants of comets. Melosh (1989) graphically demonstrates this whole process through the next series of figures. It is important to notice the extent of the back-filling and the ability to trap melt at extreme depths in the crater floor.

The depth of the transient crater is the depth to which the impact is felt and thus the depth to which projectile materials may be

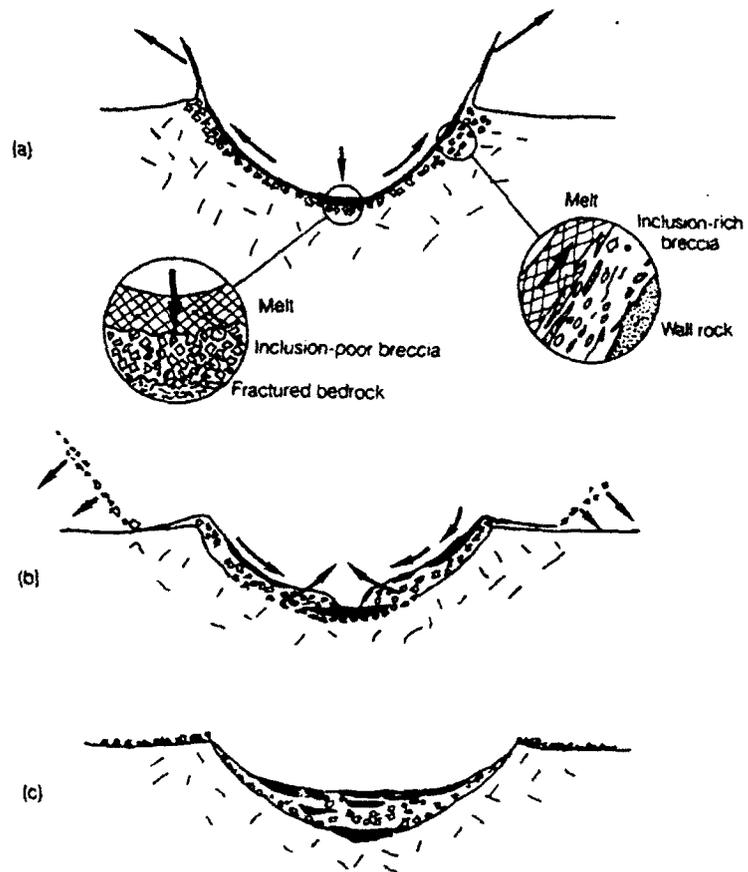


Figure 7
Breccia Lens Back-Filling

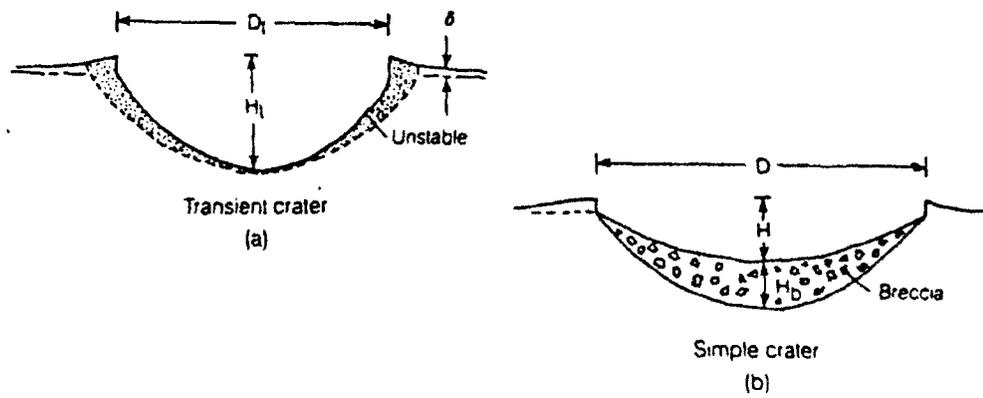


Figure 8
Simple Crater Dimensions (Transient and Final)

buried. Melosh presents the equation which equates the volume of the breccia lens to the volume of the debris which leaves the crater walls and rim by collapse to get the transient crater width, D_t (1989). The values are all described subsequently in Figure 8 where H_b is the breccia lens thickness. The right side of equation 6 is written entirely in terms of observable quantities.

$$D_t = \left(1 - \frac{5}{4} \frac{H_b}{(H+H_b)}\right)^{1/3} D \quad (\text{III-7})$$

If we use $H_b = H/2$ we get that $H_t/D_t = 1/2.7$. For example a 20 km simple crater, the depth of the transient crater is 7.4 km while with the breccia lens in place it is observed to be at a maximum 3.7 km in depth. This is a clear indication that the material trapped at this depth, a substantial depth, could contain material which has not been closely examined. Melosh touches lightly on this as he states that the amount of shock heated and melted rock buried by the modification process on the crater is immense, and the depths at which it is buried is also extreme. This results in the cooling times of this material to be very high. The thermal diffusive time of the melt pocket is on the order of H^2/κ where κ is the thermal diffusivity, about 1×10^{-6} m^2/second for rock. This translates to about 100,000 years cooling time for a 15 km diameter crater (Melosh, 1989). This time scale is short compared to the percolation time scale for volatiles trapped by the overlying material. This element of cratering mechanics is not addressed further by Melosh, and we contend it provides a substantial

opening for research into these regions where substantial amounts of volatile elements can be preserved over geological times.

We turn now to the analysis of impact mechanics in the lunar environment presented by John D. O'Keefe and Thomas J. Ahrens. We study their assumptions, findings, and conclusions.

IV. STARTING POINT AND ASSUMPTIONS

O'Keefe and Ahrens (1982) present the most comprehensive study of cratering in the lunar environment, and, in addition, their analysis is focused primarily on cometary impacts. They attack this problem via the effects of gravity or escape velocity on the accretion of material versus material lost during various impact events. Their variables include the impact velocity which varies from 5 to 45 km/sec and the comet density which they vary from 0.01 g/cm^3 to 1.0 g/cm^3 . They study how these variables affect the final crater shape and the partitioning of energy.

The effect of varying densities is not important to this study as we assume cometary densities only of 1.0 g/cm^3 . As O'Keefe (1982) states, this is not a bad assumption, "there is much evidence that the density of comets is $\approx 1 \text{ g/cm}^3$ ". We simply assume that the comet is an icy and not extremely porous body as Carl Sagan and many others believe. O'Keefe and Ahrens examine atmospheric effects briefly on the survivability of a comet as it approaches the planet, but they eliminate it as an effect on the lunar impact process. This is very reasonable, and we assume that most impacts on the moon are caused by projectiles that are intact, unaffected by any atmospheric degradation. Finally, they provide complete simulations of the impact events based on Eulerian code representations of the impactor and the planetary half

space. They yield accurate estimates of the amount of planetary surface melted and vaporized and the quantity of high speed ejecta at early times. Their restriction to short time periods is why this can only be the starting point for this work. Furthermore, as we stated previously in the motivation for this work, they do not attempt to address the retention of volatiles in the impact surface during the complete impact event. Remember, the complete cratering process can take hundreds of seconds, not simply the few seconds for the contact and excavation stages.

We first examine cratering for two different impact velocities. O'Keefe and Ahrens present data for impacts of 5 km/sec and 15 km/sec for a 1.0 g/cm^3 comet. The two events are shown in Figures 9 and 10 (O'Keefe and Ahrens, 1982). In both cases the shaded region represents the vaporized or melted comet and the arrows represent the flow field created by the shock wave propagating into the surface. It is easy to see the symmetric, radial growth of the crater. As expected, the flow field is developed sooner in the higher velocity impact event. The flow field in the 5 km/sec event is dominated by the projectile remains while in the 15 km/sec event the flow is more equalized and the projectile melt is large and more dispersed. The peak pressure in the low velocity event is some two projectile diameters below the surface. In the high velocity event, the peak pressure is felt about 1.8 projectile diameters below the surface (O'Keefe and Ahrens, 1982). This is important in the fact that again for a one kilometer diameter

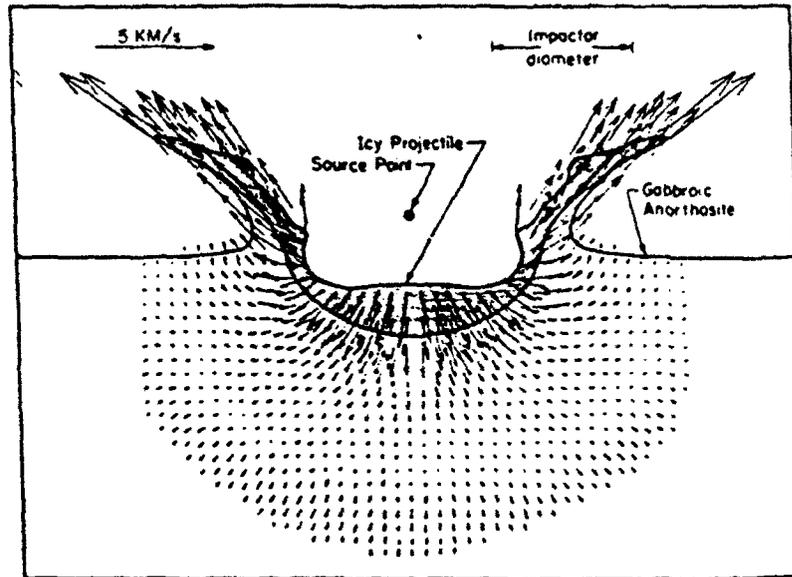


Figure 9
5 km/s Impact of 1 g/cm³ Comet

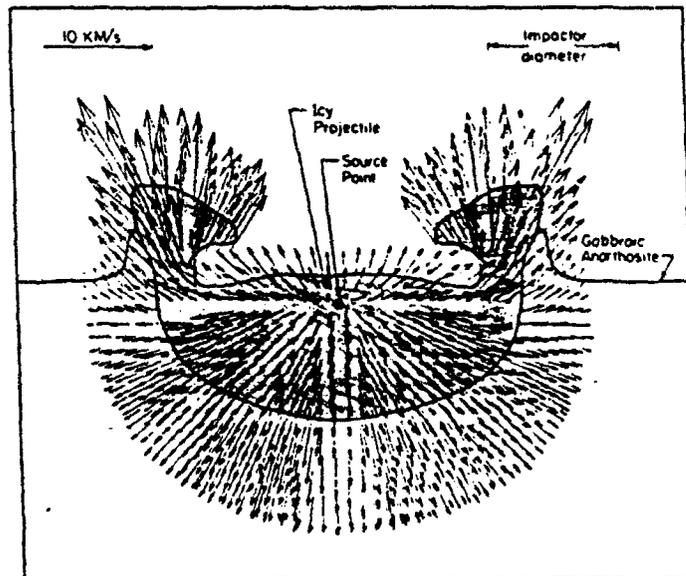


Figure 10
15 km/s Impact of 1 g/cm³ Comet

comet the effect of the impact is felt up to two kilometers into the lunar surface. O'Keefe and Ahrens (1982) also point out that for solid ice impacts the effects are the same as a solid silicate object. The result of such impacts create simple, bowl-shaped craters described earlier in this work.

They also address the partitioning of energy of 1.0 g/cm^3 density impacts. The basic conclusion is that the internal energy of the moon absorbs about 60% of the total energy of the entire event. This is demonstrated below in Figure 11 which depicts the energy fractions for various comet densities and for silicate impacts events as a comparison.

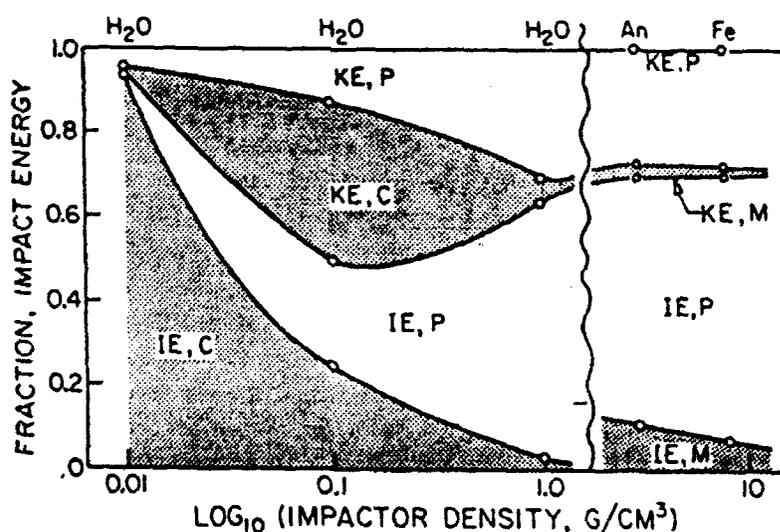


Figure 11
Energy Partitioning of Cometary Impacts

This plot is for 15 km/sec impact events only. IE and KE are the internal energy and kinetic energy for the planet (moon), P, and comet, C, respectively. IE specifically defines the thermal and compressional energy of the Comet or Planet respectively. These change dramatically after impact as most of the IE, C is lost. KE is the energy stored in the flows of the Comet and Planet respectively. It shows that for 1 g/cm³ impactor the partitioning is similar to iron and silicate impacts.

The final question concerns the efficiency with which lunar-like planets accrete volatile objects. Because of the fact that there is water and ice on the Mars surface and that it did not accrete it during the initial formation of the solar system, there had to be another method of deposition later in the lifetime of the solar system. The period of heavy bombardment is the most probable time for this accretion. Figure 12 on the next page exhibits the ratio of ejected mass to comet mass versus the escape velocity of material on the impact surface. We notice first the factor of 2 to 5 more ejecta which is produced from the 15 km/sec impact over the 5 km/sec impact. This is consistent with the situation shown in Figures 9 and 10. The zero line indicates when the amount of mass ejected equals the mass accreted on the lunar surface (O'Keefe and Ahrens, 1982). The value of the escape velocity for this situation describes the case for which the mass of the planet does not change after the event. For 1.0 g/cm³ comets this critical velocity is 1.2 and 2.5 km/s for 5 km/s and 15 km/s impactor velocities respectively (O'Keefe and Ahrens, 1982). The actual escape velocity of the moon is 2.38 km/s at the equator. Thus, for a 15 km/s

impact event on the moon the mass does not change. This is the essence of our argument. If such a large amount of the projectile is accreted during the impact event and if the projectile is water-based as is a comet, where has it gone if the moon is completely dry?

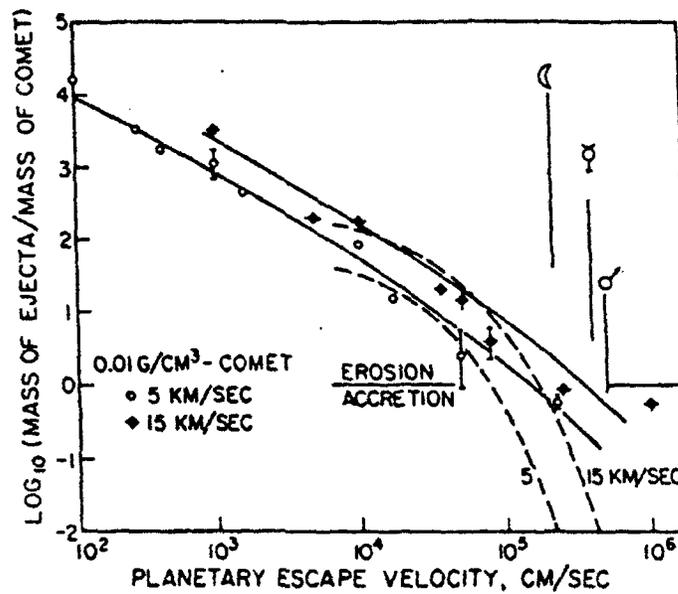


Figure 12
Accretion Rate vs. Planetary Escape Velocity

V. BURIAL CALCULATIONS AND ANALYSIS

Our first task is to approximate the amount of water that impacted the moon during the heavy bombardment period. From this we can estimate the amount that survives the impact process to be deposited in the crater floor. Then, lastly, we examine the cross-section of the craters, whose development we understand, to determine where and to what depths water could be stored.

Impact Projectile Amounts and Survivability

As O'Keefe and Ahrens (1982) stated, the impact of an icy projectile like a comet onto an atmosphereless planetary surface creates the same type crater of dimensions up to 20 km as a normal density meteorite impact. Chyba (1987) writes explicitly on the cratering record of the moon in support of his theory that enough water could have been deposited on the earth during the period of heavy bombardment to almost entirely account for the mass of the terrestrial oceans. Equation (V-1) gives the amount of projectile (not only cometary) mass which impacted the lunar surface and left craters.

$$M(D) = 0.089 (\rho/v)^{6/5} g^{3/5} \delta^{-1/5} D^{18/5} \quad (V-1)$$

M is the impactor mass of density, δ , and incident velocity, v , excavating a crater of diameter, D , on a body of density, ρ , and

surface gravity, g (Chyba, 1987). For the moon, $g = 161 \text{ cm/s}^2$ and $\rho = 2.9 \text{ gm/cm}^3$. He calculates the root mean square velocity of impact which is difficult to obtain directly, and his empirical result is 16.1 km/s^2 (1987). This is conveniently close to the value of 15 km/s^2 used by O'Keefe's group in the cometary impact analysis which we use as our basis for understanding impact mechanics on the moon. Because of wall collapsing and mixing, the amount of material produced is dependent on the fact that the diameter continues to grow after the maximum depth is reached. Thus, the diameter, D , is scaled by a factor of 1.3 for the 30% growth of the diameter from the transient crater dimensions (see Figure 3). This amount includes all craters up to 300 km in diameter (Chyba, 1987). This value is much larger than our simple craters. We will correct for this later. The result of this estimation is that $5.7 \times 10^{21} \text{ g}$ of mass impacted the lunar surface to create the crater record we have today (Chyba, 1987).

This is a large amount of water, but now we must narrow this down to cometary impact mass. Furthermore, we must determine how much actually survives the hypervelocity impact we have described. Firstly, it is commonly assumed that 10%-30% of the projectiles during the bombardment period were cometary. We use the accepted estimate that 50% of the comet is sustained as ice through the time of its orbit until impact. In addition, since the impact is on the moon and no atmosphere is penetrated, we neglect any ablation of the comet from frictional heating. We assume the worst possible scenario and accept

that 10% of the projectiles are comets. Furthermore, to limit the number of impacts which create craters above 30 km in diameter, we scale this mass by a factor of 10^3 because of the volume of a spherical impactor goes as r^3 . The result of this simple calculation gives 2.85×10^{17} g as the amount of H_2O from comets impacting the lunar surface. This compares closely with the amount of $10^{16} - 10^{17}$ g presented by Arnold (1979). For $\delta = 1.0 \text{ g/cm}^3$ a 1 km diameter comet has a mass of the order of 10^{15} g. This would require 285 1 km comets to deliver 10^{17} g of water to the lunar surface. Carl Sagan and Chyba (1990) site that 75% of all comets are less than 1 km in diameter. Basically, this mass is a conservative estimate since the cratering record shows over 7400 impact sights of varying size of which not all are comet impacts. In addition, the large comets which are tens of kilometers in diameter have created large basins which provide an amount of projectile mass incident on the moon on the order of 10^{23} g (Chyba, 1987). For our estimate, we will use the value of 2.85×10^{17} g of water delivered to the moon in simple craters as our basis for determining how much water may actually survive on the moon.

Depth of Final Crater and Water Burial Depth

The delivery of the water to the moon by cometary impact is not questioned. However, the retention of the water is. No method of survivability has been addressed besides Arnold's (1979) theory of polar cold traps. The fact that such an abundant amount of water was

delivered produces the basis for our belief that other ways of water accretion and retention may exist in the complex cratering process. Furthermore, O'Keefe and Ahrens (1982) discuss how the distribution of volatiles in the inner solar system was mostly accomplished late because the small planets like Mars and Mercury were unable to accrete volatiles as the solar system cooled. It is obvious from the oceans on Earth and the polar ice caps on Mars that there was an abundant supply of volatiles after the cooling period. The moon had access to these same volatiles. However, the impact process is extremely violent which obviously complicates the retention process. The heat of vaporization for a cometary impactor is 1.6 MJ/kg while for an iron impactor it is 5 MJ/kg (Chyba, 1987). Shock pressures created during an impact are 50 to 100 GPa and the material strength of ice is ~ 1 GPa. This obviously implies vaporization of the projectile. Melosh (1989) depicts this in Figure 13.

The idea that some of the impactor material survives does not seem possible, but we must look further at the size of the impactor and see that at lower velocities, <10 km/s, heating and pressures may allow some of the projectile to actually encounter the melt zone as water vapor or perhaps even ice. Sagan and Chyba (1990) discuss this by looking at a 5.9 km/sec impact and find that 100% of the mass is exposed to temperatures below 1800 K (1990). The high specific heat of water accounts for the survivability of organics and volatiles in comets.

Therefore, some fraction, which we will define, of the cometary

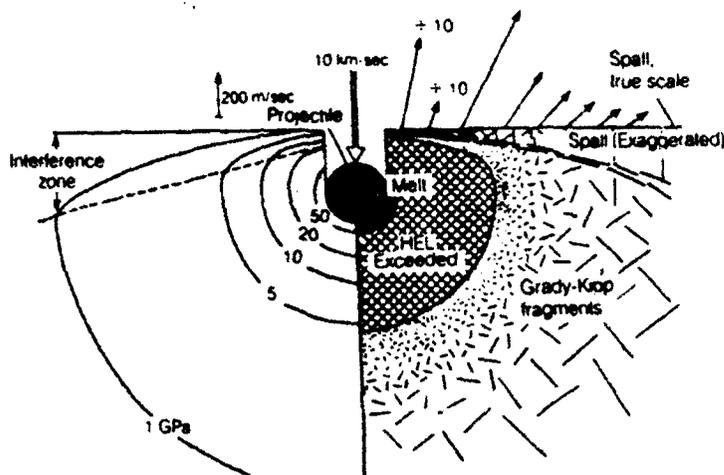


Figure 13
Impact Melt Scheme and Pressure Gradients

mass is not vaporized and ejected from the crater. The vapor or ice particles interact with the melt zone which experiences extensive mixing during the impact process on long time scales. This time period, up to 60 seconds which we defined as T_p , extends to when all ejecta has settled and mixing has stopped. The transient crater as described previously has a depth of one-third the diameter. For a 10 km crater the transient depth is on the order of 2.7 km. Then with the back-filling process the final crater depth will be only 1.3 km. The region we must investigate is the interface and the 1-1.5 km of breccia lens. This is where the surviving vapor and ice is trapped. The impact interface which is defined as the transient crater line where the projectile materials encounter the shock heated melt of the impact

surface is where the deposition process begins. If some fraction of the comet survives the impact in this region it is buried and mixed rapidly within 1.5 km of breccia lens. Because they are studying processes on the impact contact and excavation stage time scale, this is exactly the process which O'Keefe and Ahrens (1982) do not attempt to address. As importantly, O'Keefe finds that for 15 km/s cometary impacts as much mass is accreted as is ejected for the lunar escape velocity (See Figure 12). If even a small fraction of this water can be retained, this is an abundant mass of water.

We must assume some percentage of water which survives the impact to be buried in the crater floor. Arnold (1979) addresses this from two directions. For high velocity impacts of greater than 30 km/sec the comet mass may decompose chemically. This implies further that most of the mass is lost as it escapes the moon's gravitational field. Now for velocities under 20 km/s much of the H₂O does not escape the moon's gravitational field, but is liberated into the lunar atmosphere. From this and the fact that the mass of the moon is constant at 15 km/s impacts (O'Keefe and Ahrens, 1982) we can see that a small mass is actually trapped in the crater region. Much of the mass that the moon accretes during the impact of a comet is not trapped within the crater floor. Therefore, we assume for a ~10 km crater created by a < 20 km/s, 2 km comet which has a mass of 10^{15} g which 50% is ice that 1% of the mass survives the impact event to be buried within the crater floor, then $\sim 10^{12}$ g of water is deposited in the impact melt. This is one million metric tons of water. Because of dissociation through various

methods, of course this may not be what remains today. As Roush and Lucey (1988) discussed, the rate of hydration of silicates through an impact event is unknown. In addition, we do not know how much is hydrolyzed on the infall time scale. This is the process by which the water could still be accreted and retained.

VI. IMPACT INTERFACE REACTION ANALYSIS

The accretion of volatiles deep into the lunar surface is what must be accomplished for any substantial amount of water to be found there. This water could be in the form of hydrated silicates in the surface interface and throughout the breccia lens of shallow craters. The moon's surface to a depth of several meters is ~45% silicon based. This issue has simply not been addressed as a method of volatile deposition in an environment which, unlike the earth, is not conducive to the trapping of volatiles.

Comet/Lunar Surface Interaction

O'Keefe and Ahrens (1982) state that, though the impact process is violent and the projectile is vaporized in most cases, the growth and, more importantly, the chemistry of volatile accretion on the moon is not well understood. The interaction at the impact surface is where the process begins. The compression and ejection of materials occurs rapidly and violently. The shock heating of both the projectile and the surface create melt zones in the surface which extend hundreds of meters in depth. The cometary projectile, though almost completely vaporized, brings as we discussed large amounts of water to the impact event. As shown in Figure 6, the creation of cracks and fractures by the comet in the depths of the crater are extensive. Also depicted

well in Figure 6, we see the complete coverage of the cracks and melt pools by the back-filling of the breccia lens. The temperatures created in the impact event are extreme. Sagan and Chyba (1990) write that temperatures as high as 4000 K are easily attained for ~15 km/s impact events. The melting point of Silicon is about 1800 K so the melt of the impact surface is quite extensive.

The vaporization of the comet obviously creates water vapor. We believe that with the large size of a comet not all of the cometary material is ejected permanently from the surface at impact. For a 15 km/s comet, O'Keefe (1982) states that amount of planetary mass displaced and ejected is equal to the accreted mass of the impactor. This implies a reservoir of water vapor in the region of the impact. The process which occurs to accrete this material is the burial of volatiles. In addition, Feldman and Reedy (1991) discuss the ability of the vapor to be driven deep into the regolith and megaregolith where it is subsequently physically trapped by melt and infall breccia. We believe further that in some cases at lower velocities even water survives the impact event to be buried in the crater. The entire process occurs very quickly, and the regions where water and vapor can be deposited are numerous. We now must determine if it will remain there in some form over geological times.

Cooling Time of Shock Heated Breccia

The melt created by shock heating a few tenths of seconds after

incident impact lines the transient crater floor. See Figure 7a. This material is extremely hot and reactive. The interaction of the cometary material with the melt begins here. The mass of this melt may exceed several projectile masses; thus there is ample volume for reactions to take place (Melosh, 1989). Figure 7b displays the first burial of impact melt in the center of the crater floor. This will be several hundred up to thousands of meters deep within the megaregolith.

The second burial of melt occurs as the melt along the walls of the crater slides to the center of the crater also shown in Figure 7b. This melt is not buried to extreme depths compared to the central melt pool, but the depths are still on the order of -100 meters. Finally, on the longest time scale, there is the infall of the breccia lens which carries with it vapor and cometary materials. This region in the first 100 meters has to be the most practical area to search for water. To excavate below such a depth becomes difficult especially on the moon since we must transport any tools there to recover the volatiles.

We have defined how the water becomes trapped. Next, we must understand how it can survive over geological times. As presented earlier, Melosh (1989) discusses the cooling times of deep, melt breccia as high as 100,000 years. The conditions for survival of the water in this buried area is strictly dependent on whether or not the water, instead of evaporating in the extreme temperature or diffusing by the outgassing of the melt region, can be transformed into a stable state, like in hydrated rocks. Regardless, some fraction of the implanted water will diffuse to the surface and be lost as Feldman and

Reedy (1991) stated.

The only way to address this entire process is to take one cometary impact, and (1) assume some amount of water or vapor survives the impact to be buried in the breccia lens as we stated in Chapter V (2) assume some fraction of this amount is lost by various dissociation methods, and (3) analyze the hydration process of various silicates, which comprise almost half of the lunar regolith by mass, to get a final estimate of the amount of water which survives in hydrated rocks which are stable over extreme time scales.

Silicon-Based Hydration

As we have calculated, the mass of a 2 km comet impacting the moon is on the order of 10^{15} g. If we assume as before only 1% of the comet actually survives the impact and is buried in the breccia lens, we have 10^{13} g of material in the crater floor. Assuming only half of this is water, we restrict this value to $\sim 10^{12}$ g of actual water or water vapor per impact. This is a large amount especially when generally concentrated in the small area of a crater floor.

The task now is to determine if some can survive over geological times primarily through the means of bound water on Silicon products which make up a large portion of the lunar soil. Arnold (1979) states that the H_2O molecule is bound very strongly on many surfaces. The binding energy can range from the heat of vaporization up to the chemical bonding energies. In laboratory test surface H_2O has been held

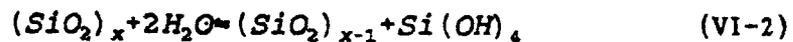
in vacuum at temperatures much higher than the maximum surface temperature on the moon of 400 K (Arnold, 1979). This relates directly to the fact that H₂O is the most radiation resistant molecule known. Once the water is bound it is resilient to removal.

There are melted silicon products at the impact interface and in the buried melt region to bind this surface H₂O. Within the same region there is an abundance of primarily water vapor. These are the reactants needed to form hydrated silica. The small amount of hydrogen present in the mature regolith which L.A. Haskin (1989) discussed will aide in this process as some of the silica may already be lightly hydrated. The ability of water to bind to this compound appears more probable. However, this is not the only process which can occur.

There is no evidence that Silica, SiO₂, is soluble to any appreciable degree in any other liquid besides water. The dissolution of silica involves a chemical reaction or hydrolysis in an excess of water:



This is not as simple as just sugar dissolving in water. The hydration and dehydration reaction is similar (Iler, 1979).



There are many states of silica, from glassy to amorphous, all of which are present on the lunar surface in varying amounts. Glassy silica or quartz will be present in the melt zones because of the extensive heating (Heiken, 1991). Also, exposed to high concentrations of water,

it reaches an equilibrium concentration of 0.22% H₂O. This water is present as internal SiOH groups (Iler, 1979). This is tightly bound water.

The presence of water on the silicon molecule is based primarily on surface hydration as Arnold (1979) discussed. Thus, the size of the particle drives how much water can be attached to it. The value, d , is the diameter of the anhydrous particle in nanometers. The percent of water in the hydrated equilibrium for amorphous silica is given in the equation (VI-3) (Iler, 1979),

$$\%H_2O = 32d^{-1} - 23^{-2} + 5.45d^{-3} \quad (\text{VI-3})$$

The diameter, d , increases with the value of n , or the number of atoms in a particle. Thus, with more complex structures of many Si atoms, the ability to bind water increases. For $n = 11,500$ the hydroxyl content in (VI-3) is 3% (Iler, 1979). The result is a density measurement of the number of OH groups per nm. The average value is 4.6 OH/nm for Si with a spherical surface.

Another fact which is important to our analysis is the reaction of silica at high temperatures and pressures. In Si(OH)₄, at high temperatures and pressures, the solubility is greatly increased, and it can exist in an equilibrium phase with bound water as vapor in the steam. For impacts on the moon, the silicate surface is elevated to high temperatures, thus, this allows some of the reactions which take place at the surface interface where there is an abundance of water

vapor and melted or vaporized surface material.

We must define a hydrolysis rate for silica to determine the likelihood of these products on the moon to actually hydrate during the impact process. The result of hydrolysis is silicic acid, $\text{Si}(\text{OH})_4$. This occurs through the surface splitting of Si-O-Si bonds to form a hydrated silicic acid molecule adsorbed on the surface (Iler, 1979). The production rate of silicic acid is (Iler, 1979):

$$\frac{dn_H}{dt} = (n_0 - n_{ads}) k \exp\left(-\frac{A}{RT}\right) \quad (\text{VI-4})$$

where n_f is the number of silicic acid groups released per unit of surface area, k is the kinetic constant for hydrolysis, A is the activation energy for hydrolysis, R is the universal gas constant, and T is temperature (Iler, 1979). Adsorption occurs only on the surface which is not already covered by $\text{Si}(\text{OH})_4$. This rate equation is simplified if we can assume that the temperature remains constant during the hydrolysis process. This is not the case during the hydrolysis which occurs during the impact process. However, the time scale at which cooling takes place within the breccia lens is very long. This assumption then of constant T is not unreasonable even for our study. Thus,

$$K = k \exp\left(-\frac{A}{RT}\right) \quad (\text{VI-5})$$

K is the hydrolysis constant. n_{ads} is the adsorbed $\text{Si}(\text{OH})_4$ concentration,

$$n_{abs} = \frac{n_0 bc}{1 + bc} \quad (\text{VI-6})$$

where c is the silicic acid concentration and b is the adsorption constant. We can simplify equation (VI-4) to

$$\frac{dn_H}{dt} = \frac{n_0}{1 + bc} K \quad (\text{VI-7})$$

which depends on K and b , the hydrolysis and adsorption constants respectively (Iler, 1979). This is the rate equation which defines the time period required for the surface hydration of silica. The value, b , for quartz and vitreous silica which are present on the moon is 0.7 ml/ μ g. For K , the value varies greatly. K equals 1.7 day⁻¹ for quartz and 90 day⁻¹ for vitreous silica. The hydrolysis of vitreous silica is much more efficient.

The hydration is a surface adsorption process as we stated previously. The key characteristic of this process is that the siloxane (SiOSi) surface of SiO₂ reacts with water so that at ordinary temperatures the surface becomes covered with silanol (SiOH) groups. The results of many studies state that in equilibrium the concentration of silanol groups on the silicate surface is 11 ± 1 micromoles/m² or 6.6 OH groups nm⁻¹ (Iler, 1979). A pictorial representation of this method of surface hydration is presented below in Figures 14 and 15 (Iler, 1979).

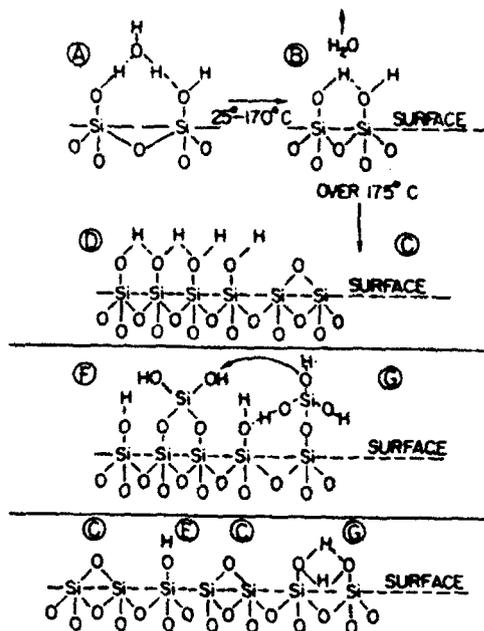


Figure 14
Hydroxyl Groups on Amorphous Silica

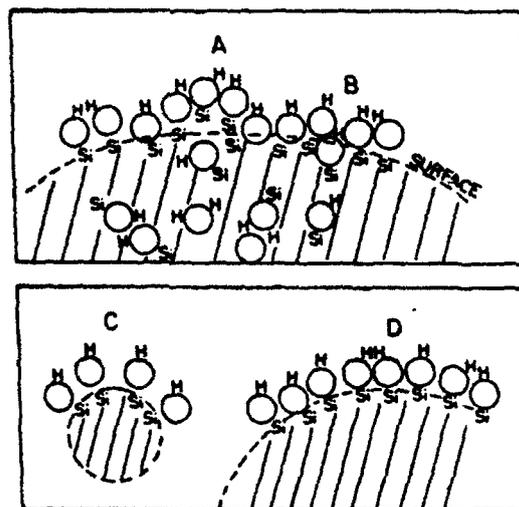
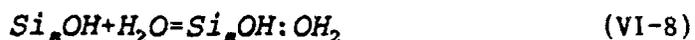


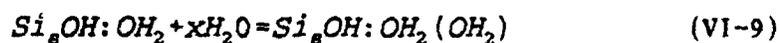
Figure 15
Factors Effecting Surface Hydroxyl Groups

The information in Figure 15 depicts several ways the OH groups are bound on the surface. In *A* some SiOH groups are buried within the siloxane network. These are removed only at very high temperatures. Some are located just within the surface as in *B* which increases the packing density of OH groups there. In small radius particles as in *C* the binding is weaker and less densely packed which leads to easy dehydration unlike in *D* where the density of OH groups is high for the larger radius particles. This phenomena of the dependence on particle size was discussed above quantitatively in the hydrolysis rate equations. Lastly, not shown in the figure, pores in the particle trap the OH groups because these regions have a negative radius of curvature. These regions are very difficult to dehydrate.

As water attaches to this SiOH network there are two processes which add to the hydration of silanol. First, the SiOH absorbs water to cover its surface by the following reaction.



The second method which is the adsorption of water onto the already adsorbed water is more stable than the previous method and follows the following reaction.



Si_s is a silicon atom at the surface. The stability of water in groups of 5 or 6 molecules matches that of bulk stability (Iler, 1979). This is important as the hydration of the silicates on the moon must result

in a very stable compound. The stability of these two types of bonding is defined by the temperature of removal. The temperature to reverse the reaction in equation (VI-8) is 25-105°C. This type of adsorbed water is "physically adsorbed". The second type defined in (VI-8) is reversed at temperatures ranging from 105-180°C. This type of adsorbed water is "hydrogen bonded" (Iler, 1979). The average lunar temperature is approximately 300 K thus the dehydration of these groups is not likely once they are hydrated. Furthermore, in the floors of craters the temperature will remain lower due to shading, and we are not looking at surface particles directly exposed to the radiation of the sun. The hydrated silicon products we examine are buried within the crater floor.

The most stable of hydroxyl groups bound to silica is formed by heating the particles to high temperatures where internal pores open and water and OH groups can be trapped internally. The removal of these trapped groups is virtually impossible as extremely high temperatures must be reached again to liberate them. When performed in the laboratory, the percentage of internal water per gram of SiO_2 was 1%. This is actually a significant volume of water. This process could easily occur with the heating and fracturing created by an impact on the moon. The result is a very stable hydrated rock.

The ability to remotely detect these hydrated silicon particles is also possible. This was suggested by Roush and Lucey (1988) as they discuss the fact that the spectral signatures of OH^- and H_2O bearing silicates indicate the best wavelength region for observation is from

2.4 to 3.5 μm . These two compounds have vibrational modes which result in absorption in this wavelength region. This agrees with the data presented by Iler (1979) in his discussion on the creation of these hydrated silicates. A specific experiment to look in the basins of large craters on the moon could prove to be the first step to the verification of this method for the formation of hydrated silicates. The only problem is the surface silicates may not remain hydrated because of the rapid dissociation of the water because of the lack of a lunar atmosphere. It may be only the large amount of buried rocks which have retained their water over the geological time scales we are addressing here.

These are the primary means for the simple hydrolysis of basic silicate products. The question still remains of whether or not these processes occur during the impact event on the moon. Within the first 100 meters of the buried surface in the breccia lens, the cooling time is on the order of a hundred years based on the heat of diffusion Melosh (1989) discussed. Therefore, water must be trapped in this region with heated target materials until low enough temperatures are reached for the water to cool, bound to the silicates. The temperatures needed are below about 400 K which will happen rather quickly at the depths we suspect water to be found. When we examine the rate equation (VI-7) we see that n_0 is large because of the abundance of silicon in the lunar surface. K is dependent on the kind of silica we are using. The vitreous silica has the highest rate. Besides the dissociation of water out of the surface, the fraction of

water that survives the impact will encounter conditions favorable to hydration of the rock there. The activation energy, A, will be met by the immense energy delivered by the impact. Finally, if we can retain a small percentage of the delivered water in the form of physically and hydrogen bonded water on the silicon compounds the retention is favorable as the temperatures remain low and exposure is limited due to the burial of these materials.

VII. DISCUSSION OF RESULTS AND CONCLUSIONS

The analysis of the impact of 2 km comet into the lunar surface provides the basis for the deposition of water into the lunar crater floors. Depending on the velocity of impact, various size craters are made, with the average being approximately 10 km in diameter. We find for this case that a breccia lens of 1-1.5 km in depth is created and over 10^{15} g of water is delivered to the lunar surface. A large fraction of this water is never retained as it is ejected from the lunar environment due to the large amount of impact energy. The comet is almost always completely vaporized so the breccia lens traps primarily shock heated water vapor. At low impact velocities, < 5 km/s, actual water may be trapped. Furthermore, a large melt region is created in the crater floor whose mass is greater than the projectile mass by several times in some cases. Thus, we obtain a large quantity of reactants concentrated in a relatively small region. We assumed for this case, based on various reasons presented earlier, that about 1% of the impact water mass is actually accreted into the crater. This is done in several ways: 1) by hydration of the deep melt at the impact interface, 2) the burial of vapor and melt by crater back-filling, and, 3) the collection and burial of water vapor and heated surface materials through the infall of ejected cometary and target materials. This value, even though a small compared to the amount of total water

delivered, represents over 10^{11} g of H_2O . This is still one million metric tons of water.

The amount of water which is retained over the geological times which is required for us to find water in hydrated rock today is obviously less than this. Arnold (1979) has shown that surface bonding of H_2O is very strong and stable. The conditions created in the first 100 meters of the crater floor are conducive to the formation of hydrated rock. A large portion is still lost due to the lack of an atmosphere and a low gravitational force which allows a fairly easy escape compared. Temperatures in this region cool in a relatively short amount of time to values which allow the hydrated rock of the heated and fractured breccia to be permanently deposited in the crater floor. This volatile mixture of water, water vapor, shock heated target rock, and melt pools cannot be ignored as a region for the deposition of water in hydrated rock.

We contend that through the cratering mechanics described and the description of the hydration process of silicate products that a large reservoir of water still resides on the moon in the depths of simple crater floors from extensive cometary impacts. If only 1% of the water survives in hydrated rock over the geological time scale required for it to still be there today, there is 10^{10} g of water per impact of a 2 km comet. If some 250 comets this size have impacted the moon, we are representing 2.5×10^{12} g of water or 2.5 million metric tons. The space shuttle uses about 13 tons of H_2 per launch in its external tank. This is an extremely large number of launches from the complete lunar water

supply, so the necessity to mine every region where there is water is not required. The density of water in these is crater floors would be higher than the density of the mature lunar soil, 50 μg H per gm of lunar soil, which L.A. Haskin (1990) discussed. Calculating this density for the amount of water trapped in the breccia lens with surface density of 3.34 gm/cm^3 (Heiken, 1991) for a spherical shaped crater we get 1 milligram of H_2O per gram of lunar soil. Haskin discusses H only in his estimate, but even with H_2O we find a higher density in the crater floors. Thus, a concentrated effort at the bottom of a cometary crater will yield a substantial amount of water or hydrogen.

A simple test of this hypothesis is by spectral absorption of whether the basins of craters store hydrogen in detectable amounts. A failure in this respect, however, is not a complete refutation of the hypothesis presented here. Due to the depth of burial of several hundred meters which we discussed, remote sensing may not detect the large concentrations of hydrated silicates deep in the breccia lens. We then must return to the moon and actually search several crater floors for hydrogen by probing deep in the breccia lens.

The development of a more complete understanding of the impact process by comets on the moon beyond the short time scale cratering process described by O'Keefe and Ahrens (1982) creates questions as to the deposition and accretion of volatiles in the lunar environment. This was our goal. The cratering process extends far beyond just the impact event and the creation of the transient crater especially when

we examine the what the comet or any projectile can leave on the surface. We must look further as the moon should be the next step into the further exploration of our solar system.

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