**SURFACE RUNOFF FEATURES ON MARS: TESTING THE CARBON DIOXIDE FORMATION HYPOTHESIS.** S.T. Stewart, *California Institute of Technology, Pasadena, CA 91125, USA, (sstewart@gps.caltech.edu)*, F. Nimmo, *Bullard Labs, Cambridge, CB3 0EZ, UK, (nimmo@esc.cam.ac.uk).*

### Introduction

Recent Mars Orbital Camera (MOC) images of gullies provide evidence for recent fluid erosion at the surface (Malin & Edgett 2000). However, the hypothesis that liquid water formed these features is problematic since current geothermal models of the Martian crust put the $H_2O$ liquid stability field a few to several kilometers below the surface (Clifford 1993; see also Fig 1). Based on the equilibrium phase diagram of $CO_2$ (see Fig 1), several authors (e.g. Hoffman 2000, Draper et al. 2000, Kargel et al. 2000, Lambert & Chamberlain 1978) have suggested that $CO_2$ (in liquid or vapor form) or $CO_2$ clathrate hydrate may be responsible for the gullies and other features. We will examine this hypothesis, and conclude that $CO_2$ and $CO_2$ clathrates are unlikely to exist in the crust in sufficient quantities, and would not produce erosional gullies of the kind observed.

### Pure $CO_2$

In some areas, $\sim 100$ gullies are observed within a few 100 m of each other (Malin & Edgett 2000). The local source reservoir required to produce such gullies is about $10^8 - 10^9$ kg of liquid (either $CO_2$ or water). There are considerable thermodynamic difficulties with storing such large volumes of $CO_2$ in the near surface on Mars. In order to store such masses of $CO_2$ in the crust the reservoir must be sealed from the atmosphere and the $CO_2$ placed under lithostatic pressure. Solid $CO_2$ will sublime and cannot therefore provide a cap, and any cap will tend to be disrupted by impacts over geological time. Moreover, we will argue that neither adsorption from the atmosphere nor volcanic outgassing are likely to provide the masses of $CO_2$ required.

### $CO_2$ clathrate hydrates

Since it is difficult to create a pure $CO_2$ reservoir in the crust and the presence of $H_2O$ is likely, we will also examine the possible formation mechanisms of $CO_2$ clathrate hydrate ($CO_2 \cdot 6H_2O$, $\rho \sim 1100$ kg m$^{-3}$). Clathrates are only stable for long periods when $CO_2/H_2O > 1/6$ (Larson 1955). Unless sealed from the atmosphere, any clathrate within pores will decompose for any temperature greater than about 150K, the clathrate stability curve evaluated at atmospheric pressure (see Fig 1). Away from the poles, clathrate formation is unlikely unless rapid gas flowthrough is occurring. We will therefore argue that the combination of low $CO_2$ concentrations in the regolith and the clathrate stability requirements make clathrate formation unlikely, except near the poles.

### Gully formation

Even assuming that enough $CO_2$ could be accumulated to account for the volume requirements of the gullies, we will argue that it is unlikely that liquid or vaporized $CO_2$ could account for the gully morphology. If suddenly exposed to atmospheric pressure, for instance by slope failure on a crater or valley wall, the phase diagram (Fig 1) shows that the decompression will be accompanied by generation of $CO_2$ vapor. The volume change accompanying the vapor generation will tend to accelerate the $CO_2$ vapor into the atmosphere, in a manner similar to terrestrial volcanic eruptions.

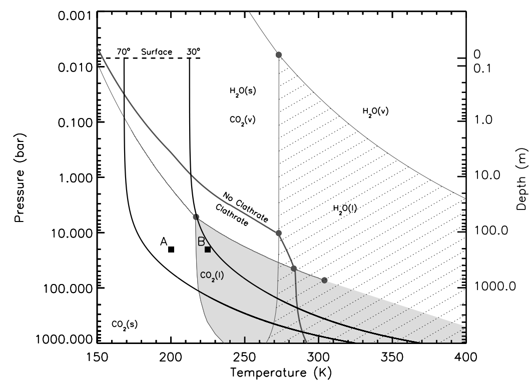


Figure 1: $H_2O$-$CO_2$ equilibrium phase diagram with Martian geotherms at 30 and 70° latitude, the observed latitude range of the gullies. Geotherms assume an internal heat flux of 30 mW m$^{-2}$ and thermal conductivity at the surface of 0.3 Wm$^{-1}$K$^{-1}$ exponentially increasing to 3.0 Wm$^{-1}$K$^{-1}$ at depth. Regolith structure assumes 20% surface porosity with decay constant 2820 m (Clifford 1993). The surface pressure is 7 mbar.

The velocity of the flow escaping to the atmosphere can be calculated from the change in enthalpy of the system resulting from the generation of vapor and the temperature drop upon decompression (Kieffer & Delaney 1979). This enthalpy change, $\Delta H$, is given by

$$\Delta H = H_0 - xH_v - (1-x)H_s \qquad (1)$$

where $x$ is the vapor mass fraction, $H_0$ is the enthalpy of the original material, and $H_v$ and $H_s$ are the enthalpies of the vapor and solid at 7 mbar. Assuming that most of the energy is converted into kinetic energy of the expanding vapor mixture, the exit velocity $u$ is given by (Smith et al. 1979)

$$u^2 = 2\Delta H. \qquad (2)$$

Under typical Martian conditions the exit velocity of the vapor is predicted to be $\sim 100$ m s$^{-1}$.

On Earth, gullies are carved by water-supported debris flows with flow velocities of order 1 m s$^{-1}$. The course of the narrow Martian channels are affected by the local slope topography, over distances of 10's-100's m, indicating a relatively slow flow velocity. The initial ejection velocity from decompressing liquid $CO_2$ is likely to be $\sim 100$ times faster than fluid or debris flows on Earth which are morphologically similar to the Martian gullies. These exit velocities are more characteristic of terrestrial pyroclastic flows. Such flows at Mt Saint Helens produced tongue-shaped flows with sharp edges and roughly constant widths (Rowley et al. 1981), quite different from the Martian gullies.

**Conclusions**

We will argue that neither solid or liquid $CO_2$ nor $CO_2$ clathrate can be accumulated in significant quantities. Even under the most optimistic $CO_2$ trapping scenarios, the mass fraction of $CO_2$ in the crust must be small. Hence, the mass of $CO_2$ required to support a single debris flow must be drawn from a large volume of the crust, making it difficult to accommodate the formation of clusters of gullies and repeat flow events. Furthermore, sudden exposure of condensed $CO_2$ to the surface produces volcanic-like jets of $CO_2$ vapor which are unlikely to form the observed tapering V-shaped channels and depositional aprons. We conclude that $CO_2$ could not have formed the gullies. The only reasonable alternative is liquid water formation. Since liquid water is not stable near the surface, the formation mechanism of the Martian surface runoff features probably involves rapid melting or transport of liquid water from depth.

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