**Introduction:** Lunar features classified as “dark mantle deposits” (DMDs) were initially identified based on their relatively low albedos, surface smoothness, mantling relationship to underlying terrain, and spectral absorption bands due to the presence of iron- and titanium-bearing volcanic glasses (herein called “pyroclastics”) produced from explosive volcanic eruptions [1-5]. These pyroclastics vary in color and reflectance owing in part to differences in Fe and Ti content [3, 6-8], and to differences in physical properties. Apollo 17 glasses at the Taurus Littrow DMD formed between 3.4-3.7 Ga [9] while other DMDs are thought to be 3.2 to 3.7 Ga in age [10]. DMDs may be composed of sub-mm glasses and/or crystallized beads, depending upon the optical density (concentration of gas and clasts for a given volume) of the plume and time spent within the erupting plume.

Because all pyroclastic glasses were emplaced by volatile-rich explosive eruptions, they provide clues to the nature of the lunar interior and volcanism on the Moon [e.g., 11-13]. Carbon monoxide and water are believed to be the dominant gas species driving explosive lunar volcanic eruptions [14-20]. Hence, the pyroclastic samples have yielded important insight into volatiles within the lunar interior. Work using Moon Mineralogy Mapper (M3) data [21-22] has shown that all the larger DMDs except Sinus Aestuum exhibit water contents as high as 300-400 ppm, with the water interpreted to be sourced from the lunar mantle and brought to the surface during explosive eruptions that produced the DMDs.

**Geologic Mapping:** To further understand the geologic context and distribution of pyroclastics within the larger DMDs, we are producing a USGS geologic map of the Moon at 1:1M scale from 18.5° W to 9.5° E and 0° N to 16° N on a WAC basemap (Fig. 1), which includes the DMDs in Sinus Aestuum, Rima Bode, and Mare Vaporum. Multiple data sets were used to better refine the extent of pyroclastics for these three DMDs, identify and characterize plausible source vents for the DMDs, map and determine the compositions of the mare and highlands within the study region, perform crater counting to establish ages, explore the geologic setting and history of the mapping region, and attempt to characterize the eruption(s) that emplaced each DMD. An improved understanding of the distribution, composition, and eruption conditions that produced the pyroclastic deposits gained through stratigraphic, morphologic and mineralogic characterization has the potential to reveal important information about the thermal and volcanic history of the Moon.

Although the Sinus Aestuum DMD appears as several distinct patches on highland materials along southern Aestuum basin, the DMD has been interpreted as a single deposit formed during an explosive volcanic eruption [23]. Analyses of M3 data has shown that the Sinus Aestuum DMD likely contains Al- and Fe-rich pleonaste spinel produced during the same volcanic eruption that emplaced the pyroclastics [24]. Additionally, the Sinus Aestuum DMD is the only regional pyroclastic deposit that lacks a mapped indigenous water component [21-22]. These observations are consistent with all of the DMDs at Sinus Aestuum resulting from a single explosive eruption. The Rima Bode DMD, located adjacent and to the northeast of the Sinus Aestuum DMD, lacks the spinel signature and has an elevated water content compared to Sinus Aestuum. The Mare Vaporum DMD is situated along the southern highlands of the Vaporum basin and also has a high water content. A smaller localized DMD was confirmed at Rima Hyginus [25].

We mapped thirty-nine different geologic units and divided them into four groups: Crater Units, Dark Mantle Deposit Units, Mare Units, and Highlands Units. All craters >5 km in diameter have been mapped and are identified in age as either Copernican (Cc), Eratosthenian (Ec), Imbrian (Ic), and Nectarian (Nc) based upon the characterization and extent of their rim and ejecta. Larger craters have been mapped into distinct units including their central peaks, smooth floors, rough floors, crater rim, and dark ejecta. Crater statistics were used to establish absolute ages of geologic units.

Ten mare units were mapped based upon location and brightness, which is related to variations in TiO₂ and FeO abundance. Units include several smaller dark mare, basin mare, highland mare, intermediate and disrupted mare, bright mare, and mixed brightness mare. Several previously unmapped/unknown small mare units were mapped in the highlands.

Thirteen highlands units were mapped based on roughness, topography, relative brightness, and presence or absence of lineations. Five DMD units were mapped, including a localized DMD unit at Hyginus crater, a highlands mare DMD unit, a diffuse DMD unit, a thick DMD unit, and a thin DMD unit. Surface features mapped include secondary craters and
crater rays marked by bright ejecta predominantly from Copernicus crater, light-colored ejecta, high Ti ejecta, high Ti+Fe lavas, high Ti+Fe pyroclastics, and high Ti+Fe+spinel pyroclastics (Fig. 1). Many linear features were mapped, such as sinuous volcanic rilles, wrinkle ridges, faults, scarps, and grabens.

**Implications for DMD Eruptions**: Studies suggest that submillimeter beads in lunar pyroclastic deposits may have been produced in Hawaiian fire fountain-, volcanian-, or strombolian-style eruptions [17]. To eject submillimeter pyroclastic beads to large (>100 km) distances, the majority of clasts in the eruption must have been larger than a few centimeters in size [17,26]. A model of the origin, ascent, and eruptions of the Apollo 17 glass magma [27] showed that the source region was at 50 km depth: as the magma approached the surface a C-O-H-S gas phase formed between 50-500 m and at depths above ~450 m the magma exsolved H$_2$O and S, then fragmentation of the magma occurred to form the pyroclastics at depths of 300-600 m. Magma was carried to the surface rapidly within a dike that allowed open-system degassing in the upper part of the dike where the gas volumes were large enough to fragment the magma into glasses and then expel them to great (>20 km) distances from the vent [28-29]. It is assumed that the vents that erupted the larger regional pyroclastic deposits were buried by younger mare, as were the DMDs that once extended into the basins but are now buried [3,23].

We used the distribution of each pyroclastic signature (high Ti, Fe, and/or spinels) to evaluate the size of the eruptions and plausible source vent locations. Our mapping shows the pyroclastics extend further out for all three DMDs than was mapped previously, indicating the volcanic plumes must have been larger than formerly thought to expel pyroclastics to these greater distances (~260 km from a central vent at Sinus Aestuum).

**Future Exploration of the DMDs**: In situ exploration of the pyroclastics would address many science goals listed in the National Research Council report *The Scientific Context for Exploration of the Moon* [2007]. Lunar pyroclastic deposits may be potential resources (e.g., Fe, Ti, REE, OH/H$_2$O) for future human activities [30-35]. The Ti- and Fe-rich pyroclastics also make good insulators from solar radiation for buried habitation modules. Ground truth measurements of H abundance for comparison to those determined from M$^2$ data [21,22] are critical to validate the relatively high H$_2$O (300-400 ppm) estimated for the pyroclastics. If humans are ever going to live away from the lunar poles, assessment of non-polar sites that possess water and elements necessary for habitation and sustainability is vital. Robotic exploration of lunar DMDs is a critical next step for future human exploration on the Moon.