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PATHFINDER LANDING SITE: ALTERNATIVES TO CATASTROPHIC FLOODS AND AN ANTARCTIC ICE-FLOW ANALOG FOR OUTFLOW CHANNELS ON MARS. B.K. Lucchitta, U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001. E-mail: blucchitta@flagmail.wr.usgs.gov

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Introduction

The Pathfinder spacecraft landed successfully at the mouth of the outflow channels Ares and Tiu Valles, returning a wealth of information about the surrounding landscape [1]. One goal of the mission was to ascertain that catastrophic floods formed the outflow channels, the prevailing hypothesis for their origin [2]. The follow-up reports on the mission [1,3] proclaim that observations are "consistent" with an origin by catastrophic flood; no alternative mechanisms for channel origin are considered. Thus, the impression is given that the problem of channel origin has been solved. Yet none of the observations are diagnostic of origin by catastrophic floods. Other origins are possible but have been ignored, for instance origin as liquefaction mudflows [4,5], debris flows [6,7], mass flows [8], or ice flows [9,10]. Here I will examine landing site observations that have been used to infer origin by catastrophic flooding [1,3] and suggest alternative origins. Finally, I will highlight some new observations from Antarctica that make an ice-flow mechanism plausible for the origin of some of the outflow channels.

Landing site observations

The following observations were used as evidence that catastrophic floods shaped the landing site. <u>The rocky surface is consistent with being a depositional plain.</u> Pre-mission analyses of rock distributions were conducted by Golombek and Rapp [11] for various landscapes, including catastrophic-flood plains, alluvial fans, an eroded volcanic surface, and the Viking 1 and 2 landing sites. Curves of cumulative number of rocks versus rock diameter and of cumulative fraction of area covered by rocks versus rock diameter were generated for the various areas. The curves dominantly reflected rock fragmentation laws from fracturing of rocks due to weathering or transport [11]; they were less diagnostic for processes of emplacement of rocks. Even though the Mars Pathfinder curves are similar to those of catastrophic-flood deposits, they more closely resemble those of an ancient alluvial fan. The results are consistent with rock emplacement in a depositional environment, but they do not indicate that catastrophic floods formed the Pathfinder landscape. <u>Large rocks (>0.5 m) appear tabular and semi-rounded.</u> Images showing the surface of the Ephrata Fan of the Channeled Scabland of Washington State, a deposit of catastrophic flooding (Fig 6 in Rice and Edgett [12]) show many more rounded boulders than seen at the Pathfinder site. Also, cross-sectional outcrops of catastrophic-flood deposits are loaded with rounded cobbles and boulders. The semirounded boulders at the Pathfinder site are not very abundant; those that occur could have formed in debris flows or glaciers, or in any other mass movement with corrosive ability. <u>Rocks in the Rock Garden may be imbricated blocks generally tilted in the direction of flow.</u> Imbrication can be expected in any material transported by a fluid. The minor possible imbrication observed could have formed equally well by debris or ice flows. <u>Rocks appear perched.</u> Some of the perched appearance may be due to the acknowledged local deflation in the area of 5 to 7 cm [3]. Perched rocks are common on glacial moraines.

<u>The Twin Peaks appear to be streamlined hills in lander images. A gentle ridge trends northeast from the hills.</u> On Earth, streamlined hills of the dimensions seen on martian images are more commonly formed by flowing ice (drumlins) than by floods, as are long ridgelike tails behind obstacles (drumlinoid forms). Given the right material, streamlined forms can also be formed by wind (yardangs). The streamlined, flood-eroded hills in the Channeled Scabland are composed of easily erodible loess [13]. The Twin Peaks, one of which may show layering, could be composed of basalt, consistent with surface material covering many plains on Mars, or of older mass-flow deposits [8]. Streamlining would require larger discharges than those of the Channeled Scabland floods to accomplish erosion of these materials, which are more resistant than loess, but estimated discharges for the landing site are not that large (see below). <u>Boulder trains on the twin hills resemble landforms found in the lee of obstacles in large terrestrial floods.</u> Boulder trains also occur on alluvial fans and are common downslope from outcrops on steep slopes, especially in a periglacial environment. They are also associated with glacial deposits. <u>The northern Twin Peak is banded with possible terraces.</u> The use of the word terraces implies river or flood activity. Yet the banding could equally well be layers, as the Ares and Tiu Valles are carved into highland plateaus that are locally surfaced by basalts [14]. The light color could well be drift deposited on benches. The abrupt termination of the layers on the upstream side of the hill is consistent with erosion by glaciers at the stoss side of drumlins, and the banding could be glacial grooves. The vertical stripe on the southern Twin Peak could be sand from kame deposits. However, these suggestions are very speculative.

<u>The Pathfinder site has a pronounced ridge-and-trough texture, with amplitudes as high as 5 m and 15 to 25 m crest-to-crest.</u> Ridges in flow directions are found in landslides, debris flows, and glacial flutes. For instance, flutes at the base of Antarctic ice streams in till are about 8 m in relief [15], similar to the relief at the landing site. However, the Antarctic grooves are wider than those at the Pathfinder site. <u>Ridges and trough trends comparable with the large-scale Tiu and Ares flow directions are modestly expressed.</u> Debris flow and ice flow would also give a texture in the main flow direction. In addition, the

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fairly disordered topography showing enclosed depressions [1, Plate 4] resembles a morainal surface more than a fluvial one.

Flow velocities at the landing site are computed to have been about 8 m/s and the flow depth 10 to 20 m. These values are inferred from the size of the largest boulders transported and from the local topographic slope [16,17,18]. Smith et al. [3] admit that these depths and velocities do not agree with those commonly used or computed for catastrophic floods on Mars and that they are more like those of large floods in Iceland and Washington State. This velocity is 3 to 10 times less than that generally inferred for floods on Mars. Yet, a 15-km-long tail behind a hill only 30 km south of the site (Far Knob) suggests that floods in the landing area were just as energetic as martian floods elsewhere. Discharges at the landing site are estimated to have been between 10^6 and 10^7 m^3/s in the immediate vicinity of the lander. These values are estimated from the generally small size of the inferred bed load at the landing site. Again, Smith et al. [3] state that these values are one to two orders of magnitude smaller than previous estimates for floods in Ares Valles [19]. The discrepancy is explained by proposing that deposition at the landing site reflects a waning phase of flooding resulting in late-stage deposition [3], comparable, for instance, to what can be observed in floods in Iceland [20]. The landing site surface characteristics are also likened to those of the Ephrata Fan of the Channeled Scabland, a plain of deposition from catastrophic flooding. However, there is no clear evidence that the landing site is indeed located in a basin of deposition, as shown by the tail behind Far Knob. Landforms in the landing-site region suggested to Komatsu and Baker [19] that flood power was expected to be very high. What is clear is that the landing site characteristics do **not** match those expected for a deposit from a catastrophic megaflood.

In conclusion, the Pathfinder landing site characteristics may be consistent with an origin by catastrophic flooding, but none of the observations are diagnostic. An origin by debris flows or by rock-laden ice flows is just as likely. Considering that ice flow is a possibility, I present below some new data from Antarctica that support the ice-flow idea.

Antarctic ice-flow analog

It is commonly accepted that some form of ice flow occurred in the fretted channels [10,21,22], but the influence of ice flow on landscape development in the outflow channels is generally relegated to a minor, subordinate role [23,24]. An exception is the hypothesis by Lucchitta et al. [9] and Lucchitta [10] that suggests that ice sculpture in the outflow channels may have played a major role. The following observations from Antarctica support this contention. Sounding of the sea floor in front of the Ross Ice Shelf in Antarctica recently revealed large persistent patterns of longitudinal megaflutes and drumlinoid forms [25], which bear remarkable resemblance to longitudinal grooves and highly elongated streamlined islands on the floors of martian outflow channels. The flutes are interpreted to have formed at the base of ice streams during the last glacial advance [25]. The Antarctic ice streams are thought to slide over longitudinally grooved, deforming till, where much of the movement is within the till [15]. The till is saturated with water at high pore pressures that nearly supports all of the weight of the ice [15,26]. A similar mechanism of sliding may have operated at the base of outflow channels on Mars. It could have permitted the movement of rock-laden debris that may have crept through the outflow channels (like the fretted channels) at some stage in their early development, or it could have aided flow of ice derived from cleaner water erupted from springs or flowing from lakes.

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WEST-ANTARCTIC ICE STREAMS: ANALOG TO ICE FLOW IN CHANNELS ON MARS

B. K. Lucchitta, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001.
blucchitta@flagmail.wr.usgs.gov

Sounding of the sea floor in front of the Ross Ice Shelf in Antarctica recently revealed large persistent patterns of longitudinal megaflutes and drumlinoid forms, which are interpreted to have formed at the base of ice streams during the last glacial advance [1]. The flutes bear remarkable resemblance to longitudinal grooves and highly elongated streamlined islands found on the floors of some large martian channels, called outflow channels. In addition, other similarities exist between Antarctic ice streams and outflow channels. Ice streams are 30 to 80 km wide and hundreds of kilometers long, as are the martian channels. Ice stream beds are below sea level [2]. Floors of many martian outflow channels lie below martian datum [3], which may have been close to or below past martian sea levels [4,5]. The Antarctic ice stream bed gradient is flat and locally may go uphill, and surface slopes are exceptionally low [6]. So are gradients of martian channels [7]. The depth to the bed in ice streams is 1 to 1.5 km [8]. At bankful stage, the depth of the fluid in outflow channels would have been 1 to 2 km. These similarities suggest that the martian outflow channels, whose origin is commonly attributed to gigantic catastrophic floods [9], were locally filled by ice that left a conspicuous morphologic imprint [10].

Unlike the West-Antarctic ice streams, which discharge ice from an ice sheet, ice in the martian channels came from water erupting from the ground. In the cold martian environment, this water, if of moderate volume, would eventually freeze. Thus it may have formed icings on springs [8], ice dams and jams on constrictions in the channel path [10], or frozen pools [11]. Given sufficient thickness and downhill surface gradient, these ice masses would have moved; and given the right conditions, they could have moved like Antarctic ice streams.

The Antarctic ice streams are thought to slide over longitudinally grooved, deforming till, where much of the movement is within the till [8,12]. The till is saturated with water at high pore pressures that nearly supports all of the weight of the ice [12,2]. For pore pressures to remain high, the ice streams have to act as a seal that blocks the flow of water through them, and the rock underneath has to be of low permeability to prevent the water from draining away. A similar mechanism of sliding may have applied to ice in martian channels. In situ rubble from weathering products may have served as the deformable layer. The channel ice forms the seal above the sliding horizon, the bedrock the seal below so that water could accumulate under high pore pressures. The water could have been derived from remaining liquids associated with the icings, ice jams and dams, or frozen pools.

However, if no such water remained in the liquid state, water had to be liberated by other means. Under current average equatorial surface temperatures on Mars of 218 K [13], a heatflow of 30 mWm^{-2} [13], and a thermal conductivity of ice of 2.6 $J\ m^{-1}\ s^{-1}\ K^{-1}$ (after Glen [14]), water ice would freeze to a depth of nearly 5 km and ice in the channels would be welded to the ground. Warmer climates in the past would have to be invoked to make the Antarctic ice-stream mechanism work. Most outflow channels, however, date from the martian mid-history [15], when the existence of warmer climates is conjectural.

On the other hand, heatflow in channel regions may have been elevated. Martian channel floors tend to be littered with dark, mafic [17] materials; some channels originate at grabens [16]; and channels are locally associated with volcanoes [18]. Assuming a heatflow of 90 mWm^{-2}, representative of some volcanic regions on earth [19], and using the other parameters given above, melting could have occurred at less than 2 km depth. Thus, in volcanic regions, water could have been liberated on the floor of ice-filled, 1- to 2-km-deep outflow channels.

Elevated heatflows also existed in the past. Schubert and Spohn's [20] model estimates mantle heatflows of about 40 mWm^{-2}, 1 b.y. ago; of about 70 mWm^{-2}, 2 b.y. ago; and of about 100 mWm^{-2}, 3 b.y. ago. Accordingly, 2 b.y. ago and earlier, melting could have occurred at depths of 1 to 2 km. Thus, at the time when many of the outflow channels formed, ice contained in the channels could have slid on rubble under high pore pressures like Antarctic ice streams.

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ICE IN CHANNELS AND ICE-ROCK MIXTURES IN VALLEYS ON MARS: DID THEY SLIDE ON DEFORMABLE RUBBLE LIKE ANTARCTIC ICE STREAMS? B. K. Lucchitta, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001. blucchitta@flagmail.wr.usgs.gov

Recent studies of ice streams in Antarctica reveal a mechanism of basal motion that may apply to channels and valleys on Mars. The mechanism is sliding of the ice on deformable water-saturated till under high pore pressures. It has been suggested by Lucchitta [1] that ice was present in outflow channels on Mars and gave them their distinctive morpholoy. This ice may have slid like Antarctic ice streams but on rubbly weathering products rather than till. However, to generate water under high pore pressures, elevated heatflow is needed to melt the base of the ice. Either volcanism or higher heatflow more than 2 b.y. ago [2] could have raised the basal temperature. Regarding valley networks, higher heatflow 3 b.y. ago could have allowed sliding of ice-saturated overburden at a few hundred meters depth. If the original, pristine valleys were somewhat deeper than they are now, they could have formed by the same mechanism.

Recent sounding of the seafloor in front of the Ross Ice Shelf in Antarctica reveals large persistent patterns of longitudinal megaflutes and drumlinoid forms [3], which bear remarkable resemblance to longitudinal grooves and highly elongated streamlined islands found on the floors of martian outflow channels. The flutes are interpreted to have formed at the base of ice streams during the last glacial advance [3]. Additional similarities of Antarctic ice streams with martian outflow channels are apparent. Antarctic ice streams are 30 to 80 km wide and hundreds of kilometers long. Martian outflow channels have similar dimensions. Ice stream beds are below sea level [4]. Carr [5] determined that most common floor elevations of martian outflow channels lie below martian datum, which may have been close to or below past martian sea levels [6,7]. The Antarctic ice stream bed gradient is flat and locally may go uphill, and surface slopes are exceptionally low [8]. Martian channels also have floor gradients that are shallow or go uphill locally and have low surface gradients [9]. The depth to the bed in ice streams is 1 to 1.5 km [10]. At bankful stage, the depth of the fluid in outflow channels was 1 to 2 km, according to the height of bordering scarps [1]. The similarity between Antarctic ice streams and martian outflow channels suggests that ice may have flowed through and shaped the outflow channels [1], and that perhaps the mechanism of motion of Antarctic ice streams also operated in outflow channels. In addition, sliding on deformable rubble may explain the formation of small valley networks.

The large Siple Coast Antarctic ice streams are thought to slide over longitudinally grooved, deforming till, where much of the movement is within the till [10,11]. The till is saturated with water at high pore pressures that nearly supports all of the weight of the ice [10,4]. The small differential between overburden pressure and pore pressure at the bed is more important than the volume of water, but water needs to be supplied to the till interface [4]. For pore pressures to remain high, the ice streams have to act as a seal that blocks the flow of water through them, and the rock underneath has to be of low permeability to prevent the water from draining away. The water is thought to have been derived from melting ice due to geothermal heat and perhaps volcanic heat [10]. Once moving, frictional heat will tend to keep the water from refreezing.

A similar mechanism of sliding on deformable rubble may have operated at the base of outflow channels and small valleys on Mars. Indeed, such a mechanism has recently been proposed by Carr [5] for fretted channels and valleys on Mars. Most of the conditions for the Antarctic sliding mechanism are met for martian outflow channels. In situ rubble from weathering products may have served as the deformable layer. The channel ice may have come from ice dams and jams [1], from frozen or partially frozen lakes [12], from segregated masses akin to ice sills or laccoliths [13], from glacier ice [7,14], or from icings above springs [1]. The channel ice forms the seal above the sliding horizons, the bedrock the seal below so that water could accumulate under high pore pressures. For small valleys in highlands, deformable breccia with mechanical properties similar to till [15,16] likely occurs at 1 to 2 km depth. Layers that may represent impermeable horizons have also been recognized in many places at these depths [17,18]. Such layers may form the seal below the sliding horizons. The ice-saturated ground above [19,5] would provide the seal in the overburden and furnish the water needed to pressurize the pores.

Water needs to be liberated at the base of the sliding masses to generate high pore pressures. The depth to melting can be calculated from the heatflow equation $z = k/Q\ (tp-ts)$; where z=thickness of the measured layer, here the depth to melting; k=thermal conductivity; Q= heatflow; tp= temperature at the lower boundary of the layer, here the melting temperature; and ts=annual mean surface temperature. Depth to melting can be measured to the 273 K isotherm for water ice, or to the 252 K isotherm for NaCl brines, which are likely to occur on Mars [21]. The depth at which water ice overburden would melt on Mars under current equatorial surface temperatures (218 K [20]) is nearly 5 km, using a heatflow of 30 mWm^{-2} [20] and a thermal conductivity of ice of $k=2.6\ J\ m^{-1}\ s^{-1}\ K^{-1}$ (after Glen [21]). Clearly, this depth is in excess of the common depth of outflow channels. Evidently, warmer climates would be needed to make the ice-stream mechanism work. However, outflow channels date from the martian mid-history or even late history [22], when the existence of warmer climates is conjectural. Therefore, elevated heatflow is needed to liberate water from ice at the base of the outflow channels.

The possible association of channels and valleys with regions of elevated heatflow is suggested by proximity to grabens [23]; dark, most likely mafic, materials [24]; and volcanoes [25]. Assuming a heatflow of 90 mWm^{-2}, representative of some volcanic regions on earth [26], and using the other parameters given for ice above, melting of ice overburden would have occurred at a depth of 1.6 km using the 273 K isotherm (water ice) and at 1.0 km using 252 K (NaCl brines). Thus, on the floor of ice-filled, 1- to 2-km-deep outflow channels, water could have been liberated in the equatorial areas of Mars if the region had elevated heatflow due to volcanism.

Past heatflows have been addressed by Schubert and Spohn [2]. Their model estimates mantle heatflows of about 40 mWm^{-2}, 1 b.y. ago; of about 70 mWm^{-2}, 2 b.y. ago; and of about 100 mWm^{-2}, 3 b.y. ago. Accordingly, 2 b.y. ago and earlier, melting would occur at depths of 2.0 km or less (273 K isotherm, water) or 1.3 km or less (252 K isotherm, NaCl brine), and ice could have flowed in outflow channels.

Most valleys on Mars are ancient (upper Noachian, [22]) and formed during a time when heatflow was elevated and melting occurred at much shallower levels than today. The depth to melting critically depends on the thermal conductivity used for the martian highlands. Clifford [20] proposed a thermal conductivity of 2.O $J\ m^{-1}\ s^{-1}\ K^{-1}$ (an average between frozen soils and vesicular basalt). Rossbacher and Judson [19] used a thermal conductivity of 0.8 $J\ m^{-1}\ s^{-1}\ K^{-1}$ (frozen limonitic soil). Applying current surface temperatures, Schubert and Spohn's [2] heatflow values of 3 b.y. ago, and Clifford's [20] thermal conductivity, the depth to melting of ice-rich rock overburden would have been 1.1 km (273 K isotherm, water) or 0.7 km (252 K isotherm, NaCl brine). Using Rossbacher and Judson's [19] thermal conductivity, the depth to melting of ice-rich overburden would have been 0.4 km or 0.3 km, respectively. The latter depths fall within the range of depths of small valleys on Mars [27], especially if one assumes that the valleys have been infilled with erosional debris. Thus, about 3 b.y. ago, during times of elevated heatflow, water may have been liberated at the floor level of small valleys, allowing pore pressures to build. Given lack of restraint at the bottom of slopes and local concentration of fluids, the ice-rich ground could have become mobilized and slid in the manner of Antarctic ice streams.

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KASEI VALLES, MARS (I); THE WATER STORY; B.K. Lucchitta, U.S. Geological Survey, Branch of Astrogeology, 2255 N. Gemini Dr., Flagstaff, AZ 86001.

The Kasei Valles were explored to establish to what extent the morphologic signature and lay of the land were compatible with formation or modification of channel features by water or ice processes. All available images and geologic and topographic maps were used for the study. Even though the error of the topographic maps is evaluated to be on the order of ±1 km [1], only regional slopes over long distances were used, giving information of a very general nature. Thus, the gradients used are very approximate, but they nevertheless give an indication of the overall situation. Quantitative evaluation shows that discharges must have been extremely large if the channels were formed by floods. Lesser discharges would be needed if the erosional forms were sculpted by ice.

Morphology. The Kasei Valles apparently arise from Echus Chasma, but the actual channel showing streamlined forms and fluting, attesting to a moving fluid, only starts at lat 12° N. Upstream (south) of this latitude is chaotic terrain [2], similar to that of the other Chryse channels, but partially drowned by lavas from Tharsis. This chaotic terrain appears on the valley floor near the 4-km contour on the adjacent plateau, similar to the situation of the other peripheral Valles Marineris troughs [3].

For about 500 km below the chaotic terrain, the Kasei Valles parallel the regional slope in a strike or structural valley formed between the Tharsis volcanoes to the west and the scarp delineating the Lunae Planum plateau to the east. The apparent gradient is 0. The gradient steepens to near 0.005 only where the Kasei Valles bend to the east, break through the highlands of the Lunae Planum Plateau and the Chryse Basin rim, split into two (the north and south) channels, and become incised to about 1-2 km below the adjacent valley floor. Below and beyond the bend the gradients are again extremely low (about 0.0005 over 1500 km).

Kasei Valles had at least two flow episodes, and the surface was lowered by about 1 km between these episodes [2, 4, 5, 6,]. This erosion affected the Lunae Planum Plateau and Tempe Terra region, where the Kasei Valles cut through the highlands, and formed Labeatis Mensae. Both a fretting process and river erosion may have lowered the land in this region. The lower erosional platform upstream from the break through the Lunae Planum highlands is intensively scoured, showing longitudinal grooves more than 40 km long in places, 300 to 500 m wide, and 30 to 200 m deep (from shadow measurements) across a valley width of 100 to 300 km. These grooves extend into the northern incised channel, marking its walls and floor continuously without cut-and-fill structures. Apparently, the flow episode that eroded this platform also carved the 1-km-deep incised channel. Shadow measurements, photoclinometry, and eroded crater rims show that erosional scour on this platform may have been as much as 600 m deep and that the eroding fluid was at times at least 200 m deep when considering the size and depth of the grooves that must have been overtopped by the fluid.

Discharges. The Kasei Valles generally are considered to have been formed by cataclysmic floods [7]. Velocities and discharges of flood waters are difficult to calculate because assumptions concerning the water-surface gradient, the precise depth and width of the fluid (the wetted channel perimeter), the Manning coefficient, etc. have to be made. Here the equations for velocity and discharge used by Carr [8] and Baker [9] were applied to facilitate comparison with earlier reports. We used a Manning coefficient of 0.04 in keeping with Baker's [9] value for the Missoula flood and channels on Mars. Lower Manning coefficients would increase the discharge volumes. The value of 0.01 given by Baker [9] for the Mississippi River, if used for the Kasei Valles, would increase the discharges by a factor of 4.

The gradient of the Kasei Valles is near 0 above the gorges where the channels cut through the Lunae Planum and Chryse Basin rim highlands, and the Kasei Valles may have been a lake before the water broke through this at least 1-km-high barrier. Using a gradient of 0.001 (from the upstream margin of fluted valley floor to the mouth of the Kasei Valles, 2500 km downstream) and a minimum 200 m water depth, the velocity would have been about 15 m/sec. Assuming a 100-300 km width of the channel, the discharge would have ranged from $3x10^8$ to $9x10^8$ m^3/sec. For a 200-km-long section of the incised, more rapidly dropping channels (water depth 1000 m, width 20 km, gradient 0.005), the velocity would have been near 90 m/sec and the discharge $1.8x10^9$ m^3/sec. (This water depth was used because the scour inside the incised north channel shows no cut and fill structures, indicating that flow was not interrupted during channel formation.) This velocity value compares with that of 32 to 75 m/sec (depending on the Manning coefficient used) and a discharge of $1.4x10^9$ m^3/sec calculated by Robinson and Tanaka [10] for a section of the incised

Lucchitta, B.K., 1995, Kasei Valles Mars (1): The water story (abs.), in Lunar and Planetary Science XXVI, The Lunar and Planetary Institute, Houston, Texas, p. 867-868.

KASEI VALLES, MARS (I); THE WATER STORY; B.K. Lucchitta, U.S. Geological Survey, Branch of Astrogeology, 2255 N. Gemini Dr., Flagstaff, AZ 86001.

The Kasei Valles were explored to establish to what extent the morphologic signature and lay of the land were compatible with formation or modification of channel features by water or ice processes. All available images and geologic and topographic maps were used for the study. Even though the error of the topographic maps is evaluated to be on the order of ±1 km [1], only regional slopes over long distances were used, giving information of a very general nature. Thus, the gradients used are very approximate, but they nevertheless give an indication of the overall situation. Quantitative evaluation shows that discharges must have been extremely large if the channels were formed by floods. Lesser discharges would be needed if the erosional forms were sculpted by ice.

Morphology. The Kasei Valles apparently arise from Echus Chasma, but the actual channel showing streamlined forms and fluting, attesting to a moving fluid, only starts at lat 12° N. Upstream (south) of this latitude is chaotic terrain [2], similar to that of the other Chryse channels, but partially drowned by lavas from Tharsis. This chaotic terrain appears on the valley floor near the 4-km contour on the adjacent plateau, similar to the situation of the other peripheral Valles Marineris troughs [3].

For about 500 km below the chaotic terrain, the Kasei Valles parallel the regional slope in a strike or structural valley formed between the Tharsis volcanoes to the west and the scarp delineating the Lunae Planum plateau to the east. The apparent gradient is 0. The gradient steepens to near 0.005 only where the Kasei Valles bend to the east, break through the highlands of the Lunae Planum Plateau and the Chryse Basin rim, split into two (the north and south) channels, and become incised to about 1-2 km below the adjacent valley floor. Below and beyond the bend the gradients are again extremely low (about 0.0005 over 1500 km).

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Lucchitta, B.K., 1995, Kasei Valles Mars (2): The ice story (abs.), in Lunar and Planetary Science XXVI, The Lunar and Planetary Institute, Houston, Texas, p. 869-870.

KASEI VALLES, MARS (II); THE ICE STORY; B.K. Lucchitta, U.S. Geological Survey, Branch of Astrogeology, 2255 N. Gemini Dr., Flagstaff, AZ 86001.

Morphologic features in the Kasei Valles outflow channels resemble those of cataclysmic floods on Earth [1], an observation that leads to an inferred origin for these channels by similar large outbursts of water [1, 2, 3]. Yet, outflow-channel features in Kasei Valles are generally an order of magnitude larger than those caused by terrestrial catastrophic floods, implying that Kasei floods were much larger, perhaps by as much as one to three orders of magnitude than those on Earth and in other Martian outflow channels [4]. Releasing such gigantic volumes of water from the ground in one sudden event is difficult, and explanations offered for such releases [5, 6] are not entirely satisfactory. As an alternative to flooding, many of the morphologic features in the Kasei Valles possibly were carved by ice and sub-ice water channels [7, 8], an idea supported by several observations.

The morphology [4] of the Kasei Valles region is consistent with an origin by ice. About 500 km downstream of the Kasei Valles chaotic terrain, the channels abandon their northward course and turn to the east, where they break through the Lunae Planum Plateau and split into two incised branches (the north and south channels). The north channel and other scoured incised channels are U-shaped and have smooth transitions from valley walls to valley floors, like glaciated valleys on Earth. Scour marks occur both on the walls and on unburied parts of floors of incised channels. Grooving on valley walls is very common in glaciated terrain, but not in flood-scoured valleys. Grooves on the wide, scoured platform upstream from the channel bend to the east are also U-shaped. The grooves on these platforms are more than 40 km long in places, 300-500 m wide, and 30-200 m deep (from shadow measurements) and are an order of magnitude larger than those commonly found associated with cataclysmic floods on Earth. Flood-formed grooves in the scablands of Washington and Oregon are about 50 m wide and 5 m deep. A statistical comparison of grooves in the Kasei Valles and other channels on Mars with glacially carved grooves in Alaska and the Northwest Territories of Canada show that the widths of grooves in the Kasei Valles overlap with those carved by ice on Earth as seen on Landsat images. The comparison also shows that grooves in the Kasei Valles are of similar shape but somewhat larger than those in the Kahiltna Valley in Alaska, as measured on a topographic map. However, ice features exhibit fractal behavior over certain ranges of spatial scale (including those applicable here [9]), indicating that similarities in shape may be significant. Measurements on ice stream B in Antarctica also reveal large longitudinal grooves below this rapidly moving ice mass [10].

Grooves made by floods are thought to have formed by roller vortices [11]. It is difficult to envision that roller vortices would not have disintegrated on certain pre-existing gaps on the floor of the Kasei Valles (joints in the channel beds) that are as much as 400 m wide and are crossed by grooves without deflections or offsets. Also, some ridges at the downstream side of gaps have drumlin-like shapes. Craters as much as 6 km wide are similarly overridden without deflection in the scour marks. Ice would readily overtop obstacles in the flow path without divergence. Furthermore, the overridden craters have no recognizable sediments in their interiors, as would be expected if flooded. This observation is more compatible with filling and overriding by ice, because ice would leave no trace after evaporation or sublimation [12].

Robinson and Tanaka [2] described a "mega pothole," located in a segment of the north channel of Kasei. This feature is a smooth depression 100 km long and 350 m deep with linear, parallel scour marks on its floor. Its origin is attributed by them to intense erosion facilitated by supercritical flow and cavitation. However, the morphology of this depression is more like that of hollows in glaciated terrain on Earth. The carving of hollows and overriding of swells is typical for ice, whose movement is controlled by the ice-surface gradient.

Deeply incised, V-shaped channels that cut the grooved valley floor of Kasei Valles locally acquire a labyrinthine appearance. Sub-ice channels, such as the labyrinth of the Dry Valleys of Antarctica, are common underneath glaciers and icestreams.

I offer the following explanation for the conspicuous "ice sculpture" in the Kasei Valles. The gradient of the upper Kasei Valles, where they trend parallel to the regional slope and upstream from where they break through the barrier of Lunae Planum and the Chryse Basin rim highlands, is near 0 [4], so that the water may have ponded and frozen. According to Clow [13], the ice thickness on a river is very sensitive to the discharge and the slope, mostly because of the importance of the frictional heating. If ice carved the features in Kasei Valles, there is no need to invoke gigantic outbursts of water; moderately sized springs could have supplied the flow. And if the water ponded behind the barrier of Lunae Planum, the surface gradient would be 0 and the term for frictional heating would have been eliminated in the flow equations, so that the water froze. Also on Earth, ice jams commonly form where river beds are constricted, such as would have occurred at the breakthrough of the Kasei Valles through the Lunae Planum highlands. Ice drives occur mostly in spring during breakup, when the discharge of water increases from behind [14]. Analogous situations may have been obtained in the Kasei Valles region, where discharges may have occurred in several pulses.

Overall, floods of moderate volume may have come from Echus, the chaotic terrain below it, and from Tharsis, but the water was blocked and ponded where it encountered the highlands at the Kasei Valles bend. The ponding accelerated freezing of water that was probably already loaded with frazil ice, and gigantic ice jams piled up. Increased discharge from Echus and the Tharsis volcano region may eventually have floated and mobilized the ice masses and forced them through openings in the highlands. Such openings were probably present because the area is structurally disturbed and weakened, showing many pre-existing joints [3, 12]. The ice, when forced through the highlands, carved the conspicuous, deeply incised, U-shaped channels. North Kasei Valles consequently now looks like a valley in terrestrial glaciated terrain. South Kasei Valles may have looked similar, as indicated by still visible local scour marks, but it was later modified by masswasting and sapping processes [1, 12, 15].

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SCARP HEIGHTS ON MARTIAN CHANNELS FROM SHADOW MEASUREMENTS: **B.K. Lucchitta and J. Dembosky, U.S. Geological Survey, Flagstaff, Arizona 86001**

The volume of water and sediments transported through the outflow channels remains one of the major important outstanding questions on Mars. Not only is this volume important to assess the water inventory of Mars [1], it is also needed to shed light on the events that shaped the northern plains and their influence on the atmosphere. To arrive at channel volumes, their width and depth have to be established. The width can be readily measured on available maps, but the depth remains an unknown for most channel reaches. Contours furnished on topographic maps mostly are in 1-km (±1 km, [2]) increments, and are thus not sufficient for many channel features that have heights below this value. The photoclinometric method to arrive at topographic profiles requires areas of uniform albedo and has other restraints that are difficult to meet for many places with the available images. Shadow measurements give fairly accurate height determinations where adequate illumination conditions exist, and the method has been tried for many individual localities [3, 4, 1, 5, 6]. The present study is an attempt to systematically measure shadows on scarps along and within all channels where adequate images exist.

To implement the study, we devised latitude and longitude blocks containing all major channels on Mars. Then we conducted a computer search and inspected all images within these blocks that met the following parameters: resolution less than 250 m/pixel, incidence angle, 45°-75°, emission angle, 0°-30°, moderate to good quality, clear or red filters. From the inspected images, we compiled a final list of the specified range in resolution.

Images in the final list were processed on the computer to level 1 quality (adding labels, removing reseaux marks and noise, and correcting the radiometry). Then a computer program (TVPHOTOST in PICS system) was implemented that permitted the interactive measurements of shadows: a line giving the down-sun direction was plotted on each image, the pixels at the beginning and end point of each shadow were registered, and the height of the scarps corresponding to the measured shadow was calculated using the appropriate trigonometric functions. Variations of the sun and camera geometry within individual images were taken into account.

Obtaining shadow measurements on level-1 processed images by computer is better than obtaining shadows on hard-copy prints, because it is easier to establish that the shadows are real and not grazing light that mimics shadows on scarps. Criteria to establish true shadows are: (1) high density contrast between the area in shadow and the terrain onto which the shadow is cast, (2) persistent low-density (dark) values within the shadow, and (3) matching in shape of the feature and its shadow. Shadows cast onto undulating terrain were not used. For most measured shadows the contrast was sharp and the edge of the shadow could be determined to within 1 pixel. Shadows that could not be determined to better than 3 pixels at the end of the shadow were flagged as unreliable. At a 3-pixel uncertainty errors would be as follows: resolution 250 m--errors ±220 m at 60° incidence angle and ±100 m at 75°. Resolution 20 m--errors ±20 at 60°, and ±10 m at 75°. Error values between these end members would vary accordingly.

We investigated Ares Vallis, Al-Quahira Vallis, Kasei Valles, Ma'adim Vallis, Maja Valles, Mamers Valles, Mangala Valles, Nanedi Vallis, Nirgal Vallis, Tiu Vallis, Shalbatana Vallis and Uzboi Vallis. Several other small channels did not have adequate images, and no measurements were obtained. We looked at 326 images, but not nearly as many contained shadows that could be measured. We made about a thousand measurements. The following highlights some findings.

Ares Valles (20 images, 62 measurements): The trunk channel arises from chaotic terrain and has a fan-shaped, grooved intake area. Many tributary channels have similar appearances. The channel walls descend gradually through a series of scarps. The floors are marked by irregular grooves and small streamlined islands. Upper channel-wall scarps generally do not exceed 800 m in height. Most wall scarps are around 200 m. Channel islands measure 200 to 500 m in height. Grooves on channel floors are mostly less than 100 m high. It is difficult to establish the total channel depth because the gradually descending walls make them unsuitable for shadow measurements.

Al-Quahira Vallis (8 images, 23 measurements): The channel, a modified graben, traverses highlands with many old craters. Channel depth generally ranges from 500 to 800 m, but varies unsystematically because of the irregular topography of the surface it cuts.

Ma'adim Valles (21 images, about 60 measurements): The channel starts where tributaries merge, increases gradually in width and depth, and debouches into an old crater near the highland boundary. For most of its length it has a well defined trunk with only minor tributaries. The walls are steep and locally have scarps; the floor is generally flat, but has terraces in places. The channel is 300 to 500 m deep in its upper part, and 1500 to 2000 m deep in its main part. Terraces on the channel floor and on a dissected mesa at the channel mouth inside the crater are 100 to 300 m high.

Nanedi Vallis (7 images, 14 measurements): The channel has two merging branches. They are deeply entrenched, flat floored, and meandering. The shape of widened sections appears to follow exhumed small craters. The steep channel scarps measure less than 200 m in the V-shaped upper reaches and are about 300 m high throughout most of the flat-floored reaches.

Nirgal Vallis (9 images, 21 measurements): The meandering channel is deeply entrenched and has dendritic tributaries similar to channels on earth. An upper V-shaped section gives way to a lower flat-floored section. The gradual increase in width is accompanied by a gradual increase in depth from about 400 m to 800 m.

Shalbatana and Simud Valles (4 images, 23 measurements): Shalbatana has two distributaries, one is merging with a chaotic section of Simud Vallis, the other entrenched and flat floored in its wider sections and lacks meanders. The scarps in the entrenched section are 1300 to 1400 m high. The mesas and knobs in the chaotic section of Simud Vallis range from over 1000-m high in the south to less than 500 m in the north; they are gradually decreasing in height toward the channel mouth.

Tiu Vallis (13 images, 90 measurements): The channel comes from chaotic terrain. It has chaotic sections like Simud Vallis, and grooved and scarped sections like Ares Vallis. The channel-wall height also decreases northward. Scarps facing the chaotic terrains or located nearby are over 2000 m high in places. Channel walls in the upper reaches measure 1600 to 1800 m, but for the main part of the channel the walls are generally 800 to 1000 m high and decrease gradually to as little as 400 m on interior-mesa scarps in the north near the channel mouth.

We have compiled the measurements of the remaining major channels on 1:500 000-scale maps and, for Mamers Vallis where no such maps exist, onto a mosaic compiled from images. We are in the process of analyzing these channels in more detail. Eventually we will combine height and width measurements to arrive at cross sectional areas of the channels and volumes of water or ice that may have moved through them.

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