

3.2. Gypsum Deposition Mechanisms and Properties

[23] Three principal solid phases occur in the calcium sulfate-water system: $\text{CaSO}_4 \bullet 2\text{H}_2\text{O}$ (gypsum), $\text{CaSO}_4 \bullet 0.5\text{H}_2\text{O}$ (bassanite), and CaSO_4 (anhydrite) [e.g., *Deer et al.*, 1992]. Of these three, only gypsum and anhydrite are stable phases; however, anhydrite is only dominant in water above 44°C on Earth at standard pressure and neutral pH, although the stability temperature decreases as pressure increases [*Deer et al.*, 1992; *Holland and Malinin*, 1979]. With the exception of environments involving such high-temperature waters, anhydrite is generally considered to be a secondary mineral assemblage to gypsum, although reforming gypsum through hydration of anhydrite is possible [*Deer et al.*, 1992].

[24] As a dry solid, gypsum is stable up to temperatures of 70°C at standard pressure, at which point bassanite is generated. Above 200°C , anhydrite is generated [*Deer et al.*, 1992; *Holland and Malinin*, 1979]. Gypsum is not stable under burial of more than a few hundred meters, at which point anhydrite is generated, with a volume loss of $\sim 50\%$ [*Schreiber and El Tabakh*, 2000]. Solid gypsum also dehydrates to anhydrite when exposed to high salinity solutions [*Deer et al.*, 1992].

[25] Gypsum has been shown to be stable at Martian surface pressures for periods of a few months on the basis of spectral analysis [*Cloutis et al.*, 2007]. This result can most likely be expanded to much longer time scales, as the structural integrity of gypsum is dependent on the presence of H_2O , and would require either extreme pressure excursions (down to a few Pa) or modest thermal input to dehydrate, as discussed above [*Cloutis et al.*, 2007].

[26] On Earth, gypsum is the most common sulfate mineral, and is most often associated with shallow and deep marine precipitate deposits as well as coastal (sabkha or salina) and continental (playa) evaporite deposits [*Schreiber and El Tabakh*, 2000; *Warren*, 1982]. Typical seawater contains approximately 0.15% dissolved CaSO_4 , which equals about 1.7 cm precipitated gypsum per 100 m of evaporated seawater [*Deer et al.*, 1992; *Holland and Malinin*, 1979]. Gypsum is generally the second mineral to precipitate from evaporating seawater, after calcite [*Spencer*, 2000; *Holland and Malinin*, 1979]; however, highly acidic conditions that are plausible to have occurred on Mars may have inhibited carbonate deposition [e.g., *Catling*, 1999; *Fishbaugh et al.*, 2007]. In shallow marine environments, gypsum is most often deposited as crusts and clusters, while in deep marine environments, gypsum is most often deposited as fine grained beds, known as alabaster gypsum [*Schreiber and El Tabakh*, 2000].

[27] In salinas and playas, gypsum is present as (1) gypsite, a fine grained ($<60\ \mu\text{m}$) gypsum crust dissolved and redeposited by rain, (2) gypsarenite, sand-sized ($60\ \mu\text{m}$ -1 mm) gypsum crystals deposited in unstable or periodic salinity environments, and (3) selenite, large ($>2\ \text{mm}$) and often twinned gypsum crystals deposited below the water table in a continuously subaqueous environment [e.g., *Warren*, 1982]. Gypsum may also occur as a continental evaporite when it is dissolved in and transported by percolating groundwater, which is pulled to the surface by capillary action, depositing gypsarenite, selenite, and anhydrite crystals as the water evaporates [*Deer et al.*, 1992; *Langford*, 2003].

[28] Gypsum may also be formed without the presence of surface water. Sulfuric acid solutions moving through Ca-

rich rocks may result in gypsum and anhydrite deposition. Such waters are often either created by volcanic gases interacting with meteoric water or by weathering of sulfides [*Deer et al.*, 1992; *Holland and Malinin*, 1979]. Ferric sulfate formation via weathering of sulfides has been shown to be plausible on Mars on the basis of mineral assemblages at the Viking landing sites [e.g., *Burns*, 1987, 1988; *Burns and Fisher*, 1990, 1993]. Likewise, gypsum and anhydrite rich mineral assemblages are often produced by the action of sulfurous volcanic vapors on Ca-rich rocks [e.g., *Golden et al.*, 2005]. These assemblages are commonly found in fumarole deposits [e.g., *Stoiber and Rose*, 1974]. Finally, gypsum can also be produced by sulfurous fog acting on Ca-rich materials [e.g., *Eckardt and Schemenauer*, 1998; *Golden et al.*, 2005].

[29] Gypsum is an especially weak mineral (hardness ~ 2) [*Deer et al.*, 1992], and likely would not survive for long as intact grains under the high saltation velocities that are postulated to occur on Mars [e.g., *Sagan et al.*, 1977]. Even under the much slower saltation velocities of Earth, gypsum sand at the White Sands dune field, NM has been observed to decrease in grain size with distance from the gypsum source [; *Ghrefat et al.*, 2007; S. G. Fryberger, Geological overview of White Sands National Monument, available online at <http://www.nps.gov/archive/whsa/Geology%20of%20White%20Sands/GeoHome.html>, 2002]. This may imply that the gypsum source region must be near the highest concentration of gypsum in eastern Olympia Planum [*Fishbaugh et al.*, 2007].

3.3. Gypsum Deposition Hypotheses

[30] *Langevin et al.* [2005a] initially proposed a suite of gypsum deposition mechanisms, including (1) atmospheric weathering of iron sulfides, (2) the interaction of Ca-rich rocks with acidic snow during a period of extensive volcanic activity, (3) sulfate-rich groundwater sourced from basal melting of Planum Boreum, or (4) hypersaline, sulfate-rich surface water sourced from polar outflows. *Fishbaugh et al.* [2007] evaluated several possible water-related gypsum deposition mechanisms and supported the hypothesis for gypsum deposition via the direct interaction of hypersaline, sulfate-rich surface water from a polar outflow. They proposed that the sulfur-rich outflow emanated from Chasma Boreale and traveled hundreds of kilometers through channels running along the base of Planum Boreum to a putative gypsum source area that today is ringed by dunes with a minor gypsum component. However, the channels identified in MOLA topography have alternately been interpreted as the result of erosion by katabatic winds off of Planum Boreum [*Warner and Farmer*, 2007]. Additionally, outflows from Planum Boreum would most likely be directed into the large basin to the south of Hyperborea Lingula, which in turn would have been dissected by such flood events occurring during the Amazonian, which is not observed [*Tanaka*, 2006].

[31] Alternatively, *Tanaka* [2006] proposed that the sulfate deposit is not late Amazonian in origin, but is rather considerably older than the dunes. In this hypothesis, the sulfates were originally generated by volcanically introduced sulfur and hydrothermal alteration of Ca-bearing volcanic rocks in the Scandia region and extending north to Olympia Planitia