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Large-scale impacts and the evolution of the Earth's crust: The early years

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ABSTRACT

Modeling the effects of differential scaling of impact melt and transient cavity volumes indicates that impact melt volumes exceed transient cavity volumes at transient cavity diameters greater than ~500 km on the Earth. This condition is not realized on the Moon until transient cavity diameters are greater than ~3000 km. A reasoned case is made that because of this "differential scaling," the large impact "basins" comparable in size to such lunar basins as Orientale, which must have been formed on the Hadean Earth, did not have an Orientale-like form. While their exact form is unknown, they were likely shallow structures, and they would have been characterized by voluminous central impact pools. These melt pools with their closed-system environment would likely differentiate, leading to the crystallization of more felsic rocks. This reprocessing of the Hadean crust by large-scale impacts provides a mechanism to produce pre–3.9 Ga zircons, without calling for plate-tectonic–related or other mechanisms of crustal recycling to produce felsic rocks. While the impact melting at a single one of such Hadean impact "basins" would be impressive, the cumulative effects would be potentially staggering, particularly if impact velocities during Hadean time were, as believed, lower than current velocities. Based on the number of large multi-ring basins on the Moon scaled to terrestrial conditions, cumulative melt production on the Hadean Earth by such basins alone would reach ~10^{11}–10^{12} km^3. With the assumption that the impact melt pools were basaltic in composition, modeling with the crystal-melt fractionation software MELTS suggests the cumulative volume of felsic rocks potentially produced through the evolution of such impact melt pools could be significant.

Keywords: impact melting, multi-ring basin, differentiation, zircons, continental crust.

INTRODUCTION

It is a widely held view that the terrestrial planets were formed in an equivalent manner through the rapid accretion of planetismals, with the conversion of much of their kinetic energy to heat resulting in melting and the formation of magma oceans. In the case of the Earth, accretion is believed to have been completed ca. 30 Ma after the condensation of solids in the solar nebula (e.g., Kleine et al., 2002). Following accretion and separation of the initial crust and mantle through differentiation,

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the evolutionary paths of the terrestrial planets diverged depending on their thermal regime, size, gravitation acceleration, and the presence or not of water. It is also widely held that there is another commonality in the early evolution of the terrestrial planets, namely that following the formation of their initial crusts, they were subjected to continued intense impact at a variety of scales. There is, however, continued debate based on interpretations of the lunar impact record as to whether this flux of impacting bodies rapidly declined from 4.4 to 3.5 Ga (Hartmann et al., 2000; Neukum and Ivanov, 1994) or was punctuated by a period of intense bombardment at ca. 3.9 Ga (e.g., Tera et al., 1974; Kring and Cohen, 2002; Ryder, 2002; Koeberl, 2003).

No direct evidence of this period in Earth's evolutionary history, sometimes referred to as the Hadean, is preserved beyond some zircons with U-Pb ages greater than 3.9 Ga (e.g., Amelin et al., 2000). There are also some Lu-Hf isotopic data suggesting the formation of some felsic crustal rocks by ca. 4.3 Ga (Bizzarro et al., 2003), with some evidence also for possibly an earlier mafic protocrust (e.g., Chase and Patchett, 1988). Similarly, Sm-Nd isotopic data result in model ages compatible with large-scale, initial differentiation of the Earth's mantle relatively soon after planetary formation (Harper and Jacobsen, 1992). They also suggest that the protocrust may have been isolated from its mantle source and that crustal recycling in the early Hadean was relatively inefficient (Caro et al., 2003).

If reliance on relatively limited isotopic data to address issues of the evolution of the earliest crust of the Earth can be regarded as having a degree of uncertainty, then the effects of impact on the Hadean Earth must be considered highly speculative at best. Most discussions consider the evidence from the Moon as a proxy for the contemporaneous bombardment of Earth after scaling upward the numbers of impacts that result from the greater gravitational cross section of the Earth and for the higher impact velocity, due to the effect of the higher escape velocity of the Earth. Reasoned speculations as to the effects of such a bombardment on the Hadean Earth have included the frustration of the development and evolution of surface life (e.g., Maher and Stevenson, 1988; Chyba, 1993), the erosion of the atmosphere (e.g., Melosh and Vickery, 1989), and the evaporation of portions, if not all, of the hydrosphere (e.g., Sleep et al., 1989; Zahnle and Sleep, 1997). Models of the effects on terrestrial crustal evolution have generally made analogies with the effects of the formation of the large, multi-ring basins on the Moon (Fig. 1), albeit allowing for a thinner lithosphere and the presence of water on the Earth (e.g., Green, 1972; Frey, 1980; Grieve, 1980).

In this contribution, we present the case that the effects of very large impacts on the crusts of Hadean Earth and the Moon were not equivalent. This arises from the fact that in an impact event, the size of the transient cavity produced directly by the cratering flow field is a function of projectile size, impact velocity, the physical properties of the projectile and target, and planetary gravity. Planetary gravity acts to limit transient cavity growth and is thus relatively more effective in inhibiting growth on planetary bodies with higher gravity and in larger impacts (longer event times) on a given planet. The absolute rate of shock-wave attenuation and thus the distance from the point of impact at which the target rocks experience a specific shock pressure is a function of the same variables, with the exception that it is not a function of planetary gravity. The concept of this differential scaling with respect to the relative sizes and geometries of the transient cavity and the portion of the target that is melted is illustrated schematically in Figure 2. Here, we summarize the consequences of this differential scaling for the relative amount of impact melting and the nature of large terrestrial impact "basins" in the Hadean, compared to the lunar case, and offer some reasoned speculations on the evolution of such "basins" and their potential role in early crustal evolution on Earth.

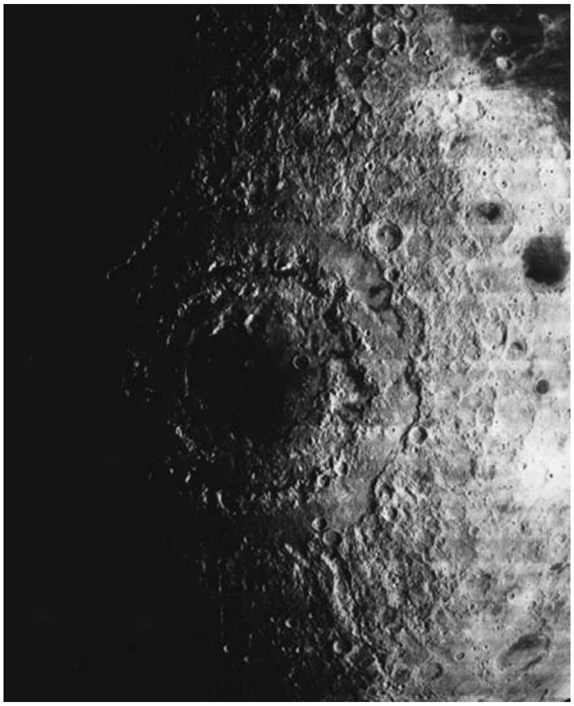

Figure 1. Multi-ring basin Orientale, which has a diameter of ~930 km as defined by the outer ring, the Cordillera mountains. Orientale is the youngest and best-preserved multi-ring basin on the Moon (Lunar Orbiter photograph).

DIFFERENCES BETWEEN THE EARTH AND THE MOON

In determining the first principles of the differences between very large impact events on the Earth and Moon, we have used a previously described thermodynamic model to estimate impact melt volumes (Grieve and Cintala, 1992, 1997; Cintala and Grieve, 1994, 1998). In this model, phase changes are determined by calculating the change in entropy, as a function of pressure, temperature, and density on the Hugoniots of

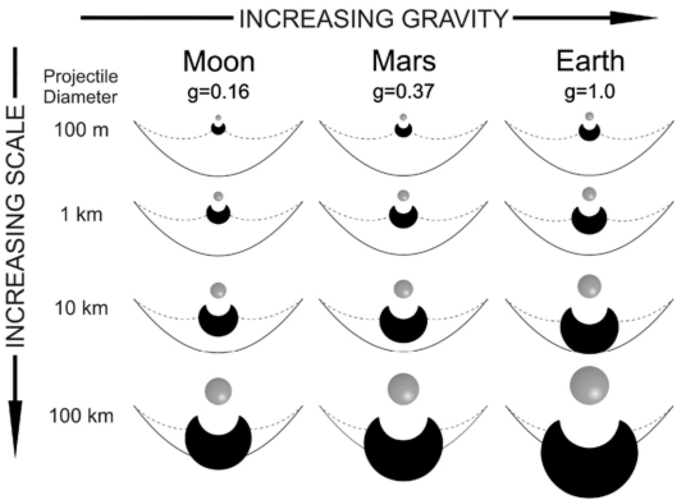

Figure 2. Schematic representation, scaled to transient cavity size, of the concept of differential scaling. Indicated are the relative sizes and geometries of impactor (gray), melt (black), transient cavity (solid line), and ejected volume (between dashed line and the ground surface), with increasing gravity (g) relative to the Earth (left to right) and/or increasing event size (top to bottom), all other impact parameters remaining fixed.

the projectile and target materials. The calculated impact melt and vapor volumes and decay of shock stress in the model are similar to those of more complex, finite-difference models (e.g., O'Keefe and Ahrens, 1977). The calculated melt volumes also compare favorably with empirical estimates of the volumes of impact melt rocks over seven orders of magnitude at terrestrial impact structures (Grieve and Cintala, 1992) and with more recent hydrocode calculations (Pierazzo et al., 1997).

Various materials can be used for the projectile and target through use of their modified Murnaghan equations of state (e.g., Duvall, 1958). To exemplify the first principles and "average" behavior, we have confined the model calculations to chondritic projectiles, which were approximated by the equation of state of basalt with a chondritic density of 3.58 g cm^{-3} (Grieve and Cintala, 1992). Other types of impacting bodies can be considered but for specific impact conditions, melt volumes produced by "chondritic" bodies are intermediate to those produced by ice and iron bodies and can be considered to represent an "average" volume (Cintala, 1992; Grieve and Cintala, 1992).

The target materials were assumed to be anorthosite for the Moon and basalt for the Earth, and all impacts were assumed to be vertical. In reality, the impact angle would vary and average 45°. Hydrocode modeling indicates that vertical impacts are the most efficient in producing impact melt, with the volume of impact melt decreasing by somewhat less than 20% at impact angles of 45° (Pierazzo and Melosh, 2000). While impact angle and impacting body composition are variables in determining melt production, their net average effect is small in comparison to melt production variations due to impact velocity variations and do not affect the basic conclusions and first-order principles outlined here. The model formulations and the values of the specific thermodynamic variables used have been given previously (Cintala, 1992; Grieve and Cintala, 1992; Cintala and Grieve, 1994) and are not repeated.

Transient cavity dimensions resulting from the impact conditions that yield specific melt volumes were modeled with the scaling relationships of Schmidt and Housen (1987). For the purposes of a standard geometric comparison and discussion, it was assumed that the transient cavity at its maximum growth in all directions defines an idealized paraboloid of revolution, with a depth-to-diameter ratio of 1:3, regardless of event size (Melosh, 1989; Turtle et al., 2005). Transient cavity diameters were scaled to final crater diameters, using the empirical "modification-scaling" relationship of Croft (1985). As this empirical scaling relationship was developed from observations of lunar impact structures with the diameter range from 30 km to 300 km, it likely degrades on extrapolation to very large impact structures such as multi-ring basins. There is also some debate as to what constitutes the rim-crest diameter and the relative location of the transient cavity at multi-ring basins (e.g., Spudis, 1993; Turtle et al., 2005). Nevertheless, for the purposes of comparison and facilitating visualization with respect to the sizes and appearance of known lunar multi-ring basins, the modification-scaling relationship is assumed to be valid, regardless of event size.

The exact details of the geometry of the volume in the target from which impact melts are initially generated are not known. The conditions imposed by the model, however, result in nearly spherical geometries, which are similar to those in other works (e.g., Croft, 1982; Melosh, 1989). The relative fraction of melt ejected from the transient cavity was not explicitly calculated for specific impact events. As gravity acts against the ejection process, the relative fraction of melt ejected decreases with higher planetary gravity and with increasing event size, i.e., longer times (Fig. 2; Melosh, 1989). While these details may affect the exact values of particular parameters, they do not negate the first-order principles of the relative changes in volumes and comparative initial spatial geometries of the impact melt and transient cavity, with the volume of melt increasing as approximately the fourth power of the transient cavity diameter and occupying an ever-increasing fraction of the transient cavity volume, as event size increases (Fig. 2).

Figure 3 illustrates the modeled changes in relative melt and transient cavity volumes for large impact events, with chondritic impactors, under lunar and terrestrial gravity at an impact velocity of 20 km s^{-1}. In the case of the Earth (target-basalt), the impact melt volume exceeds that of the transient cavity at transient cavity diameters >500 km (Fig. 3). This condition is not reached on the Moon (target-anorthosite) until transient cavity diameters are >3000 km (Fig. 3), which is essentially equivalent to whole-Moon melting (radius 1738 km). The melt volumes in these very large impact events are minimum estimates for the specified model impact conditions, as at these

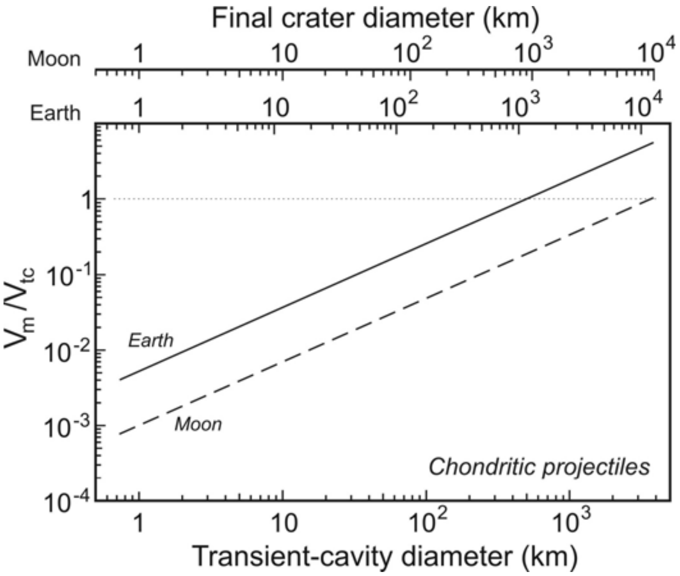

Figure 3. Logarithmic plot of the variation in the ratio of the volume of melt (V_m) to the volume of transient cavity (V_{tc}) with transient cavity (lower horizontal scale) and/or final crater (upper horizontal scale) diameter for the Earth (target-basalt) and the Moon (target-anorthosite), for chondritic impactors at an impact velocity of 20 km s^{-1}. See text for details and implications.

sizes the increase in temperature of the target rocks with depth, due to the geotherm, will increase overall melt production (Ivanov and Melosh, 2003).

Also shown in Figure 3 are the equivalent final crater diameters for structures on the Earth and Moon, using the modification-scaling relationship of Croft (1985). The canonical lunar multi-ring basin is Orientale, with a generally quoted rim diameter of ~930 km (Fig. 1; Spudis, 1993). A potentially equivalent-sized "basin" on the Earth would correspond to the situation in which the transient cavity and impact melt volumes were approximately equivalent (Fig. 3). Given that such a transient cavity on Earth is largely within material with no strength (i.e., melt; Fig. 2), it is not likely that Croft's modification-scaling relationship is applicable, as noted earlier. Nevertheless, it is clear that an impact event of such a size on the Hadean Earth would not result in an impact basin with the form of Orientale (Fig. 1) even with the appropriately scaled reduction in topography due to the higher terrestrial gravity. If the early terrestrial lithosphere was relatively thin, tectonic ring theory (McKinnon and Melosh, 1980; Melosh, 1989) could favor Valhalla-like structures as observed on Callisto, with multiple external graben features as the final form. This, however, is speculative. While the detailed final form of impact structures at such scales on the Hadean Earth may be unknown, an essential feature of such structures would have been a very voluminous central melt pool.

While impacts sufficient to produce an Orientale-size, multi-ring basin on the Moon did not produce similar multi-ring basin morphologies on the Earth, this is not equivalent to stating that no lunarlike, multi-ring basins were formed on the Hadean Earth. Smaller impact events are likely to have produced the more classic multi-ring basin form. For example, the three largest known terrestrial impact structures, Chicxulub, Sudbury, and Vredefort, with estimated original diameters in the 200–300 km range, have been ascribed some attributes of multi-ring basins (e.g., Morgan and Warner, 1999; Stöffler et al., 1994; Therriault et al., 1997). It is not clear, however, how their various attributed annuli correspond, in detail, to the obvious topographic rings observed in lunar multi-ring basins (Grieve and Therriault, 2000). Lunarlike, multi-ring basin forms (Alexopolous and McKinnon, 1994) for the four largest impact structures on Venus (i.e., Klenova, Meitner, Mead, and Isabella; ~150–270 km in diameter) are probably the best evidence for the case of lunarlike, multi-ring basins on the Hadean Earth, given the similar planetary gravities. At these size ranges, the amount of impact melting within the transient cavity approaches or exceeds the depth of the cavity but is only on the order of 30%–40% of the volume of the transient cavity (Fig. 3).

While no real case can be made for impact-induced volcanism by decompression melting in the Archean and younger Earth (e.g., Ivanov and Melosh, 2003), this may not be the case for the Hadean Earth. In addition to direct impact melting, recent model calculations indicate that subsolidus shock heating from post-accretion impacts could raise the temperature of the lithosphere by 200–400 °C, relative to the geotherm (Ivanov, 2004). Depending on the lithospheric thickness, there may be a contribution from shock heating to the underlying asthenosphere sufficient to overcome the latent heat of fusion. It would be possible to evaluate the extent of this contribution to impact-related melting if the thermal structure of the Hadean Earth and, more importantly, the post-impact, geometric configuration of the subsurface isotherms beneath such Hadean impact "basins" were known, as they determine the post-impact pressure and temperature (impact plus geotherm) relations (Ivanov and Melosh, 2003). As the Hadean "basins" are unlike known large, terrestrial complex impact structures or the traditional multi-ring basins of the Moon, this post-impact subsurface geometry is unknown. Accordingly, and as we are illustrating first-order principles, no attempt has been made to model this potential effect, and it is offered only as a possibility for the production of additional melted material, as a result of these very large impacts on the Hadean Earth.

Cumulative Effects

We have assumed that the earliest crust of the Earth was a partial melt of the mantle, i.e., basaltic in composition. Therefore, the composition of the massive impact melt pools, which were a principal feature of these large Hadean impact "basins," would have ranged from basaltic to more mafic compositions for the largest events, where the melt volume could have reached into the mantle. The depth of the melt pools within these "basins" is unknown, as the final post-modification configuration and form of the "basins" is unknown. The depths would have been variable and in the range of many kilometers to many tens of kilometers. What seems clear is that the surface and crust of the Hadean Earth would have had extensive and voluminous impact-produced melt pools of mafic composition (Fig. 4). Given the appropriate cooling times, bodies of basaltic melt >300 m thick differentiate in the terrestrial environment, with the potential degree of differentiation being a function of the thickness of the body (Jaupart and Tait, 1995). It is therefore expected that these thick, closed-system melt pools would have differentiated into an ultramafic-mafic base and a more felsic top, much in the same manner as the ~2.5-km-thick impact melt sheet, now manifested as the Sudbury Igneous Complex, at the originally ~200–250 km diameter Sudbury impact structure, Canada (Therriault et al., 2002). The results of individual impacts on the Hadean Earth would have been impressive. For example, a terrestrial impact event with the magnitude of the one that resulted in the Orientale basin on the Moon would have generated in excess of 10^7 km^3 of impact melt. If only 10% of the initial melt volume took the form of felsic differentiates, they would have been comparable in volume to the Columbia River basalts (Swanson et al., 1989).

In order to derive some sense of the cumulative effects of these impacts on Hadean crustal evolution, we used the number of well-known impact basins on the Moon as a starting point. Spudis (1993) provided an inventory of multi-ring basins on the Moon, and the 10 identified basins with diameters (main topographic ring) >700 km were used to calculate the numbers of similar-sized impacts on the Hadean Earth. The relative numbers of impacts on the Earth and Moon are a function of their relative gravitational cross sections, which are, in turn, a function of impact velocity. The result of the calculation of the relative gravitational cross sections for impact velocities of 7.5, 10, and 15 km s^{-1} on the Moon and the equivalent terrestrial impact velocities are given in Table 1. At the higher impact velocities, which are similar to today's average asteroidal impact velocities, the Earth would receive ~25 impacts of comparable magnitude for every lunar impact. It is generally held, however, that impact velocities in the solar system have increased with time (Wetherill, 1975), due to the action of gravitational forces. The lower impact velocities and considerably larger ratios for the gravitational cross sections are likely more appropriate for Hadean times on Earth.

To calculate the appropriate cumulative amount of impact melt produced by the scaled numbers of terrestrial impacts, it was necessary to estimate the size distribution of impacting bodies for the various specified impact velocities as follows.

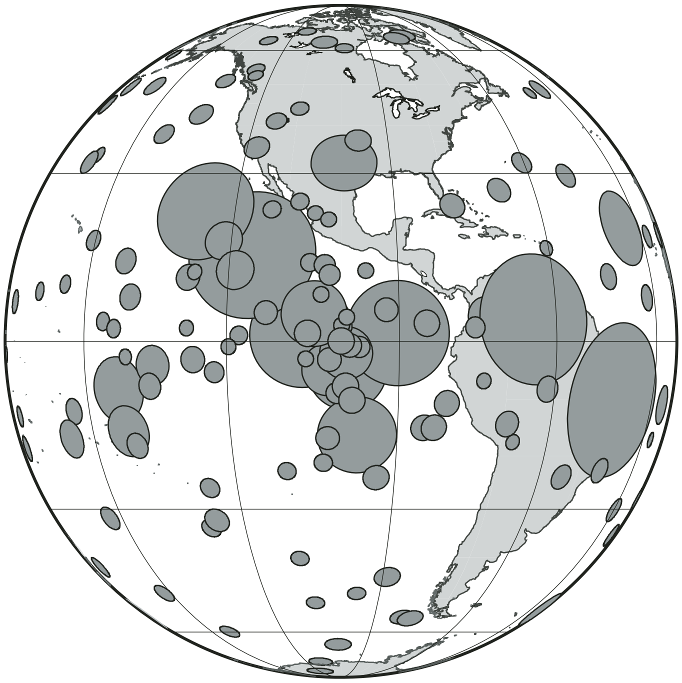

Figure 4. Cartoon of the number of impact melt pools (approximated by transient cavity diameters), in which melt volumes exceed transient cavity volumes, on the Hadean Earth for the minimizing condition of an impact velocity of 22.4 km s^{-1} (Table 2). The number of potential terrestrial impact basins (melt pools) was based on the lunar record of multi-ring basins formed at ca. 4.5–3.8 Ga (see text for details of the transformation to terrestrial conditions). Locations of melt pools were generated by random numbers, and current land mass is shown for comparison.

The transient cavity diameter for each of the 10 lunar basins was estimated from the "modification-scaling" relationship of Croft (1985). The scaling relationships of Schmidt and Housen (1987) were then applied to determine the diameter of the assumed spherical chondritic impactor that made each of those transient cavities, for each assumed lunar impact velocity (Table 1). The intrinsic approach velocity, v_∞, corresponding to each impact velocity, was then extracted by taking into account the lunar escape velocity and the escape velocity of the Earth (at the current lunar distance).

As each assumed impact velocity generates a different size distribution of impactors, a least-squares fit was applied to each set of 10 lunar impactors. Those fits were then used in calculating the impacting population for the Earth for each value of the impact velocity corresponding to the different v_∞ and resulting

TABLE 1. RELATIVE GRAVITATIONAL CROSS SECTIONS AND TERRESTRIAL IMPACT VELOCITIES FOR SPECIFIC LUNAR IMPACT VELOCITIES

V_i, Impact velocity, Moon (km s^{-1})	V_i, Impact velocity, Earth (km s^{-1})	Gravitational cross section, Moon (km^2)	Gravitational cross section, Earth (km^2)	Ratio cross-sectional areas, Earth/Moon
7.5	14.9	1.34×10^7	1.29×10^9	96.14
10	17.4	1.09×10^7	5.41×10^8	49.76
15	22.4	9.91×10^6	2.54×10^8	25.76

different capture cross sections. For instance, 10 km s^{-1} lunar impacts correspond to terrestrial impacts at 17.4 km s^{-1}, because of the greater terrestrial mass, and the resulting terrestrial capture cross section would then be almost 50 times greater than that of the Moon. The least-squares fit to the cumulative number of impactors as a function of impactor diameter gives a diameter of 66.5 km for the body that, at 10 km s^{-1}, created the smallest lunar basin, Tsiolkovsky-Stark, on the list of Spudis (1993). As there were 10 lunar impactors of this size or larger, it is assumed from the ratio of cross-sectional areas that there were 498 terrestrial impactors of this size or larger. It is then a straightforward process to apply the least-squares fit incrementally to each impactor to calculate its size.

Recently, Petro and Pieters (2004) estimated the transient cavity diameters of 42 lunar basins, ranging in rim diameter from ~365 km to 1100 km, based on a mean trend derived from the geophysical constraints of Wieczorek and Phillips (1999). At basins the size of Tsiolkovsky-Stark (~700 km), the transient cavity diameter estimates of Petro and Pieters (2004) are similar to those used here, based on the "modification scaling" relationship of Croft (1985). At diameters equivalent to that of Imbrium (~1160 km), the transient cavity diameter estimates of Petro and Pieters (2004) are ~25% larger than those used here and would therefore require larger impactors for a given impact velocity. The size of the impactors used here, therefore, could be considered a set of minimum estimates.

Having the size distributions and impact velocities for the impactors, the sizes of the transient cavities and the accompanying volumes of impact melt can be calculated for the different terrestrial impacting populations. The cumulative melt volumes for those terrestrial impact events, in which the impact melt volumes equal or exceed the transient cavity volume, are given in Table 2 for the various impact velocities. Although higher impact velocities in a single event result in the production of relatively more impact melt, the net effect of the increase in the relative gravitational cross-section ratio with lower impact velocities (Table 1) results in a larger number of individual impact events and a considerably larger cumulative volume of impact melt having been produced on the Hadean Earth (Fig. 5; Table 2).

TABLE 2. CUMULATIVE IMPACT MELT VOLUMES FOR IMPACTS ON THE HADEAN EARTH, IN WHICH MELT VOLUMES EQUAL OR EXCEED TRANSIENT CAVITY VOLUMES

V_i (km s^{-1})	Cumulative impact melt volumes (km^3)
14.9	1.31×10^{12}
17.4	3.25×10^{11}
22.4	7.87×10^{10}

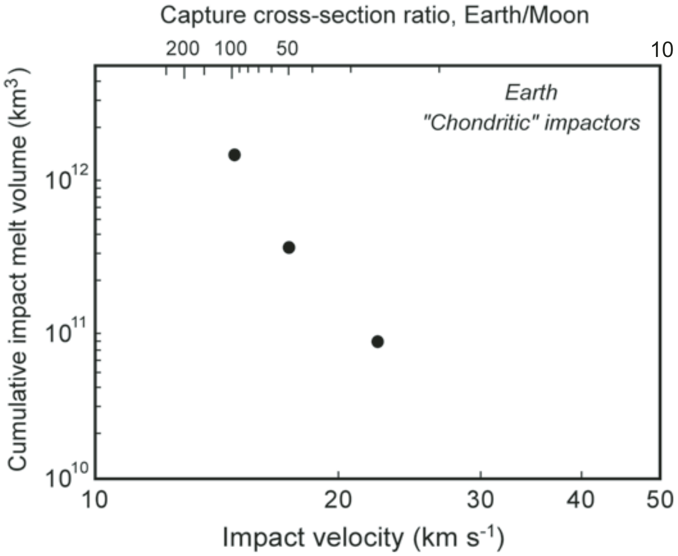

Figure 5. Logarithmic plot of cumulative volumes of impact melt produced on the Hadean Earth, in which melt volumes exceed transient cavity volumes, as a function of impact velocity (lower horizontal scale) and/or capture cross-section ratio (upper horizontal scale) of the Earth/Moon (Table 2).

POST-IMPACT EVOLUTION

It is a widely held view that impact melts are a compositionally homogenous mixture of the target lithologies that were shock-melted. While this is true for impacts that result in impact structures in the size range of tens of kilometers (e.g., Grieve et al., 1977; Koeberl and Reimold, 2003), it does not necessarily hold for very large impact structures. For example, small compositional variations in impact melt rocks are evident at some terrestrial impact structures 100 km in diameter (Grieve and Floran, 1978; Kettrup et al., 2003). Some of this compositional variation may be due to the assimilation of different populations of lithic and mineral clasts. In the very large impact events under consideration here, however, the absolute distances are so large that differential particle velocities within the melted volume were likely insufficient to result in complete homogenization. Accordingly, and in keeping with the spirit of dealing only with first-order principles, the post-impact evolution of the melt pools within these Hadean impact "basins" was modeled as if the melts had the composition of basalt.

The use of the crystal-melt fractional modeling procedures in the software MELTS (Ghiorso and Sack, 1995) indicates that if differentiation were 100% efficient, crystallizing basaltic liquid at a pressure of 0.1 GPa would produce a residual liquid of tonalitic composition at 1200–900 °C on the quartz-fayalite-magnetite (QFM-1) buffer, with a volume of ~20%–30% of that of the original basaltic liquid. For the purposes of illustration here, it is assumed that differentiation is only 10% efficient at physically separating crystallizing phases and residual liquid. For the end-member estimates of the cumulative volumes of impact melt produced in these large Hadean "basins" (Table 2), this corresponds to a potential volume of ~1.5×10^8 km^3 to 4×10^9 km^3 of tonalitic magma. This can be compared to the volume of the present-day continental crust of ~8×10^9 km^3. These estimates for the model conditions used here are best regarded as upper limits. In reality, the largest Hadean impact events would result in impact melts more mafic than basalt in terms of average initial composition, while others would overlap spatially (Fig. 4), and some of the Hadean crust would be impact-melted and subsequently differentiated more than once.

Whatever the case, it is apparent that the model considerations here raise the possibility of considerable volumes of felsic rock being generated in a near-surface environment, even at 1% differentiation efficiency of an initial basaltic composition for these Hadean impact melts. These felsic differentiates could provide a source for pre–3.9 Ga zircons, without necessitating the recycling of an initial basaltic crust. Impact melt systems are also closed systems and preserve the isotopic signatures of the preexisting target rocks in such isotopic systems as Nd-Sm and Re-Os, while resetting isotopic clocks such as U-Pb (e.g., Deutsch, 1994; Dickin et al., 1999; Morgan et al., 2002).

Neither the effects of these large-scale impacts nor the evolution of the Earth's crust by internally driven processes existed in isolation during the Hadean. The Earth differs from the other terrestrial planets in having both oceanic and continental crust with subduction zones and plate tectonics, providing the physical environment for the production of continental crust throughout most of Earth's post-Hadean history. The presence of water is essential in the production of continental crust by the subduction of hydrated oceanic crust (Stern, 2002) and appears critical in reducing the strength of the lithosphere to permit plate tectonics to operate in the first place (Solomatov, 2003). The onset and character of the earliest generation of continental crust through the regime of plate tectonics is speculative, but the partial melting of subducted or delaminated, hydrated, and metamorphosed oceanic crust beneath more buoyant crust is the common theme for the production of early tonalitic and trondhjemetic rocks (e.g., Foley et al., 2002, 2003; Rapp et al., 2003). While the crystallized impact melt pools with their upper felsic differentiates would not inherently have had a lower density, delamination of their mafic lower regions could have produced residual blocks of more buoyant, felsic rocks. If this occurred, one could speculate that such buoyant crustal blocks could also possibly have played a role in the onset and development of protocontinental crust, through some form of regime more akin to traditional plate tectonics.

CONCLUDING REMARKS

It has been suggested that the lack of preservation of pre–3.9 Ga rocks on Earth was due to destruction by impact bombardment (e.g., Nutman et al., 2001). While the experience of the preserved lithologies from the lunar highlands in the Apollo collection would suggest that this would be unlikely, the sense of the massive amount of impact melting in the Hadean suggested here calls for a decidedly nonlunar case for the Earth. If the impact bombardment was punctuated at ca. 3.9 Ga (Tera et al., 1974; Kring and Cohen, 2002; Ryder, 2002), it conjures the scenario of a period of massive crustal remelting or reprocessing at ca. 3.9 Ga on the Hadean Earth. The lack of preservation, however, of terrestrial rocks from this period, including any that can be attributed directly to impact [assuming they could be recognized as such (Grieve et al., 1991)], is a testament to the powerful endogenic geologic processes that have shaped subsequent terrestrial crustal evolution. While this work has focused on the effects of large impacts on the Hadean crust, these endogenic forces must have been operating in the Hadean, and what is presented here would be incremental to the effects of endogenic terrestrial geologic processes.

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