6. Discussion

Impact craters are important tools for the study of planetary surfaces, processes that affect surfaces, surface ages, properties of planetary crusts or near-surface material, impact physics, and impact flux through time. Specifically for the work presented here, I constructed a new global Martian crater database and analyzed the global and regional crater properties in several of those applications. The database contains a large amount of detailed positional, geometric, and topographic data as well as descriptive interior morphologies, degradation states, and ejecta morphologies and morphometries. These parameters informed the various studies presented here, but they are also generalizable to dozens more that should make this database a useful contribution to the planetary science community for many years.

In proving this database, I explored a large number of previously observed trends. The global distributions of all craters, fresh craters, craters with central peaks, pits, or summit pits, and craters with dunes emplaced were all examined and compared with previous work. The results were comparable and validate this catalog in light of other published results in these areas.

I performed five major analyses of the craters in this database or related work, presented in this thesis. The first deals with the quantification of crater depth-to-diameter ratios, a relationship which is dominated by the collapse process of a crater under gravity but controlled by the strength of the surface. These have been examined previously with coarser data, isolated sub-regions, or other more limited methods. My work is the first to examine this with a global dataset with full morphologic and modification state discriminators. I used the large numbers of craters to examine this relationship of crater depth/Diameter across the entire globe and then by latitude range and terrain type, and mine is the first to compare three different groups of craters in this kind of study – all craters, fresh craters, and the deepest craters. The bulk of the results were incremental updates from previous work in the field and summarized in Table **5**. The three main new results from this examination were that particularly deep craters are found in northern

Chryse basin (in addition to southern Utopia and Isidis which had been known before), the equatorial/polar dichotomy of depth/Diameter ratio is not completely mirrored across the equator but the northern and southern hemispheres display some significant differences (Fig. **28**), and craters at both high latitudes and on just polar terrain are significantly shallower than elsewhere on the planet but increase in depth more rapidly as a function of diameter than the general population. The first new finding is likely explained by lithologic, volcanic, or fine-grained material that can support deeper craters. The second is probably due to differences in crustal and/or ice table thickness. The third finding is explained below in the context of the simple-to-complex crater transition.

The second substantial analysis I conducted with this database was to reexamine the transition between simple and complex craters – simple craters being the classic bowl-shaped type while complex craters form from a larger impact that, because of its size, will experience a broad rebound that creates a flat floor, can undergo collapse circumferential to its rim and show terraces, and/or have an elastic rebound in the center that creates a central peak. Basic cratering physics indicates this is a process significantly dominated by the surface gravity of the object being impacted, but the surface strength has secondary control. Pike (1988) showed this with a finality that has caused people to test his work for the past two decades, revising and refining the basic numbers. In that tradition, this database was used to examine the transition between simple and complex craters based on several different criteria. This is another incremental/revisional result from this database. The final value of ~6.0 km agreed very well with Pike (1988), but it clearly showed there is a terrain dependence of this transition diameter on the planet wherein polar craters had a significantly larger transition diameter (Figs. **31**, **32**). This new result, in the context of the crater depth/Diameter values, led to my proposal of a formation mechanism for these shallow yet large simple high latitude / polar craters: A crater forming in a volatile-rich surface with vaporize nearby and melt them farther away, weakening the crust so that it cannot support a deep crater cavity nor form typical complex crater characteristics.

The third and fourth major results from this database both deal with secondary craters because of the significant application of crater counting to age-dating surfaces. The basic assumption of age dating is that older surfaces will have a higher density of craters. This assumption requires that (a) cratering be stochastic with time but occur at a predictable rate on average, and (b) cratering be independent with location on the surface such that any given area is as likely as another to be impacted and form a crater. The process of secondary craters belies these: Secondary craters form when large, cohesive ejecta blocks from a primary impact event are launched with sufficient energy to form more craters when they land. Secondary crater formation at this basic level is well understood in theory, but significant observational and experimental work in characterizing secondary craters is lacking. Observations of the distribution of the secondary crater population relative to the primary and the size-frequency distribution of these is an ongoing topic of crater studies: No unified model yet exists that can adequately predict the size distribution of secondary craters from any given primary nor the geographic distribution of where to expect these enigmatic craters. To this end, the global database was used to study two different types of secondary craters – distant clusters and nearby fields.

The former is the third main study discussed in this thesis. In Robbins and Hynek (2011a) (Section 4.1, this thesis), I showed that a single large impact crater on Mars - Lyot Crater - can produce $>10^4$ secondary craters $D \geq 1$ km and emplace clusters of them over 5000 km from the primary – 25% of the way across the planet. While this has been known to happen on the Moon (*e.g.*, Wilhelms *et al.*, 1978) which has a smaller diameter and lower surface gravity, showing this was possible under a larger gravity field had not yet been accomplished. The only previous in-depth case study on Mars examined Zunil Crater (*e.g.*, Preblich *et al.*, 2007) and its distribution is dissimilar to Lyot's. More case studies of distant secondary crater fields are needed in order to develop any model to explain their characteristics. My findings for Lyot show that even if these secondary craters were not from Lyot and their properties are not typical of distant secondary crater clusters, one cannot assume they are "safe" from secondary crater contamination even if there is no large primary crater for hundreds or even thousands of kilometers, even if they are using only kilometer-scale craters. This has the potential to significantly affect geologic mapping, stratigraphic relationships, and any age-dating work via crater counting.

The fourth main analysis examined secondary craters, as well, where I studied 24 primary craters' nearby secondary crater fields in Robbins and Hynek (2011d) (Section 4.2, this thesis). I used the database in the first-of-its-kind global, uniform study of the statistical distribution and properties of secondary crater fields near to their primary crater. The results (Table **7**) showed a general variation between different fields though there were a few generalizable trends and properties. The trends suggest the diameter and geographic distributions of secondary craters relative to their primary crater may be dependent upon terrain type, in support of previous work by Hartmann and Barlow (2006). At a practical level, the work showed that nearby secondary craters have a predictable distribution of where they are on the planet's surface and hence one may be able to account for them by automated means without characterizing every crater as either a primary or secondary. This can speed the modeling of surface ages and estimates of primary crater populations, for it was found to be valid for crater diameters ranging from 5 to 220 km. An extension of this is that particularly large craters - such as Holden Crater with $D \approx 150$ km - will have a secondary crater field that affects a large region of the planet's surface (>3% in Holden's case) and these secondary craters contaminate the crater statistics at diameters larger than 1 km.

With this in mind, the final work in this thesis addressed the age-old application of craters to date surfaces via the additional identification of order 10^5 small craters within major volcanic calderas on the planet to reconstruct the "last gasps" of major summit volcanism for Mars. This was also an incremental result, revising some numbers appearing recently in the literature (mainly Neukum *et al.*, 2004, and Werner, 2009), but in a more uniform application of *just* age-dating the last eruptive events from the Martian volcanic calderas: Mars has 24 primary shield volcanoes, and the calderas of 20 were geologically mapped and high-resolution imagery allowed the identification of craters as small as a few 10s of meters in diameter (the remaining four lack adequate high-resolution coverage). While relative age dating was done at a basic level to show which calderas were older than others, the frequency of craters was compared with established isochrons from the literature (Neukum *et al.*, 2001) to estimate model ages for the surfaces. This chronology system was chosen because it was used in all of our comparisons with ages in the published literature. These were reconstructed into a timeline for each volcano (Fig. **57**) and then combined to give an overview of the major eruptive timeline from each volcanic summit over Mars' history (Fig. **59**). The results agree with previous work that argue for early, widespread volcanism across the planet that steadily became more localized until the most recent eruptive events from the youngest calderas occurred approximately 100-150 million years ago from the large Tharsis montes.

The work throughout this thesis and their applications show a sample of the wide range of studies that can be done with craters, but they can be simplified back to the fundamentals: (1) Craters show that terrains on planets have different properties and (2) different ages, and (3) they can be used to refine our models and understanding of the physics that governs the impact process. Bringing the application closer to home in terms of planetary hazards, knowing more about craters can impact our survival because they inform the population and frequency of extraplanetary impactors. The scaling laws derived from observations, models, and experiments allow for an informed assessment of risk from an approaching bolide. From a military standpoint, understanding craters formed by bombs and missiles is the same as that from an extraplanetary impactor and, historically, those on the forefront of studying craters were employed by the U.S. Department of Defense (*i.e.*, Eugene Shoemaker and David Roddy) and studied bomb detonation sites. Beyond this, though, studying impact craters furthers our knowledge of planetary surface properties under different regimes and criteria, whereby a greater understanding of their characteristics under different environments and circumstances constrains our knowledge of how they form, what they inform us about the surface, and other questions of basic science intrigue.