Georgia Univ. Athens

The Origin and Evolution of Terrestrial and Martian Rock Labyrinths

Final Technical Report
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The overall objective of the research was to compare the morphological characteristics and evolutionary development of rock labyrinths on Earth--in sandstone, volcanics, and carbonates--with those on Mars. On Earth rock labyrinths originate as parallel, en echelon, or intersecting narrow grabens, or develop where fault and joint networks are selectively eroded. Labyrinths frequently contain both downfaulted and erosional elements. Closed labyrinths contain closed depressions; open labyrinths do not, they are simply part of of a fluvial network generally of low order. As closed labyrinths made up of intersecting grabens or made up of connected erosional depressions are extremely common on Mars, the research focussed on an understanding of these labyrinth types. Field investigations were carried out in Canyonlands National Park, Utah, and in the Chiracahua Mountains of Arizona. Martian laybrinths were investigated using Viking orbiter images. In addition, research was undertaken on apparent thermokarst features in Lunae Planum and Chryse Planitia where closed depressions are numerous and resemble alas topography.

Open Labyrinths

Open labyrinths on Earth are well developed in a limestone/sandstone/shale sequence at Bryce Canyon, Utah; in sandstones at Arches and Canyonlands National Parks, Utah; and in volcanic rhyolites in the Chisos Mountains of Texas and Chiracahua Mountains of Arizona. In each area the labyrinths form part of a stream channel network. Linear, joint-controlled

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channel segments, which often intersect at right angles, box valleys, and buttes are characteristic landform elements. Open terrestrial labyrinths develop in fractured rocks where chemical and mechanical weathering followed by denudation operate preferentially in joints, which represent lines of increased secondary permeability. Labyrinths are most common in areas of steep hydraulic gradient and so they tend to be located back from steep fault or erosional scarps, and at steep valley headwalls. Sapping with suffosion of weathered detritus are the significant processes bringing about headward extension of open labyrinth networks. Open labyrinths are also quite common on Mars and closely resemble their terrestrial counterparts. For example, Viking images 664A08-664A13 reveal a well-developed labyrinth in Kasei Vallis. Martian networks appear to erode headward by loss of frozen volatiles at the valley headwall--a process akin to sapping of liquid water on Earth. As the frozen volatiles are concentrated in the more weathered fracture zones, headward retreat is directed along criss-crossing structural weaknesses.

Closed Labyrinths

1. Erosional

Erosional closed labyrinths on Earth are most frequently formed by solution of karst rocks. Examples in other rock types are relatively rare. The Channelled Scablands of eastern Washington in basalt, and the Antarctic Wright Dry Valley labyrinth in dolerite are the only known deep erosional labyrinths in non-carbonate rocks. The Channelled Scablands were produced by catastrophic flood erosion. A similar origin has been suggested for the Wright Valley labyrinth although other hypotheses including glacial erosion, subglacial meltwater erosion, and salt weathering followed by deflation of the weathered products have been proposed. A significant difference between karst labyrinths and the Wright Valley and eastern Washington labyrinths is that the latter show preferential development of elongated depressions in one major direction suggesting a subaerial formation by a moving medium such as water or ice. Significantly, morphologically similar labyrinths are present in localized parts of the Martian outflow channels.

Terrestrial closed erosional labyrinths in karst and in volcanic rocks appear to contain the same relief elements: pits, streets, platea, towers, and marginal plains. Furthermore, there is a simple developmental sequence (Fig. 1). Strings of elliptical, vertical-walled pits develop in intersecting fracture systems. Pits gradually enlarge and coalesce so that steep-walled linear depressions or streets are formed. As streets deepen and widen, intervening rock ridges are dissected and ultimately destroyed. Angular closed depressions called platea are produced which frequently contain residual rock towers. As platea increase in number and size, the landscape is reduced to a series of isolated rock towers separated by broad marginal plains.

Closed erosional labyrinths on Mars are generally much larger than those on Earth but have virtually identical form. In the southeast portion of Memnonia Southeast Quadrangle, for example, a depression 90 km long and 10-15 km wide has developed in the old cratered surface. The eastern one-third of the depression is formed of two intersecting craters; the western two-thirds is an angular platea with residual rock towers 0.5-10 km in

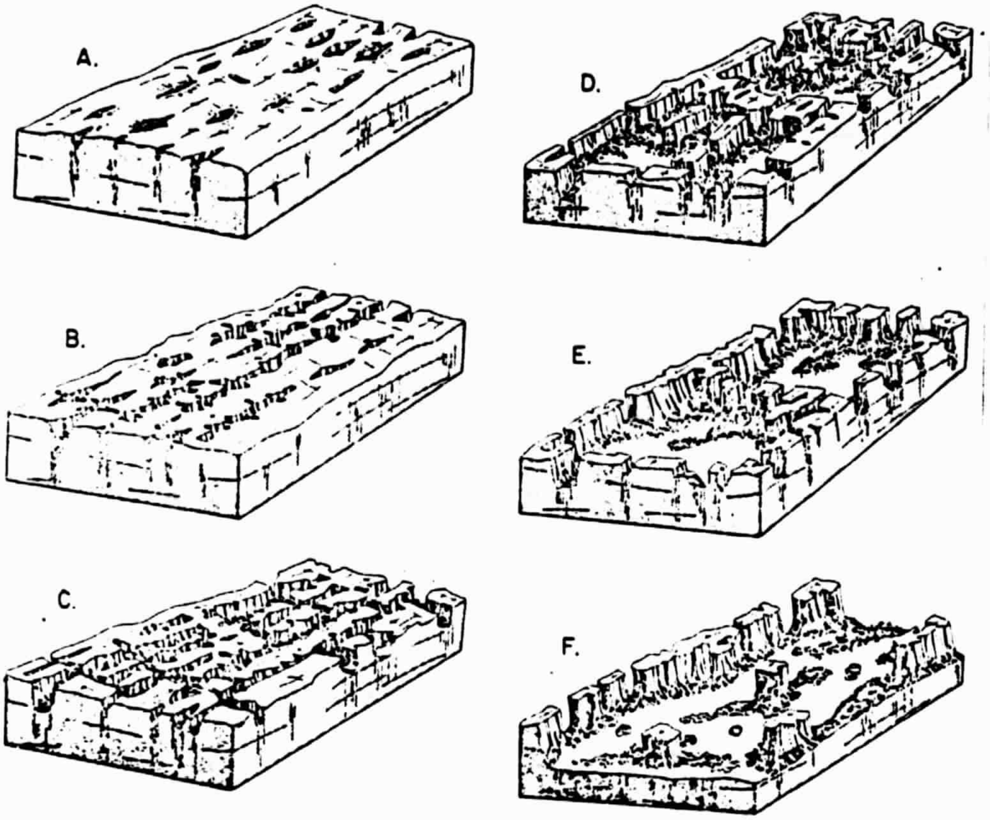


Fig. 1. Stages in the evolution of closed erosional labyrinths on Earth and Mars. During early stages strings of pits (catenas) develop in vertical fractures (A). By enlargement and coalescence along the fractures strings of pits are converted to intersecting networks of streets (B and C). As streets deepen and widen the intervening rock ridges are dissected and ultimately destroyed. Replacing them are large closed depressions called platea (D and E). As platea expand rock towers are left which rise from a marginal plain (F).

diameter. Walls of the platea are structurally controlled. West of the depression are strings of elliptical pits (catenas) developed in regional fractures.

Strings of pits or catenas, the first stage of closed erosional labyrinth development, are found on upland surfaces surrounding Noctis Labyrinthus and Valles Marineris. South of Coprates Chasma and parallel to it are three catenas, the largest is 350 km long. Other strings occur east of Ophir Chasma and south of Tithonius Chasma. All are developed in regional fractures. There is no doubt that the strings of pits eventually evolve into narrow linear troughs equivalent to the streets of labyrinth karst. Where parallel troughs develop it is also apparent that slope recession gradually erodes the intervening upland surfaces. This has occurred in Coprates Chasma, at the western end of the Chasma a plateau remnant 60 km long and 5 km wide is preserved as the crest of a narrow ridge separating two troughs. Where Coprates Chasma joins Eos and Capri Chasma, a second ridge is in a more advanced stage of evolution; receding slopes have intersected so that no plateau remnants remain. If some Martian troughs have developed in the manner described, they can be regarded as huge platea formed by erosion acting along vertically and horizontally persistent regional fractures which surround the Tharsis uplift. Closed erosional labyrinth relief is also evident in many areas of fretted terrain. For example in Nylosyrtis Mensae catenas on the ancient cratered uplands are clearing evolving into elongated troughs equivalent to streets.

2. Structural

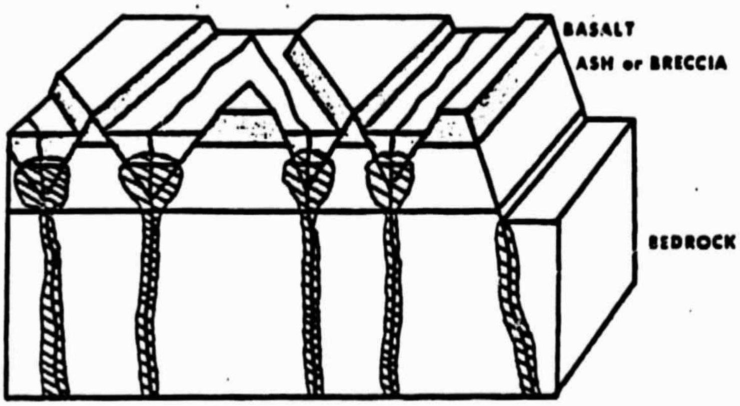
Structural labyrinths formed of intersecting grabens are by far the largest and most common labyrinths on Mars. Noctis Labyrinthus is the classic example. It is a network of grabens tens of km wide and hundreds of km long at the summit of the Tharsis-Syria Rise. The labyrinth is 1,000 km across. A terrestrial labyrinth, similar in many respects to parts of Noctis Labyrinthus, has developed in the Grabens District of Canyonlands National Park, Utah. Numerous parallel and en echelon grabens 100-600 m wide, 0-100 m deep, and several km long, have floors covered by stream alluvium, aeolian deposits, and rubble derived from graben wall collapse.

Field and aerial photographic studies indicate that prior to graben development a surface stream system drained the region northwards into the Colorado River. Block faulting disrupted this drainage. The streams were diverted into the closed grabens, the water was absorbed by the unconsolidated sediments covering the floors, and eventually it escaped underground along zones of high secondary permeability in the bedrock--namely the normal faults that criss-cross the region. Our field investigations have revealed numerous locations where ground water in the sediments covering the depression floors is draining underground into faults. This water emerges elsewhere in springs. Water frequently sinks into the faults at the graben side walls or where one or more faults intersect near the centers of graben floors. The sinking points are frequently marked by subsidence depressions where the surficial sands have subsided into subsurface cavities. The largest depressions are 10-15 m deep. Subsurface cavities are believed to originate by the solution of the calcareous matrix of the sandstone bedrock. Leading into the subsidence depressions are shallow (1-5 m deep) valleys with steep sides and headwalls. These valleys were almost certainly produced by groundwater sapping in the surficial sands with suffosion of the finer particles underground. Significantly, collapse or subsidence depressions are also numerous in the graben floors of Noctis Labyrinthus, Mars, attesting to the existence of subsurface cavities in this region also.

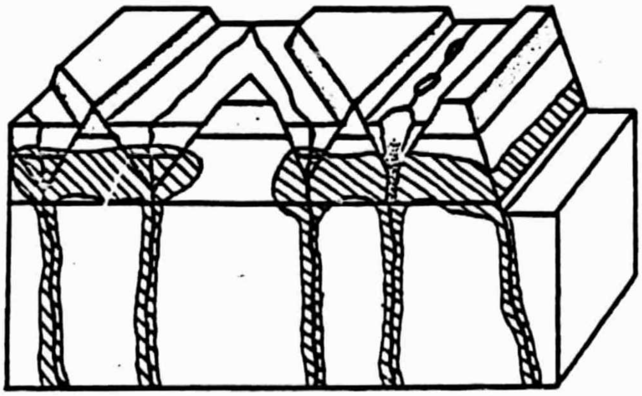
Origin of the Closed Labyrinths

The striking morphologic and evolutionary similarities between labyrinth karst on Earth and closed erosional labyrinths on Mars, and the similarities between the karst-modified Grabens landscape of Canyonlands National Park, Utah, and parts of Noctis Labyrinthus, Mars, suggest that the Martian terrains were produced by surface collapse into subsurface cavities produced by chemical denudation in the sub-permafrost ground water zone over millions of years, or that collapse resulted from localized permafrost degradation. In the latter case the labyrinths would be thermokarst features. Alternatively a combination of both processes could be responsible for the labyrinths of Mars.

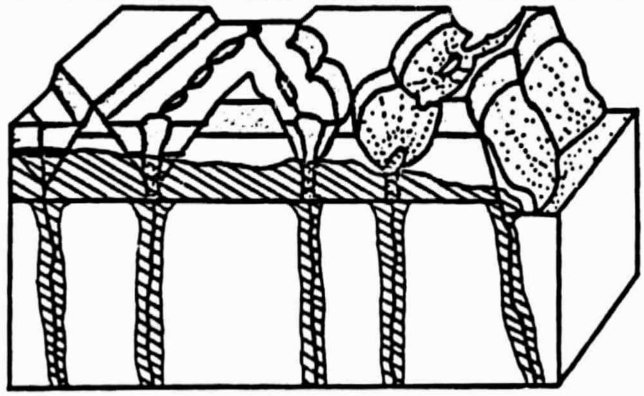
A model for the development of topography like that of Noctis Labyrinthus is presented in Fig. 2. The model assumes that permafrost degradation at depth occurs preferentially along fractures because of increased geothermal heat flow. This causes compaction of volcanic ash layers and eventually leads to subsidence of the surface. Instability of volcanic ash layers overlain by basalt causes scarp retreat by mass wasting so that troughs and depressions grow in size. The finer sediments of the volcanic ash layers are removed by wind and re-deposited at the Martian poles.



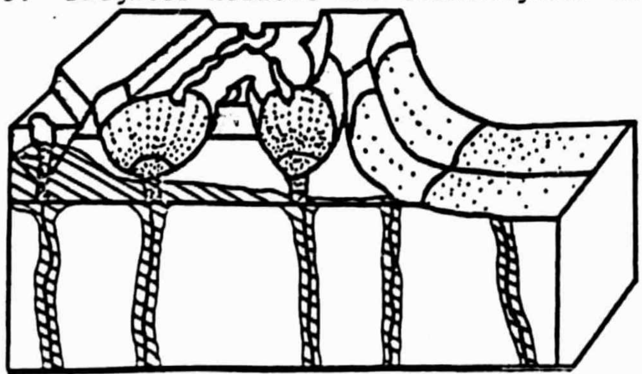
Stage 1: Fault Heat Flux



Stage 2: Thaw Zone Coalescence and 1st Generation Pits



Stage 3: Daughter Hollows and Grandaughter Catenas



Stage 4: Canyon Expansion and Hollow Abandonment

Fig. 2. Topographic Development in Noctis Labyrinthus as a Result of Permafrost Degradation

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