TESTING THE PSEUDOCRATER HYPOTHESIS. M. C. Payne[1] and J. D. Farmer[1], [1]Arizona State University (Department of Geological Sciences, PO Box 1404, Tempe, AZ 85287, mcpayne@asu.edu, jfarmer@asu.edu)

Introduction: In a regional study of the margin of the north polar cap, a field of coniform features was observed in the Olympia Planitia region and hypothesized to be a pseudocrater field (Figure 1). Volcano-ice features located at the margin of a polar cap has great significance for astrobiology. Such interactions could provide potential shallow subsurface habitable zones of liquid meltwater, as well as a mechanism for transporting a subsurface biota into near-surface environments via convecting hydrothermal systems. Such a biota, or prebiotic organic chemistry, could be subsequently cryopreserved in shallow polar ground ice formed as such systems cooled and died. In this study, a number of methods were employed to test the pseudocrater hypothesis, including feature profiling (using MOLA data), geomorphic measurements (e.g. crater diameter/ cone diameter ratios), nearest neighbor analysis, and comparisons to potential terrestrial analogs. Candidate analog terrestrial landforms studied included Icelandic pseudocraters, cinder cones, shield volcanoes, maar craters, pingos, and hummocky moraine. Comparisons were also made with martian rampart craters, and features previously interpreted as martian pseudocraters.

Description of Knobby Terrain: On the margin of the remnant ice cap of the north pole, centered at approximately 75°N latitude, 216°W longitude, lies a region of partially ice-covered hummocky terrain. The knobby topography covers an extensive region marginal to the remnant north polar cap and extending south to ~70° N latitude. Portions of this knobby terrain are visible in Viking image 063B21 (Figure 1). The knobs have very low relief, although central craters are present at the summits of many of the larger features. The knobs sit on pedestal-like surfaces that are raised above the surrounding polar plains. Elevation measurements made using a Digital Elevation Model (DEM) (constructed from MOLA data) indicate that the bases of the knobs are raised on average, 5-10 m above the surrounding terrain. Associated linear features may be fissure-ridges.

As previously mentioned, the knobs appear to be roughly coniform in nature, many of the larger forms having summit craters of circular to elliptical form. Poor resolution may account for the seeming absence of central craters in the smaller knobs.

Resolution played an important role in the interpretations of the features. In general, the enhanced resolution (~58 m/pixel) of the Viking image for the area proved more helpful than the DEM, which had a spatial resolution of ~230 m/pixel.

Comparisons with Analog Landforms: A number of volcanic, as well as cold climate landforms, were proposed as potential analogs for the field of coniform features at the study site. Methods for the analysis of these features were adapted from previous authors [1-4]. A brief overview of the analysis of the observed coniform features and comparisons with potential analog landforms follows.

Rampart craters. Figure 2 compares MOLA profiles of two rampart craters present on the nearby northern plains of Mars near the study site, with a profile of Meteor Crater (a small terrestrial impact crater), and the knobby features at the study site. There are clear profile differences observed between each of these features. A nearest neighbor analysis of the knobby features yielded a random distribution expected for impact craters, but the geomorphology of these features, as noted above, suggests a different origin.

Volcanoes. The random distribution pattern for the knobby features, established through nearest neighbor analysis, is consistent with a volcanic origin, as there is no reason, *a priori*, to assume that the conduits from a magma body should organize themselves in a systematic (non-random) pattern. In MOLA profiles, slopes of the knobby features range from 0.01 to 0.02. Comparable terrestrial low shield volcanoes, such as Sandfell volcano in Iceland, have similar slopes. However, the average crater diameter/cone diameter ratio for the knobby features is 0.39, which is most similar to the value for terrestrial cinder cones (~0.40) and not shield volcanoes (0.06-0.12) [1]. Indeed, a comparison of the Martian knobby features with a variety of terrestrial volcanic constructs (including spatter cones, cinder cones, pseudocraters, maars, and shield volcanoes) and small coniform features on the Moon [1], showed that, in general, the features compare most closely to terrestrial maar craters and cinder cones. We note that features in the region of the northern plains in close proximity to the polar cap were previously compared to terrestrial shield volcanoes [2]. However, without a detailed knowledge of the scaling factors used to correct terrestrial features for differences in martian gravity, it was not possible in the present study to reproduce those analysis methods in this work. It is noted that the reduced martian gravity and atmospheric density has a substantial effect on the morphometry of martian pyroclastic cones [1]. All other factors being equal, the lower gravity and atmospheric density of

Mars produce pyroclastic eruption features that are wider and lower in relief than their terrestrial counterparts [3,5].

The crater diameter/cone diameter ratio of the coniform features is ~0.40-0.60. These values overlap with values for both terrestrial pyroclastic features [1], and martian rampart craters. Hence it seems clear that this ratio cannot be regarded as diagnostic. While some of the knobby features observed in Figure 1 are similar to terrestrial cinder cones, further modeling is needed to understand the differences between terrestrial cinder cone profiles and those for cones formed under the low gravity and thin atmospheric conditions of Mars. Furthermore, similar knobby features were observed over a vast area, stretching from the margin of the remnant ice cap, extending south to ~70° N latitude. This distribution pattern is hard to explain with a volcanic hypothesis.

Maar craters. Almost half of the data points for the coniform features observed at the study site compared well with terrestrial maar craters [1]. Slopes of some terrestrial maar craters measured on DEMs ranged from 0.012 to 0.053; however, diameters over this range of slopes varied widely from a few hundred meters to over six kilometers. Maar crater morphologies could be expected to have an even broader morphological range on Mars, due to the effects of lower gravity and thinner atmosphere on the trajectory of material excavated by the explosion, as well as the depth of point source phreatic explosions. Therefore, even though the profiles of the knobby features observed in the study site (Figure 1) do not show good agreement with terrestrial maar crater profiles, this interpretation is difficult to rule out *a priori*. Again, as with the volcano hypothesis previously discussed, a maar crater hypothesis is hard to justify, given the broad distribution of the knobby features over the northern plains.

Pseudocraters. Pseudocraters are rootless pyroclastic cones formed where lava flows over wet or icy ground, triggering phreatic eruptions that produce fields of small scoria cones on the surface of a lava flow. Many authors have postulated these features to be terrestrial analogs for landforms observed on Mars [3-7]. A variety of pseudocrater types have been described in Iceland, adjacent to inland lakes and on glacial outwash plains. The morphologies of pseudocraters are thought to depend on the abundance of water during their formation [5]. Many authors have used the crater diameter/cone diameter ratio to identify potential martian pseudocraters [1, 3-5]. We used size-frequency histograms to compare the knobby features observed at Olympia Planitia (this study), with martian and terrestrial pseudocraters identified by previous authors [3-5]. *Wood's* [1] average value for the crater diameter/cone diameter ratio for terrestrial pseudocraters (0.42) is slightly higher than the average value measured for the features observed in this work (~0.39). In addition, no data points for the knobby features in the present study fell within the range for terrestrial pseudocraters reported by previous authors [3, 4]. However, a significant overlap was observed with previously reported martian pseudocraters [4] (see Figure 3). Specifically, we note that the smallest features observed in the present study area are larger than any pseudocraters identified by *Greeley and Fagents* [3] (Figure 3). At the other end of the distribution, features in the study region with diameters larger than the Martian pseudocraters proposed by *Frey and Jarosewich* [4] (see Figure 3) were reinterpreted in the present study, to be rampart craters (see feature profiles 21 and 22, Figure 2). While examples of pseudocraters as large as the knob-like features observed in the Olympia Planitia study site have not been reported in the previous literature, authors have demonstrated that the reduced gravity and atmospheric density on Mars could produce martian pseudocraters many times larger than terrestrial pseudocraters (although lower in relief) [3, 5]. (Similar arguments were made previously for cinder cones). Furthermore, it has been shown that, compared with Earth, far less ice is needed on Mars to create terrestrial-sized pseudocraters [3,5]. Hence, it may be inferred that in the north polar region of Mars, where ice is abundant, pseudocraters could grow to much larger proportions than achievable on Earth.

Pseudocraters develop on the surface of a single lava flow as it cools, and their distribution pattern is governed by heat loss. Hence, pseudocraters and related features (e.g. tumuli on ash flows) may be expected to have a somewhat uniform, to systematically varying distribution, and not the random pattern observed in a nearest neighbor analysis of the knobby features in the present study. And similar to conclusions for a cinder cone or maar crater origins, the broad distribution of the features, along the remnant ice cap margin, extending over a broad region of the northern plains, is hard to explain by a pseudocrater hypothesis. We therefore dismiss the pseudocrater hypothesis as problematic.

Pingos. Pingos are terrestrial landforms that form in cold climates where a freezing front advances on a talik (an unfrozen lens of water existing in permafrost), forcing the water upward and deforming the overlying bedrock into a dome-like feature. Pingos have a conical to elliptical form, often with a central crater-like depression. Pingos were rejected as a possible analog for the features observed at the study site because they are unlikely to exceed 1 km in diameter, even under martian conditions (S. D. Gurney, University of Reading, personal communication, 2002). However, should a dense eutectic brine be substituted for pure water on Mars, it might be possible to create large pingos (> 1 km in diameter), similar to those found in the study area [8, 9]. Terrestrial pingos in open aquifer systems often form in clusters [10]. However, a new pingo is more likely to form in the footprint of an older, collapsing pingo, creating overlapping features. This process results in features quite different from the coniform features observed in our study area [10]. Furthermore, terrestrial pingos are not known to exist in dense groupings as numerous and as extensive as the knob-like features observed in the study area (S. D. Gurney, University of Reading, personal communication, 2002). Lastly, pingos often display radial cracking, with fractures extending from their central depression to the outer flanks of the cone. Radial cracking was not observed in any of the knob-like features observed at the study site, nor was such a pattern evident in MOLA data, although that may be beyond the limits of detectability with those data. As with terrestrial pseudocraters, terrestrial pingos are too small to appear on topographic maps, so that comparable feature profiles were unavailable. However, even if the knob-like features observed at the study site are pingos, direct, same-scale comparisons with terrestrial pingo profiles, may be irrelevant because the processes necessary to form such large pingos do not exist on Earth. Although the knob-like features observed at the Olympia Planitia study site are not interpreted to be pingos, these features are of interest to astrobiology because they form where subsurface liquid water rises to the surface and freezes.

Hummocky moraine. On Earth, ice loading along stagnant glacial margins has been postulated to deform fine-grained till into hummocks, depressions, and ridges [11, 12]. These subglacial till deformation features, called "hummocky moraine," are prevalent along the border of Canada with the United States, where they formed along the margin of the Laurentide Ice Sheet during the Pleistocene [e.g. 11, 12]. Hummocky moraine covers vast areas, occurring in broad belts tens of kilometers wide [12]. Hummocks are typically 1-50 m high, 25-300 m wide, and have slopes ranging from 1°-25° [13]. They are often closely spaced, although their distribution is chaotic [11, 12]. Previous models to explain the origin of hummocks emphasized a supraglacial origin. However, hummocks have been found to contain cores of fine-grained till [11-14]. Therefore, recent work postulates a subglacial pressing mechanism based on the liquefaction of tillites during glacial loading [11, 12]. Ice-loading and deformation of subglacial till can produce a wide variety of hummocky forms, including both flat-topped mounds and mounds with central depressions (also known as doughnuts). The subglacial processes responsible for forming hummocky moraine involve partial liquefaction of the underlying till during glacial stagnation and recession. Such features may apparently also form during basal melting of a glacier [12], or erosionally during catastrophic, jökulhlaup-type glacial outflood events [13, 14]. The morphometry of hummocky moraine shows good agreement with the knobby features observed at the Olympia Planitia study site. Mound-shaped hummocky moraine can occur in a wide variety of sizes and morphologies, but are typically low-relief coniform features. Hummocks within the same region may or may not have a central depression. The mounds comprising hummocky moraine have a random distribution, and extend over broad regions, generally parallel to glacial margins of formerly glaciated terrains. Thus, a hummocky moraine interpretation satisfactorily explains the wide distribution of similar knobby features present on the northern plains of Mars. As argued for pingos, the replacement of pure liquid water by dense eutectic brines on Mars [8, 9] may produce features much larger than those created on Earth. In any case, subglacial, water-rich environments are of great interest to astrobiology. Because hummocky moraine forms along glacial margins during recessional intervals, the hummocky features observed in the study area are probably younger than similar features located further south and therefore would be more likely to preserve subsurface zones of liquid water. And if the knob-like features observed in this study are hummocky moraine features, their present distribution reveals the former extent of the martian north polar cap.

Conclusions: Almost certainly, the region of study includes a mixture of geomorphic features, having several different origins. Some knobs may even be polygenetic, having been initiated by impact cratering or volcanic events and subsequently modified by glacial ice. For most of the knobby features observed at the Olympia Planitia study site, however, a hummocky moraine hypothesis is preferred. This explanation accounts for not only the morphology of the landforms, but also their distribution as well. Specifically, the hummocky moraine hypothesis provides a satisfactory explanation for the existence of similar landforms at lower latitudes, and is consistent with the recent suggestion of large amounts of ground ice persisting at lower latitudes during periods of higher obliquity at Mars [e.g. 15-17].

Astrobiological Significance: Within the study area, habitable environments of subsurface liquid water could have been created in a variety of ways, including the following: shallow hydrothermal systems associated with pseudocraters, deeper hydrothermal systems associated with centralized volcanic eruptions and impact craters, upwelling of shallow groundwater during pingo formation, and subglacial melting associated with the formation of hummocky moraine. All of these processes provide effective ways for creating: 1) shallow subsurface zones of liquid water and 2) mechanisms for transporting a subsurface biology near surface environment cryosphere, where it could be sequestered and cryopreserved in ground ice. For these reasons, the region encompassed by the study site at Olympia Planitia is considered an important astrobiological target for future landed missions.

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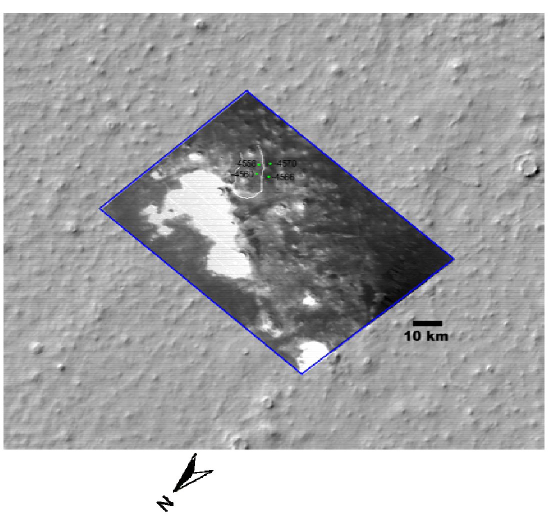

Figure 1: Viking image 063B21, in polar stereographic projection, overlain on the hill-shaded DEM. This image shows that some of the knob-like features sit on elevated platforms or pedestals. The white line denotes the edge of the lobe of material upon which three knob-like features sit. Point elevation values were compared on either side of this boundary and showed an elevation difference of ~10 m.

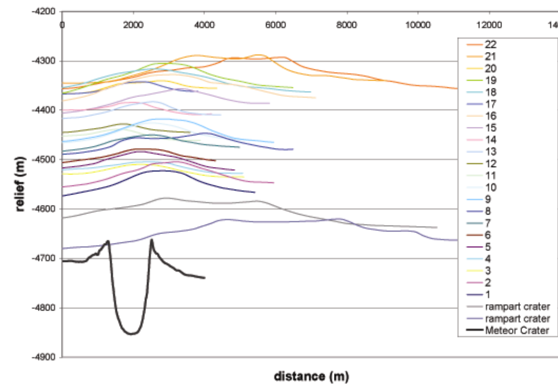

Figure 2: Profiles of 22 of the knob-like features observed in Viking image 063B21. Profiles of two northern plains rampart craters and Meteor Crater (a terrestrial impact crater) are also included for comparative purposes. Features 22, 21, and 8 appear to be in relatively good agreement with the rampart craters. No martian feature sampled here seems to correspond to the terrestrial impact crater, although ejecta trajectories on Mars would produce broader and lower relief features due to lower gravity and thinner atmosphere. VE = 13.8.

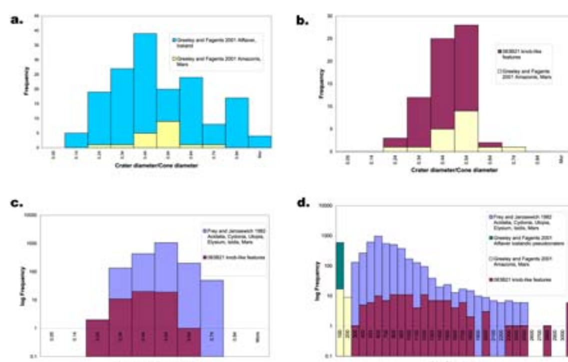

Figure 3: Histograms of crater diameter/Cone diameter (a-c) compare the knob-like features observed in Viking image 063B21 and pseudocraters identified by previous authors (b&c). (c) Histogram comparing proposed martian pseudocraters with Icelandic pseudocraters from Greeley and Fagents (2001). (d) Histogram showing the overlap in size between the knob-like features in Viking image 063B21 and the martian pseudocraters proposed by Frey and Jarosewich (1982). Note also the lack of overlap between the 063B21 features and either the martian or terrestrial pseudocraters identified by Greeley and Fagents (2001).