interval required to form the EE population when the necessary icy deposit was emplaced. The time needed to form the observed population is necessarily greater than ∼200 Myr because the ice-rich material is not currently present and a robust solution for the last 20 Myr of martian obliquity history shows low obliquity periods for the last 3–5 Myr, and potentially widely variable obliquity for the last 250 Myr (Laskar et al., 2004). Given the rarity of EE – only 10 of the 572 fresh craters measured by Black and Stewart (2008) qualified – and the 200 Myr formation timescale, Black and Stewart (2008) suggest that EE production is associated with an episodic phenomenon. They conclude that EE ages are likely to have spanned the Amazonian period, forming in conjunction with multiple distinct ice-emplacement episodes, and that the fresh appearance of EE supports the interpretation that they are young (Black and Stewart, 2008).

The dating of Pr is complicated by the fact that the ejecta deposits have undergone noticeable modification, including mantling, burial and morphologic degradation. If the crater interior has been filled by a significant volume of sediment, then it is reasonable to believe that material has also accumulated on the ejecta deposits. This process also infills and erases craters, leading to the calculation of artificially young ages. Because of this, the age range of Pr is not well defined. Their degraded states strongly imply that they are older than EE. Boyce et al. (2005) used stratigraphic relationships between Pr and the Vastitas Borealis Formation to determine that Pr are likely Late Hesperian or Early Amazonian in age.

The timescale of formation of Pd was calculated using the mid-latitude Pd population and the corresponding area on which they formed. Similar to the EE time interval, this method leads to a derived formation timescale of approximately 100 Myr (Kadish et al., 2009). Using the same logic outlined for the accumulation of EE, this result implies that Pd are likely to have formed throughout the Amazonian during episodic periods of mid-latitude ice-rich deposits. The episodic emplacement of Pd has also been confirmed by stratigraphic relationships in which one Pd is partially draped over another Pd (Kadish et al., 2010). Additional work on dating 50 individual pedestal surfaces revealed that 70% of those measured are younger than 250 Myr. These individual ages are, however, lower-limit calculations due to modification and resurfacing of the pedestals. In addition, 20% of the pedestal surfaces were calculated to be more than 1 Gyr in age. These examples appear significantly more degraded, and show evidence of infilling of their crater interiors, similar to the morphology of Pr.

The combination of these dating efforts for each of the three crater types provides a general timeline for their formation. The probable recurrence of the ice-rich paleodeposit from which EE, Pr, and Pd form suggests that none of the populations resulted from a single phase. In addition, multiple crater types may have formed from the same phase. Despite these possible overlaps and extended formation timescales, it is likely that Pr are generally the oldest of the three morphologies. Pr consistently display the most degradation, and the observation that some show partial burial by the Vastitas Borealis Formation implies a Hesperian age. Pd appear to be generally young (tens to a few hundred Myr), but some individual examples show that they can be much older (a few Gyr). As a population, EE are necessarily fresh and are likely to be the youngest of the crater types.

6. Geographic distribution comparison

The initial survey for EE by Black and Stewart (2008) noted that, within the study region, nine of the 10 EE identified were located in Utopia Planitia (Fig. 10). The only other EE was located in Acidalia Planitia. Black and Stewart (2008) also identified nine moderately excess ejecta craters (MEE), with $V_{\mathrm{above}}/V_{\mathrm{cavity}}$ between 2 and 2.5, five of which were in Utopia, three in Acidalia, and one in Isidis. Due to the common modification of craters near the poles from mantling, high latitudes were not included in the study. As such, the limited latitudinal range at which EE were identified, primarily between 32°N and 44°N, is not a comprehensive assessment of the distribution of EE. Black and Stewart (2008) specifically note that it is likely that other EE have formed in their study region, but have subsequently been modified and/or degraded, and that many EE may exist outside their survey area.

Surveys detailing the distribution of Pr also covered regions exclusively in the northern hemisphere (Boyce et al., 2005; Meresse et al., 2006). These studies found that the highest concentrations of Pr are in Utopia, Acidalia, and Arcadia Planitia between 40°N and 55°N (Fig. 10), but they have been identified as far south as 25°N. Given the sheer number of confirmed Pr – 414 in the limited survey area of Boyce et al. (2005) – it is clear that they are significantly more common than EE. Fig. 10 shows that both Pr and EE are most heavily concentrated in Utopia and somewhat less so in Acidalia, with only Pr being present in Arcadia. As we will show in the following section, both EE and Pr are present, but less common, in the southern hemisphere of Mars.

The distribution of more than 2300 Pd larger than 0.7 km in diameter has been well established between 60°S and 60°N (Kadish et al., 2009). This study shows that, like EE and Pr, the highest populations of northern hemisphere Pd are in Utopia and Acidalia. Pd are also concentrated in Arcadia (Fig. 10). Of the Pd measured, four times as many exist in the northern hemisphere than in the southern hemisphere. Those that are present south of the equator tend to be focused in Malea Planum, with much smaller populations in Terra Cimmeria and Terra Sirenum. Latitudinally, Pd extend as far equatorward as 33°N and 40°S. Subsequent high-latitude studies have confirmed that Pd are common near the poles, and can even form on the polar caps (Kadish and Head, 2011). These data confirm that, of the three crater morphologies, Pd are the most common and widespread (Fig. 10).

7. New examples of excess ejecta craters

Due to the geographic limitations of previous surveys for EE and Pr, as outlined in Section 2, we expanded the search for these crater morphologies into the southern hemisphere. This was necessary in order to provide a more complete geographic comparison of the locations in which EE, Pr, and Pd are capable of forming, an observation that is a key aspect of understanding the relationship between the crater types. We performed a survey from 0° to 70°S using a THEMIS IR mosaic and MOLA altimetry. The combination of images and topography allowed us to select fresh craters, as well as some that had both the crater interior and ejecta perched above the surrounding plains.

Fresh craters with clear ejecta were generally included down to 2 km in diameter unless good quality CTX coverage was available, and then we were able to measure some smaller examples. This cutoff was necessary because, without high resolution images of small craters, it is not possible to confirm that they are fresh. Some craters that would classify as both Pr and Pd were previously identified in the southern hemisphere from the Kadish et al. (2009) survey for Pd. We expanded the search for new examples of Pr that would not be classified as Pd. Overall, our analysis revealed that EE, like Pd, are much rarer in the southern hemisphere, and Pr are similarly uncommon.

Using high resolution HRSC DTMs (50–150 m/pix resolution) and 1/128 degree gridded MOLA data (463 m/pix), we created eight profiles of each fresh crater we studied. This was done to identify and compensate for outliers. Although these two datasets have significantly different resolutions, they produced remarkably