D LACK, J. B. (1967). Aniso-
and the clouds of Venus.
, 469.
197). Sulfuric acid in the Venus
nm *Lunar Planet. Lab.* **9**, 191–
M. AND STRONG, J. (1960). Radio-
ervations of Venus. *Astrophys. J.*
90.
, YOUNG, D. A., SMITH, E. N., AND
C. C. (1963). The structure and
of carbon suboxide polymer.
Chem. **2**, 829–838.
, J. (1960). "The Physical–Chemical
of Binary Systems in Concentrated
Vol. IV. Interscience, New York.
B., AND POLLACK, J. B. (1973).
properties of the stratospheric
Geophys. Res. **78**, 7051–7056.
ST, H. C. (1957). "Light Scattering
Particles." John Wiley, New York.
). (1973). Private communication.
T. (1974). Venus clouds: structure
osition. *Science* **183**, 407–409.
T. (1973). Are the clouds of Venus
id? *Icarus* **18**, 564–582.
). (1972). High resolution spectra of
arus **17**, 632.
. 1970). "Infrared Handbook."
Coating Laboratory, Santa Rosa,
. 102–107.
. (Circular variable filters.
, 78.

ICARUS **23**, 27–41 (1974)

Erosion by Catastrophic Floods on Mars and Earth

VICTOR R. BAKER

Department of Geological Sciences, University of Texas at Austin, Austin, Texas 78712

AND

DANIEL J. MILTON

U.S. Geological Survey, Menlo Park, California 94025

Received March 18, 1974; revised May 6, 1974

The large Martian channels, especially Kasei, Ares, Tiu, Simud, and Mangala Valles, show morphologic features strikingly similar to those of the Channeled Scabland of eastern Washington, produced by the catastrophic breakout floods of Pleistocene Lake Missoula. Features in the overall pattern include the great size, regional anastomosis, and low sinuosity of the channels. Erosional features are streamlined hills, longitudinal grooves, inner channel cataracts, scour upstream of flow obstacles, and perhaps marginal cataracts and butte and basin topography. Depositional features are bar complexes in expanding reaches and perhaps pendant bars and alcove bars. Scabland erosion takes place in exceedingly deep, swift floodwater acting on closely jointed bedrock as a hydrodynamic consequence of secondary flow phenomena, including various forms of macroturbulent votices and flow separations. If the analogy to the Channeled Scabland is correct, floods involving water discharges of millions of cubic meters per second and peak flow velocities of tens of meters per second, but perhaps lasting no more than a few days, have occurred on Mars.

INTRODUCTION

The channel-like landforms on Mars revealed by the 1971 Mariner 9 Orbiter are diverse in character and presumably are equally diverse in origin. Those Martian channels that resemble the sinuous rilles of the Moon may have been produced by thermal incision of lava flows (Carr, 1974), the steep-headed valleys of the fretted terrain may have been produced by headward sapping by ground-ice decay (Sharp, 1973) or artesian processes (Milton, 1973), and so on. This paper is concerned with a distinct class of Martian channels characterized generally by breadths of several kilometers or tens of kilometers, slightly sinuous courses, and locally anastomosing patterns. The largest are Ares, Tiu, and Simud Valles (Chryse Channels[1]); the best high-resolution photographic coverage is of Mangala Vallis (Amazonis Channel) and Kasei Vallis (Lunae Palus Channel). These channels are of particular importance because they have been adduced as evidence for the former presence of liquid water on the Martian surface (McCauley *et al.*, 1972; Milton, 1973; Sagan *et al.*, 1973), which has profound implications for Martian history.

We believe that these channels were created by catastrophic floods. Comparable floods occurred on Earth during the Pleistocene Epoch, as documented in the Channeled Scabland of eastern Washington produced by breakouts of ice-dammed Lake Missoula (Bretz, 1923, 1932, 1969; Baker, 1973, 1974), in the Snake River Plain of Idaho, flooded by the overflow of Lake Bonneville (Malde, 1968), and as are inferred in the scabland terrain of Wright Valley, Antarctica (Smith, 1965; Warren, 1965). Table I lists the characteristic features produced by these floods

---

[1] Martian topographic features were assigned names by the International Astronomical Union in late 1973. Earlier papers used informal names based on pre-Mariner areography.

Printed in Great Britain

with examples from the Channeled Scabland and probable equivalents in the Martian channels. Our identification on the Mariner photography is made with confidence for some features; for less distinctive features, our identification is correspondingly tentative. Finally, identification of some critically diagnostic but small features may (or may not) await recognition during future exploration of Mars.

EROSIONAL FORMS AND PROCESSES

The catastrophic-flood hypothesis proposed for the Channeled Scabland by

TABLE I

CHARACTERISTIC EROSIONAL AND DEPOSITIONAL FEATURES OF SCABLAND CHANNELS AND PROBABLE MARTIAN EQUIVALENTS AS INTERPRETED FROM MARINER 9 ORBITER IMAGERY

	Scabland examples		Martian examples	
Feature	Location[a]	Scale	Location[b]	Scale
Overall Regime:				
Large-scale bedrock channels requiring erosion to depths of hundreds of meters	Grand Coulee and Cheney–Palouse Scabland	See Table II	Mangala Vallis, Kasei Vallis, Ares Vallis, Tiu Vallis and Simud Vallis	See Table II
Low sinuosity	Grand Coulee and Cheney–Palouse Scabland	See Table II	Mangala Vallis, Kasei Vallis, Ares Vallis, Tiu Vallis and Simud Vallis	See Table II
Regional anastomosis of bedrock channels	Entire Channeled Scabland	300 × 300 km	Ares, Tiu and Simud Valles	1800 × 1200 km
Erosional Features:				
Streamlined Hills	Cheney–Palouse Scabland	Smaller ones, 0.5 × 2 km; larger 3 × 6 km	Ares Vallis (1° N, 17° W) Elysium Planitia (31° N, 229° W)	10 km in length 5 km in length
Longitudinal Grooves	Lenore Canyon and Hartline Basin	Spacing 100–500 m	Kasei Vallis	Spacing about 500 m–2 km
Inner Channel Cataracts	Dry Falls	6 km wide, 120 m high	Kasei Vallis	10–20 km wide
Erosionally exhumed circular structures	Crab Creek Scabland near Odessa (sag-flowout structures)	80–250 m	Kasei Vallis (craters)	About 6 km
Tributary alcoves to main channel (marginal cataracts)	Grand Coulee	2 km wide, 250 m high	Kasei Vallis? (middle reach) Mangala Vallis?	5–10 km wide
Scour upstream from flow obstacle	Dry Coulee and High Hill Anticline (Park Lake 7.5′ Quadrangle)	500 m wide[illegible]0 km long	Kasei Vallis	4 km wide, 10 km long
Etching of regional joint patterns	Cheney–Palouse Scabland (Starbuck 15′ Quadrangle)	Linear fractures, 10 km long over an area 25 × 20 km	Kasei Vallis	Fractures 10–20 km long in an area approximately 20 × 20 km
Butte and basin topography	All scoured basalt channels	Buttes 100 m wide and 30 m high	Mangala Vallis?	May be below the resolution capability of the Mariner imaging system
Depositional Features:				
Expansion bar complexes	Quincy Basin	500 km²	Mangala Vallis	1000 km²
Pendant bars	Wilson Creek Area (Wilson Creek 15′ Quadrangle)	4 km long, 1 km wide	Ares Vallis? (1° N, 17° W)	10 km long, 2 km wide
Eddy bars	Grand Coulee	10 km long, 2 km wide	Perhaps Kasei Vallis (middle reach) but difficult to distinguish from terraces	20 × 50 km
Giant current ripples	Most scabland channels especially Cheney–Palouse Scabland tract	Spacing, 30–130 m; Height 1–7 m	Below the resolution capability of the Mariner imaging system.	

[a] Named features are shown in Fig. 1, located by latitude and longitude in Table II, or found on the indicated U.S. Geological Survey topographic map.

[b] Named Valles are located by latitude and longitude in Table II.

s (or may not) await
l future exploration of

AL FORMS AND PROCESSES

trophic-flood hypothesis pro-
he Channeled Scabland by

AND PROBABLE MARTIAN EQUIVALENTS AS
ERY

Martian examples	
Location[b]	Scale
ngala Vallis, Kasei Vallis, Ares Vallis, Tiu Vallis and Simud Vallis	See Table II
ngala Vallis, Kasei Vallis, Ares Vallis, Tiu Vallis and Simud Vallis	See Table II
es, Tiu and Simud Valles	1800 × 1200 km
es Vallis (1° N, 17° W)	10 km in length
lysium Planitia (31° N, 229° W)	5 km in length
asei V	Spacing about 500 m–2 km
as	10–20 km wide
as s (craters)	About 6 km
asei Vallis? (middle reach) Mangala Vallis?	5–10 km wide
asei Vallis	4 km wide, 10 km long
Kasei Vallis	Fractures 10–20 km long in an area approximately 20 × 20 km
Mangala Vallis?	May be below the resolution capability of the Mariner imaging system
Mangala Vallis	1000 km^2
Ares Vallis? (1° N, 17° W)	10 km long, 2 km wide
Perhaps Kasei Vallis (middle reach) but difficult to distinguish from terraces	20 × 50 km

Below the resolution capability of the Mariner imaging system.

---

ble II, or found on the indicated U.S. Geological

J Harlen Bretz (1923) initially found little favor and has won general acceptance only after 50 yr of contention with a variety of hypotheses thought to be more in accord with uniformitarian principles. The principal objection to Bretz' hypothesis was the lack of any evident source for the immense quantities of water required, an objection not answered until the volume and rate of emptying the 640-m-deep ice-dammed Lake Missoula were shown to be adequate (Pardee, 1942). The hypothesis of the occurrence of floods on Mars is likewise based on morphologic evidence, and its acceptability should not depend on that of specific hypotheses for the cause of floods (Milton, 1974). It is interesting that some of the alternative explanations for scabland features have reappeared in the brief history of discussion of Martian channels: incision of alcoves by spring sapping (Snake River Plain–Stearns, 1936, reinterpreted by Malde, 1968, as subfluvial cataracts; Mars–Sharp, 1973; Milton, 1973); salt weathering and eolian removal of debris (Wright Valley–Selby and Wilson, 1971; Mars–Malin, 1973); erosion during drainage of a lake (Channeled Scabland–Allison, 1933; Mangala Vallis–Milton, 1973); lava channels (Channeled Scabland–W. C. Alden in 1927 as recounted by Bretz, Smith, and Neff, 1956; Mars–Carr, 1974).

The Channeled Scabland region (Fig. 1) coincides with the part of the Columbia Plateau that was subjected to periodic catastrophic flooding during the late Pleistocene. Bretz (1923) introduced the term "scabland" to refer to the chaotically eroded tracts of bare basalt that occupy the floors of channels cut through the thick loess cover of the plateau. These channels

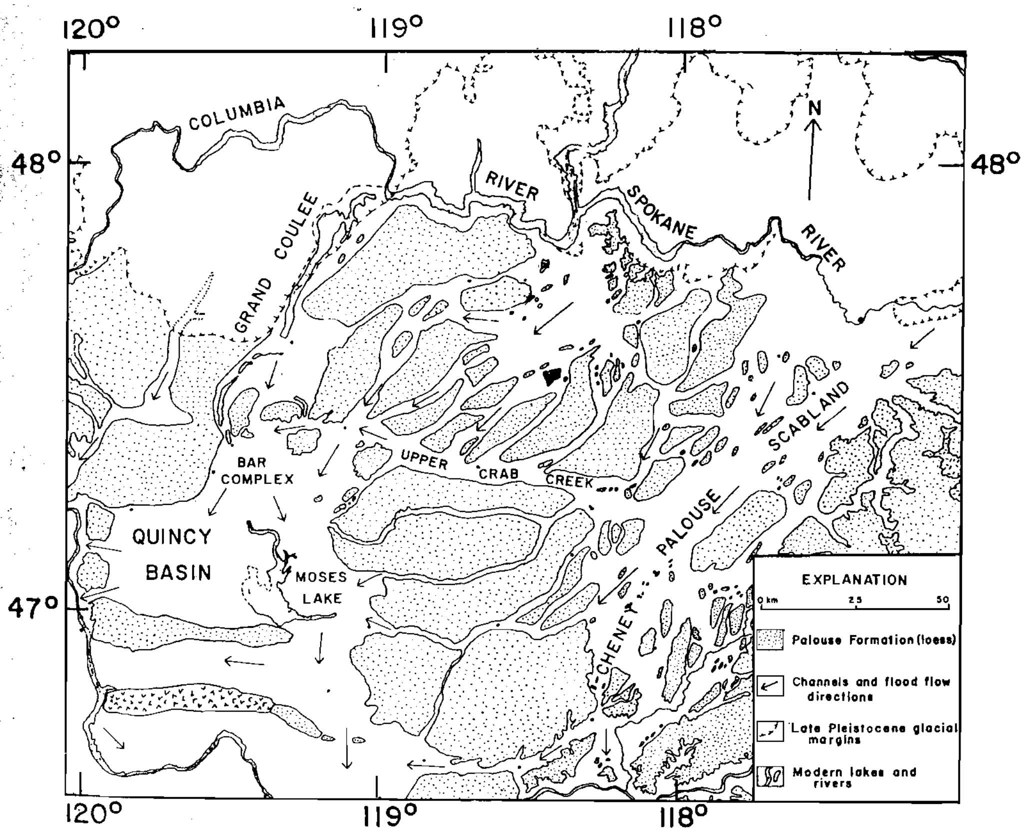


FIG. 1. Map of the Channeled Scabland in eastern Washington showing the distribution of channels and the remaining loess cover.

FIG. 2. ERTS orbital photograph of the northern part of the Channeled Scabland (composite of multispectral imagery, July 26, 1972). Scabland channels form the dark-toned anastomosis in the southern part, contrasting to the patchwork of wheat farms on the lighter Palouse loess. Colombia and Spokane Rivers at top, Crab Creek at bottom, Grand Coulee at left; area is approximately 90 × 120 km.

FIG. 2. ERTS orbital photograph of the northern part of the Channeled Scabland (composite of multispectral imagery, July 26, 1972). Scabland channels form the dark-toned anastomosis in the southern part, contrasting to the patchwork of wheat farms on the lighter Palouse loess. Colombia and Spokane Rivers at top, Crab Creek at bottom, Grand Coulee at left; area is approximately 90 × 120 km.

are remarkably conspicuous, even when viewed from orbital altitudes (Fig. 2).

A variety of features serve as high-water marks of the last major scabland flood, now thought to have occurred about 18 000 yr ago, and allow reconstruction of high-water surfaces and flow depths. Combining these with the channel geometry, Baker (1973) utilized hydraulic engineering procedures to calculate discharges and mean flow velocities. Additional paleohydraulic information is provided by the numerous giant current ripples that occur throughout the region. From such evidence it was shown that discharges as great as $21.3 \times 10^6 \, m^3/sec$ were conveyed through the Channeled Scabland. Because this discharge was sustained by $2.0 \times 10^{12} \, m^3$ of lake volume, flooding at the peak rate would have persisted less than a day. Even with gradually waning flows, flooding probably lasted only a week or two. Most of the erosion, however, probably occurred in the day or two of sustained high discharge. The amazingly rapid outflow of Lake Missoula is in accord with what is known of historical glacial breakout floods (Clague and Mathews, 1973). Water flowed 100–200 m deep down the steep regional dip slope of the Columbia Plateau (6–8 m/km) so that preflood valleys were reduced to mere channel-bottom roughness elements. Accordingly, the erosive process in the Scabland was subfluvial channel scour. Subfluvial erosion has been documented experimentally and field examples suggest that the process may be much more important than formerly believed (Schumm and Shepherd, 1973). It was remarkably effective in the Scabland; during the brief duration of the flood, channels were incised in bedrock as deep as 200 m. The Scabland channels differ fundamentally from normal valleys of comparable size that are the product of many thousands of years of valley incision. Although rare narrow gorges have been cut almost

TABLE II

COMPARATIVE GEOMETRY OF SELECTED MARTIAN CHANNELS WITH MISSOULA FLOOD CHANNELS ON THE COLUMBIA PLATEAU, EASTERN WASHINGTON. VALUES ARE ONLY APPROXIMATE, BUT THEY ALLOW A RELATIVE COMPARISON OF THE TWO REGIONS

Regional name	Approximate location Latitude	Longitude	Channel width[a] (km)	Channel length (km)	Channel depth (m)	Sinuosity[b]
Kasei Vallis (northern channel)	26°N	65°W	10	450	Indeterminate	1.15
Kasei Vallis (southern channel)	22°N	66°W	20	600	2500	1.06
Mangala Vallis	6°S	151°W	6	350	Indeterminate	1.05
Ares Vallis	5°N	20°W	40	1500	Indeterminate	1.04
Grand Coulee				80	250	1.07
Upper Coulee	47° 50′N	119° 8′W	8			
Hartline Basin	47° 35′N	119° 20′W	20			
Cheney–Palouse Scabland Tract				120	100	1.05
Lamont	47° 12′N	117° 53′W	15			
Benge	46° 53′N	118° 5′W	40			
Upper Crab Creek	47° 20′N	118° 30′W	6	100	100	1.01

[a] Individual channel width at the approximate location rather than total width of a channel complex.

[b] Calculated as the length of the channel center line divided by length of a straight line joining the end points of the measured reach.

wholly by fluvial action, normally in river valleys material is transported to the valley bottom by slope processes and then removed by the river, especially during floods. For example, the Grand Canyon of Arizona is a valley in which the channel of the Colorado River now (or at any point in past time) occupies only a small fraction. A subfluvially scoured channel, unlike a river valley, can have locally reversed gradients and closed depressions, since it is only necessary that the upper surface of water have a continuously downward gradient from head to mouth.

The mechanical aspects of devastating floods are poorly understood (Scheidegger, 1973). Nevertheless, the distinctive scabland erosional forms seem to be a hydrodynamic consequence of exceedingly swift, deep flood water acting on closely jointed bedrock (Baker, 1974). Scour was most pronounced in the constricted reaches of the western Scabland, where flow depths of 60–120 m and water surface gradients of 12 m/km indicate peak flood flow velocities as high as 30 m/sec. Under these conditions, secondary flow phenomena, including various forms of vortices and flow separations termed "macroturbulence" (Matthes, 1947), produced intense pressure and velocity gradients that plucked fragments of columnar basalt from the irregular channel boundaries. The plucking of the columnar colonnade and the undermining of the more resistant massive entabulature of the basalt flows produced butte and basin topography as the characteristic channel-bed scour feature.

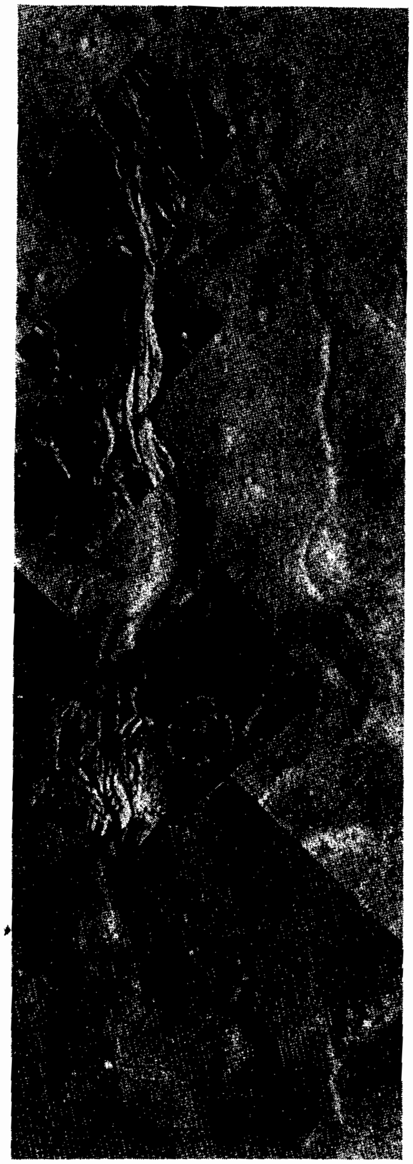


FIG. 3. Mangala Vallis. The almost straight single channel in middle section appears to be structurally controlled. Small features on the adjacent plain suggest butte and basin topography and notches in the bank may be marginal cataracts, which would indicate overbank flow. Downstream, an expansion bar complex occupies the widened reach of the channel. Composite of Mariner 9 wide- and narrow-angle frames. Narrow-angle frames in a larger format may be seen in Schumm (1974).

CHANNELS ON MARS

The Martian channels are larger than their terrestrial counterparts (Table II). The evidence for catastrophic floods is not sufficient to indicate whether they excavated the Martian channels (corresponding to the Missoula flood and the major Scabland channels) or only modified preexisting valleys (corresponding to the Bonneville flood and the Snake River Plain). Analytic photogrammetry (Blasius, 1973) is possible in a small segment of Kasei Vallis for which stereoscopic coverage is available. Approximate height measurements (kindly furnished by K. R. Blasius) indicate a total relief of more than 5km (Fig. 5). The upper 2km is occupied by a scalloped cliff that shows no sign of fluvial erosion and may be part of an older valley wall preserved above the high-water mark. Mangala Vallis (Fig. 3) and Ares Vallis, on the other hand, show evidence of overbank flow. If the downcutting occurred during a flood or floods, it is not necessary that the water depth ever equalled the difference in elevation of the high water mark and the low point of the channel floor. Nevertheless, the width and depth of the apparently flooded sections of the Martian channels are enormous.

The general pattern on both Earth and Mars is one of large channels eroded in bedrock, forming a regionally anastomosing complex with individual channels that have a low sinuosity (Table II). Normal rivers transporting a fine-grained load usually have a single meandering channel with a sinuosity greater than 1.5. This pattern represents an adjustment of a graded longitudinal profile over a period of years to continuous transport of water and sediment (Mackin, 1948). Catastrophic flood channels, in contrast, follow established preflood topography. Anastomosis occurs in the Channeled Scabland because preflood valleys did not have the capacity to convey the Missoula flood discharges without spilling over preflood divides into adjacent valleys. This would be expected wherever preflood topography is regionally smooth, as on Mars in the complex of channels of which Mangala Vallis is the largest. Individual channels may be controlled by relatively straight geologic structures, such as High Hill anticline in the Channeled Scabland or the fault scarp that may bound the west side of the middle reach of Mangala Vallis (Fig. 3) (Milton, 1973). Aside from this, the high shear stress gradient that occurs on the inside of meander curves in extreme floods may lead to channel straightening and partly account for the relatively straight character of scabland channels.

Erosional features of catastrophic floods vary greatly with the nature of the material eroded. Lithologies on Mars can only be inferred from the topography. In Kasei Vallis there appears to be a resistant

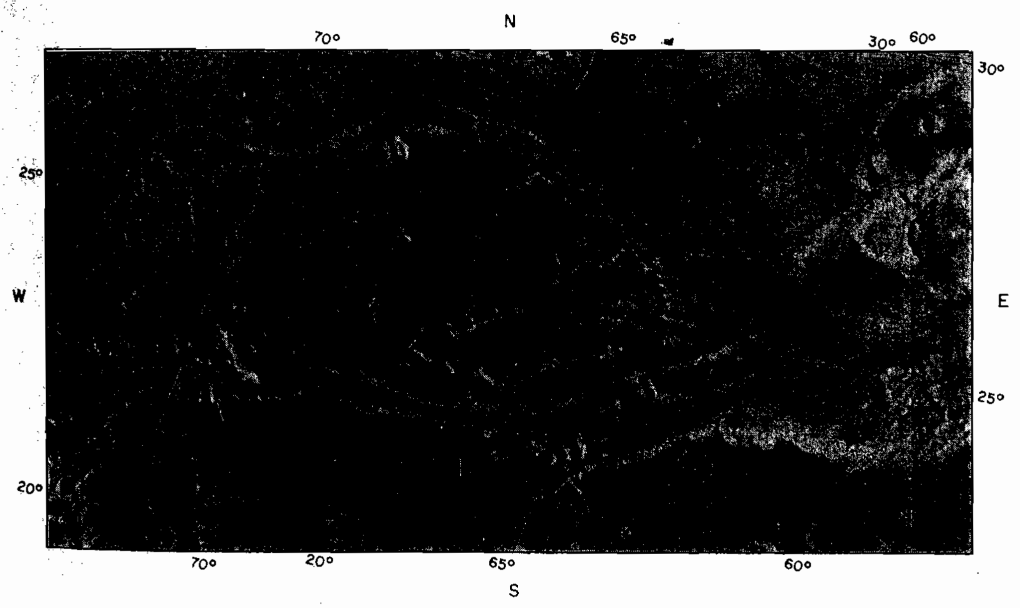


FIG. 4. Kasei Vallis (bottom) and unnamed channel (top), apparently formed or modified by floods flowing from west to east. Part of U.S. Geological Survey rectified mosaic of quadrangle MC-10, prepared from Mariner 9 wide-angle frames. Scale 1:1 000 000.

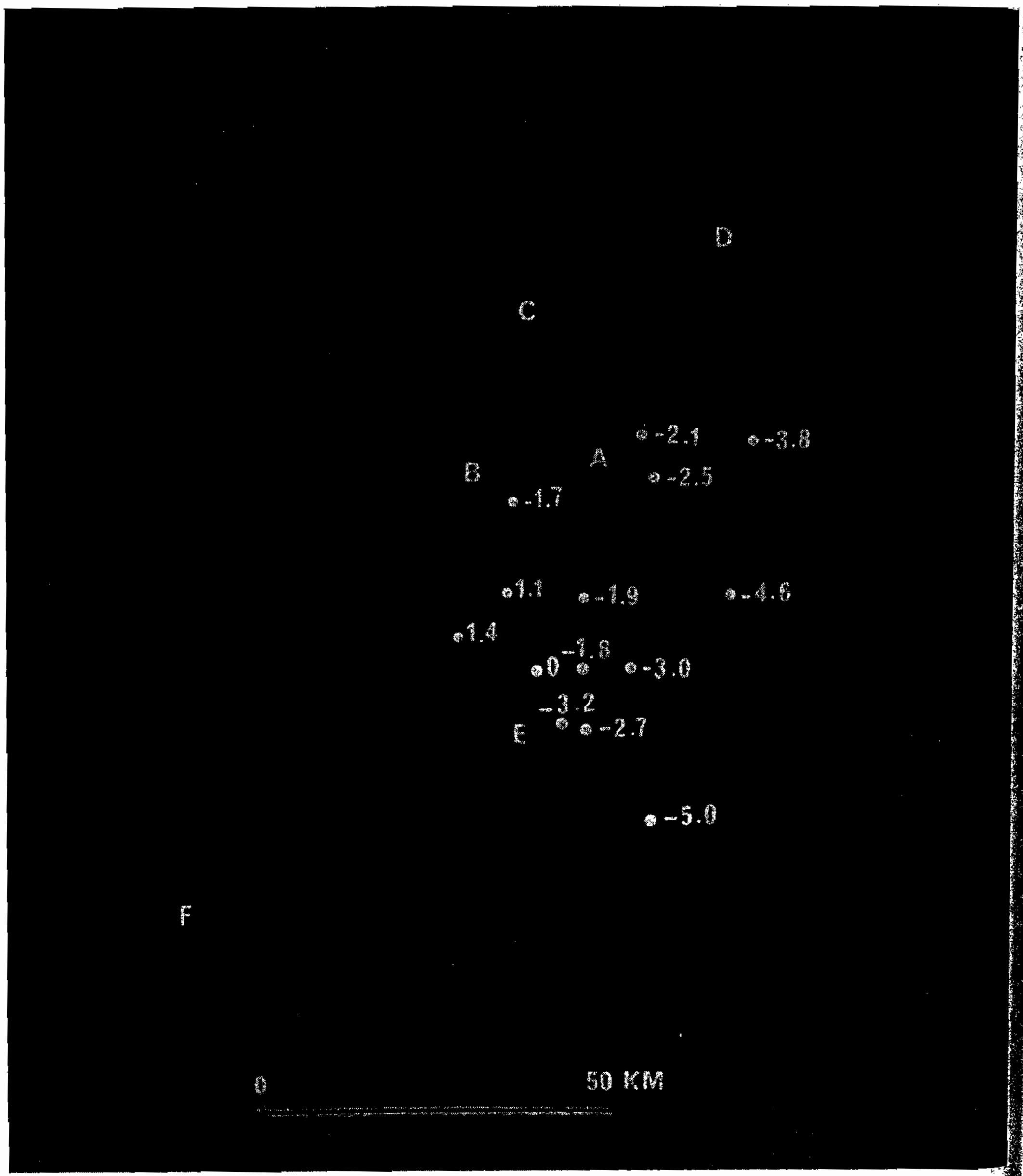


FIG. 5. Part of lower Kasei Vallis near 62°W, 25°N, with landforms indicating catastrophic flood erosion. Features discussed in the text include: (A) streamlined hill; (B) a horseshoe cataract that has worked around the head of the hill; (C) a complex of horseshoe cataracts; (D) a crater apparently controlling the site of a lower cataract; (E) a partly exhumed crater; and (F) stratification in a talus-free section of cliff. Spot elevations (in km from an arbitrary datum) are subject to individual errors of ±0.3km and an error in overall tilt of the model of ±1.5°. Light streaks originating at some craters and promontories indicate recent winds blowing westward. Rectified mosaic of Mariner 9 narrow-angle frame 10277404, 10277474, 12866133, and 12866203.

basal unit overlain by a weaker bedded unit (note stratification in the cliff at F, Fig. 5). This is capped by a thinner resistant unit, probably basalt from the evidence of structural features in nearby areas that resemble those of the lunar maria.

The characteristic landform of the loess eroded by the Missoula flood is the streamlined hill with a blunt rounded upstream prow and a pointed downstream end, eroded as islands or entirely subfluvially to a form offering minimum resistance to rapidly flowing water (Fig. 6). Streamlined hills are found in several Martian channels, but it is not always possible to determine whether they are eroded country material or bars of sediment deposited in the channel. A large streamlined hill in the mouth of Kasei Vallis (Figs. 4, 5) is clearly eroded bedrock since transverse lineaments exposed on the channel floor and on the adjacent plateaus also extend across the hill. The material composing the hill appears to correspond to the bedded unit in the island to the west.

Characteristic forms of erosion in basalt in the Channeled Scabland are longitudinal grooves, subfluvial cataracts, and butte and basin topography. Grooves (Fig. 7) were apparently produced by powerful roller vortices (also called secondary circulation cells) that develop with their filaments parallel to the flow direction. Allen (1971) described the morphologic effects of these vortices from laboratory flume experiments and noted (Allen, 1970) that the very regular spacing of longitudinal vortices is a function of velocity and depth of flow. Flume studies in simulated bedrock (Shepherd, 1972; Shepherd and Schumm, 1974) indicate that longitudinal

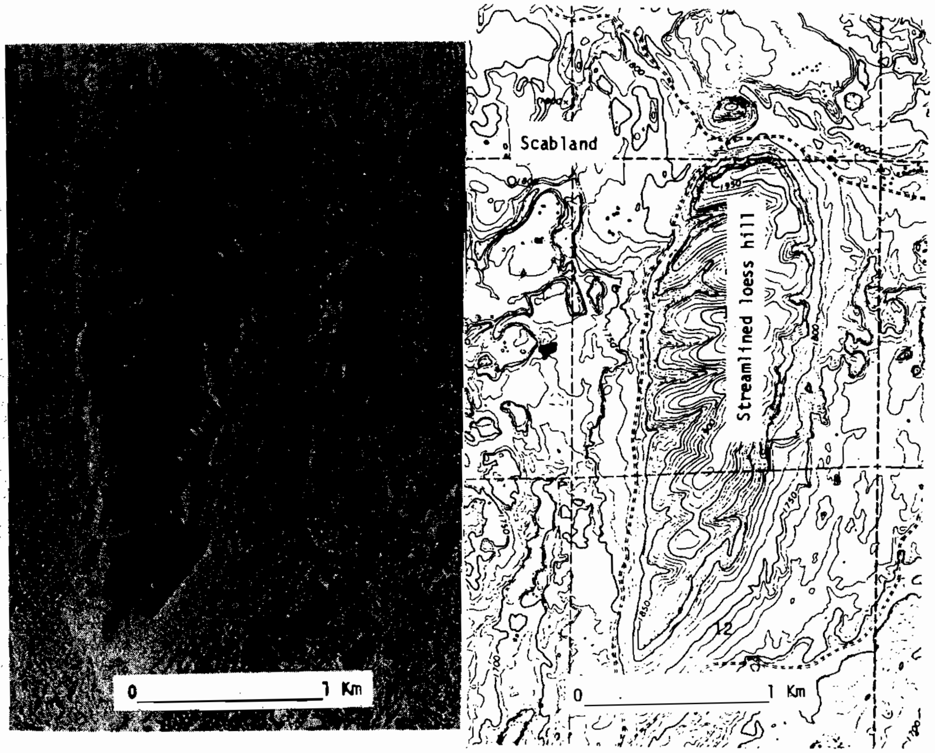


FIG. 6. Loess hill near Macall, Washington streamlined by flood erosion. A small cataract, heading an inner channel, has worked its way around the blunt upstream end of the hill (on map). Longitudinal grooves and butte-and-basin topography can be seen in the marginal scablands. Water depths and velocities averaged 12m/sec for depths of 30–40m in this area during the flood maximum. Map contour interval is 10ft (~3m).

dforms indicating catastrophic
›d hill; (B) a horseshoe cataract
ırseshoe cataracts; (D) a crater
ned crater; and (F) stratification
datum) are subject to individual
ight streaks originating at some
. Rectified mosaic of Mariner 9

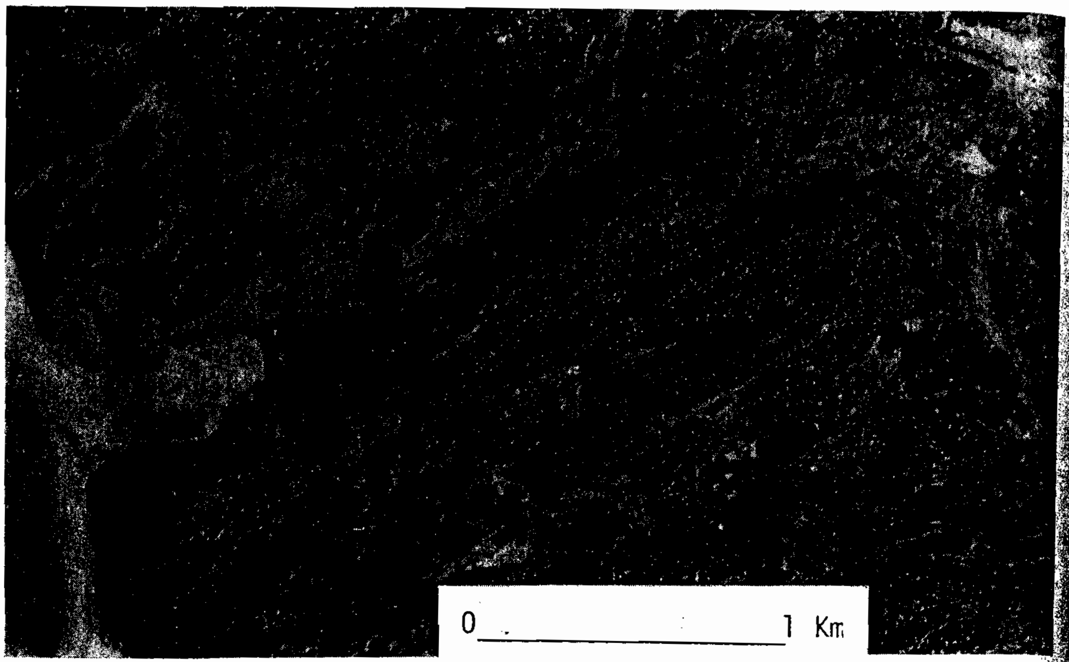
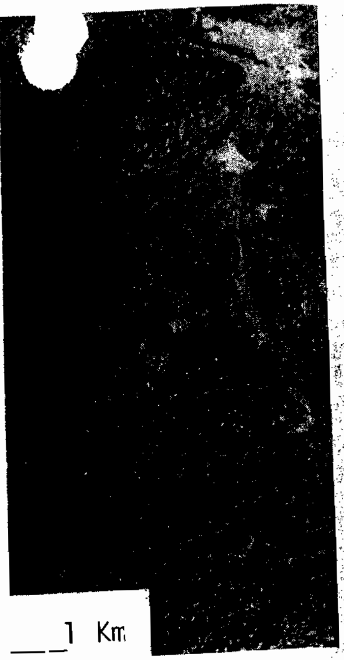


FIG. 7. Longitudinal grooves and butte-and-basin topography on a basalt scabland surface east of Jasper Canyon in the Lower Grand Coulee. Small mounds of eolian silt in the swales emphasize the linear pattern. A horseshoe-shaped inner channel cataract is at left.

grooves develop early and are eventually replaced by a deep inner channel headed by a nickpoint that migrates upstream. The scabland form corresponding to the latter is the abandoned cataract, largest of which is Dry Falls in Grand Coulee (Fig. 8). These developed subfluvially rather than by the plunge pool undercutting classically illustrated by Niagara Falls.

Grooves on a giant scale and dry cataracts are excellently developed in Kasei Vallis. Conformity of the grooves to the general channel geometry, their deflection around the streamlined hill, their absence in the lee of the high island, and their relation to the cataracts indicate that they are fluvial features rather than the superficially similar wind-etched joints that occur on Mars. Linear features in the same area clearly related to regional structural patterns rather than to the channel geometry could have been etched by either fluvial or eolian action, although their large size suggests the former. Dry cataracts in Kasei Vallis have the same scalloped rims composed of horseshoe-shaped segments as those in Grand Coulee (Fig. 5C). An upper horseshoe cataract (Fig. 5B) appears to have worked around the head of the streamlined hill to a point at which it would have been opposed to the general flow direction. Analogous situations are found in the Scabland, for example, at Dry Coulee around High Hill anticline or, on a smaller scale, the unnamed coulee around the streamlined loess hill (Fig. 6).

Butte and basin topography in the Channeled Scabland is a product particularly of the plucking of columnar basalt to form potholes and basins. Butte and basin topography cannot be identified with certainty in the Mariner photographs. Typical scabland buttes and basins are of a size that would be near B-frame resolution, although one might expect them, like the longitudinal grooves, to be larger on Mars. Nevertheless, some irregular Martian terrain may be analogous, for example on the marginal channels of Mangala Vallis (Fig. 3). The ability of deep, high-velocity flow of catastrophic floods to lift debris from channel floors and hence form basins



ι basalt scabland surface east of
silt in the swales emphasize the

se in Grand Coulee (Fig.
r h shoe cataract (Fig.
o worked around the
rea...ned hill to a point at
d have been opposed to the
rection. Analogous situations
the Scabland, for example,
around High Hill anticline
er scale, the unnamed coulee
reamlined loess hill (Fig. 6).
basin topography in the
abland is a product parti-
plucking of columnar basalt
oles and basins. Butte and
aphy cannot be identified
y in the Mariner photographs.
and buttes and basins are of
ould be near B-frame resolu-
h one might expect them, like
nal grooves, to be larger on
heless, some irregular Martian
be analogous, for example on
l channels of Mangala Vallis
ability of deep, high-velocity
strophic floods to lift debris
l floors and hence form basins

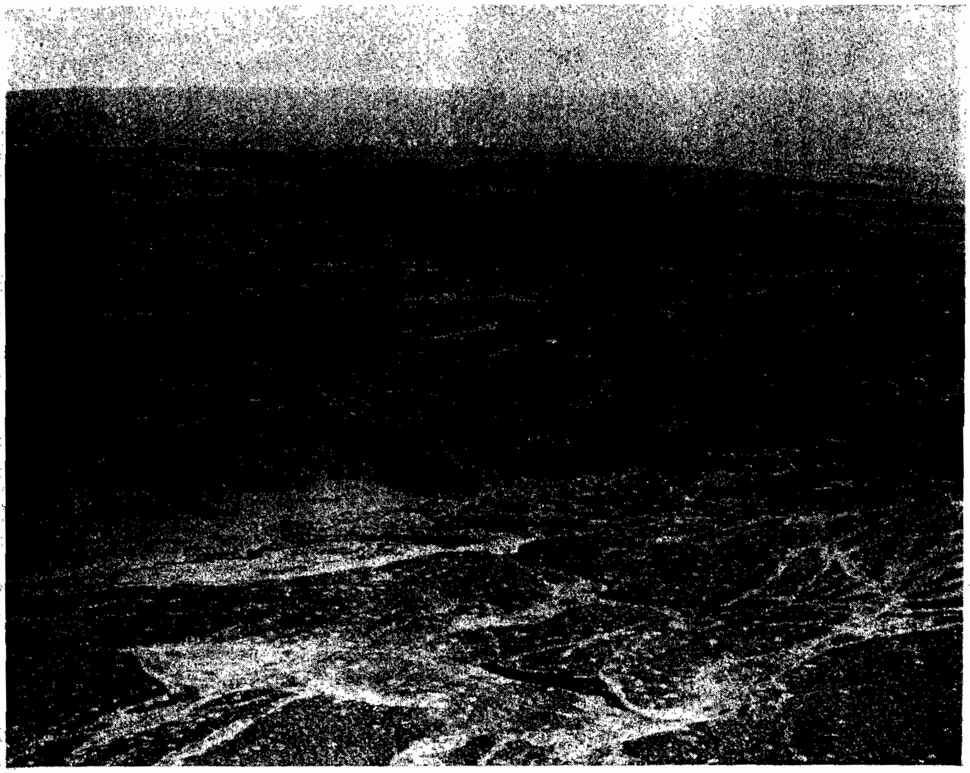


FIG. 8. Dry Falls cataract, 120m high, with upper Grand Coulee in background. Longitudinal grooves are visible just upstream from the cataract.

may be evinced in some closed depressions on the floor of Martian channels. The larger craters in Kasei Vallis appear to predate the channel cutting and to have been buried and exhumed (note the large crater only partly emergent from beneath the high island (Fig. 5E) and the crater that appears to have controlled the outline of the inner channel (Fig. 5D). Although it is evident that material has been moved out of many closed depressions elsewhere on Mars where no traces of floods are seen, these craters may have been scoured out by floodwaters. An intriguingly similar landform in the Channeled Scablands is produced by the sag flowouts of the Columbia River Basalt (McKee and Stradling, 1970). Although their structural origin is very different from a crater, they owe their morphologic expression to stripping of overlaying basalt flows by Missoula flooding (Fig. 9).

Tributary alcoves to the main Scabland channels were produced by headward erosion of marginal cataracts (Bretz, 1932). Such an origin is possible for alcoves in the middle reach of Kasei Vallis (Fig. 4), but this would imply an overbank flow on the adjacent plateau that is not otherwise indicated. More probable examples are found in Mangala Vallis (Fig. 3) where erosional features on the adjacent plateau indicate overbank flooding.

DEPOSITIONAL FEATURES

In environments where the velocity of flow is lowered, bedload is deposited to form subfluvial bars. Expansion bars form downstream from constrictions, as in Quincy Basin downstream from the lower Grand Coulee. The bar complex occupies $500 km^2$ and is composed of streamlined bar forms truncated by scour channels (Fig. 10). The basin fill has 60m of relief and includes channels with reverse down-

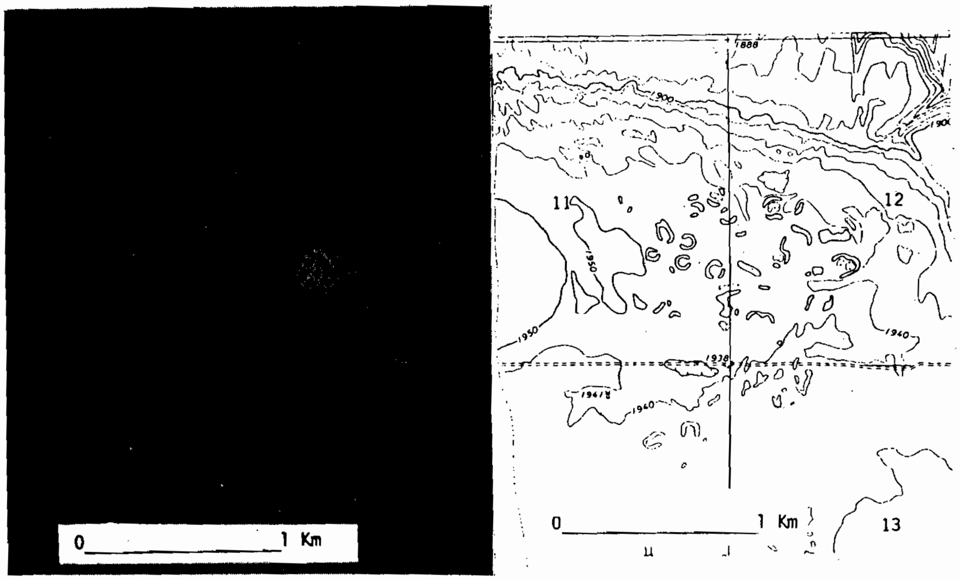


FIG. 9 Sag flowout structures near Karakul Hills in the Cheney–Palouse scabland tract. The ringlike forms are dikes that formed when lava escaped through tension joints surrounding sags on the cooled flow crust. Hydraulic plucking by the Missoula floods caused the rings to stand in relief, exhumed from overlying flat layers of basalt.

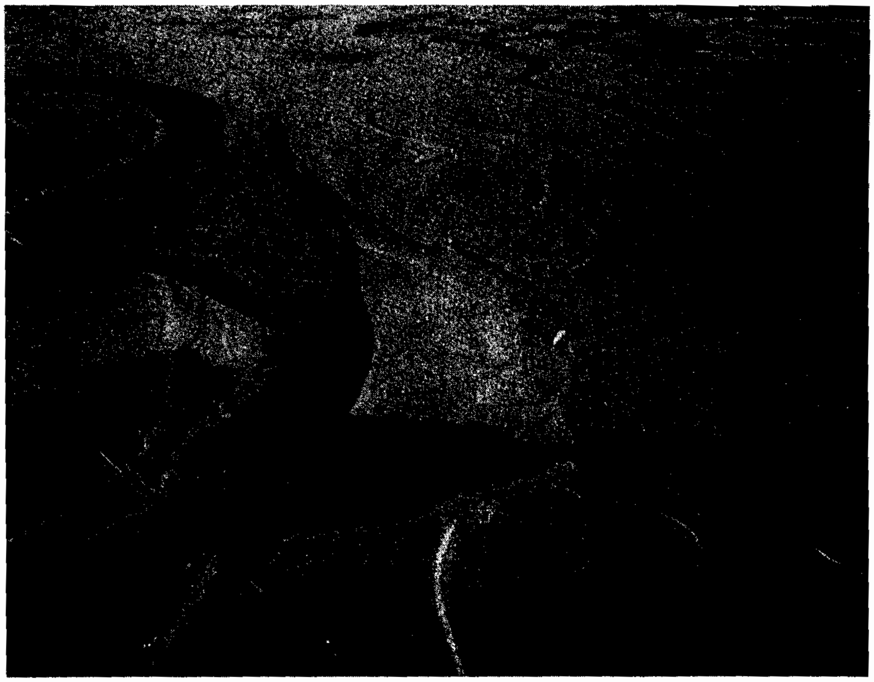


FIG. 10. View south (downstream) of a part of the Quincy Basin expansion bar complex. Moses Lake (left) occupies one of several sinuous channels that truncate the streamlined bars. Compare to Mangala Vallis (Fig. 3). (Photograph by David A Rahm.)

---

stream
pression
preted t
of one fl
Baker (
the prod
at peak f
stages. A
ment of
the pres
upstrean
constrict
velocity
while tl
hydrauli
rising pl
curred a
Subsequ
channels
probably
Forms
Basin ar
in the r
between
stream.
appear t
forms as
do not a
but some
direction
Although
reach to
terrestria
believe t
provides
analog. T
in the w
entire co
was form
overall a
much as
Pendan
eddy bars
downstre
on the ma
or in th
respective
is difficult
lined hills
but some
Ares Vall
features
the marg

stream gradients and many closed depressions. Bretz and others (1956) interpreted the bar complex as a gravel fill of one flood incised by several later floods. Baker (1973) reinterpreted it as mainly the product of a single flood with deposition at peak flow and incision during the waning stages. An important factor in the development of the Quincy Basin bar complex is the presence of flow constrictions both upstream and downstream. The upper constriction allowed an influx of high-velocity water carrying much sediment while the lower constriction provided hydraulic damming of the basin during the rising phase of the flood. Deposition occurred as the flood-wave filled the basin. Subsequently, the network of scour channels developed as the basin drained, probably while the inflow decreased.

Forms very similar to those of the Quincy Basin are found on Mars in Mangala Vallis in the reach where it widens to 30 km between 5-km narrows up- and downstream. Channels truncate and cut what appear to have once been streamlined bar forms as much as 10 km long. The channels do not all grade uniformly downstream but some appear to rise in a downstream direction or contain closed depressions. Although one of us has compared this reach to a braided section of an aggrading terrestrial river (Milton, 1973), we now believe that an expansion bar complex provides a more satisfactory terrestrial analog. This accords with the location only in the wide reach rather than along the entire course, as would be expected if it was formed by an aggrading river, and the overall appearance of an erosional as much as depositional pattern.

Pendant bars, longitudinal bars, and eddy bars form in terrestrial flood channels downstream from bedrock projections, on the margins of channels, and in alcoves or in the mouths of tributary valleys, respectively. In the Mariner photograph it is difficult to distinguish these from streamlined hills or terraces eroded from bedrock, but some of the midchannel features of Ares Vallis may be pendant bars and the features occupying broad reentrants on the margin of middle Kasei Vallis (Fig. 4) and particularly in the constricted reach of Mangala Vallis (Fig. 3) may be eddy bars.

Trains of giant current ripples were not discovered until late in the investigation of the Scabland but have become generally accepted as the clearest proof of the catastrophic flood hypothesis. In form and spacing they resemble transverse sand dunes (and were so interpreted when first noted on aerial photographs), but they contain foreset bedded basalt fragments as large as 1.5 m. Their chords range from 20 to 130 m and their heights from 0.5 m to 7 m. This is below the resolution of the Mariner or Viking orbital imaging systems. A prime Viking landing site, near the mouths of Ares and Tiu Valles, could well be in a giant-ripple terrain, however. Although ripple trains in the Scabland are far less conspicuous from a fixed viewpoint on the ground than from the air, the possibility of their presence should be kept in mind during interpretation of the landscape viewed by the television camera on the Viking Lander.

CONCLUSIONS

Many of the individual features described in this paper could reasonably be explained by alternative hypotheses. For example, eolian phenomena in extremely arid deserts produce remarkably streamlined erosional forms and lineations. Again, some of the broader features of the channel systems might be taken to indicate fluvial action without extreme flooding. But the hypothesis of catastrophic flooding appears uniquely able to account for the entire assemblage of features in the major channels of Mars. Several points should be significant in seeking a cause for the floods.

1. Flooding was a local phenomenon. The water was concentrated in a small number of discrete channels generally flowing northward from the equatorial cratered terrain to the lower plains.

2. Vast quantities of water were supplied so rapidly as to provide peak discharges of millions of cubic meters per second. Even the dense terrestrial atmosphere cannot provide water fast enough to yield

such discharges from comparable-sized catchment areas. On Earth, only dam bursts or subglacial volcanic eruptions have yielded flows capable of significant macroturbulent erosion.

3. Water need only have persisted briefly on the Martian surface. Macroturbulent scour by Missoula floods was accomplished in a matter of at most a day or two.

4. When the flooding occurred, whether it was coeval in the separate channels, and whether in individual channels it was a single or a repeated event, are questions still to be answered.

Normal continuous processes of erosion and deposition act with so much greater intensity on Earth than on Mars that traces of catastrophes are soon erased. The Channeled Scabland of the Columbia Plateau preserves the record of events perhaps rare in the history of the Earth. The dominant geomorphic processes operating in this area throughout the Pleistocene have been catastrophic floods and episodic eolian activity (loess deposition) in a region of arid climate and basalt bedrock. Perhaps no terrestrial landscape finds a closer analogue on Mars than this.

ACKNOWLEDGMENTS

Preliminary versions of this paper were read by W. D. Manley, Jr., and R. G. Sheperd, C. A. Hodges and M. H. Carr. Work by D. J. Milton was supported by Planetology Programs, NASA Headquarters, under contract W-13204, and Mariner Mars 1971 Project, Jet Propulsion Laboratory, California Institute of Technology, under contract WO-8122. Financial aid to V. R. Baker was provided by National Science Foundation grant GA-21478 and by The Geological Foundation of The University of Texas at Austin.

REFERENCES

ALLEN, J. R. L. (1970). "Physical Processes of Sedimentation." American Elsevier, New York.

ALLEN, J. R. L. (1971). Bed forms due to mass transfer in turbulent flows: a kaleidoscope of phenomena. *J. Fluid Mech.* **49**, 49–63.

ALLISON, I. S. (1933). New version of the Spokane flood. *Geol. Soc. Amer. Bull.* **44**, 675–722.

BAKER, V. R. (1973). Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington. *Geological Society of America Special Paper 144*, 79 pp.

BAKER, V. R. (1974). Erosional forms and processes for the catastrophic Pleistocene Missoula floods in eastern Washington. *In* "Fluvial Geomorphology" (Marie Morisawa, Ed.), Proceedings 4th Annual Geomorphology Symposium, Binghampton, N.Y. Publication of Geomorphology, State University, New York, Binghampton, N.Y.

BLASIUS, K. R. (1973). A study of Martian topography by analytic photogrammetry. *J. Geophys. Res.* **78**, 4411–4423.

BRETZ, J H. (1923). The channeled scablands of the Columbia Plateau. *J. Geol.* **31**, 617–649.

BRETZ, J H. (1932). The Grand Coulee. *American Geographical Society Special Publication 15.*

BRETZ, J H. (1969). The Lake Missoula floods and the channeled scabland. *J. Geol.* **77**, 505–543.

BRETZ, J H., SMITH, H. T. U., AND NEFF, G. E. (1956). Channeled scablands of Washington: new data and interpretations. *Geol. Soc. Amer. Bull.* **67**, 957–1049.

CARR, M. H. (1974). The role of lava erosion in the formation of lunar rilles and Martian channels. *Icarus* **22**, 1–23.

CLAGUE, J. J., AND MATHEWS, W. H. (1973). The magnitude of jökulhlaups. *J. Glaciol.* **12**, 501–504.

MACKIN, J. H. (1948). Concept of the graded river. *Geol. Soc. Amer. Bull.* **59**, 463–512.

MALIN, M. C. (1973). Salt weathering on Mars (unpublished manuscript).

MALDE, H. E. (1968). The catastrophic late Pleistocene Bonneville flood in the Snake River Plain, Idaho. *U.S. Geological Survey Professional Paper 596*, 52 pp.

MATTHES, G. H. (1947). Macroturbulence in natural stream flow. *Amer. Geophys. Union Trans.* **28**, 255–262.

MCCAULEY, J. F., CARR, M. H., CUTTS, J. A., HARTMANN, W. K., MASURSKY, H., MILTON, D. J., SHARP, R. P., AND WILHELMS, D. E. (1972). Preliminary Mariner 9 report on the geology of Mars. *Icarus* **17**, 289–327.

MCKEE, B., AND STRADLING, D. (1970). The sag flowout: A newly described volcanic structure. *Geol. Soc. Amer. Bull.* **81**, 2035–2044.

MILTON, D. J. (1973). Water and processes of degradation in the Martian landscape. *J. Geophys. Res.* **78**, 4037–4047.

MILTON, D. J. (1974). Carbon dioxide hydrate and floods on Mars. *Science* **183**, 654–656.

(1933). New version of the Sp kane
Soc er. Bull. **44**, 675–72
(1 Paleohydrology an sedi.
f e Missoula flooding in c stern
. *eological Society of A erica
er 144*, 79 pp.
(1974). Erosional forms an pro-
e catastrophic Pleistocene M soula
astern Washington. *In* "I uvial
logy" (Marie Morisawa, Ed.),
s 4t Annual Geomorphology Sym-
ngl ampton, N.Y. Publicat on of
logy, State University, New York,
on, N.Y.
R. (1973). A study of Martia topo-
analytic photogrammet . *J.
es.* **78**, 4411–4423.
(1923). The channeled scabla ds of
bia Plateau. *J. Geol.* **31**, 61 -649.
1932). The Grand Coulee. *A rican
al Society Special Publicatio 15.*
(1969). The Lake Missoula loods
channeled scabland. *J. Ge .* **77**,

SMITH, H. T. U., AND NEFF, G. E.
anneled scablands of Washi gton;
and interpretations. *Geo Soc.
l.* **67**, 957–1049.
(1974). The role of lava ero on in
tion of lunar rilles and M rtian
Icarus **22**, 1–23.
J., AND MATHEWS, W. H. 1973).
itud jökulhlaups. *J. Glac l.* **12**,

(1948). Concept of the raded
l. . Amer. Bull. **59**, 463–51
C. (1973). Salt weathering o Mars
hed manuscript).
E. (1968). The catastroph late
e Bonneville flood in the Snake
ain, Idaho. *U.S. Geological urvey
al Paper 596*, 52 pp.
G. H. (1947). Macroturbul ce in
stream flow. *Amer. Geophys. nion*
, 265–262.
, J. F., CARR, M. H., CUTTS, J. A.,
N, W. K., MASURSKY, H., M LTON,
HARP, R. P., AND WILHELMS D. E.
Preliminary Mariner 9 report n the
of Mars. *Icarus* **17**, 289–327.
, AND STRADLING, D. (1970). e sag
A newly described volcanic str cture.
. Amer. Bull. **81**, 2035–2044.
. J. (1973). Water and proc ses of
tion in the Martian landsc e. *J.
. Res.* **78**, 4037–4047.
. J. (1974). Carbon dioxide drate
ds on Mars. *Science* **183**, 654–6 .

PARDEE, J. T. (1942). Unusual currents in glacial Lake Missoula, Montana. *Geol. Soc. Amer. Bull.* **53**, 1569–1600.

SAGAN, C., TOON, O. B., AND GIERASCH, P. J. (1973). Climatic change on Mars. *Science* **181**, 1045–1049.

SCHEIDEGGER, A. E. (1973). Hydrogeomorphology. *J. Hydrol.* **20**, 193–215.

SCHUMM, S. A. (1974). Structural origin of large Martian channels. *Icarus* **22**, 371–384.

SCHUMM, S. A., AND SHEPHERD, R. G. (1973). Valley floor morphology: evidence of subglacial erosion? *Area* (*Inst. British Geog.*) **5**, 5–9.

SELBY, M. J., AND WILSON, A. T. (1971). The origin of the labyrinth, Wright Valley, Antarctica. *Geol. Soc. Amer. Bull.* **82**, 471–476.

SHARP, R. P. (1973). Mars: fretted and chaotic terrains, *J. Geophys. Res.* **78**, 4073–4083.

SHEPHERD, R. G. (1972). A model study of river incision. Unpublished M.S. thesis, Colorado State Univ., Fort Collins, Colorado, 135 pp.

SHEPHERD, R. G., AND SCHUMM, S. A. (1974). Experimental study of river incision. *Geol. Soc. Amer. Bull.* **85**, 257–268.

SMITH, H. T. U. (1965). Anomalous erosional topography in Victoria Land, Antarctica. *Science* **148**, 941–942.

STEARNS, H. T. (1936). Origin of the large springs and their alcoves along the Snake River in southern Idaho. *J. Geol.* **44**, 429–450.

WARREN, C. R. (1965). Wright Valley: Conjectural volcanoes. *Science* **149**, 658.