Formation [*Scott et al.*, 1987; *Tanaka et al.*, 1988, 2003], but the density of large, incompletely buried craters is comparable to that in the highlands [*Frey et al.*, 2002], suggesting that the age of the northern lowlands basement is also Noachian. The Tharsis rise, a huge dome containing massive shield volcanoes, separates these terranes along part of their join. The volcanic surfaces on and around these volcanoes are relatively young (Amazonian), although Tharsis itself has been a locus of plume volcanism for billions of years [*Phillips et al.*, 2001]. The lithosphere under this bulge may be >100 km thick if the load is supported isostatically [*Solomon and Head*, 1982]. Elysium is another, smaller plume containing large volcanoes and Amazonian flows. Figure 1, which schematically illustrates salient features of the various major subdivisions of the Martian crust, will serve as a useful guide as we consider constraints on crustal composition and origin.

[4] Early formation of the bulk of the Martian crust is inferred from its bombardment history [*Hartmann and Neukum*, 2001] and the ~4.5 Ga measured crystallization age of ALH84001 [*Nyquist et al.*, 2001], the only Martian meteorite that directly sampled the ancient crust. The ~4.0 Ga $^{40}Ar/^{39}Ar$ age of this meteorite is thought to reflect the late heavy bombardment [*Ash et al.*, 1996]. The extraction of incompatible elements during formation of this early crust depleted mantle source regions that later melted to produce younger Martian meteorites, which still carry the geochemical signature of this 4.5 Ga fractionation event in their strontium [*Borg et al.*, 1997] and lead [*Chen and Wasserburg*, 1986] radiogenic isotope systems. Moreover, the former existence of short-lived radionuclides like ^{146}Sm in the Mars mantle, as documented in Martian meteorites [*Harper et al.*, 1995; *Borg et al.*, 1997], demands early crustal differentiation. Some additional crust formation occurred during the Hesperian, when lavas flooded the northern plains to depths of 1–2 km [*Frey et al.*, 2002], and significant amounts of accompanying plutonic rock must also have been added to the northern plains crust during this time.

[5] Mars exhibits a rich variety of volcanic landforms, leading to speculation that its crust consists mostly of igneous rocks [e.g., *Greeley and Spudis*, 1981]. If layering in the walls of Valles Marineris consists entirely of lava flows [*McEwen et al.*, 1999] and such layering were globally distributed, it would suggest that virtually the entire crustal thickness is of igneous origin. However, *Malin and Edgett* [2000, 2001] have interpreted some Valles Marineris layers as well as thick (~10 km) layers covering other parts of the Martian surface as sedimentary rocks, albeit likely derived from igneous precursors. There is little doubt that both volcanic and sedimentary units and landforms are common on Mars, but the relative proportions of these materials within the crust remains controversial.

[6] A related controversy is whether the Martian crust experienced chemical (as opposed to only mechanical) weathering processes with accompanying chemical fractionations. The preservation of igneous mineralogy on Mars is indicated by the spectral identification of pyroxenes, plagioclase, and sometimes olivine in regions not blanketed by dust [*Mustard et al.*, 1997; *Bandfield et al.*, 2000; *Hamilton et al.*, 2001; *Bandfield*, 2002]. However, a variety of alteration phases (e.g., sheet silicates, amorphous silica, zeolites, and palagonites) in modest proportions have been suggested as analog components in thermal emission spectra of low-albedo Martian surface materials [*Wyatt and McSween*, 2002; *Kraft et al.*, 2003; *Ruff and Christensen*, 2003; *Morris et al.*, 2003]. Evidence for crystalline phyllosilicates has not been observed in visible/near-infrared (VISNIR) spectra, leading to speculation that any hydrous silicates must be poorly crystalline or amorphous [e.g., *Bell et al.*, 2000]. Hydrogen in equatorial regions analyzed by the Mars Odyssey Gamma-Ray Spectrometer [*Boynton et al.*, 2002] can be interpreted as mineral-bound OH, supporting the idea of chemical weathering. Pervasive erosional striping and widespread overland deposition, as inferred from MGS MOC images [*Malin and Edgett*, 2001], would have facilitated both chemical and mechanical weathering of volcanic rocks.

[7] Despite decades of spectral mapping of the planet's surface by orbiting spacecraft, chemical analysis of surface materials by several landers and rovers, and laboratory study of several dozen Martian meteorites, the bulk composition of the Martian crust remains undefined and its origin poorly understood. Here, we critically evaluate constraints on the chemistry and petrology of the ancient crust, derive new geochemical data from TES spectroscopy for different parts of the crust, and explore how crustal components having these compositions might have arisen on Mars.

2. Constraints on Mars Crust Composition

2.1. Petrology of Martian Meteorites

[8] ALH84001 offers an extremely limited and biased sampling of the ancient crust. This ~4.5 Ga-old ultramafic (orthopyroxenite) cumulate cannot represent the bulk composition of the highlands, because partial melting of an ultramafic mantle cannot yield an ultramafic crust. Instead, it has been suggested that ALH84001 formed by fractional crystallization of a basaltic parent magma [*Mittlefehldt*, 1994]. The apparent failure of impacts to dislodge more meteorites from the ancient crust may stem from an inability of old crust to transmit the requisite shock waves because of scarcity of coherent rocks within these terranes [*Head et al.*, 2002a; *McSween*, 2002].

[9] The other Martian meteorites, collectively called SNCs (an acronym for shergottite, nakhlite, chassignite), have young crystallization ages, ranging from 175 to 1300 Ma [*Nyquist et al.*, 2001]. Shergottites are subdivided into basaltic shergottites (tholeiitic basalts, sometimes with modest amounts of cumulus pyroxenes), olivine-phyric shergottites (basalts containing olivine xenocrysts or phenocrysts), and lherzolitic shergottites (plagioclase-bearing peridotites). Nakhlites (olivine-bearing clinopyroxenites) are similar to pyroxenites in some terrestrial komatiite flows, and Chassigny (a dunite) is chronologically and geochemically linked to the nakhlites. All these meteorites are basaltic rocks or plutonic cumulates likely formed by fractional crystallization of basaltic magmas. Compositions of basaltic shergottites (including olivine-phyric samples) and nakhlites plot within the field of basalt on a chemical classification diagram for volcanic rocks (Figure 2).

[10] The young crystallization ages of SNCs point to their derivation from young volcanic centers, probably Tharsis or Elysium, apparently the only regions on Mars geologically