IMPLICATIONS FOR THE ABUNDANCE OF WATER ON EARLY MARS AS EVIDENCED BY THE PRESENCE OF SECONDARY MINERALS IN MARTIAN METEORITE ALLAN HILLS 84001. C. M. Corrigan¹ and R. P. Harvey²; ¹Dept. of Mineral Sciences, Smithsonian Institution, National Museum of Natural History, MRC-0119; 10th St. and Constitution Ave., Washington DC, 20560-0119; corrigan.carl@nmnh.si.edu, ²Dept. of Geological Sciences, Case Western Reserve University, 10900 Euclid Ave., Cleveland, OH 44106-7216.

Evidence for Water on Early Mars: Although numerous lines of evidence suggest that Mars must have been a “wet” planet at some time in its past, there is no universal agreement on the volume of hydrous activity, its style, or the characteristics of the corresponding climates through time. Morphological evidence for the presence of surface water on Mars is abundant [1-3] as is evidence for the existence of ground ice [4-9]. Evidence for glacial activity on Mars supports a colder, though still hydrosphere planet [10,11]. Other features suggest that some fluid and ground ice activity on Mars has not been limited to the ancient past [6,8,9,12]. Mineralogical and geochemical evidence for a wet Mars arise from hematite deposits found on the surface [13,14] and from igneous minerals in the martian meteorites [15-17].

The question, therefore, is not whether water existed on Mars, but when it existed, in what state, its abundance, the locations of reservoirs (both spatially and in terms of depth), and if/when this water became less active. Interpretations of the martian hydrologic history range from a warm and wet Mars with oceans and an active hydrologic cycle [18] to a drier planet, where short-term hydrospheres were activated by impact events [19], to a frozen Mars where a water is present as a frozen subsurface layer [20].

Estimates for the abundance of water on Mars range from an initial 3.6 m to a current 0.2 m global thickness layer [21] to an initial depth of >100 km accreted and lost early [22] to a current subsurface 1400 m [20]. A global layer of frozen, saturated ground ice has been proposed by [18].

Little of this hydrosphere inventory is available for direct inspection. Only in the last few years have we been able to quantitatively measure the abundance of water in the outermost surface layers by remote means [23,24] though remotely sensed images have provided us with evidence for decades.

Ground Truth: The Martian Meteorites: The ~30 martian meteorites serve as “ground truth” for the examination of the historical record of Mars, including the abundance of water present in the crust over time. The record of alteration within these rocks should be an indication of the pervasiveness of water in the crust. The fact that the amount of aqueous alteration present in the martian meteorites is very low suggests that either the availability of liquid water at the depths in which these rocks resided must be drastically overestimated by some models, or that the martian meteorites mated by some models, or that the martian meteorites are an unrepresentative sampling of the martian crust.

The meteorites represent a wide range in age from ~160 Ma [25] to ~4.5 Ga [26]. Although they have been extensively mechanically altered, possibly by numerous impact events [27,28] these 30+ meteorites exhibit a surprisingly low abundance of secondary minerals lacking the alteration expected in rocks continuously exposed to liquid water. The martian meteorites are all mafic, and contain olivine, pyroxene and glasses [29]. No observation of the conversion of these vulnerable minerals to phyllosilicates has been reported on anything larger than the nanometer scale.

The very small quantities of secondary minerals the martian meteorites do contain instead indicate limited exposure to water over time. The abundances of secondary minerals in these rocks vary with their age. Allan Hills 84001, by far the oldest of the martian meteorites at 4.5 Ga, contains ~1% carbonate minerals [30]. These carbonates likely formed early in the history of the rock, around 3.8 Ga [31]. In addition, these minerals represent depositional events, not weathering of the rock’s minerals. Rare occurrences of phyllosilicates have also been reported in ALH 84001 [32]. Smaller abundances of alteration minerals, including iddingsite, occur in the intermediate age (~1.3 Ga) Lafayette, Nakhla and other nakhlites [33,34]. Some evidence of glass alteration exists in these rocks, but it is very minimal. The youngest martian meteorites, the shergottites, contain only trace amounts of secondary minerals, and, in fact, are almost pristine.

Evidence of multiple generations within carbonate occurrences studied by [35] still only suggests a maximum of three secondary mineral precipitation events, none of which exhibits evidence of having been the result of long-term, hydrous mineral-water interaction. In fact, the microcrystalline and possibly metastable compositions of the carbonate suggest that these events were very short in duration, not measured in years but in hours and/or days. The lack of abundant hydrous silicates, the presence of feldspathic and silica glasses and the presence of only two or three generations of carbonate in ALH 84001 strongly suggest that this rock has seen only limited interaction with water during its duration on Mars, and that these hydrous events were stochastic, rare and short-lived.

In sharp contrast to martian meteorites of equivalent ages, terrestrial rocks rapidly show pervasive signs of aqueous alteration and metamorphism. Very few
Earth rocks of 100 Ma lack signs of weathering or metamorphism, and by the time terrestrial rocks reach 1.3 Ga, signs of alteration are ubiquitous. The extreme example of ALH 84001 at 4–4.5 Ga does not even have applicable terrestrial weathering analogs - Earth rocks of that age have long been destroyed. In environments such as those found on Earth, where water is ubiquitous and volcanism and plate tectonics are active, aqueous alteration begins to affect rocks immediately and atoly and glass have lifetimes measured in hundreds to thousands of years, not billions.

Possible Scenarios Consistent with the Martian Meteorites: It is difficult to reconcile the lack of alteration in martian meteorites with the obvious presence of at least minor volumes of water on Mars and the likely existence of more extensive volatile inventories and possibly more active hydrologic cycles in the past. Possible explanations for this conundrum are: 

(1) Dry/Frozen Mars: Aqueous alteration in the martian crustal rocks may be limited because the martian hydrosphere has always been frozen and is nearly inactive compared to that of the Earth. For this to be true, either Mars has never contained a large abundance of water (though most evidence points to the contrary) or if water did exist, most of it present in the surface units must have remained frozen through time, sporadically released during impact and/or volcanic events. This hypothesis is not implausible given the "Iceball Mars" scenario [36] but it is an extreme. It says nothing, however, about the abundance of water present deeper in the crust or in the mantle, which, according to recent studies [17] suggest that martian volcanic rocks may have originally contained up to ~1.8% water in their parent magmas. This water, outgassed during magmatic ascent, may have provided a mechanism for a hydrologic cycle on Mars and for the formation of surface reservoirs, frozen or liquid.

Therefore, it is possible that early Mars was just not as warm or as wet as hypothesized. ALH 84001, and to a lesser extent, the rest of the martian meteorites, are not entirely void of secondary minerals, thus, they have experienced some exposure to hydrous activity, though they suggest that interactions between surface rocks and the crustal fluids of Mars were sporadic and discontinuous. The activation and mobilization of fluids and the fracturing within many of the meteorites was likely driven by impact. The evidence for punctuated impact-driven melting (and therefore interaction between fluids and the rocks) supports hypotheses [19] that large impacts may have created temporary hydrous environments. This process, taking place at a variety of scales from hemispherical/global to extremely local, would produce a crust that is heterogeneous in terms of aqueous alteration of samples.

(2) Not the whole story. It is also possible that the martian meteorites are unrepresentative of the martian near-surface. There are only ~30 distinct rocks represented by the martian meteorites and not all substrates shed rocks that would survive impact [37]. A small number of impacts into the earth similar to the n=7 thought to supply the martian meteorites [37] would not likely produce a representative sampling of the planet's broad geologic spectrum. Even if martian meteorites are not representative of the entire surface of Mars, the fact that impact is a random event combined with the fact that the rocks that we do have must come from places where aqueous alteration was essentially absent, suggests that major parts of the planet were unaffected by thermal and/or aqueous metamorphism for billions of years.

Most of the martian meteorites are young and are thought to come from surface volcanics post-dating proposed large-scale wet periods. However, even if the warm and wet period ended in the late Noachian/early Hesperian [38], which would explain the lack of alteration in the younger meteorites, the ALH 84001 conundrum still remains, as it has experienced very little aqueous alteration.