Reports

Release of Juvenile Water on Mars: Estimated Amounts and Timing Associated with Volcanism

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The amount of water released on Mars in association with volcanism is estimated to equal a layer 46 meters deep over the entire planet. Most of this water was released in the first 2 billion years of martian history. The estimate is based on mapping the volcanic materials and by inferring the volatile content of the lavas. Water from other sources, such as plutonic activity and cometary contributions, is not included in the estimate.

THE AMOUNT OF WATER AND OTHER volatile materials on and near the surface of Mars and their effects on the climate history have been the focus of the MECA (Mars: Evolution of Its Climate and Atmosphere) Project and the subject of considerable interest and debate (*1*). Previous estimates (*2*) of the total volume of water on Mars have been based on models of elemental solar system distributions, considerations of the SNC (shergottite, nakhlite, and chassigny) meteorites which are thought to be derived from Mars, results from the Viking landers, and considerations of the outflow channels; these estimates range from about 1 m to approximately 1 km for an equivalent water layer that would cover the planet. However, few of these estimates consider the rate or timing of volatiles released to the surface from the interior. The results in this report are derived from the amounts of volatiles inferred for release in association with volcanic eruptions that occurred during the evolution of Mars, as determined from geological mapping.

Volcanism has played a dominant role in the evolution of the martian surface. Volcanism has occurred from at least the close of the period of heavy impact cratering (~3.9 billion years ago) to the age of the youngest rocks visible on the planet. Materials that are considered to be of volcanic origin cover more than half the surface of Mars. The assumption in the results presented here is that, as with Earth, juvenile water was released on Mars in association with the eruption of these volcanic materials. By determining the volumes and ages of volcanic units and inferring the volatile content for the magmas, the amounts and timing of associated water release can be estimated.

Volumes of martian volcanic materials were derived from maps that show their areal distribution and their estimated thicknesses. Initial geological mapping was based on Mariner 9 data and was synthesized by Scott and Carr (*3*). The types and ages of various volcanic units were identified in a review of martian volcanism (*4*). Mapping was refined and detail was added by using recently prepared global geological maps based on Viking Orbiter data (*5*). These maps were synthesized to determine the total areal extent of volcanic materials on Mars. To account for the volcanic materials potentially buried by younger rocks, a ratio of volcanic-to-nonvolcanic materials for each segment of geological time was determined from exposed units on geological maps. This ratio was then extrapolated to the area buried by younger units to estimate the amount of additional volcanic materials.

Thicknesses of the volcanic plains are derived from DeHon (*6*), who developed a method to estimate thickness of mare basalts on the moon that was based on partial burial of impact craters. By using this method he also estimated that thicknesses of similar materials on Mars range from 0.25 to 2.0 km and average about 1 km (*7*). As noted by DeHon, this method indicates a minimum thickness; thus the volume estimates of volcanic materials are conservative. As on the moon, most of the martian plains are inferred to be basaltic flood lavas analogous to those of the Columbia River plateau, which also average about 1 km in thickness. In addition to volcanic plains, central volcanoes such as the Tharsis shield volcanoes constitute a significant component of volcanic materials on Mars. Paleostratigraphic maps for the Tharsis area (*8*) were combined with topographic maps to estimate flow thicknesses; DeHon (*7*) also estimated thicknesses on the basis of partially buried impact craters. Both methods yield values of 0.25 to 1.5 km for each set of flows (many sets of flows compose each central construct). Although refinements in estimates can be made, for simplicity an average thickness of 1 km is used here for both plains and central-volcano flow sequences.

Geologic mapping (*5*) provides a framework for relative age dating of formations on Mars. In the absence of dates derived from rock samples, impact crater frequencies are commonly used to date planetary surfaces (*9*). Such dating depends on knowledge of impact flux; although such knowledge is available for the moon, there is debate with regard to impact flux for Mars. Thus data are presented here (Fig. 1) from models that represent two "end members" for the cratering flux on Mars (*9, 10*).

On Earth, the amount of juvenile water associated with volcanism varies with magma composition. Determinations range from 4.9 ± 0.5% by weight of water for rhyolitic magma (*11*) to less than 1% for some potassium-poor oceanic tholeiite basalts (*12*). Carr (*13*) reviewed possible martian volcanic compositions and reported that most materials are probably mafic in composition. Although silicic units have also been

Table 1. Estimated amounts of water on Mars released in association with volcanism. Geologic ages are from Tanaka (*18*).

Age	Volcanic materials (10^6 km^3)	Water (10^6 km^3)	Water layer* (m)
Late Amazonian	5.3	0.17	1.2
Middle Amazonian	20.78	0.69	4.8
Early Amazonian	33.87	1.12	7.7
Late Hesperian	48.81	1.61	11.1
Early Hesperian	71.62	2.36	16.3
Late Noachian	21.03	0.69	4.8
Middle Noachian	0.28	0.01	0.1
Early Noachian			
Totals	201.69	6.65	46.0

*Values are given for a layer that would completely cover the planet.

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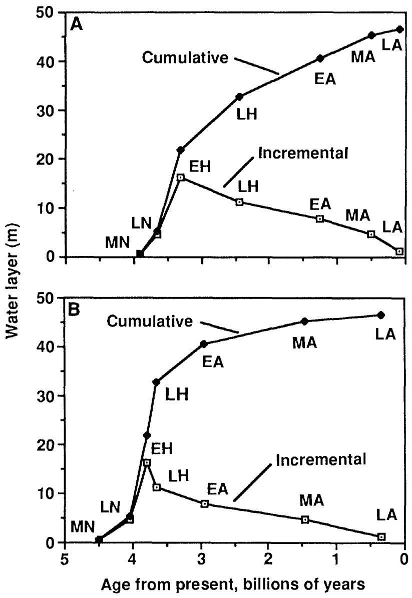

Fig. 1. Plot of water release on Mars inferred in association with volcanic processes (expressed as the thickness of a water layer that would cover the entire planet) for each geologic epoch Abbreviations: MN, Middle Noachian; LN, Late Noachian; EH, Early Hesperian; LH, Late Hesperian; EA, Early Amazonian; MA, Middle Amazonian; and LA, Late Amazonian. The "absolute" age scale is from Tanaka (*18*) and is derived from impact crater distributions based on work of Hartmann *et al.* (*9*) (model 1, **A**) and Neukum and Wise (*10*) (model 2, **B**).

suggested (*14*), they constitute less than 0.5% of the total volume of volcanic units. By using Earth as a first-order analog and by assuming that martian volcanism is dominated by mafic materials, a value of 1.0% by weight of water was used as an average for Mars.

Estimates of the amount of water on Mars released from the interior in association with volcanism are given in Table 1. Little can be said of the fate of the volatiles after their release to the surface, as a "martian water cycle" has not been formulated for either present or past conditions. Moreover, it is not known if water remained near its release area or migrated to other locations. By terrestrial analogy, some water probably migrated to shallow subsurface reservoirs in the regolith. Values given here pertain only to juvenile or "new" water released from the interior and not to recycled water. Because volcanism has spanned much of the "visible" history of Mars (the last ~4 billion years), water may have been released continuously from the interior, although not necessarily at a uniform rate. Figure 1 shows the incremental and cumulative release of water with time. Of particular interest is the very early history of Mars. Relatively little volcanic material is identified, yet most of the oldest terrain on Mars displays extensive valley networks and other evidence for the existence of water (*13, 15, 16*). This suggests that either there were other sources of water early in martian history (such as cometary contributions), or unidentified volcanic units of an early age, or both. Most of the ancient martian crust has been degraded or buried and thus its origin cannot be ascertained. However, by analogy with the moon, the martian crust probably developed by magmatic differentiation and extrusion of flood lavas. Thus, although few traces of earliest volcanism are visible, substantial water may have been released early in martian history and this water is not included in the estimates given here.

The greatest volumes of water appear to have been emplaced in Mars 3 to 4 billion years ago and coincided approximately with the development of the large outflow channels. Photogeologic evidence shows that the formation of outflow channels was episodic (*17*) and extended over a long interval of martian history (Late Hesperian through Middle Amazonian) and reflects on the availability of large volumes of water at or near the surface in some parts of the planet.

There are several uncertainties in the estimates presented here. Principal among these is lack of knowledge of volatile content for magmas; even terrestrial values, as used here, have large uncertainties and extrapolation to martian values is difficult. Uncertainties that stem from estimates of volcanic unit volumes can be reduced through more detailed mapping and determination of flow thicknesses. The values given here represent only amounts associated with volcanism. It is likely that significant additional volumes were released in association with plutonic intrusions. Thus the results substantiate the growing perception of Mars as a "wet" planet in the first third of its history.

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19. This work was supported by the NASA Office of Planetary Geology through grant NSG-7548 and the Office of Planetary Atmospheres through grant NAGW-580. I thank C. Moore and J. Moore for helping compile the data in this report.

27 January 1987; accepted 8 May 1987

Interocean Differences in Size and Nutrition of Coral Reef Sponge Populations

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Sponges consume an order of magnitude more organic matter on Caribbean coral reefs than on the Great Barrier Reef. This rate of consumption is attributed to Caribbean sponge biomass being five to six times greater than that on the Great Barrier Reef, on average, and to the absence in the Caribbean of phototrophic sponges, which are a feature of clean water regions of the Great Barrier Reef. The long temporal and spatial separation of the Atlantic and Pacific oceans has resulted in the evolution of dissimilar sponge faunas, with Caribbean sponges being heterotrophic, whereas many Great Barrier Reef sponges rely on nutritional input from photosynthetic symbionts.

THE CORAL REEF FAUNA OF THE Caribbean and Great Barrier Reef (GBR) regions show remarkable differences. There are few species of corals, mollusks, echinoderms, and fishes in common (*1*). Coral reefs of the western Pacific are comparatively richer than the Caribbean in some animal groups; for example, there are 75% more genera and 85% more species

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