Introduction: Ma’adim Vallis is a Martian channel system that extends ~900 km northward from the highlands of Terra Cimmeria into Gusev crater. This system has attributes of both outflow channels and valley networks, and is characterized by geomorphic features such as terraces, inner channels, and immature tributary valleys [1-4]. Ma’adim Vallis has been widely interpreted as a product of aqueous processes involving surface runoff from adjacent plains, overflow from one or more large lakes, large effusions of groundwater, and/or groundwater sapping. Some researchers have interpreted this system as a product of multiple discrete episodes of aqueous flow that collectively occurred over a time frame extending from the Noachian to the Amazonian [2,3]. Others have suggested catastrophic formation of the system as a result of the sudden partial drainage of a large and long-lived lake hypothesized to have existed in the Eridania basin during much of the Late Noachian [5-7].

Problems with Past Aqueous Interpretations: Some landforms and geological units at Ma’adim Vallis have previously been interpreted as products of aqueous processes [1-6], but obvious examples of fluvial or lacustrine sedimentary deposits have proven difficult to identify here. In contrast, impact and aeolian features are abundant [2-4], and many features associated with channel reaches and terminal basins have properties consistent with volcanic origins [8,9].

Much of the Ma’adim Vallis region is blanketed by anhydrous fines that partly obscure the mineralogy of underlying materials, but the mouth of the system at Gusev crater is known to be substantially mantled by pristine volcanic flows of mafic and ultramafic composition and of Hesperian age [9-12]. The unaltered character of these materials is not expected of former lacustrine environments [12-15], and though hydrated minerals are locally present at sites associated with the Noachian-aged Columbia Hills [14,16-18], these minerals formed in low water-to-rock ratios that do not suggest development in lakes [15,19,20].

Eridania units are hypothesized by some workers to have been deposited in lacustrine environments, but these interpretations are equivocal, and clear geomorphological evidence for the past existence of a large lake in the Eridania basin is lacking. Existence of a lake over geological timescales should have resulted in the accumulation of extensive and thick sedimentary mantles across the basin, and the gradual loss of lake waters should have resulted in the generation of a series of progressively lower shoreline and nearshore deposits. Yet no obvious shoreline features have been identified within the Eridania basin [6,7,21] and there is no clear evidence that extensive lacustrine sedimentary mantles have ever existed here.

The mineralogical properties of the Eridania basin are also not consistent with the past existence of a long-lived lake that released a proportion of its volume in catastrophic floods and then lost its remaining waters within closed basins. Exposures of hydrous minerals are widespread in the Eridania region [22], but they are in many cases of very modest geographic extent [23,24], are typically separated by vast expanses of little altered materials [25], and are distributed at elevations and in locales that are not consistently associated with hypothesized paleolake extents [7]. Extensive and thick outliers of the full range of evaporite minerals expected of the past sites of large lakes that were gradually lost through evaporation or sublimation [26] are missing within the Eridania basin [7]. The limited exposures of chloride minerals within and near the Eridania basin need not have been generated within lacustrine environments, and instead could have been derived from local volcanic units [27]. Mechanisms similarly exist for formation of local sulfate minerals by volcanic processes [28].

The extensive ridged plains units of the Eridania basin have properties aligned with those expected of flood basalts, and in many cases are spectrally bland apart from signatures related to minerals such as pyroxenes [29]. The large highland exposures of pristine olivine-rich materials that exist both inside and outside of the Eridania basin [30,31] would have been especially susceptible to alteration in younger aqueous environments of any kind.

From a global perspective, the persistence of pristine olivine-rich units of Noachian age at numerous locales on Mars [30,32-37] is not compatible with the past existence of extensive wet surface conditions on this planet over geological time scales [26,38-42], including the long-term existence of a large highland lake at the end of the Noachian. The absence on Mars of spatial correlations between hydrous minerals and both highland channel networks and outflow channels [25,34,36,43] contradicts hypothesized aqueous origins for these features and reinforces the perspective that cold and dry surface conditions have dominated over the history of the planet [26,38-42]. Congruent with this perspective, the expected signatures of hypothesized lowland oceans and highland lakes are also yet to be identified on Mars [26,42-46].
Past aqueous interpretations of the Ma‘adim Vallis system were partly based on implicit and explicit assumptions that lava plains within basins such as impact features should not form bowl-shaped surfaces [6] and should mark the highest elevations attained by associated flows. However, the levels of lavas within enclosed basins can indeed drop as a result of processes such as lava degassing, contraction during solidification, and drainage into local magmatic plumbing systems [26]. It is also not unusual for large impact basins that are partly filled by flood lavas to have developed distinct bowl shapes of the type common within the Eridania basin.

**A Volcanic Interpretation of Ma‘adim Vallis:**
The properties of Ma‘adim Vallis strongly suggest dry volcanic origins involving effusions of low-viscosity flood lavas from multiple highland sources mainly during the Noachian and Hesperian. As is typical of flood lavas emplaced on bodies such as the Moon, Mercury, and Venus, most of these volcanic sources are expected to have been buried by the plains units with which they are associated. Globally, Martian highland terrains were extensively resurfaced by low-viscosity lavas in the Noachian and Hesperian [1], and mare-style ridged plains correspondingly extend across highland regions adjacent to the Ma‘adim Vallis system, including key areas within the Intermediate basin and the Eridania basin. Accumulation of low-viscosity lavas at the mouth of Ma‘adim Vallis is indicated by the extensive presence of ridged plains here [8,9]. The geochemical properties of Adirondack class lavas, which are especially abundant at Gusev crater, suggest liquidus viscosities at least as low as 0.5 Pa·s [47]. Martian lavas with such viscosities have a clear capacity for deep incision into bedrock substrates if erupted at sufficiently high rates and with high total volumes [39,40,48-53].

Thermal calculations suggest that formation of Ma‘adim Vallis would have required a minimum erupted lava volume of ~112,000 km³, but a total volume approaching ~275,000 km³ is more likely. Assuming 20-m-deep flows with viscosities of 1 Pa·s, peak discharge rates of at least ~4 x 10⁶ m³/s are estimated for channelized lavas that formed this system. A volcanic origin for Ma‘adim Vallis is especially significant as it resolves past discordance between aqueous interpretations of this system and the results of the Spirit mission [26]. Furthermore, the general style of volcanic development of Ma‘adim Vallis is expected to have been similar to that involved in the formation of many other highland channel networks on Mars [53-55], including nearby systems such as Al-Qahira Vallis.