Summary
The four youngest megaflood channels on Mars – Mangala Valles, Marte Vallis, Grjotá Valles and Athabasca Valles – date to the Amazonian Period and originate at fissures. The channels show common in-channel morphological indications of flood activity (streamlined forms, longitudinal lineations, scour), as well as evidence for volcanic, tectonic, sedimentary and/or glacial/ground ice processes. The fissure sources and channel termini have varied expressions, suggesting various triggering mechanisms and fates for the floodwaters. Possible triggering mechanisms include magmatic processes (dyke intrusion), tectonic processes (extensional faulting) and a combination of both types of processes. Surface morphology suggests that each of these mechanisms may have operated at different times and locations. Upon reaching the surface, the water likely would have fountained at least a few tens of metres above the surface, producing some water and/or ice droplets at the fountain margins. The likely sources of the floodwater are subsurface aquifers of a few kilometres’ thickness and a few tens of degrees Celsius in temperature.

10.1 Introduction
Megaflooding on Mars has varied in origin and amount throughout the history of the planet. During the Noachian Period, the most ancient period, flooding originated from crater basins (Irwin and Grant, this volume Chapter 11). During the Early Hesperian Epoch, megafloods originated at chaos terrain often set within Valles Marineris chasmata (Coleman and Baker, this volume Chapter 9). During the Amazonian Period, the most recent period, megaflooding originated from fossae produced by extensional tectonism.

This chapter provides a review of the four megaflood channels originating at fossae that experienced flow during the Amazonian Period. These megaflood channels are the largest examples of a suite of aqueous flow channels that originate at volcanotectonic fissures. Granicus Valles originate from the Elysium Fossae on the flanks of Elysium Mons (Mouginis-Mark et al., 1984). Other smaller channels originate at the Ceraunius and Olympica Fossae in the northwest Tharsis region (Mouginis-Mark, 1990), and from unnamed fractures on Ascræus Mons and the Olympus Mons aureole (Mouginis-Mark and Christensen, 2005). These channels show that aqueous flows from fossae have occurred throughout volcanic provinces on Mars. The focus of this chapter is megaflood flow; thus, this review focuses on the four largest known and best investigated to date of these channels. These four channels are very roughly an order of magnitude smaller in each dimension than the largest flood channels, the Hesperian-aged circum-Chryse channels (Coleman and Baker, this volume Chapter 9), but still discharged geomorphically significant volumes of water.

Because the youth of these megaflood channels is noteworthy, this chapter starts with a brief overview of age-dating of young features on Mars before then giving the inferred ages of these tectonic megaflood channels. Next, the morphology of each channel is reviewed, including the source morphology, in-channel bedforms, any inferred flow characteristics, and possible floodwater sinks. Then a synopsis is provided of the possible mechanisms that may have triggered groundwater release from fossae and led to surface flood flow. Finally, some thermal and mechanical aspects of the inferred groundwater movement to and within the source fossae are discussed.

10.2 Ages
10.2.1 Issues related to dating of Amazonian-aged channels
The most recent period on Mars is the Amazonian (Tanaka, 1986), lasting from ~3.0 Ga to the present (Hartmann and Neukum, 2001). The absolute dating of the surface features on Mars is accomplished by comparison of actual impact crater size–frequency distributions with model size–frequency distributions for fixed ages, referred to as ‘isochrons’ (e.g. Hartmann and Neukum, 2001). Crater counts in support of dating a flood in a channel are performed on terrain in the channel interpreted to have been created or modified by the floodwaters, e.g. flood-scoured channel floors. The actual size–frequency distributions of impact craters on channel floors indicate the age of only the most recent, geomorphically effective flood. This supposition is founded upon the fact that floods are ‘self-censoring’,
i.e., more recent, larger floods have been shown to erase the
sedimentological evidence of previous smaller floods (e.g.
House et al., 2001). Likewise on Mars, previous smaller
floods would not be visible in the channel floor cratering
record, although the existence and ages of previous floods
may be indicated by flood terraces (Berman and Hartmann
2002, Burr et al., 2002b). Ideally, to derive the age of a
flood from crater counts, a flood should have erased all
craters completely but this may not always be the case (see
e.g. Figure 13 of Burr et al., 2002b).

A second issue with regard to age-dating of young
Martian flood channels is the uncertain effect of secondary
craters. Secondary craters are those formed by impact
of material thrown out from the surface of a planet by a
(larger) primary impact. Because secondaries are smaller
than primaries, they are erased more quickly; thus, they
affect the age-dating primarily of the young surfaces
of Mars, where they are subject to the least amount
of erasure and where larger craters are not present for
use in age-dating. The discovery of efficient secondary
production in young lava flows on Mars (McEwen et al.,
2005) raises the question of whether Martian isochrons,
derived from and tied to radiometrically dated lunar
samples, properly account for secondary crater production
(see McEwen and Bierhaus, 2006, for a review). Because
of significant secondary production, dates of the inferred
youngest flood channel have varied by up to two orders of
magnitudes (compare the ages of Athabasca Valles in Burr
et al., 2002b and McEwen et al., 2005). However, even
with this variance, this channel still retains an age-date
of late Amazonian. Older surfaces should have still less
error and, overall, age-dating of features to within the
Amazonian Period appears robust (Hartmann, 2005). Each
of the four fissure-headed channels discussed below has
been inferred to have seen flooding during the Amazonian
Period (see next section, 'Channel ages').

A final point about the ages of these channels is the
possibility of channel exhumation. The documentation of
extensive layered terrain on Mars (Malin and Edgett, 2000)
and of exhumation of inverted fluvial channels from within
the rock record (Williams and Edgett, 2005; Williams
et al., 2005) suggest that Martian outflow channels also
could be exhumed. Extensive burial and partial exhu-
mation of one fissure-headed channel (Athabasca Valles) has
been argued on the basis of inferred scour upslope of its
source (Edgett and Malin, 2003). In such a case, the derived
model crater-count age for the channel floor would reflect
an exposure age, not a formation age. However, in this
particular case, the scour has an alternative interpretation,
namely, as an effect of floodwater gushing upslope from
the fissure due to the force of the water eruption (Burr
et al., 2002b; Head et al., 2003; Manga, 2004). Evidence
for the proposed exhumation is not apparent within this
channel and no evidence for exhumation has been deduced
for other Amazonian-aged fissure-headed channels.

Bearing in mind these issues with regard to age-
dating of young channels, the ages of each of the four
largest tectonic outflow channels are now discussed.

10.2.2 Channel ages

Mangala Valles  The oldest and largest tectonic outflow
channel is Mangala Valles (Plate 23). The most up-}

slopes end of Mangala Valles coincides with the Men-
mni Fossae, flat-floored features inferred to be a graben
system formed at the coincidence of dyke emplacement
and normal faulting (see Hanna and Phillips, 2006). Flooding
down Mangala is inferred to have coincided with faulting
on the Memnonia Fossae on the basis of crater counts and
stratigraphic relationships (Tanaka and Chapman, 1990) as
mapped at 1:500,000-scale on Viking images (Chapman
and Tanaka, 1993; Craddock and Greeley, 1994; Zimbel-
man et al., 1994). Two periods of coeval faulting and flood-
ing originally were inferred from Viking data, the first dated
as late Hesperian age and the second originally dated at the
Hesperian–Amazonian boundary (Tanaka and Chapman,
1990). Subsequent analysis on improved images interpreted
the youngest materials in Mangala Valles as Amazonian in
age, based on superposition relationships and lack of craters
greater than 2 km in diameter (Zimbelman et al., 1992).

Marte Vallis  Marte Vallis (Plate 24) is the largest and
oldest of the three Amazonian-aged outflow channels that
surround the Cerberus plains, where it is located at the
eastern end of the plain (Burr et al., 2002b). The channel
originally was interpreted as being continuous with one or
both of the other two Cerberus plains channels (Tanaka
and Scott, 1986; Berman and Hartmann, 2002, Figure 1; Ples-
scia, 2003). However, topography from the Mars Orbi-
ter Laser Altimeter (MOLA; Smith et al., 1998) and crater
counts on the channel floor both suggest that the three Cer-
berus channels are spatially and temporally distinct (Burr
et al., 2002b; Berman and Hartmann, 2002). Marte Vallis
has been dated by counting craters on Mars Orbiter Camera
(MOC) images (Malin and Edgett, 2001) of both the chan-
nel floor, inferred to date to the last flood, and the dark
lobe material that embays much of the channel, inferred to date
since the last flood. These crater counts produced similar
ages spanning a few to ~200 Ma (Berman et al., 2001; Burr
et al., 2002b; Berman and Hartmann, 2002).

Gjøtót Valles  A previously unnamed channel to the north
of the Cerberus plains (Plate 25) (Burr et al., 2002b) has
been named Gjøtót Valles (Plescia, 2003). Age-dating of
the Gjøtót Valles floor is affected by its weathered char-
acter, its indistinct flood boundaries, and the presence of
some aeolian dunes (Burr et al., 2002b). Despite these
factors, crater counts on MOC images of inferred flood-formed surfaces – i.e., longitudinally grooved surfaces adjacent to streamlined forms – fall along the isochrons of Hartmann (1999) and give an age of $\sim$10–40 Ma (Burr et al., 2002b).

**Athabasca Valles**  Athabasca Valles (Plate 26) are at the western end of the Cerberus plains. They have the most pristine geomorphology of all the Amazonian-aged, fissure-headed channels, and crater counts on the channel floor have yielded the youngest model ages. Crater counts on MOC images of the longitudinally grooved terrain in the topographic channel give an age of $2\sim8$ Ma (Burr et al., 2002b) based on comparison with the Hartmann (1999) isochron model. Other crater counts within the topographic channel give an age of 3 Ma (Werner et al., 2003) based on the Neukum and Ivanov (1994, described by Hartmann and Neukum, 2001) model. This 3 Ma unit is not characterised morphologically but is attributed to volcanism; the most recent flood erosion in that study is dated to 1.6 Ga, characterised morphologically but is attributed to volcanism; the most recent flood erosion in that study is dated to 1.6 Ga, and Fagents, 2001; Lanagan, 2004). The age of 3 Ma is derived by Werner et al. (2003) from a MOC image that shows features of the type interpreted by Lanagan et al. (2001) and Lanagan (2004; Jaeger et al., 2007). Because water is unstable near the surface of Mars in the present climate, the presence of rootless cones implies that lava emplacement was preceded closely by flooding (Lanagan et al., 2001; Lanagan, 2004). The age of 3 Ma is derived by Werner et al. (2003) from a MOC image that shows features of the type interpreted by Lanagan et al. (2001) and Lanagan (2004) to be rootless cones. On this basis, an age of 3 Ma, if correctly attributed to lava, would still imply flooding of a similarly young age. Subsequent investigation with Thermal Emission Imaging Spectrometer (THEMIS) infrared (IR) images (Christensen et al., 2003) and crater counts on MOC images showed that $\sim$80% of the craters on the Athabasca Valles grooved channel floor are secondaries (McEwen et al., 2005). Because this efficient secondary production called into question the use of isochrons for young surfaces, the channel was re-dated using statistical methods, with an age of 1.5–200 Ma (McEwen et al., 2005). The possible exhumation of Athabasca Valles is discussed in the previous section.

**10.3 Morphology**

As shown above, all four known outflow channels that experienced mega-flooding in the Amazonian Period have tectonic sources, either fissures or graben. The channels also all show common in-channel morphological indicators of flooding, including streamlined forms, scour and longitudinal lineations. However, the morphologies, both at their sources and at their termini, vary. Channel location, source and channel morphology, and possible floodwater sinks are discussed below.

**10.3.1 Mangala Valles**

Centred near 15° S 210° E, Mangala Valles (Plate 23) are located in the southern highlands just south of the hemispheric dichotomy boundary of Mars. They are situated to the west of the Tharsis rise and to the south of Amazonis Planitia, and begin at an elevation of about 0 m. From this origination point at Mangala Fossa, one of the Memnonia Fossae, the main channel stretches $\sim850$ km northward to its dual outlets at the south side of the eastern Medusae Fossae Formation (Plate 23). The upper (southern-most) $\sim550$ km of the channel is a single reach situated between north–south trending fault blocks (Zimbelman 1989). The most proximal $\sim150$ km show primarily scoured terrain with a few smaller streamlined forms, and the next $\sim400$ km show less scour with much larger streamlined forms behind impact craters or other obstacles. The upper reach expands rapidly from 5.5 km through a notch in an eroded impact crater north of Mangala Fossa to $\sim50$ km in width within a few kilometres downstream. Channel depth varies from a few tens of metres to a few hundred metres, and the overall slope of the upper reach is $\sim0.0005$ m m$^{-1}$ ($\sim0.03\%$). Downslope (northward) of this upper reach, the channel diverges into two separate branches. These two divergent branches are as narrow as approximately 10 km and as deep as 1000 m in some locations. The northwestward branch has a number of in-filled impact craters along its path, whereas the north-northeastward branch shows a more anastomosing plan-view form.

The channel system was inferred to have been formed by catastrophic flooding on the basis of streamlined bars within the channel (see Carling et al., this volume Chapters 2 and 3) and braided plan-view morphology (Milton, 1973; Sharp and Malin, 1975). The oblique orientation of the most proximal streamlined forms (Tanaka and Chapman 1990) originally suggested that water may have been released from more than one location (Zimbelman et al., 1992). The most recent analysis, using THEMIS and MOLA data (Ghatan et al., 2005), suggests that the groundwater filled and overflowed the source trough, generating oblique overland flow, and that this sheet flow then coalesced into channelised flow through the 5.5 km wide notch to the north side of the source trough. The time scale for the initial trough filling may have been from as little as $\sim2$ hours (Leask et al., 2007) up to $10^{7}$ hours (Ghatan et al., 2005).
indicating the considerable uncertainty associated with these estimates.

The context and morphology of Mangala Valles suggest a complex history providing multiple hypotheses. Early interpretations of Mangala Valles as an outflow channel suggested the origin to have been breaching of a large surface reservoir or lake (Sharp and Malin, 1975). In subsequent analysis, the origination of the channel at a fissure or graben radial to the Tharsis rise was interpreted as indicating that water release resulted from fault-induced cracking into a perched aquifer (Tanaka and Chapman, 1990). To other workers, the proximity of the channel to the Tharsis rise suggested floodwater generation by Tharsis magmatic melting of near-surface ground ice, which would have then migrated in the subsurface to the tectonic fissures to be released to flow down the channel (Zimbelman et al., 1992). Under this scenario, water release likely would have been artesian (Zimbelman et al., 1992).

The most recent analyses of the Mangala Vallis source region by Ghatan et al. (2005) and Leask et al. (2006) also inferred tectonic tapping of a pressurised aquifer, with Tharsis being the most likely source of the groundwater. This most recent hypothesis builds on the global hydrosphere model of Clifford (1993) and Clifford and Parker (2001), in which the crust of the planet is divided into the cryosphere (the uppermost portion that remains below the water freezing temperature) and the hydrosphere (a sub-cryospheric zone where liquid water accumulates), and on the interpretation of the graben as reflecting subsurface dykes (Wilson and Head, 2002). In this hypothesis, dyke emplacement resulted in graben formation and cracking of the cryosphere, which released pressurised groundwater to the surface; the minimum duration of the flooding is estimated to have been 1–3 months (Ghatan et al., 2005; Leask et al., 2007). The interpretation of sub-parallel symmetric ridges around the eastern end of Mangala Fossa as dunes emplaced by a phreatomagmatic eruption plume resulting from dyke emplacement, cryosphere cracking and magma–groundwater mixing (Wilson and Head, 2004) is consistent with this hypothesis.

As an alternative to the idea of a pre-pressurized aquifer due to cryosphere growth, the high aquifer pore pressures responsible for the flooding at Mangala Valles may have been a direct result of the stress release during the tectonic event forming the graben (Hanna and Phillips, 2006). The presence of chaos within a crater near the Mangala Valles source graben may be a consequence of elevated palaeopore pressures and thus provide circumstantial evidence consistent with this model (Hanna and Phillips, 2006).

In addition to catastrophic aqueous flow, phreatomagmatism and tectonism, the channel also shows evidence of ice processes. The pitted proximal channel floor (Figure 10.1) has been interpreted to be the result of ice blocks stranded during early stage sheet flow of meltwater and ice, possibly in association with temporary ice dams (Zimbelman et al., 1992). Lobate ridges deposited on the Mangala Fossa margins adjacent to the Mangala Valles channel origin (Figure 10.2) have been interpreted to be glacial deposits, with the glaciation being the consequence of floodwater release (Head et al., 2004). A candidate opportunity for ice formation is the cooling of the thin sheet of water that would have spread across the floor of the Mangala Fossa graben in the first stages of water release from graben-bounding fractures (Leask et al., 2007). Additional surface ice formation could have occurred during the filling of the graben if the temperature of the released water were less than 4 °C; the fact that water has its maximum density at this temperature suppresses convection as the water is cooled from above by evaporation at its surface (Leask et al., 2007).

The terminal pathways and eventual sinks for Mangala Valles floodwaters are ambiguous. According to the interpretation of Ghatan et al. (2005), the topographic data suggest that the eastern branch formed first but was later pirated by the western branch, whereas previous crater statistics support the opposite sequence (Chapman and Tanaka, 1993). Ghatan et al. (2005) suggest that, as flooding subsided, residual water froze and

![Figure 10.1. Portion of THEMIS visible image V23283003 located near 12.2° S 208.7° E showing pitted terrain in Mangala Valles, where irregular pits were interpreted to be the effects of ice blocks deposited by the flood flow (Zimbelman et al., 1992). North is up, illumination is from the left.](image)
sublimated, leaving a residue in the deepest parts of the channel.

Additional sinks for the floodwater are suggested by morphology and may have been different for the northeastern and northwestern branches. The northeastern branch terminates at the southern side of a broadly level plains unit surrounding Medusae Fossae Formation deposits (Tanaka and Chapman, 1990). Approximately 300 kilometres to the north, a group of streamlined forms with impact craters or knobs at their southern ends is apparent in images and MOLA topography (centred near 1° N 207° E). The kilometre-scale size and large width:length ratio of these forms distinguish them from the aeolian streamlining (yardangs) that overprints this region and suggest their formation by floodwater flow. The forms are large in width relative to the northeastern branch but also shallower. A possible scenario for their formation is that upon exiting the deep and narrow northeastern branch, the Mangala Valles floodwaters spread out and became more quiescent, depositing their sediment load in the lee of flow obstacles.

The northwestern branch terminus is largely embayed by Medusae Fossae Formation deposits. To the west of those deposits is a 75 km diameter impact crater with a terraced fan sourced by a short broad valley. This fan is similar to a terraced fan in Coprates Chasma that is interpreted as representing erosion and redistribution of fan material during lake-level drops (Weitz et al., 2006; see also Di Achille et al., 2006). Thus, this fan-shaped deposit may indicate ponding and episodic recession of Mangala Valles floodwaters within this crater. However, any path between the outlet of the northwestern branch terminus and this impact crater is largely covered by the Amazonian-aged Medusae Fossae Formation.

In summary, morphology and modelling of Mangala Valles suggest a tectonovolcanic release of pressurised groundwater resulting in a catastrophic water flood and possible glaciation during the late Hesperian to early Amazonian Epochs.

10.3.2 Marte Vallis

In its current topographic expression, Marte Vallis originates near 180° E, 10° N at the eastern side of the Cerberus plains at an elevation of approximately ~3100 m. Situated between the Orcus Patera structure to the northwest and southern highland outliers to the southeast, Marte Vallis stretches first ~250 km northeastward and then ~750 km north-northeastward to Amazonis Planitia (Plate 24). The channel system is consistently broad, spanning several tens of kilometres in width, and a few tens of metres deep, with an overall slope of ~0.0002 m/m (0.013°). It is embayed by a dark lobate material interpreted as lava (Plescia, 1990). This dark embaying material surrounds a number of brighter streamlined forms. The low, contrasting albedo of this embaying material caused the channel’s streamlined forms and anastomosing morphology to be readily visible in Viking images, leading to its early identification as an outflow channel (Tanaka and Scott, 1986). Multiple levels along the sides of Marte Vallis are interpreted as terraces (e.g. Berman and Hartmann, 2002), which may reflect multiple flood events (Burr et al., 2002b). Pirating of anastomosing channels within Marte Vallis as inferred from MOC images also suggests at least two episodes of flooding (Fuller and Head, 2002). The (post-embayment) depth of the channel is only on average a few tens of metres.

Marte Vallis may have had its source in the other (more western) Cerberus flood channels (Tanaka and Scott, 1986; Berman and Hartmann, 2002; Plescia, 2003), although MOLA topography and crater counts on MOC images indicate that the three Cerberus channels – Marte, Gjotá and Athabasca – are distinct (Burr et al., 2002b). To the southwest (i.e., upslope) of the first topographic expression of Marte Vallis, MOLA topography of the eastern Cerberus plains shows broad, shallow channels leading from a subdued linear depression, which is collinear from the Cerberus Fossae (Plate 24). The broad, shallow channels are not visible on the southern side of the linear
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The broad, shallow channels stretching from the subdued linear depression (interpreted as a buried fissure segment) are hypothesised to have conveyed the floodwater from the now-buried fissure to the topographic channel that remains visible today, and then to have been buried by lava (Burr et al., 2002b). Another possible source for the Marte Vallis floodwaters is breaching of a lake (Scott and Chapman, 1991) emplaced behind a debris dam, ice dam or wrinkle ridge (Moller et al., 2001). Evidence for this lake is lacking but may be buried beneath subsequent lava. The presence of rootless cones in Amazonis Planitia (Lanagan et al., 2001; Greeley and Fagents, 2001) supports the idea derived from the channel’s larger scale morphology (Tanaka and Scott, 1986; Fuller and Head, 2002) that Amazonis Planitia was the sink for the Marte Vallis water flows.

10.3.3 Grjotá Valles

Grjotá Valles are the least well-defined of the tectonic outflow channels. Located in remnants of southern highland terrain north of the Cerberus plains, they are oriented east–west and centred near 165° E, 15° N (Plate 25). The channel originates at the most northern major Cerberus fossa as indicated by local scour, orientation of nearby flood-formed features (scattered mesoscale streamlined forms and longitudinal lineations), and MOLA topography (Burr et al., 2002b; Plescia, 2003). Recent mapping using THEMIS and MOC images shows that the origin of the floodwater was distributed discontinuously over a 250 km stretch of fissure as measured end to end; the summed lengths within this stretch from which water actually emerged total ∼150 km (Burr and Parker, 2006). The elevation of this distributed source ranges from approximately −2100 at the eastern end to −2400 m at the western end. The water flowed both to the north and to the south of the fissure, anastomosing through the remnant highland terrain knobs in which it originated, thus making a conclusive determination of flow cross-sectional area difficult. The better-defined, northern branch is up to several tens of kilometres in width and of order ten metres in depth on average, although a small number of short segments are up to a few tens of metres deep. The overall slope of the channel is ∼0.0006 m/m (0.035°).

This broadly distributed plan-view morphology and small channel depth may be due to the lack of any significant surface topography controlling channel development (Burr et al., 2002a; Burr and Parker, 2006). Mangala Valles are located between north–south trending fault blocks, Marte Vallis sits between Orcus Patera and southern highland outliers, and Athabasca Valles are bounded by an Elysium Mons wrinkle ridge (see next section). In contrast, Grjotá Valles have no such apparent topographic structures to confine surface flow. The distributed nature of the outflow at the fissure-source of the channel may be another factor in this distributed plan-view morphology. 

The sink for the floodwaters is uncertain. Some of the floodwater appears to have flowed southward toward the Cerberus plains (Burr et al., 2002b; Berman and Hartmann, 2002; Plescia, 2003) but the termination of this southward flow is poorly defined (Burr and Parker, 2006). Inferred rootless cones in the channel imply that some of the water infiltrated (Burr and Parker, 2006). However, infiltration may have been minimised by freezing (see Clifford and Parker, 2001; see Burr et al., 2002b for discussion) and the inferred rootless cones are limited in extent and open to other possible interpretations (Burr et al., 2008). Rootless cones in the far western Amazonis Planitia (Lanagan et al., 2001; Lanagan, 2004; Greeley and Fagents, 2001), which is to the northeast of Grjotá Valles, raise the possibility that some floodwater may have gone to the northeast, and streamlined forms hint at flow to the northeast (Burr and Parker, 2006). However, the continuation of that flow as far as Amazonis Planitia is not discernible in available data (Burr and Parker, 2006). Previous suggestions for the lack of an obvious sink – embayment by lava, blanketing by tephra, aeolian erosion/deposition, mass wasting and poor data coverage (Burr et al., 2002b) – now appear unlikely, given the improved extent and quality of MOLA and THEMIS data used in recent mapping (Burr and Parker, 2006). This mapping, in conjunction with recent modelling (Bargery and Wilson, 2006), suggests that the floodwaters of Grjotá, with their shallow depth and widely distributed nature, either evaporated or froze and sublimated during and/or after flow. On this basis, the sink for the floodwaters is hypothesised to have been primarily the atmosphere (Burr and Parker, 2006).

10.3.4 Athabasca Valles

Athabasca Valles have the most pristine morphology of any outflow channel system on Mars. The main topographic channel originates at two locations along the southernmost major member of the Cerberus Fossae near 10.2° N 157.2° E (Plate 26). The easternmost of these linear sources is ∼18 km in length along the fossae and the western source is ∼22 long, with elevations of approximately −2400 m. The channels emanating from these two sources come together ∼20 km to the south of the fossae to create a single channel. About 40 km below this confluence, the Athabasca Valles become distributary, with smaller channels breaching through the wrinkle ridge on the southern
side of the channel and stretching southward to the Cerberus plains. Overall, the channel is \( \sim 350 \text{ km} \) in length, up to \( 100 \text{ m} \) in depth, with a slope of \( \sim 0.0005 \text{ m/m} \left( 0.03^\circ \right) \). The topographic channel varies from \( \sim 15 \text{ km} \) to \( \sim 25 \text{ km} \) in width, although the floodwaters may have locally overflown it (Keszthelyi et al., 2004b).

The Athabasca Valles system shows evidence for volcanism, tectonism, sedimentation during temporary ponding, glacial processes and ground ice. Volcanic processes are indicated by dark, lobate features surrounding the Cerberus Fossae (Figure 10.3) that have been interpreted as (spatter-fed) lava flows (Burr et al., 2002a; Head et al., 2003). Platy-ridged terrain on the edge of the channel has been interpreted as analogous to rafted lava plates in Iceland (Keszthelyi et al., 2000, 2004a). The hummocky or polygonal material in the channel may also be lava (Burr et al., 2002b; Jaeger et al., 2007). Various pitted mounds in the channel have been interpreted as being composed of lava, including hypothesised rootless cones (Lanagan et al., 2001; Jaeger et al., 2007) and/or basaltic ring structures (Jaeger et al., 2003, 2005).

Similar features also have been hypothesised to be the result of glacial and ground ice processes. A localised set of ring features has been hypothesised to be kettle holes formed by deposition of sediment-rich ice blocks (Gaidos and Marion, 2003; see also Burr et al., 2005). Pitted mounds and cones have also been hypothesised to be collapsed pingos (Burr et al., 2005; Page and Murray, 2006). Some areas of patterned ground in the channel have been hypothesised to be thermal contraction polygons (Burr et al., 2005) or hyperconcentrated flow deposits (Rice et al., 2002).

Recent tectonic activity in the Athabasca Valles region is indicated by small in-channel fissures and fissure morphology. The fissures at which the flood channel originates have sharp edges (such as are shown in Figure 10.3), which has been interpreted as evidence of post-lava flow tectonism (Berman and Hartmann, 2002). Alternatively, this sharp-edge morphology may be a result of melting due to dyke intrusion into ice-rich ground (Head et al., 2003). Smaller, open, sharp-edged fissures also cut across the channel floor. The presence of such fissures in a streamlined form (Burr et al., 2005) indicates that they formed more recently than the flooding that created the streamlined forms. Some of these small fissures are filled, possibly with lava and/or with flood sediments, whereas some are open (Keszthelyi et al., 2004b; Burr et al., 2005). This variation suggests that tectonic activity is interleaved with volcanic and/or flood events.

The pristine morphology of the Athabasca Valles has provided some indication of the floodwater flow characteristics. A set of transverse linear forms in the channel were analysed and shown to have dune morphology (Burr et al., 2004). Inferred to be flood-formed dunes, they indicate that the floodwater flow was subcritical at the location and time of their formation (Burr et al., 2004). Temporary in-channel floodwater ponding due to hydraulic damming and associated sedimentation has been hypothesised on the basis of a cluster of streamlined forms (Figure 10.4) (Burr, 2005). According to this hypothesis, a crater and its ejecta hydraulically dammed the floodwaters and produced deposition of flood sediments, which were streamlined behind in-channel obstacles during ponded water outflow. The layering of these streamlined forms (Figure 10.4) may thus be made up of layered flood sediments, likely interleaved with lava flows, volcanic ash deposits and dust (Burr, 2005).

Morphology shows that at the distal end of the channel, Athabasca Valles floodwaters flowed to both the eastern and western Cerberus plains. A shallow spillway, Lethe Vallis, is seen in MOLA topography and more recent visible wavelength images, indicating that some water flowed eastward (Plescia, 2003). The past presence of a lake in the western Cerberus plains is suggested on the basis of MOLA topography, which shows a shallow basin, and Mars Orbiter Camera images showing scarps and benches, which are interpreted to be shorelines (Lanagan and McEwen, 2003; Lanagan, 2004). The interpretation of pitted mounds
Figure 10.4. Mosaic of MOC narrow-angle images showing cluster of streamlined forms in Athabasca Valles, inferred to have been formed by hydraulic damming/ponding, surrounded by longitudinal lineations. Scattered small impact craters with bright ejecta are secondaries from Zunil (McEwen et al., 2005). See Plate 26 for location of mosaic. North is up, illumination is from the left. (Image credit: Malin Space Science Systems.)

as rootless cones both within this basin and at the mouth of Athabasca Valles also supports the hypothesis of distal floodwater ponding and suggests that the infiltration of floodwaters was quickly followed by lava flows (Lanagan et al., 2001). The morphology of the material at the channel mouth on which the inferred cones sit has been interpreted as lava (Keszthelyi et al., 2000, 2004a; see also Jaeger et al., 2007), which would have covered any flood deposits and is consistent with the hypothesis of rootless cones. Alternatively, the same platy-ridged material in the western Cerberus plains has also been interpreted as the remnants of an ice-covered lake left by floodwaters from the Cerberus Fossae (Murray et al., 2005; Kossacki et al., 2006), and pitted mounds have been interpreted as pingos. For either interpretation, the Athabasca Valles sink would be primarily the western Cerberus plains, with smaller proportions of floodwater flowing to the east.

In summary, the morphology of the four Amazonian-aged, tectonic outflow channels suggests several similar processes in addition to floodwater flow. To some extent, the number of additional processes may be partially a function of the amount of analysis a channel has received; Grijotá Valles may show the fewest additional processes because they have received little analysis to date. Marte Vallis is embayed by lava flows, which may have covered post-flood modification. Table 10.1 summarises the processes that are interpreted variously to have occurred in each channel.

10.4 Mechanisms triggering water release

Possible water release mechanisms for floods from fissures can be classified as volcanic, tectonic or a combination of both types.

10.4.1 Volcanic

The geometries of the sources of tectonic outflow channels suggest that if a volcanic mechanism is involved in causing catastrophic groundwater release, it involves subsurface dyke emplacement (Wilson and Head, 2002). Chaotic terrain has been interpreted elsewhere to be the result of sill intrusion and resultant cryosphere disruption (Leask et al., 2007) but is not evident at the source for any of these channels. (A region of chaotic terrain is located along the Mangala Valles source graben near 19.3° N, 207.3° E (Hanna and Phillips, 2006) but this chaos is ∼200 km west of the channel and confined within a crater.) The dyke-induced mechanism relies upon the presence of a sub-cryosphere aquifer system that already has been pressurised, as predicted by Carr (1979) and Clifford (1993), a consequence of the growth of a global subsurface cryosphere over geological time. As detailed in Head et al. (2003) for Athabasca Valles, this proposed mechanism entails dyke emplacement resulting in cracking of this cryosphere. In addition to causing local surface eruptions producing spatter-fed flows or phreatomagmatic deposits, this cracking provides a pathway for groundwater to rise from the pressurised aquifer to the surface. Water fountains are hypothesised to have resulted at the surface with the water then draining downslope. Subsequent collapse of the ice-rich soil adjacent to the dyke as a wave of heating spreads away from it could have produced the sharp-edged morphology of the fissures. The interpretation of geomorphic features associated with the Athabasca Valles source region as spatter-fed flows, collapse pits and exposed dyke tops supports this hypothesised mechanism (Head et al., 2003), as does the presence of possible phreatomagmatic deposits (Wilson and Head, 2004) and exposed dyke tops (Leask et al., 2007) linked to the Mangala Valles source graben. The use of aquifer permeabilities equal to those of young basalt aquifers on Earth can produce the amplitudes and durations of the discharges estimated from surface topography at Athabasca Valles (Manga, 2004). However, it is not clear that this is the case at Mangala Valles; the problem is the length of time for which the high discharge rate appears to have been maintained, rather than the size of the initial water volume flux (Leask et al., 2007).
Table 10.1. Morphological processes in fossae-fed channels

<table>
<thead>
<tr>
<th>Process</th>
<th>Inferred geologic evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanism</td>
<td>Embaying lava flows, lava burial of source</td>
</tr>
<tr>
<td>Tectonics</td>
<td>Rotated fault block, graben formation</td>
</tr>
<tr>
<td>Glaciation, ground ice</td>
<td>Kettle holes, moraines and other glacial deposits</td>
</tr>
<tr>
<td>Flood sedimentation</td>
<td>Unit Amch, In Amazonis Planitia sink</td>
</tr>
</tbody>
</table>

Sources:  
- Wilson and Head (2002)  
- Wilson and Head (2004)  
- Zimbelman (1989)  
- Tanaka and Chapman (1990)  
- Craddock and Greeley (1994)  
- Zimbelman et al. (1992)  
- Head et al. (2004)  
- Ghatan et al. (2005)

Repeated short-duration high-discharge floods (e.g. Hanna and Phillips, 2006) can explain both the high discharges and the large volumes of water required.

10.4.2 Tectonic

Tectonic mechanisms for catastrophic groundwater release involve faulting, but do not require intrusive volcanism to induce the faulting. A correlation between faulting and floodwater release was first proposed for Mangala Valles on the basis of the similar crater-count model ages of the flood channel and the associated faults (Tanaka and Chapman, 1990). The mechanism entailed breaching of pressurised perched aquifers by the faulting. It was suggested that the elevated water pressures might have been produced by groundwater circulation induced by Tharsis magmatism, Tharsis-centred tectonic uplift, or compaction of saturated sediments by the load imposed by lava flow emplacement.

A more recent hypothesis invokes dyke-induced extensional tectonism as the causal mechanism of all aspects of the process (Hanna and Phillips, 2006). Based on a recent model of the Martian crust (Hanna and Phillips, 2005), this mechanism involves a tectonic pressurisation of the aquifers as a result of the release of the extensional stresses in the crust, with excess pore pressures up to 10 MPa being produced. This extensional pressurisation
results in a discharge of water to the surface through the tectonically generated fault. Although other factors, such as perched aquifers, volcano–ice interactions, or phreatomagmatic aquifer pressurisation, may also be involved in particular cases, they are not necessary; Hanna and Phillips (2006) show that extensional tectonism alone is sufficient to produce groundwater discharges and flood volumes equal to those modelled for surficial flow in Athabasca and Mangala Valles.

### 10.4.3 Combined factors

The catastrophic release of groundwater may require both volcanic and tectonic processes. The model of Zimbelman et al. (1992) for Mangala Valles proposed that groundwater was generated through melting of ground ice as the geotherm was steepened by enhanced regional volcanic activity during Tharsis formation, and subsequently this groundwater was released through fractures associated with the Mangala Fossa graben where it intersects a north–south trending fault. However, the melting of ground ice in this way may not have been able to provide a great enough water volume or discharge to have carved the Mangala Valles (McKenzie and Nimmo, 1999; Ghatan et al., 2005), so this scenario may not be appropriate for that particular channel system (see Ghatan et al., 2005, for discussion). Nevertheless, the very recent tectonic and volcanic activity that has been documented in Athabasca Valles suggests that a combination of the two processes may well be possible in other situations.

As an example, in a more recent model of the Mangala system, Wilson and Head (2002) suggested that the Mangala Fossa graben was produced by faulting above one of a series of dykes (the Memnonia Fossae) propagating laterally from a mantle source beneath Arsia Mons. The locations and radial orientations of these dykes, and others inferred to be responsible for the graben of the nearby Sirenum, Icaria, Thaumasia and Claritas Fossae, are controlled by the strength and orientation of the regional tectonic stress field. The widths and depths of the graben are determined by a combination of the width of the dyke as its upper tip approaches the surface and the depth at which upward propagation ceases (Rubin, 1992; Schultz et al., 2004). The dyke width is controlled by the interaction between the excess pressure in the dyke magma and the regional horizontal extensional tectonic stress deviator prior to dyke injection, as described by Rubin and Pollard (1987). Water migrates through pathways provided partly by the propagation of the dyke and partly by the graben boundary faults.

In summary, multiple factors can account for the inferred catastrophic discharges of water from fissures. Given evidence for recent volcanism and tectonism on Mars, a combination of factors is reasonable, and different mechanisms may have operated at different locations or times.

### 10.5 Thermal and mechanical aspects of water release

If the origin of a fracture through the cryosphere is purely tectonic, the thermodynamics of water rise through the fracture is relatively straightforward. If the water being released is derived from just below the base of the cryosphere, thus having a temperature only just above its freezing point, and if it rises only slowly, adiabatic cooling may cause partial freezing (Gaidos and Marion, 2003). However, given the large discharge rate and water volume estimates (at least \(10^6\) to \(10^7\) m\(^3\) s\(^{-1}\) and up to at least 20 000 km\(^3\), respectively; Wilson et al., this volume Chapter 16) it seems likely that water is tapped from a wide range of aquifer depths. Then even in the absence of volcanic heat sources the mean temperature of the released water may be substantially above the freezing point. As shown in Wilson et al., hindered convection in the pore spaces occupied by aquifer water (Ogawa et al., 2003) probably reduces the vertical temperature difference across a few-kilometer-thick aquifer by a factor of \(\sim 2\) below the \(\sim 100\) °C implied by the geotherm. As a result, the mean water temperature in an aquifer with a few kilometres’ vertical extent may be up to at least \(\sim 30\) °C and possibly as much as \(\sim 50\) °C (Wilson et al., this volume Chapter 16).

If a dyke intrusion is involved, there are more factors to consider. On the basis of a detailed morphological analysis, Leask et al. (2006) proposed that the Mangala Fossa graben acting as the source of the Mangala Valles is the consequence of two dyke intrusions, each dyke having an implied width of \(\sim 250\) m with its top located at a depth varying between \(\sim 150\) m and \(\sim 550\) m below the local surface. These width and depth values lie within the range predicted theoretically by Wilson and Head (2002) for dykes sourced from the crust–mantle boundary on Mars. Leask et al. (2006) ascribed part of the present depth of Mangala Fossa to two episodes of subsidence of the graben floor as heat released from the dykes melted nearby cryosphere ice, with water escape to the surface allowing compaction to occur. Through a heat-sharing calculation, Leask et al. (2006) showed that if the cryosphere contained 10% by volume ice, a plausible amount based on the crust model of Hanna and Phillips (2005), and if all of the heat released by the dyke were contained in a hydrothermal system confined by the graben faults, the maximum temperature reached by the hydrothermal water would have been \(\sim 40\) °C. The volume of that water, summed over the \(\sim 200\) km length along strike of the graben, would have been \(\sim 155\) km\(^3\) in each event, a total of \(\sim 310\) km\(^3\). If the ice melting had extended to a greater lateral distance than the graben faults, then the absolute maximum amount of water that could have been
generated by cooling each dyke to a temperature infinitesimally above the melting point would have been $\sim 1650 \text{ km}^3$, providing a total of $\sim 3300 \text{ km}^3$ of water just above its freezing point, though this efficiency of heat transfer from magma to ice could never be approached in practice. From measurements of the volume of rock eroded to form the Mangala Valles channels and an estimate (Komar, 1980) of the maximum sediment-bearing capacity of a water flood ($\leq 40\%$ by volume), calculations of the minimum amount of water required to flow through the system give estimates ranging from 8600 km$^3$ (Hanna and Phillips, 2006) to between 13 000 and 30 000 km$^3$ (Ghatain et al., 2005). Thus it is extremely unlikely, in this case at least, that melted cryosphere ice contributed more than a small fraction of the water released, and tapping of a pre-existing sub-cryosphere aquifer seems required.

Along most of its length the Mangala Fossa graben is $\sim 2 \text{ km wide}$, and this implies that the graben boundary faults, dipping at $\sim 60^\circ$ near the surface, extended downward for $\sim 1.5 \text{ km into the } \sim 4 \text{ km thick cryosphere}$. Thus it seems inevitable that water was transferred through the lower part of the cryosphere along one or both of the margins of the dyke. Thermal interaction between chilling magma and melting ice is likely to be inherently unstable, and it is not surprising that evidence of phreatomagmatic explosive activity is seen at the eastern end of Mangala Fossa (Wilson and Head, 2004). The fact that such explosive activity is not seen at other sites of water release hypothesised to have resulted from dyke intrusion suggests that the distribution of ice-bearing pore space in the cryosphere is heterogeneous. A stable contact between dyke margin and crustal rock may then exist in some places, with minimal or no cryosphere ice melting and upward aquifer water flow, whereas water may rise relatively freely in other places through cavities created by an initial violent but short-lived dyke–cryosphere interaction. Alternatively, an absence of evidence for explosive activity at other sites may suggest an amagmatic water-release mechanism.

The typical widths of the open pathways required for water discharge, together with the flow speeds of water through them, can be estimated from the relationship between pressure in the aquifer system and pathway wall friction. Using varying assumptions about the origin of excess pressure in the aquifer, Head et al. (2003) and Manga (2004) find average pathway widths in the range 1–2.5 m and water rise speeds up to $\sim 60 \text{ m s}^{-1}$. Combining these rise speeds, pathway widths and the $\sim 30–40 \text{ km length along strike of the pathways}$, Head et al. (2003) and Manga (2004) show that the water discharges of order $1–2 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ estimated for the Athabasca Valles channels by Burr et al. (2002a) can readily be provided. A similar analysis for the Mangala Fossa/Mangala Valles system yields a typical pathway width of 2.3 m and water rise speed of $\sim 20 \text{ m s}^{-1}$ along the $\sim 200 \text{ km horizontal extent}$ of the graben to provide the $\sim 10^7 \text{ m}^3 \text{ s}^{-1}$ estimated discharge (Leask et al., 2006). All of these water rise speed and pathway width combinations lead to minimal cooling of the water during its ascent.

Water rise speeds of $\sim 20$ to more than $50 \text{ m s}^{-1}$ imply that water emerging at the surface would have formed a fountain with a height of at least 50 to as much as $\sim 400 \text{ m}$. The mechanics of water spreading away on the surface from such a fountain has much in common with the formation of pyroclastic density currents from fountains of gas and particles in some explosive volcanic eruptions (Wilson and Heslop, 1990). Thus, as it falls onto the surface, the water from the fountain causes a dynamic pressure equal to the stagnation pressure of the water flow, one-half of the water density times the square of its speed. The speed on reaching the ground is essentially the same as the speed with which water is projected upward into the fountain, $\sim 20–50 \text{ m s}^{-1}$, and so the pressure in the vicinity of the release point will be in the range $\sim 0.2$ to $\sim 1.5 \text{ MPa}$. These pressures will suppress water vapour formation and will minimise release of any dissolved carbon dioxide in the core of the fountain and in the immediate vicinity of the release point. However, on the outer edges of the fountain, and on the top surface of the water flowing away from the fountain, both processes would occur, and would lead to instabilities in the water–atmosphere interface and formation of water droplets. In the case of fountains formed from water at a temperature very close to the triple point, extraction of latent heat of evaporation could lead to freezing of some of the droplets, as discussed by Gaidos and Marion (2003). Some of these issues, together with the dynamics of water flow away from its source, are considered by Wilson et al. (this volume Chapter 16).

### 10.6 Summary and implications

The four most recent flood channels on Mars all head at tectonic features. These channels can be grouped in space and time (Table 10.1). Mangala Valles are the oldest of the four, flowing during the late Hesperian and early Amazonian Epochs (Tanaka and Chapman, 1990; Zimbelman et al., 1992). Modelling suggests that the channels may have formed through repeated short-duration, high-discharge events (Hanna and Phillips, 2006; Manga, 2004), whereas geological mapping suggests only one period of flow (Ghatain et al., 2005). The channels originate from the Memnonia Fossae graben system located off the western flanks of the Tharsis rise at an elevation of about 0 m.

The other three channels are located to the east, north and west of the Cerberus plains and originate from the Cerberus Fossae. The elevations at their origin sites range from approximately $-3100 \text{ m}$ to $-2100 \text{ m}$.
Water flowed in the channels at different times during the late to very late Amazonian Epoch (Burr et al., 2002b; McEwen et al., 2005). During the Amazonian, the loci of flow progressed from the east (Marte Vallis) to the west (Athabasca Valles) ends of the fossae. This situation mirrors the migration of volcanic activity on the fossae, which has been interpreted on the basis of superposition of lava flows to have moved westward with time (Lanagan and McEwen, 2003). This correlation is consistent with (but does not require) a volcanic triggering mechanism and admits the possibility that the regional stress field in this region is not static.

The likely sources of the floodwater are subsurface aquifers with thicknesses of at least a few kilometres and temperatures of a few tens of degrees Celsius. Mechanisms that may have triggered groundwater release from these aquifers to the surface could have been volcanic, tectonic or a combination of the two. Geomorphological evidence, or lack thereof, suggests that each of these mechanisms may have operated at different times and locations. Upon reaching the surface, the water would likely have fountained at least a few tens of metres above the surface, suppressing water vapour formation and carbon dioxide release within the fountain but promoting water and/or ice droplet formation at the margins. Continued discussion of the resultant surface processes is provided in Wilson et al. (this volume Chapter 16).

In large part, Mars exploration is the search for evidence of life. Because life as known requires liquid water, sites of astrobiological interest are those where liquid water existed, including catastrophic flood channels (National Academy of Sciences, 2007). These flood channels must have had sources within subsurface aquifers, the depths of which may be consistent with modelled water table depth (see Burr et al., 2002b). At present, the surface of Mars is inhospitable to life (e.g. Carr, 1996; National Academy of Sciences, 2007) but these source aquifers, located in volcanic terrain, may provide or have provided both liquid water and energy to sustain life. To the extent that the flood channels are draped in lava (see Jaeger et al., 2007), their utility as an astrobiology target (see Fairén et al., 2005) may be reduced. However, sediments from the subsurface deposited in post-magmatic flooding may provide chemical or spectroscopic evidence of a putative subsurface biosphere, to match the geophysical modelling of the type provided here. Ongoing exploration of the surface of Mars will continue to deepen our understanding of the aqueous subsurface as well.

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References


Floods from fossae on Mars


