But the SNCs cannot answer all the important questions about Mars. No matter how much is learned from the SNCs, they cannot replace a carefully considered successful Mars sample return mission. The SNCs are limited because they represent only one type of sample formed during a small part of Mars' history on a small part of Mars. For instance, continued study of the SNCs cannot determine: the mineralogy and origin of the martian dust; the abundances of many reactive gas species in the martian atmosphere; the natures and compositions of the martian highlands; the compositions of paterae volcanics; the natures and compositions of layered deposits; and whether living organisms ever existed on Mars. To solve these questions will require continued spacecraft investigations of Mars, including orbiters, landers, and especially sample returns.

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## TEMPORAL CHANGES IN THE GEOGRAPHIC DISTRIBUTION, ELEVATION, AND POTENTIAL ORIGIN OF THE MARTIAN OUTFLOW CHANNELS.

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**Introduction:** Observational evidence of outflow channel activity on Mars suggests that water was abundant in the planet's early crust. However, with the decline in the planet's internal heat flow, a freezing front developed within the regolith that propagated downward with time and acted as a thermodynamic sink for crustal $H_2O$. One result of this thermal evolution is that, if the initial inventory of water on Mars was small, the cryosphere may have grown to the point where all the available water was taken up as ground ice. Alternatively, if the inventory of $H_2O$ exceeds the current pore volume of the cryosphere, then Mars has always possessed extensive bodies of subpermafrost groundwater. We have investigated the relative age, geographic distribution, elevation, and geologic setting of the outflow channels in an effort to (1) identify possible modes of origin and evolutionary trends in their formation, (2) gain evidence regarding the duration and spatial distribution of groundwater in the crust, and (3) better constrain estimates of the planetary inventory of $H_2O$.

The channels studied in this analysis were compiled from a variety of sources and include virtually all major channels identified in the literature whose bedforms exhibit significant evidence of fluvial erosion. Following a review of previously published work, these channels were investigated by a detailed examination of selected Viking photomosaics and high-resolution images. Where possible, channel ages were determined by reconciling previously published crater counts with those associated with the revised stratigraphic referents of Tanaka [1]. Where inconsistencies or conflicts in these ages were noted, the discrepancies were usually resolved by examining superpositional relationships with other units whose relative ages are better constrained. In the discussion that follows, all cited elevations refer to that of the channel source region or, in those instances where no identifiable source region is visible, the highest elevation at which the channel is first visible. All elevations are based on the U.S.G.S. Digital Terrain Model [2].

**Observations and Discussion:** Although there is considerable uncertainty regarding when the first outflow channels actually formed, three of the oldest—Ma'adim Vallis (−27°,183°), Al-Qahira Vallis (−19°,199°), and Mawrth Vallis (19°,13°)—are probably Late Noachian to Early Hesperian in age [1,3,4]. A fourth and much larger channel, located near Argyre (−65°,55° to −57°,46°), is also thought to date from this period [5]. A characteristic common to all four channels is their lack of a localized and readily identifiable source region, an observation that may reflect a subsequent period of intense localized erosion or possible burial by lavas and sediments. Whatever the explanation, the highest elevations at which three of the channels appear lie between 2 and 3 km, while the highest elevation of the fourth—Mawrth Valllis—occurs near 0 km. No statistically significant geographic clustering of these four channels is observed. Although Ma'adim Vallis and Al-Qahira Vallis are located within ~800 km of each other, the area of channel activity defined by this association is geographically distinct from the areas defined by the locations of the other two channels. This spatial separation, combined with the absence of any unique geologic characteristic common to the local environment of all four channels, suggests that the earliest martian outflow channels had a polygenetic origin.

As noted by previous investigators, outflow channel activity reached a conspicuous peak during the Late Hesperian. The majority of this activity was concentrated in and around the Chryse area; however, other regions of potential activity included Deuteronilus Mensae (42°,338°), Mangala Vallis (−19°,149°), as well as a number of smaller channels to the south of the Chryse system—including Nirgal Vallis (−28°,45°) and Uzboi Vallis (−29°,36°).

The abrupt emergence of the Chryse channels from regions of chaotic terrain is usually attributed to the widespread disruption and subsidence of the crust due to the catastrophic discharge of groundwater [e.g., 6]. Areas of chaos range from ~1000 km² for the source of Shalbatana Vallis (0°,46°), to over 25,000 km² for the chaos at the eastern end of Valles Marineris in Capri Chasma (−15°,52°). These areas are comparable to those affected by prolonged, high-volume groundwater extraction on Earth (e.g., extensive pumping in the San Joachim valley of California has resulted in up to 9 m of subsidence over an area of 13,500 km² [7]).

The spatial and temporal association of the Chryse outflow channels with the development of Valles Marineris and Tharsis has frequently been cited as evidence of a possible genetic relationship [6,8]. In this context, several mechanisms for initiating outflow channel activity appear viable. For example, prior to the development of Valles Marineris and Tharsis, Mars may well have possessed an extensive aquifer system consisting of subpermafrost groundwater confined beneath a thick (>1-km) layer of frozen

ground. With the updoming of Tharsis, the resulting gradient in hydraulic head may have driven the flow of groundwater to lower elevations where the local increase in hydraulic pressure was sufficient to disrupt the confining layer and permit the catastrophic discharge of groundwater to the surface [6]. With the continued growth of Tharsis, the development of destabilizing hydraulic pressures should have occurred at progressively greater distances from the central uplift, resulting in potentially testable correlations between channel elevation [which varies from a high of 7 km for Kasei Vallis (0°,80°) to a low of 0 km for Ares Vallis (-2°,18°)], distance, and age. Alternatively, the growth of tensional fractures associated with the updoming of Tharsis and rifting of Valles Marineris may have broken the confining layer of frozen ground and permitted the discharge of groundwater to the surface as the fractures propagated to the lower elevations toward the east [8]. Recent calculations also suggest that channel activity may have been seismicly triggered [9,10]. By this mechanism, shock waves generated by impacts, earthquakes, or explosive volcanic eruptions may have generated transient pore pressures sufficient to disrupt the confining layer of ground ice, permitting groundwater to flow onto the surface driven by whatever artesian pressure existed within the confined aquifer prior to the seismic event. It should be noted that these scenarios are not mutually exclusive, nor do they exhaust the number of possible mechanisms for generating the Chryse or other Late Hesparian channels.

Unlike the majority of channels that were active during the Late Hesperian, many Early and Middle Amazonian channels appear related (both spatially and temporally) to regions of likely geothermal activity. For example, in the region east of Hellas, Dao, Reull, and Harmahkis Valles are all located within several hundred kilometers of the Early Hesperian volcano Hadriaca Patera (-31°,268°) and appear closely associated with lava flows from the Late Hesperian-Early Amazonian volcano Tyrhena Patera (-22°,254°) [11]. Another major concentration of channels occurs to the west and northwest of Elysium Mons (25°,213°) and Hecates Tholus (32°, 210°), volcanos that were also thought to have been active during this period. Both the geologic setting and chronology of these channels suggests that they may have been fed by water melted as a result of the increased heat flow associated with local volcanism. The accumulated water may then have been released to the surface either by the eventual thawing of the ground-ice layer or by its mechanical disruption through the build-up of a large hydraulic head. The average elevation of channel source regions during this period is ~1 km, or approximately 2 km lower than the apparent average elevation of Late Hesperian channels.

A number of small Middle- to Late-Amazonian-aged channels have been identified to the east and southeast of the Olympus Mons escarpment [12], a relationship that again suggests a potential geothermal origin. There is also evidence of fluvial activity within Ophir Chasma (-4°,73°), which may be water-rich debris flows [13,14]. The most significant outflow event to have occurred during this time happened near Cerberus Rupes (8°,195°), where a large broad swath of predominantly featureless, sparsely cratered terrain lies within a topographic basin that covers an area of ~10⁶ km² to the south of the fracture. With the exception of a few moderately sized areas located in the eastern half of the basin, the morphologic evidence is more consistent with a major ponding feature, such as a lake or sea, than with the type of outflow channel found in the Chryse system. The ultimate source of water that embayed this

region was apparently a subsurface reservoir that was either breached by the formation of Cerberus Rupes or which, at some later time, was able to take advantage of the structural pathway provided by the existence of the fracture to reach the surface [15].

**Summary:** Outflow channel activity has apparently spanned most of martian geologic history, from the Late Noachian to Late Amazonian. The outflow channels that date back to the Late Noachian and Early Hesparian are few in number and exhibit no strong association with any single geographic region. The Late Hesperian saw a widespread and significant increase in channel activity, much of which was concentrated in the Chryse system, a distribution that is probably linked to the concurrent development of Tharsis and Valles Marineris. During the Amazonian, the occurrence of outflow channels appears to have become more localized around regions of potential geothermal activity. One possible explanation for this geographic shift in outflow channel activity is that by the Early Amazonian the cryosphere had grown thick enough that it was no longer easily susceptible to disruption by artesian pressure alone. Alternatively, the cryosphere may have simply grown so large that no groundwater, outside that transiently produced by the melting of ground ice in active geothermal regions, survived beyond the Late Hesperian. If this last interpretation is true, theoretical calculations indicate that the amount of $H_2O$ required to saturate the pore volume of the cryosphere at this time would still exceed the equivalent of a global ocean many hundreds of meters deep [16]. A more detailed analysis of these results is currently in preparation.

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**OBLIQUITY VARIATION IN A MARS CLIMATE EVOLUTION MODEL.** D. Tyler[1,2] and R. M. Haberle[2], [1]Department of Meteorology, San Jose State University, San Jose CA 95192, USA, [2]Ames Research Center, Moffett Field CA 94035-1000, USA.

The existence of layered terrain in both polar regions of Mars is strong evidence supporting a cyclic variation in climate. It has been suggested [1] that periods of net deposition have alternated with periods of net erosion in creating the layered structure that is seen today. The cause for this cyclic climatic behavior is variation in the annually averaged latitudinal distribution of solar insolation in response to obliquity cycles [2]. For Mars, obliquity variation leads to major climatological excursions due to the condensation and sublimation of the major atmospheric constituent, $CO_2$. The atmosphere will collapse into polar caps, or existing caps will rapidly sublimate into the atmosphere, dependent upon the polar surface