IMPACTS, SALTS, AND ICE ON MARS: HOW BRINE FLOW IN YOUNG GULLIES AND ELSEWHERE COULD BE RELATED TO IMPACT CRATERING. D. M. Burt[1] and L. P. Knauth[2], [1]School of Earth and Space Exploration, Arizona State Univ., Box 871404, Tempe, AZ 85287-1404, dmburt@asu.edu, [2]School of Earth and Space Exploration, Arizona State Univ., Box 871404, Tempe, AZ 85287-1404.

Introduction: Since its beginning as a planet, impact cratering has probably been the most important single geological process affecting the surface of Mars, with wind serving mainly to move around fine impact debris and thereby abrade coarse impact debris (and outcrops). Recently, Malin et al. [1] reported both new impact craters with ejecta blankets and new fluid flow in young gullies (or at least new high albedo salt- or dust-rich residues), that had appeared on Mars during the years that MOC imaged the planet in detail. Impact cratering and gully flow were treated as independent phenomena. These two phenomena could nevertheless be related in a general way, if cratering has excavated chloride-rich salt mixtures crystallized beneath ground ice during brine freezing [2,3], and tossed them up on top. Under appropriate circumstances, this could cause ice to melt.

Because Martian ground ice lies at varying depths beneath the surface, depending on latitude, the detailed arguments must be somewhat more complex than this simple model. They involve, in addition to climate, factors such as ice sublimation, salt deliquescence, and multicomponent eutectic melting. The basic "throwing salt on an icy sidewalk" analogy illustrates the basic principle, however. This is basically our earlier eutectic melting idea [2] inverted by impact.

Young Gullies: The recent gullies occur in both hemispheres of Mars, almost always at intermediate latitudes [1]. Most occur in the steep walls of old impact craters (an obvious connection to impacts) although they can occur in other slopes. Commonly, many gullies originate in the same horizon, generally marked by a break in slope, with the more resistant layer above. The resistant layer commonly has collapsed, forming alcoves above gullies. Gullies exiting from the same horizon suggest an impermeable layer (aquiclude). The quantity of aqueous fluid (if any) involved in gully formation generally appears to have been small, because the gullies die out in a distributary debris apron. Prior to the apparent discovery of present-day gully flow in two locations by Malin et al. [1], their young age was inferred mainly by low crater counts and by debris aprons covering very young appearing dunes.

Origin: A variety of hypotheses have been put forth to explain the gullies [e.g., 4], ranging from ground water (from a shallow or deep liquid aquifer), possibly breaking through an ice dam or plug, to surficial snow or ice melting from beneath a cover of dust, to eutectic brine forming along the interface between upper icy and lower salty layers [2], to explosive carbon dioxide escape, to wet debris flows, to dry debris flows, and probably others. The latitudinal restriction suggests that climate must be involved, as in a zone that is not too hot and not too cold. The highly variable obliquity (orbital tilt) of Mars and consequent extreme climate (and sun angle) variability feature in some hypotheses. The low atmospheric pressure and cold temperatures on Mars are problems for any model involving unstable liquid water. Geothermal heating of subsurface aquifers and local solar heating of dark rocks on the surface could warm temperatures, however. Pressure problems can be alleviated by dissolving soluble salts; which lowers both vapor pressures and freezing temperatures, expanding the stability field of liquid water with regard to both freezing and boiling. Also, a flowing mass of even pure liquid water, although metastable, could form a gully before it evaporated or froze (then sublimated).

Salt Residues. The very light tone of present-day gully residues [1] suggests surface salts remaining from brine evaporation. (Some sort of light-toned dust or mud is an alternative explanation.) Surface frost is presumably not involved, because the light-toned features have persisted over months or years [1]. The lack of light-toned residues on older gullies suggests that the salt coating (or other cause) is temporary, and has either disappeared into the subsurface or attracted sufficient dust cover to become hidden. Salts could attract dust because most are hygroscopic (attract water vapor from the atmosphere) and therefore are inherently sticky. Deliquescent salts such as $CaCl_2$ could attract sufficient moisture from the atmosphere to liquify and drip into the subsurface; frost deposited on a variety of other salts could melt to brine, yielding the same result. Complex salt mixtures cause ice melting at lower temperatures than individual salts (eutectic property). Liquification of impact-excavated salt mixtures on exposure to ice, frost, or atmospheric moisture forms the main basis for our hypothesis.

Salt-Ice Layering and Impact Excavation: When the briny Martian hydrosphere froze down and dried up about 4 billion years ago [2], ground ice, brine, and salts should have become segregated by density in the Martian regolith, in that order [3]. Sulfates, being less soluble and less able to depress freezing temperatures than chlorides, would generally crystallize out earlier. Continued freezing (fractional crystallization), especially near the poles, plus ion exchange of Na-rich brines with the Ca-rich basaltic regolith, would drive brines to near-eutectic, non-acid compositions, meaning rich in common salts exhibiting the most freezing-point depression (mainly $CaCl_2$). If brines finally froze down completely (at temperatures probably below about -55 C), exotic minor salts such as LiCl and $ZnCl_2$, plus bromides, would be the last to crystallize (analogous to forming Li-pegmatites by cooling and fractional crystallization of hydrous granitic magma). Complete freezing of brine, possibly caused by an unusually shallow aquifer or a decrease in geothermal gradient with time, would then leave a salty layer covered by an icy layer (permafrost or ground ice), with the interface enriched in components such as Br, Li, and Zn. Near-surface permafrost sublimation near the equator and ice trapping near the poles would alter this regular "brine sandwich" pattern, making the ground ice layer deeper and thinner near the equator. Mars lacks plate tectonics, but lateral brine escape, impact excavation, and local magmatic heating could have perturbed the layering in many places [2]. Impact excavation of salts is what mainly concerns us here, inasmuch as Mars appears to have been largely resurfaced by impacts (late heavy bombardment) about the time that Mars lost most of its atmosphere and the surface freeze-dried.

Eutectic Melting: If salt grains are thrown on ice, some of the ice will melt, unless the temperature lies below that of the eutectic (the salt-ice eutectic for NaCl salt is about -21 C, for $CaCl_2$ salt, -50 C; and for a binary salt mixture, -52 C). If snow or frost settles on a salty outcrop, it likewise should melt on contact. On Mars, impacts probably excavated and distributed a wide variety of salts across the surface, but the icy permafrost, even in the distant past, may have been too deeply buried to react with these salts (except via deep vapor sublimation plus surface condensation), especially near the equator. Therefore, the only means of getting those salts back underground as a brine would have been to expose the surface salts to frost or other forms of ice. On dry Mars, this would be a very slow process. On exposure to frost, impact-excavated chlorides, especially $CaCl_2$, should disappear first from the surface, over a much wider temperature range, owing to their greater solubility and freezing point depression compared to sulfates. That is a possible explanation for why the present-day martian surface is enriched in neutral sulfates compared to chlorides (impact-excavated chlorides have been preferentially leached, although a high Br/Cl ratio might remain). It also might explain why active young gullies are a rare, limited feature (few chloride salts remain near the surface in most places), and why they are absent from equatorial regions (insufficient frost, plus too deep a permafrost layer). By this hypothesis, a large impact that excavated many chloride salts could rejuvenate gully formation under the ejecta blanket, at least in the right climate zone, and wind transport of fine ejecta might extend the effect.

Impact Inversion: So far, this hypothesis explains the latitude restriction, but not the tendency of many gullies to originate at the same horizon. An aquiclude is required, such as a lava flow or a layer rendered impermeable by ancient ice or salt or other cement. In this regard, impact cratering could have inverted the local stratigraphy by ejecting deep salts directly on top of impermeable permafrost, thereby laying the groundwork for later gully formation along that horizon in the walls of the crater. Also, even minor salt should provide a better clastic rock cement than subliming ice, thereby possibly explaining why many gullies emerge from collapsing alcoves. Add positive feedback for eutectic overshoot in heterogeneous mixtures (an ice grain cannot simultaneously contact different salt grains in a mixture until some brine actually forms by melting), plus time for the slow accumulation of dripping brine at an aquiclude, or for the brine to get salty enough to melt its way through an ice dam, and the apparently infrequent and episodic nature of brine release to young gullies could be explained.

Outwash Channels and Drainage Networks: Similar eutectic melting, but involving a huge increase in scale and amount of positive feedback, provides a possible explanation for large outwash channels. The positive feedback (via eutectic overshoot and possibly, heats of dissolution) could involve, e.g., the abrupt start of brine drainage or brine convection through impact-deposited layers alternating in salt mixtures (contained in impact ejecta) and ice (snow formed by slow post-impact water vapor condensation). The salt-ice separation would prevent reaction until gradual geothermal heating had directly melted enough ice to saturate the porosity; then the reaction could run away. Instead of alternating them, mix the salts and ice (or brine) condensate in fresh ejecta, and eutectic melting (plus sapping) might account for drainage networks found in the oldest areas of Mars (not uniquely, of course). These mechanisms, if viable, permit an ancient Mars climate roughly as cold as today's.

References: [1] Malin M.C. et al. (2006) *Science, 314,* 1573. [2] Knauth L.P. and Burt, D.M. (2002) *Icarus, 158,* 267. [3] Burt D.M. and Knauth L.P. (2003) *JGR, 108,* doi: 10.1029/2002JE001862. [4] Heldemann J.L. and Mellon M.T. (2004) *Icarus, 168,* 285.