

**CO<sub>2</sub>-RELATED NOACHIAN ALKALINE MAGMATISM ON MARS: EVIDENCE FROM HIGH-PHOSPHOROUS WISHSTONE-CLASS ROCKS IN GUSEV CRATER.** T. Usui<sup>1</sup>, H. Y. McSween, Jr.<sup>1</sup> and B. C. Clark III<sup>2</sup>, <sup>1</sup>Dept. of Earth Planet. Sci., University of Tennessee, Knoxville, TN 37996 (tusui@utk.edu), <sup>2</sup> Space Science Institute, Boulder, CO 80301, U.S.A.

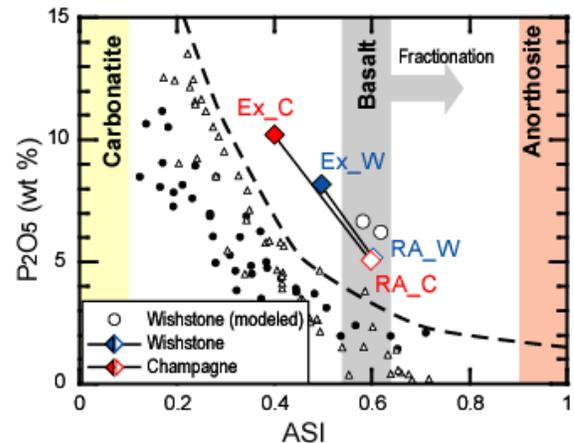
**Introduction:** It has been proposed that Mars was once warm enough to maintain persistent liquid water on its surface [e.g. 1]. Such a warm and wet environment implies an effective greenhouse gas (CO<sub>2</sub> and/or other volatiles) that was dominantly supplied by early Martian magmatism [2]. Volatiles profoundly affect the thermodynamic properties of magma and thus play an important role in generating a variety of igneous rock types. The Spirit rover has encountered volcanic and volcanoclastic rocks having diverse alkaline compositions in the Noachian-age Gusev crater [3]. Here we focus on Wishstone-class tephrites which are unusually enriched in incompatible elements (e.g. >5 wt% P<sub>2</sub>O<sub>5</sub>) with low SiO<sub>2</sub> contents. These compositions cannot readily be explained by fractionation of other magmas in Gusev and may require a different petrogenesis. We argue that the Wishstone-class rocks formed in association with carbonatitic melt/fluid. Investigating the petrogenesis of the Wishstone-class rocks may yield insights into the effects of CO<sub>2</sub> on Noachian magmatism as well as its contribution to the greenhouse gas.

**Petrogenesis of Wishstone class:** Two samples (Wishstone and Champagne) of the >95 Wishstone-class rocks were investigated by the full set of Athena instruments [4]. The APXS measured the elemental compositions of unbrushed, RAT-brushed and RAT-abraded surfaces [5]. To obtain the chemical compositions of rock interiors, we extrapolated a trend defined by RAT-brushed and -abraded surface compositions. An approximate model of x-ray fluorescence emissions is used to model the contamination by Martian soil/dust trapped in vugs on the Wishstone RAT-abraded surface. The model yields two uncontaminated rock compositions that do not significantly differ from the extrapolated value. The extrapolation analysis suggests that the high-P<sub>2</sub>O<sub>5</sub> tephrite signature is not attributable to secondary aqueous alteration but represents an igneous rock composition [6]. Assessment of the compositional trend also suggests that merrillite is the phosphate mineral in Wishstone class rocks.

Modified CIPW norm calculations using merrillite instead of apatite yield normative compositions of Wishstone and Champagne that are more consistent with their measured mineral abundances estimated by MB than the conventional CIPW norm. The modified norm calculations show that Wishstone-class rocks are

silica-saturated (hypersthene-olivine normative) and alkaline.

The high-P<sub>2</sub>O<sub>5</sub> compositions of Wishstone-class rocks are oversaturated with merrillite, suggesting that mechanical admixture of merrillites occurred. Fig. 1 shows that Wishstone and Champagne distinctly plot above the experimentally determined solubility limit for merrillite. Considering the pyroclastic textures of Wishstone-class rocks, the merrillite was probably incorporated during explosive eruption rather than being mixed by accumulation processes in a magma chamber.

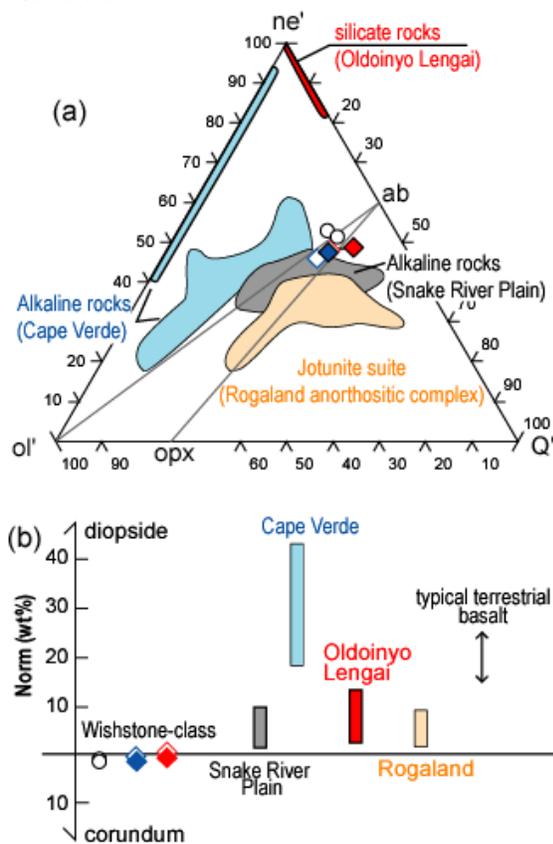


**Fig. 1:** Experimentally determined solubility of apatite (●) and merrillite (△) in silicate melts as a function of melt ASI [12, 13]. Compositional ranges of Wishstone (W) and Champagne (C) plot above both apatite and merrillite solubility limits (approximated by the dashed curve). RA and Ex indicate RAT-abraded and -extrapolated compositions, respectively. Ranges of ASI values of carbonatites, terrestrial basalts, and anorthosites are also shown. Magmatic fractionation commonly increases the ASI value of basaltic magma.

Exploring the phosphorous-rich source that supplied merrillites could constrain the petrogenesis of Wishstone-class rocks, because the phosphorous-rich source must have had distinctly lower SiO<sub>2</sub> contents and aluminosity expressed as the aluminum saturation index (ASI = molar ratio of Al<sub>2</sub>O<sub>3</sub>/[CaO+Na<sub>2</sub>O+K<sub>2</sub>O]) than for common silicate magmas (Fig. 1). Candidates of the phosphorous-rich source are a carbonatitic melt or a highly fractionated residual melt (jotunite) after anorthosite crystallization.

The petrogenesis of Wishstone-class rocks is further constrained by comparison with Earth analogs: a

jotunite suite from the Rogaland Proterozoic anorthosite massif, alkaline rocks from carbonatite volcanoes (Oldoinyo Lengai and Cape Verde Islands), and alkaline rocks from the Craters of the Moon (COM) lava field, Snake River Plain (Fig. 2). Most rocks of the jotunite suite contain normative quartz (silica-oversaturated) and distinctly lower normative plagioclase than Wishstone and Champagne, whereas alkaline rocks from carbonate volcanoes contain normative nepheline (silica-undersaturated). Neither analog is consistent with the hypersthene-olivine normative (silica-saturated) signature of Wishstone and Champagne. Moreover, their expected associations with anorthosite and carbonatite, respectively, have not been seen in Gusev crater.



**Fig. 2:** (a) Comparison of the normative compositions ( $ne'$  = nepheline,  $ol'$  = olivine,  $Q'$  = quartz) of Wishstone and Champagne with possible high- $P_2O_5$  terrestrial analogs. These data are projected from diopside onto the  $ol'$ - $ne'$ - $Q'$  plane, following [14]. (b) Comparison of the normative diopside or corundum of Wishstone and Champagne with the terrestrial analogs in (a). Diopside and corundum are mutually exclusive normative minerals. Normative data for the terrestrial analogs are from [6] and references therein. Symbols as in Fig. 1.

The alkaline rocks from the COM lava field are the most plausible analogs of Wishstone-class rocks.

COM alkaline rocks are hypersthene-olivine normative rocks characterized by predominant normative plagioclase but low amounts of diopside (Fig. 2). Some of them exhibit pyroclastic textures and contain xenocrystic apatite crystals. Geochemical studies suggest that they originated from a mantle metasomatized by  $CO_2$ -rich fluids and highly alkaline melts in the wake of the Yellowstone hotspot [7].  $CO_2$ -rich fluid should occur as carbonatitic melts within the upwelling plume. Thus, we propose that the Wishstone class represents a silica-saturated alkaline suite that has mechanically admixed xenocrystic merrillites, probably during an explosive volcanic eruption; the merrillites crystallized from carbonate-rich magma produced by melting of a  $CO_2$ -bearing Martian mantle.

**Implication for the effects of  $CO_2$  on Noachian magmatism:** It has been debated that  $CO_2$  was the effective greenhouse gas in the early Mars. To maintain persistent liquid water on the Martian surface, several bars pressure of  $CO_2$  is required, which is approximately three orders of magnitude higher than that on present-day Mars ( $pCO_2 = 6$  mbar) [2]. In contrast, other greenhouse gases (e.g. methane and ammonia) were recently proposed [8], because no carbonate deposits (carbon sinks) or significant atmospheric loss that accounts for the early  $CO_2$ -rich atmosphere have been observed [e.g. 9, 10]. Our study suggests that, at least beneath Gusev crater,  $CO_2$  should have resided in the Martian mantle. This is consistent with the existence of abundant Gusev alkaline basalts [3], because primordial melting of  $CO_2$ -bearing Martian mantle would produce transitional to alkali basalts [11]. Thus, we propose that  $CO_2$  could have played a significant role in Noachian magmatism and had the potential to have been the effective greenhouse gas as previously hypothesized.

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