# Inversion of Relief as a Geomorphic Process on Mars and its Relevance to Landing Site Selection

C. F. Pain[1], J. D. A. Clarke[2], and M. Thomas[2]

[1] 4 Sticht Place, Florey ACT 2615, Australia, colin.pain@internode.on.net
2 Australian Centre for Astrobiology, Macquarie University, NSW 2109, Australia

**Abstract.** Relief inversion has been invoked to explain a number of geomorphic features of the Martian surface. Terrestrial relief inversion occurs when former depressions become elevated because their fill is more resistant to erosion than the surrounding terrain. It is a common product of long-term landscape evolution on Earth, especially in relatively stable intra-cratonic settings and flat, or near flat lying successions. The inverted relief will preserve relicts of former land surfaces and is therefore older than the surrounding terrain. Relief inversion can occur by a range of processes, including infilling of depressions by intrinsically resistant material, selective secondary cementation via diagenesis and weathering, or surface armouring. Wind action appears the most common erosive process on Mars, unlike on Earth where both deflation and runoff are important. Crater densities of selected features show that the tops of the proposed inverted relief have considerably more craters than the surrounding plains, as is predicted by the inversion hypothesis.

**Keywords:** Mars, geomorphology, channels, relief inversion

## 1 Introduction

Inversion of relief refers to an episode of geomorphic evolution where a low part of the landscape is in some way protected from or becomes resistant to erosion. Over time the unprotected and less resistant adjacent parts are eroded leaving the more resistant and formerly lower parts standing higher in the resulting landscape [1]. On Earth, inversion of relief usually entails a former valley floor becoming a ridge, bounded by newly formed valleys on each side (Fig. 1). A less usual feature on Earth, but more common on Mars, is the inversion of impact craters. In what follows we discuss various kinds of inversion of relief, using Earth analogues to interpret Martian examples.

In this paper we present evidence of inversion of relief from Mars, and compare it with Earth analogues. We end with a discussion of the implications of inversion of relief where it occurs on Mars for the development of the total Martian landscape.

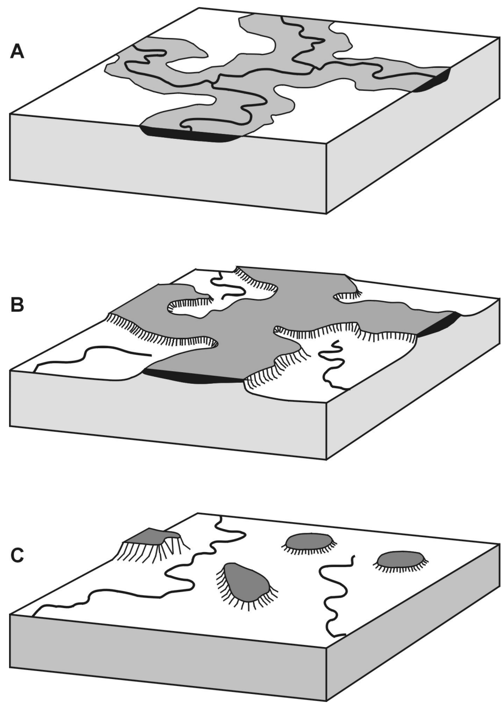


**Fig. 1.** Inversion of relief caused by induration of valley floor materials (after Summerfield 1991). A. during cementation, when the valley floor materials occupy the lowest part of the landscape, B. following erosion of the surrounding less resistant material, which causes inversion of relief, C. Following further erosion that leaves remnants of the inverted relief as mesas. On Earth the most common cementing agents are iron (ferricrete) and silica (silcrete).

## 2 Inversion of relief on Earth and Mars

### 2.1 Inverted channels

Excellent examples of terrestrial inverted channels occur in Australia including those of the Broken Hill area and the Mirackina paleochannel in South Australia (McNally and Wilson, 1995), and numerous locations in the Yilgarn Craton of Western Australia [1,3,4]. There are also many reports of inverted channels that have been recognised on orbital imagery from Mars [2,5]. For example, the Malin Space Science Systems MOC Captioned Image Releases (http://www.mss.com/mars_images/moc/) contain at least 12 references to inverted channels up to July 2006. Malin and Edgett

[5] give a list of orbiter images that contain inverted channels on Mars. We now consider different causes of inverted channels.

Relief inversion caused by lavas flowing down valleys is a well-documented process on Earth [6]. Relief inversion by lava occurs because the lava is less easily eroded than the surround, usually weathered, material. Such a contrast occurs where lavas flow out across non-volcanic landscapes, along valleys eroded into volcanic ash, or where older lavas have been weathered as well as eroded. Alluvium is commonly preserved under the lava.

Suggested Martian examples include sinuous ridges near Juventae Chasma [7]. There, sinuous dark ridges are interpreted as a result of inversion of relief caused by lava filling channels eroded into soft, pale-coloured sediments, interpreted as either volcanic ash or lacustrine sediments (Fig. 2).

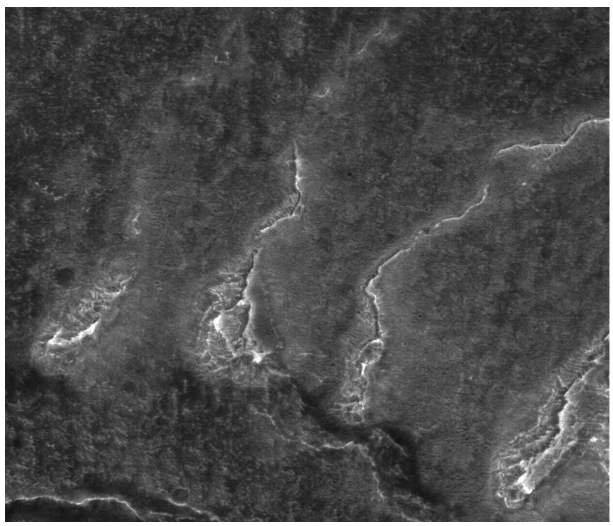

**Fig. 2.** Sinuous ridges on plain associated with dark lava materials, near Juventae Chasma. Image width ~2.5 km. Part of MOC image R11-03343, 4.18°S, 63.63°W.

On Earth the most widespread style of inverted relief involves cementing of valley floor materials (Fig. 1). There are many examples of inverted channels on Mars that appear to be of this kind. One of the most discussed areas of inverted relief on Mars is the delta that has formed on the edge of Eberswalde Crater [5]. The Aeolis region also contains many inverted channels. Some of them form a maze of inverted channels within an alluvial fan or wide floodplain. The channel materials have become cemented and then inverted (Fig 3). Both Eberswalde Crater and the Aeolis region inverted channels show that the channel materials have become more resistant to erosion that the surrounding supposedly floodplain materials, and that the latter have subsequently been removed by erosion.

In some areas single channels have become inverted. The Arabia Terra region has distinctive inverted channels (Fig. 4) that are very similar to inverted channels on Earth (c.f. Fig. 1).

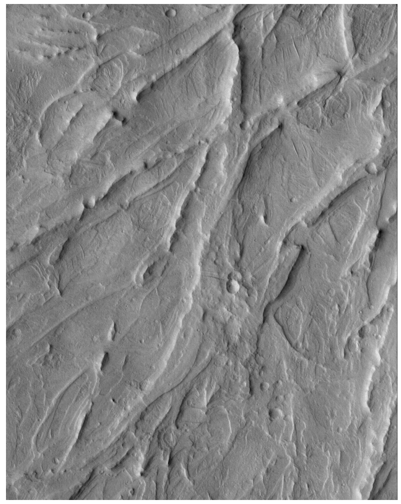

**Fig. 3.** A network of inverted channels on a fan in the Aeolis region of Mars. MGS MOC release No. MOC2-1118, 10 June 2005. Image width is about 3 km.

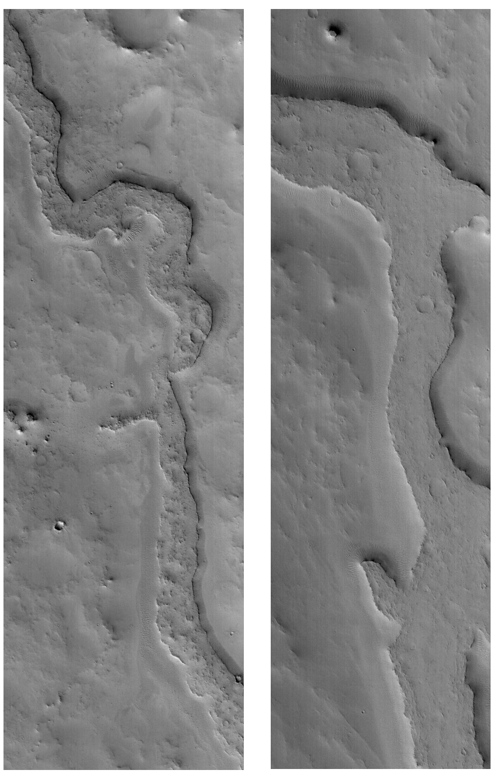

**Fig. 4.** Broad inverted channels from the eastern Arabia Terra region of Mars (compare with Fig. 1). Left. MGS MOC Release No. MOC2-1312, 15 December 2005. Right. MGS MOC Release No. MOC2-1210, 10 September 2005. Each image is about 3 km wide.

Surface armoring occurs when high-energy flows down valleys and gullies leave a lag of gravel or boulders. Even when un-cemented these large clasts can protect the underlying material from erosion and result in inversion of the channel [8]. On a small scale this process is termed "Gully Gravure" [9]. On Mars some deposits in gullies on crater walls are raised above the gully margins (Fig. 5), displacing later flows to the sides, suggesting this process occurs also on Mars.

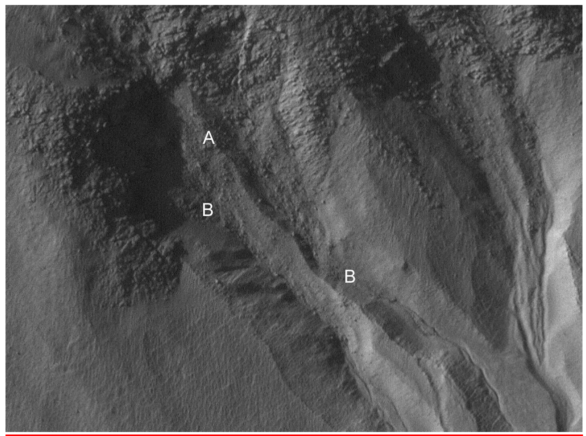


**Fig. 5**. Possible gully gravure on crater wall, image width 500 m. Part of MOC image S0500647, near 46.6°S, 151.8°W, close to crater Li Fan. Point A - Former gully floor deposit. B - Lateral incision caused by the shift of flow away from the former gully thalweg.

## 3 Inverted relief and Mars landing site selection

Areas of inverted relief are attractive sites for the attention of robotic rovers and human exploration. Scientifically, sites of inverted relief are attractive for several reasons: Their flanks may expose sections through the inverted material, basal unconformities, and the underlying bedrock without the complexity of impact deformation found in crater walls. The exposed section can provide important insights into the depositional, volcanic, diagenetic, weathering, and other processes that have operated in the area. Lastly, dating of their upper surfaces and the surrounding plains can constrain the rate of landscape evolution for that region of Mars.

One area of inverted relief is under consideration for the 2009 MSL mission. This is the inverted delta (Fig. 6] of Eberswalde crater [10]. Such a comparatively small, single focus target (only 20 km across), while ideal for a unmanned rover, is too small for a human mission with its requirement for diverse features of interest to take advantage of its ability to explore large areas rapidly and sample diverse and difficult sites. However, the broader Holden Crater region [11] contains a diversity of features that makes it very attractive as a candidate landing site for a manned landing. The presence of one of the best examples of inverted relief complements the tectonic, glacial, fluvial, aeolian, and impact features of the region.

On Earth the sand gravels and duricrusts that make up inverted channel can be important sources of construction materials. Others host economic deposits of channel ironstone and placer minerals. It is possible that that some Martian examples may have similar significance as sites for extraction of construction materials and sedimentary and diagenetic mineral deposits.

**Fig. 6**. MOC image of inverted meander loop and scroll bars, Eberswalde Delta, north east of Holden crater [12]. Image width ~ 3km.

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