

Did Atmospheric or Planetary Local Temperatures Affect the Shock Emplacement of Noble Gases in Martian Meteorites?

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Abstract

Could the elemental fractionation effects seen in Martian meteorite noble gas measurements be the result of an impact injecting gases adsorbed on cold rock surfaces? We discuss what possible effects low temperatures might have on noble gas insertion and some experimental tests.

Introduction

Gases-especially the noble gases- are excellent tracers of geochemical and cosmochemical formation and evolution, and are an appropriate tool to study interactions between the surface and atmosphere of planetary bodies as well as location of origin (interior vs. atmospheric components).

The physical (including adsorption and solution) and chemical properties of gases in rock have been extensively studied to understand cosmochemical formation reactions and reactivity, equilibrium conditions in astrophysical models, solubility in planetary nebula and systems, and partition effects (including fractionation) between phases/crystals in formed bodies.

For all these reasons, they are critical to the study of Mars. In particular, many of the Martian meteorites contain noble gases that appear to have been incorporated, either directly or indirectly, from the atmosphere of Mars. The best evidence for the SNC and ALH84001 meteorites as Martian in origin is derived from the comparison between the Martian atmosphere as analyzed by the Viking missions and the elemental/isotopic data presented from the analysis of gas in these meteorites. (1, 2)

But the mechanism and timing of incorporation is not clear, although several plausible mechanisms have been suggested, many of which have important implications, either for the recent (last 10-15 Ma) history of Martian climate, for the impacts that produced the Martian meteorites, or both. (3,4)

Among the Martian meteorites, there are differences in noble gas compositions-could these differences be due to climate conditions (temperature) at the time of their production?

One of the proposed mechanisms for the noble gas differences in the Martian meteorites is thus: the idea of a cold-surface adsorption with subsequent shock implantation. This mechanism can be quantified, and thus can be tested.

Discovering the climate history of Mars is one of the most important aspects to understanding its origin and evolution, and thus is crucial to understanding the habitability of the surface of Mars in the past and in the future.

Foundational Work in Shock: Early Shock Study

Most studies conducted on terrestrial and Martian samples have concentrated on the analysis of the gas reservoirs in un-

shocked and post shock basalts and meteorites. Attempting to duplicate the conditions which produced the Martian meteorites in analog terrestrial rock (i.e. basalt or dunite), researchers have studied the acquisition of gases as a function of pressure, grain size (where powdered, chip, mineral separate, and sliced disk have been tested), partition coefficients, and gas composition.

Two groups did extensive studies in the 1980's and 1990's on shocked Servilleta basalt in order to: quantify the shock implantation of gas (with or without fractionation) as a function of shock strength (pressure); determine emplacement/siting location in vesicles and crystals, and determine emplacement efficiency of gases. (5, 6)

Shock experiments have been carried out on heated samples of basalt (but not cooled samples) to determine detailed petrographic changes, but not gas composition changes (7)

Why Low Temperatures May Matter on Mars

Most previous work on shock processes in rock, including diverse studies on meteorites, oil field strata, and laser drilling, have focused on ambient to high temperature conditions. In almost all cases, the samples are not at low or very low temperatures at all. The thermo-chemical-petrographic-physical properties of rocks at low temperatures are different and holds some surprises, however.

Permeability is a function of temperature, and the Darcy equation can be applied to perturbations at either end of the temperature scale. Henry's law applied to geophysics also demonstrates the thermodynamic importance of temperature at all scales in calculating gas solubility by chemical potential.

A 2004 study by Park *et. al.* (8) studied the effects of low temperature in rock for the purposes of liquefied gas (propane, etc) storage. The researchers found an interesting result: for igneous rocks such as granite, the rate of thermal expansion decreased as temperature was decreased as expected all the way down to about - 50° C (223.15° K), then the thermal expansion coefficient abruptly reversed, and changed dramatically from the usual rate of change as the temperature approaches about - 150° C (123.15° K). This meant the thermal expansion coefficient was negative below - 50° C: meaning the rock *expands* below this temperature.

Thermal cracking is considered a plausible mechanism. Usually, when energy is absorbed in geologic media, the first thermal stresses occur when the colder surrounding rock retards the change in dimensions of the locally heated rock. If this stress reaches the level of the tensile strength of the rock, fractures can occur. (9)

Hence, it becomes possible to theorize that this effect-also seen at high temperatures-may be at work at low temperatures. Thus, adsorbance/absorbance effects based on temperature may be significant on the mechanism of emplacement.

It has been theorized that at the time of impact on Mars, implanted noble gases cooled very quickly and thus did not 'communicate' with other material beyond the immediate melting and absorption zone. Thus, a sample of the atmosphere of Mars was encapsulated and sent on its way.

If the launching impact occurred at night or in planetary winter, then the high expansion mechanism seen at high temperatures, and seen at very low temperatures, would substantially change both the permeability and porosity of the rock-thus the absorption and retention of noble gases at the time of the shock.

Shock Chemistry and Physics: Macro and Micro

The consequence of shock in solid material may produce three possible effects: 1) the structural modification of the object, and its physio-chemical bonds and lattices; 2) chemical activation of various species; 3) possible immediate chemical reaction *in-situ*.

Permeability and porosity of all rock-which are directly related to crystal and vesicle micro-structure in the rock-are also significantly changed as a result of both shock and temperature. This demonstrates why noble gas abundances are sensitive to phase changes-which occur in all shock.

The types of shocks in these kind of experiments are in the non-adiabatic regime, so simple MHD or 'ideal fluid' descriptions here may be incorrect, and a new 2-fluid description to model effects at the micro-structural level may be needed to understand materials effects (like the energy dissipation in the rock-both the resistivity and viscosity components), and thus determine the mechanism(s) of emplacement.

Mechanism(s) of Emplacement

The simple filling of spaces in the atomic and crystalline lattices is usually seen as a 'steric effect' which is a necessary function of the atomic orbital radius of the gas (if monatomic; the molecular radius if polyatomic). For noble gases, emplacement is a function of mass. As they are 'inert' they were considered incompatible elements in most geological processes at high temperature. Although recent research has indicated this may not be so, it is the low temperature behavior that will be examined here.

There are a variety of possible mechanisms governing incorporation (most of which are not well understood) that may emplace gases into rock: general physical or chemical solubility (this includes whether oxidizing/reducing conditions are present), clathrate formation, electromagnetic trapping (example: noble gas as a species of 'zero charge' inserted at crystal lattice sites), assimilation by parent magma, sustained high pressure of melts (10), etc.

New Experimental Protocol for This Study

The proposal is to test the mechanism of shock incorporation (implantation) of adsorbed (elementally fractionated) gas by performing impact experiments similar to those of Bogard et al. (1986) and Wiens and Pepin (1988), using the impact laboratory of F. Hörz and M. Cintala at JSC in Houston where the previous implantation experiments were performed.

The provisional protocol involves doing tests at a range of temperatures from room to dry ice. At room temperature, one can verify and reproduce the same results as those of Bogard et al. (1986) and Wiens and Pepin (1988). At lower temperatures, one can calculate the amount of adsorption using the data on crushed basalt from Fanale et al. (1978) and Podosek et al. (1981).

Once data on the effects of shock implantation on adsorption has been acquired, that data will be applied (and a variety of experimental/spacecraft data) to the question of the source of the "atmospheric-like" noble gases in the nakhlites and ALH 84001, and to the question of the origin of Martian meteorites.

Full petrography and some quantitative analysis of all available crystals and grains-both pre- and post-shock- will be carried using the CAMECA SX-50 Electron Microprobe in Prof. M. J. Drake's laboratory in LPL at the UA.

The petrologic phases to be studied (both pre and post shock) include pyroxenes, ilmenite, quartz, olivine, plagioclases (which convert under shock to maskelynite, a diaplectic glass), iron oxides, etc. This is necessary because certain Martian atmospheric components are more concentrated in opaque minerals (like ilmenite) and maskelynite than in pyroxenes; while this may be due to grain size, other effects may be at work (11).

References:

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