14

Planetary Fluvial and Lacustrine Landforms: Products of Liquid Flow

We describe the flow of liquids – water in the inner Solar System, hydrocarbons on Saturn's moon Titan – and its effects on planetary surfaces. Liquids fall onto, flow through, and emerge from planetary landscapes. The resultant entrainment, transport, and deposition of sediment are observed in a variety of forms, which can be ascribed to the variety of surficial and subsurface flow conditions. As the area within the highest topographic elevations surrounding a river network, the drainage basin provides a natural hydrologic unit for defining and discussing these various processes. In cratered landscapes on Mars and Titan, drainage divides are often obscured by impact craters and by atmospheric degradation, although in younger terrains the crater rims themselves often demarcate the drainage divides. River networks exhibit morphologies based on surface and subsurface controls on the flow. Whereas networks on Earth are primarily dendritic (branching in a tree-like fashion), the majority of network morphologies on Titan are rectangular, suggesting tectonic influence. Deposits from channelized flow provide data on the flow conditions and sediment load. Fans on Mars and Titan provide evidence of subaerial deposition. Deltaic deposits on those bodies, along with possible shorelines and inferred tsunami deposits around the northern lowlands of Mars, imply deposition and erosion in lakes, seas, and perhaps even a vast martian ocean. Fluvial, alluvial, and lacustrine landforms thereby provide insights into climate, surface, and sedimentologic processes on planetary bodies.

14.1 Volatile Landscapes

If the confluence of requirements is unusual for aeolian landscapes (Section 13.1), that description is even more apt for landscapes shaped by flowing volatiles. Earth is, once again, a poor example in this regard. Earth is 70 percent covered by vast oceans that have played a controlling role in the evolution of our planet. In addition to their overwhelming physiochemical effects on the composition of terrestrial rocks, they are both source and sink for the hydrologic cycle, which leaves unmistakable geomorphic signatures on land surfaces. No other body in our Solar System has an active hydrologic cycle in which temperature and pressure conditions permit a vast volatile reservoir to change among the three different phases of matter. So of what use for planetary geology is studying our planet's hydrologic landforms?

Exactly because water is so constrained to specific temperature–pressure conditions, hydrologic landforms provide distinct clues to changes in planetary conditions over time. Thus, the existence of ancient river (**fluvial**), lake (**lacustrine**), and even ocean (**marine**) deposits provides unmistakable evidence that Mars has not always been the cold desert that we see today. And because water is requisite for life as we know it, correctly interpreting hydrologic landforms is integral to astrobiological exploration (Chapter 16). Other volatiles besides water can participate in cycling, as on Saturn's largest satellite, Titan. And any cycling of volatiles also involves movement of sediments, which produces fundamental geologic changes in the distributions and compositions of planetary materials. Thus, for the forensic science of geology, we study volatile landforms for critical clues in the discernment both of planetary evolution and the potential for life.

Earth provides the foundation for this study, so its hydrologic processes and landforms are the basis for this chapter. Hydrologic processes also apply to Mars, whereas the operative volatiles on Titan are **hydrocarbons**, compounds like methane that – although

Table 14.1 Parameters relevant to fluvial processes on Earth, Mars, and Titan

	Earth	Mars	Titan
Sediment σ = particle density	Quartz $\sigma = 2650\ \mathrm{kg/m^3}$	Basalt $\sigma = 2900\ \mathrm{kg/m^3}$	H_2O ice $\sigma = 992\ \mathrm{kg/m^3}$ Organics $\sigma = 1500\ \mathrm{kg/m^3}$
Fluid ρ = fluid density η = dynamic viscosity	Water $\rho = 1000\ \mathrm{kg/m^3}$ $\eta = 1 \times 10^{-3}\ \mathrm{Pa{\cdot}s}$	Water $\rho = 1000\ \mathrm{kg/m^3}$ $\eta = 1 \times 10^{-3}\ \mathrm{Pa\ s}$	CH_4/N_2 $\rho = 450\ \mathrm{kg/m^3}$ $\eta = 2 \times 10^{-4}\ \mathrm{Pa{\cdot}s}$
Gravity	$9.8\ \mathrm{m/s^2}$	$3.7\ \mathrm{m/s^2}$	$1.4\ \mathrm{m/s^2}$

gaseous at terrestrial temperatures and pressures – are liquid under Titan's conditions (Table 14.1).

14.2 Liquid: Falling Down, Soaking In, Flowing Over, Flowing Through, Coming Out

Liquids and landscapes interact through various means. This interaction starts with liquid falling onto the landscapes, soaking in – to a greater or lesser degree – and eventually leaving the fluvial landscape unit, also called the drainage basin or watershed. These processes leave geomorphic signatures that can provide evidence for fluvial flow.

14.2.1 How Liquids Interact with Landscapes

As a starting point for our discussion of hydrologic (or volatile) cycling, we'll begin with rainfall. The first effect of rain on a land surface is rainsplash, in which the impact of the droplets loosens or even ejects surface material. In cohesive sediments or where the rain was limited in duration, the imprints of the raindrop impacts can be seen gigayears after the fact. Where the surface material is less cohesive or the rain drops bigger or longer-lasting, the loose material is transported preferentially downslope, which smooths the surface. Rain on early Mars, during its heyday of a thicker atmosphere, may have been relatively ineffective on the surface, whereas, as the atmosphere thinned over time (Chapter 12), rainsplash would have become more geomorphologically effective. During this transition period, precipitation likely occurred preferentially as snow, until the current aridity shut down rain entirely. On Titan, rain drops might grow several times the size of those on Earth, although the slow descent under Titan's low gravity and thick atmosphere likely limits the effect of rainsplash. Whereas rain occurred only on ancient Mars, present-day rain has been inferred remotely for Titan from the formation and dissipation of clouds.

The next process, at least on a porous surface, is infiltration. The infiltration rate decreases with time (even for a constant rainfall rate) as near-surface pores become filled with loosened sediments and/or filled with water. Liquid that doesn't infiltrate into the subsurface generates surface runoff, either because the rainfall rate exceeds the infiltration rate (of a low-porosity bedrock surface, for example) or "saturation excess overland flow" where pore space has become saturated with water (Figure 14.1). Runoff promotes the redistribution or erosion of surface material. In fact, one piece of evidence for present-day rain on Titan was a change in surface albedo associated with clouds and interpreted as removal of sediments by runoff. Surfaces with high infiltration rates are relatively immune to erosion compared to surfaces with low infiltration rates. Thus, land surfaces with low infiltration rates tend to form networks as **overland flow** coalesces downslope into channels, which promotes deeper flow and therefore enhanced landscape incision. This positive feedback mechanism leads to the formation of channel networks, which move water to streams quickly. On Mars and Titan, fluvial networks, composed of river channels within wider river valleys, provide persuasive evidence for rainfall in the past and present, respectively, of those planetary bodies.

Besides overland flow on the surface, liquid may flow through the porous subsurface (Figure 14.2). Shallow **subsurface flow** tends to move water to streams relatively

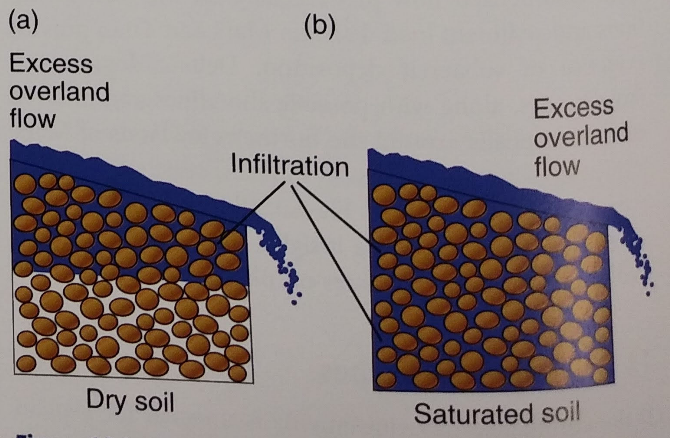

Figure 14.1 Diagrams showing excess overland flow with infiltration into dry soil (a) and soil saturation (b).

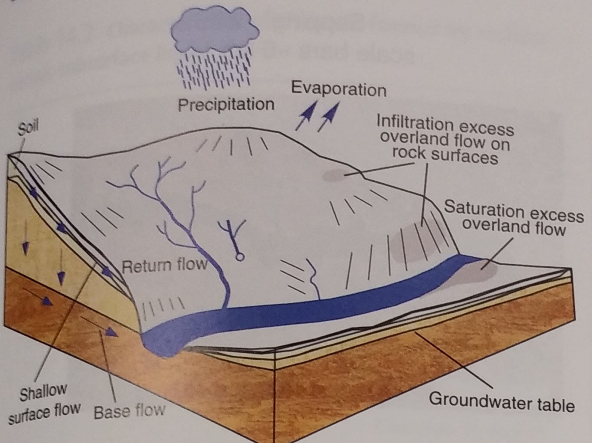

Figure 14.2 Diagram of the drainage basin including subsurface flow and surface flow. Modified from Charlton (2015).

rapidly because the path length is short and the topography provides a downslope gravitational pull. Where this shallow groundwater flow intersects the land surface before encountering a stream (termed "return flow"), it flows out of the hillside. This re-emergence of liquid carries sediment with it, thereby undermining the overlying material. The result is localized collapse of the hillside, which produces steep-sided, rounded ("amphitheater-shaped") depressions or cliff-faces that tend to incise backward into the land surface with each new rainfall. This erosional process that forms amphitheater-headed valleys through headward migration in response to fluid discharge is termed "**sapping**." It occurs on Earth, occurred on ancient Mars, and is hypothesized to occur today on Titan, where the liquid would be methane and other hydrocarbons rather than groundwater. The stubby, amphitheater-headed channels formed by sapping are morphologically distinct from the channels formed by the coalescence of overland flow, whose initiation point may be hard to determine and whose width increases with distance downstream (Figure 14.3, Table 14.2). Nonetheless, determining an exclusive or uniquely sapping genesis for a channel or channel network is challenging, as any rainfall needed to supply the shallow subsurface groundwater flow likely also resulted in at least some overland flow.

Deep subsurface flow, or base flow, is the continual slow delivery of stored groundwater to a stream. In contrast to overland or shallow subsurface flow, which are responses to discrete rainfall events, base flow keeps streams flowing between rain events and, for a while at least, even during droughts. In large, deep aquifers, stored groundwater may be thousands of years old, as is, for example, the water in the Ogallala Aquifer that supplies drinking water to cities in central North America.

14.2.2 The Drainage Basin as the Fundamental Unit in Hydrology

On the basis of the above discussion, we can now define the fundamental unit in hydrology: the **drainage basin**, also referred to as the watershed. Because liquid flows downhill, even in the subsurface (Figure 14.2), the topography of the land surface controls liquid flow. On Earth, the drainage basin, circumscribed by the highest topographic elevations surrounding an enclosed area, is that portion of the surface within which all surface water from rain, snow, or ice flows inward to lower elevations. Through branched networks of river channels, this centripetal flow converges at the basin exit, beyond which the waters join another body of water, such as another river, a lake, a sea, or eventually an ocean.

Because of its defined area and single outlet, the drainage basin provides a convenient means to evaluate the liquid budget of a landscape. Fundamentally, terrestrial water budgets are built on the principle of conservation of mass for a closed system, so that water entering the system (precipitation) minus water leaving the system (evapotranspiration and stream flow) equals the change in mass stored in the system (groundwater). This equation requires that the drainage basin be a closed system. If it is not, for example when shallow subsurface flow follows dipping strata that outcrop in an adjacent drainage basin, adjustments to the equation are required.

Drainage divides must have existed during the warmer, wetter climate of early Mars (Section 12.4.1), but have been largely erased by the pervasive pounding by impactors. The degraded or breached rims of older martian craters – and almost all craters on Titan – illustrate the concomitant atmospheric effects. In younger landscapes, where craters have experienced less degradation, it is the crater rims themselves that demarcate the drainage divides. Drainage divides, separating the flow of liquid hydrocarbons, must also exist on Titan, as evidenced by the numerous distinct fluvial networks observed there. However, the relative low-resolution and incomplete surface data make the delineation of Titan drainage divides challenging.

14.3 Processes that Channelize the Flow of Liquid

Within the fluvial landscape, liquids coalesce into channels. This channelized flow leads to movement of sediment, which can be understood through simple physical relationships. The processes include both sediment deposition into bedforms and erosion. The physics-based nature of these processes means that the same hydraulic equations can be used to understand how these processes work on different planetary bodies.

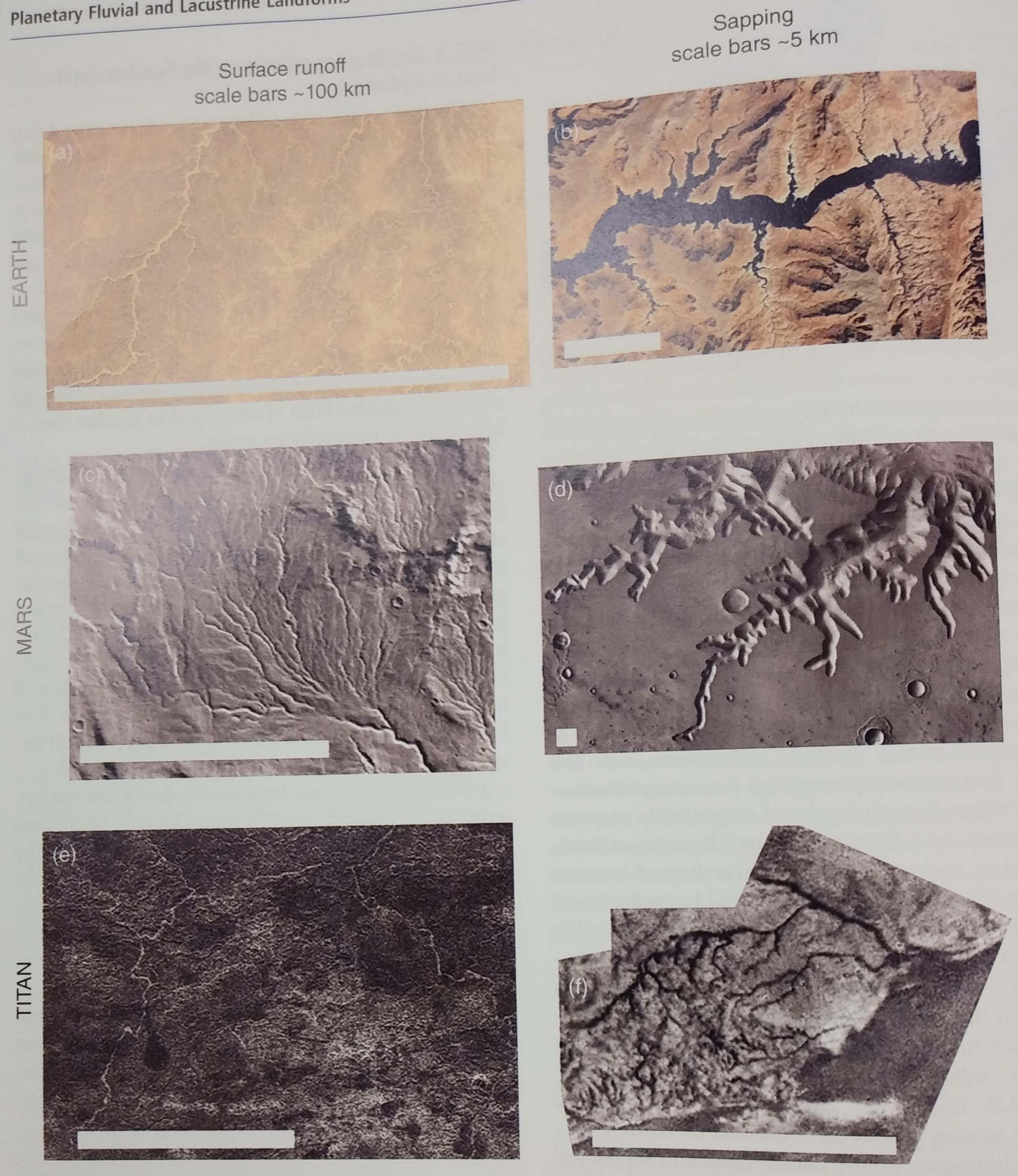

Figure 14.3 Channels formed by surface runoff and by sapping on Earth, Mars, and Titan. Earth: (a) surface runoff networks in South Yemen, (b) sapping channels on the Colorado Plateau. Mars: (c) surface runoff networks of Warrego Vallis, (d) sapping network on the Valles Marineris Pleteau. Titan: (e) (radar images) radar-bright surface runoff network on southwestern Xanadu, (f) sapping networks near the Huygens landing site. NASA images.

14.3.1 Flow Velocity Profile

Like gas (Section 13.2), liquid flowing over a surface experiences friction at that surface that decreases with height. Thus, like air, liquid in a channel exhibits a logarithmic profile with greatest flow speeds near the top and slower speeds, decreasing to zero, at the channel bed (Figure 14.4a). Unlike free airflow, channelized flowing liquid also experiences friction along the surfaces

Table 14.2 **Characteristics of channels formed by surface versus subsurface liquid**

	Valley growth mode	Drainage pattern characteristics
Surface runoff	Erosion by runoff of meteoric liquid	Fills available surface area Scale-invariant Channels: V-shaped cross-sections
Groundwater sapping	Headward undermining, collapse, and rock material removal at groundwater spring sites	Does not fill available surface area (undissected interfluves) Tends to have short, stubby tributaries Alcove-shaped heads Channels: U-shaped cross-sections

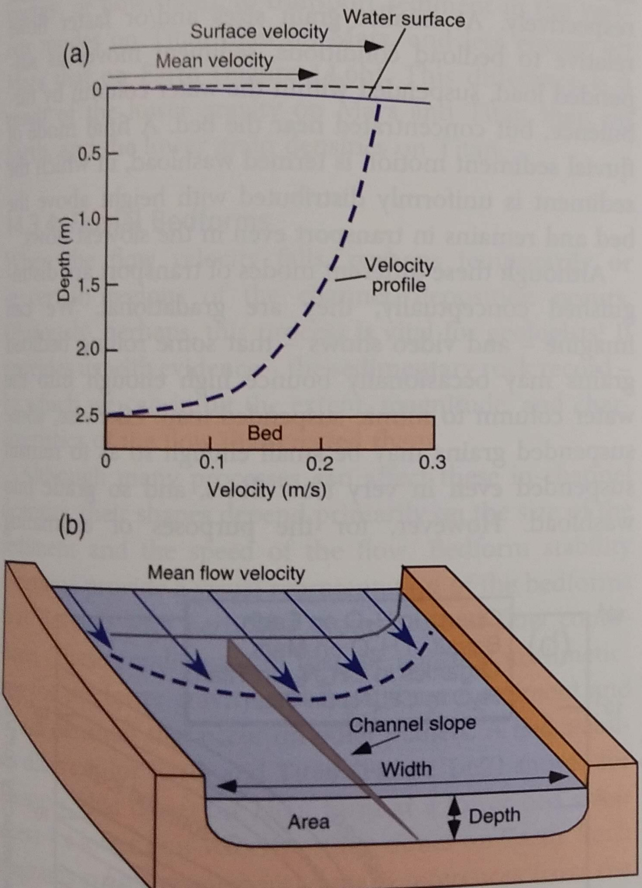

Figure 14.4 Channelized flow velocity in profile and in three dimensions.

that constitute the channel margins or banks. Thus, the flow velocity in plan view exhibits a curved profile with the maximum in the center of the channel banks (Figure 14.4b).

On Earth, calculations of discharge, or the volumetric flow rate (in dimensions of length^3/time such as m^3/s), entail measuring the velocity at multiple locations across the channel and at multiple depths to find the geometric average value, and then multiplying that value by the cross-sectional area of the channel:

$$Q = V \times W \times D \tag{14.1}$$

where Q is the discharge, V is an average velocity, W is the width of the channel, and D is representative depth.

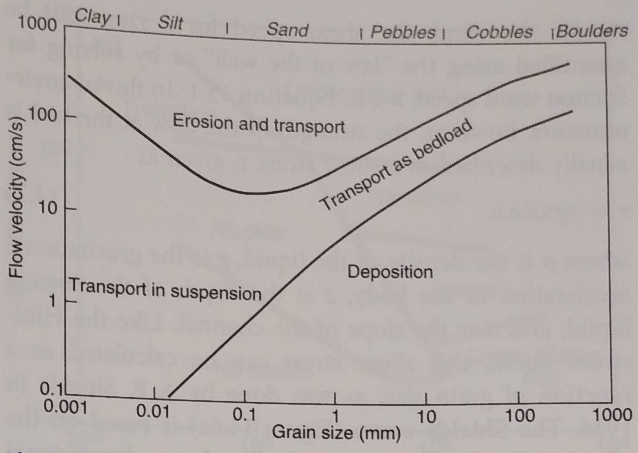

Figure 14.5 Hjulström diagram showing sediment behavior as a function of grain size for a given flow velocity.

14.3.2 Entrainment

In a river with a bed of loose transportable sediment, the immediate effect of this flow is sediment entrainment into transport. In his doctoral thesis published in 1935, Filip Hjulström published curves (different curves for different depths) that delineate the flow velocities necessary for transport (Figure 14.5). A **Hjulström diagram** illustrates that, as we might expect, transport is a function of grain size and flow velocity: Larger (heavier) grains require stronger (faster) flow for transport. At the same time, the diagram also shows that this direct correlation between grain size and flow speed, seen on the right side of the curve, does not describe the entire curve. The left side of the curve shows that the smallest grains – clay – also require high flow speeds to be entrained or eroded from the bed. So we have the same U-shaped curve that we saw previously (Section 13.2) for aeolian transport and for the same reasons: Small grains have high surface-to-volume (or mass) ratios and so have strong interparticle forces. We know these forces from experience – from walking through mud and having it stick to our shoes!

The flow velocity on the Hjulström diagram is the physical flow speed that can be measured in a stream, as explained above. However, as we learned for aeolian processes, a useful quantity when considering sediment transport is the friction or shear speed, which represents the strength of the flow exerted at the surface of the bed.

As for the wind, the shear speed for a river can be quantified using the "law of the wall" or by solving for friction wind speed, u_*, in Equation 13.1. In fluvial environments, however, the strength of the flow at the bed is usually described as a shear stress τ, given as

$$\tau = \rho g z \sin \alpha \tag{14.2}$$

where ρ is the density of the liquid, g is the gravitational acceleration of the body, z is the depth of the flowing liquid, and α is the slope of the channel. Like the Hjulström curve, this shear stress can be calculated as a function of grain size, as was done by A. F. Shields in 1936. The **Shields curve** (Figure 14.6a) is based on the equation for the shear stress, but made nondimensional using other boundary conditions for the flow. The equation for the dimensionless shear stress, τ^*, as a function of grain size, is:

$$\tau^* = \tau / \left[\left(\rho_g - \rho \right) g D \right] \tag{14.3}$$

where, as for aeolian equations, the * denotes a shear quantity, ρ_g and ρ denote grain and liquid densities, respectively, and g and D denote gravity and grain diameter, respectively.

The inclusion of gravity and material properties (densities) in the Shields curve gives it the very helpful characteristic of being translatable to non-Earth conditions. Thus, the Shields curve can be used to calculate the entrainment conditions for Mars and Titan (Figure 14.6b). From this comparison, we can see that flow velocities can be lower on Mars and Titan than on Earth and still entrain sediment. As a result, sediment deposition is likely much more areally distributed on Mars and Titan than on Earth. This comparison implies that fluvial and lacustrine deposits, such as deltas (see Section 14.5.2), might take much longer to build up into a recognizable form on these bodies compared to on Earth.

14.3.3 Transport Mechanisms of Fluvial Sediment: Three Regimes

Once sediment is entrained, how does it move? The "easiest" mode of motion – the one requiring the least energy or flow speed of the liquid – is motion as bedload. As the name tells us, bedload moves in contact with the channel bed, by sliding, rolling, or bouncing. In most rivers on Earth, bedload typically includes larger size fractions such as pebbles or cobbles, although in very slow flows or very fast flows, it may include smaller or larger grain sizes, respectively. At smaller grain sizes and/or faster flows relative to bedload conditions, sediment moves as suspended load, suspended within the water column by turbulence, but concentrated near the bed. A final mode of fluvial sediment motion is termed washload, in which the sediment is uniformly distributed with height above the bed and remains in transport even in the slowest flows.

Although these different modes of transport are distinguished conceptually, they are gradational. We can imagine – and video shows – that some rolling bedload grains may occasionally bounce high enough into the water column to mimic suspended load. Likewise, some suspended grains may be small enough so as to remain suspended even in very slow flows, and so grade into washload. However, for the purposes of estimating

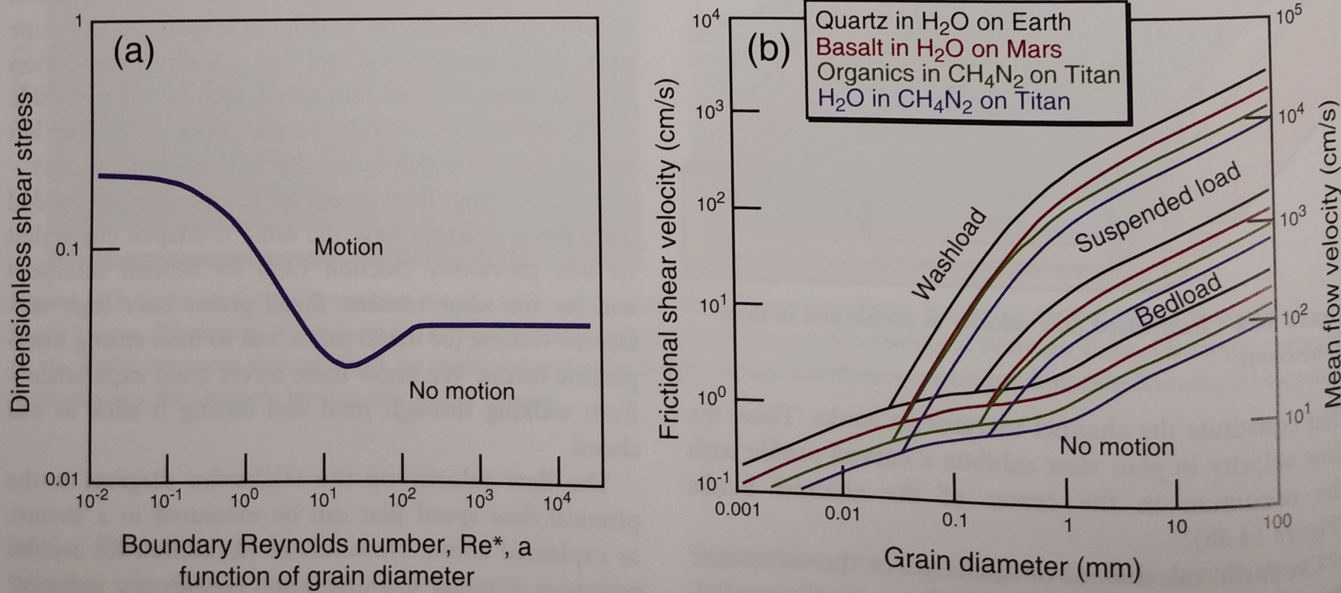

Figure 14.6 (a) Idealized Shields curve. (b) Plots of modes of transport as a function of (friction) velocity for various planetary conditions. Modified from Burr et al. (2006).

sediment discharge by rivers, hydrologists have quantified the distinction among the modes of motion using a ratio of flow velocities, denoted by k, as:

$$k = w_s/u^* \tag{14.4}$$

where w_s is the settling velocity of the particle (its rate of fall through the liquid in the absence of any turbulence) and u^* is the shear speed, related to the shear stress as $u^* = (\tau/\rho)^{1/2}$, and a proxy for the turbulence that suspends the particles. Various studies set the value of k for the bedload-to-suspended load transition at 1–1.79 and for the suspended load-to-washload at 0.05–0.13. By selecting a single value to represent the gradation from one mode of transport to another, we can plot the conditions under which each mode of transport occurs on each planetary body. Such a plot shows that it requires less energy, or flow speed, to transport sediment in the various modes on Titan than on Mars, and less energy on Mars that on Earth (Figure 14.6b). This difference is a result of the lower gravity on Mars and Titan than on Earth, and the lower grain densities on Titan.

14.3.4 Fluvial Bedforms

When the flow velocity falls, perhaps temporarily or in certain regions of the channel, deposition occurs. Obviously, perhaps, this process is vital for geologists! It provides us with evidence – the sedimentary rock record – by which we can intuit the extent, magnitude, and characteristics of the flow that created them.

Although many processes can affect these in-channel deposits, their shapes depend primarily on the size of the sediment and the speed of the flow. Bedform stability diagrams provide a visual representation of the bedforms that develop with particular grain size and flow conditions. These conditions can then be adjusted arithmetically for the lower gravity and the different sediment and liquid densities that occur on other planets. A bed stability diagram for Earth and Titan (Figure 14.7) shows, for example, that dunes on Titan form at a lower bed shear stress – a lower flow velocity – than dunes on Earth. Such diagrams enable researchers to make inferences from the observation of planetary bedforms about the liquid flow and sediment that created them. Although our current images from the surface of Titan are not yet adequate to show any bedforms (if they exist – recall that sediment dispersal is probably quite broad on Titan), images of cataclysmic outflow channels on Mars show some examples of flood-formed dunes. Modeling of these dunes, developed for modeling terrestrial dunes in the post-glacial outflow channels on Earth, provide constraints on the flow velocity that formed them. And flow velocity, in conjunction with measures of channel width and depth (see Equation 14.1), provides an estimate of flood discharge.

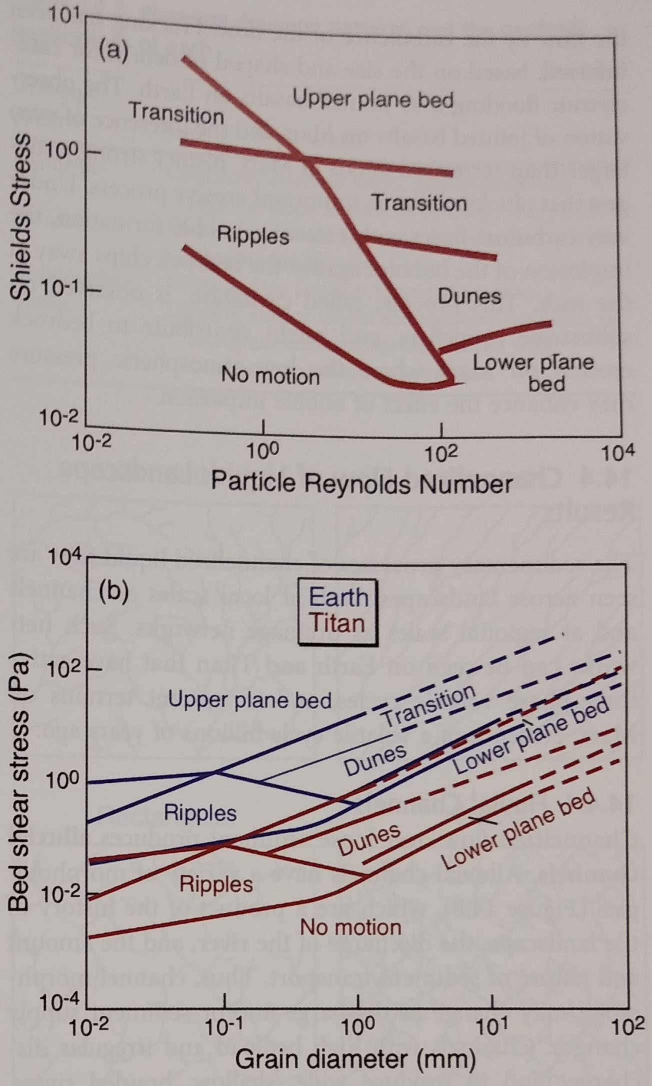

Figure 14.7 Bedform stability diagram for Earth and Titan. Adapted from Burr et al. (2013a).

14.3.5 Fluvial Erosion

In addition to the entrainment and transport of loose sediment, channelized flow erodes bedrock. This erosion may occur through one of three mechanisms. At the lowest energies, the bedload and suspended load being carried by the flow abrades the bedrock. This abrasion is more significant in faster flows and flows carrying more sediment. Calculations suggest that, because of the lower gravity on Mars, water flows more slowly than on Earth under the same discharge and slope and so may abrade less than on Earth. The same is likely true on Titan, where the lower gravity and slower flow cause abrasion to proceed at a slower rate. At higher energies, plucking can occur. During this process, blocks of bedrock are slid or even pulled into the flow by the turbulence of the flow. Plucking has been inferred, based on the size and shaped of debris, for cataclysmic flooding over jointed basalts on Earth. The observation of jointed basalts on Mars and the inference of even larger-than-terrestrial floods in Mars' history strongly suggest that plucking was an important erosive process. Under very turbulent flows with extensive bubble formation, the implosion of the bubbles against the bedrock chips away at the rock. This process, called cavitation, is observed on submarine propellers, and might contribute to bedrock erosion on Mars where the low atmospheric pressure may enhance the effect of bubble implosion.

14.4 Channelized Flow of Liquid: Landscape Results

The sedimentary processes of channelized liquid flow are seen across landscapes, both at local scales as channels and at regional scales as drainage networks. Such networks can be seen on Earth and Titan that have active three-phase volatile cycles, and in ancient terrains on Mars, evidence of a volatile cycle billions of years ago.

14.4.1 Fluvial Channels

Channelized flow over loose sediment produces **alluvial channels**. Alluvial channels have a variety of morphologies (Figure 14.8), which are a product of the history of the landscape, the discharge of the river, and the amount and nature of sediment transport. Thus, channel morphology may change as discharge and/or sediment supply changes. Channels with high bedload and irregular discharge tend to produce wide, shallow, braided rivers, where the bedload forms temporary bars or islands that are remobilized downstream during flooding. On Earth, this morphology is often displayed, for example, in coastal regions where rivers exit mountains that were formerly glaciated and thus have extensive glacial debris for fluvial transport. Such deposits have not been identified on Mars, perhaps because the lower martian gravity enables transport of most material as suspended load instead of bedload or because the bedload that does exist is broadly dispersed during deposition under low martian gravity. However, braided outflow channels have been identified on Titan, so low gravity alone may not explain their seeming absence on Mars.

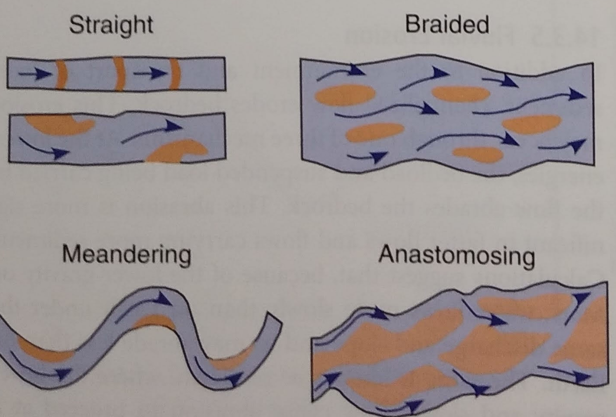

Figure 14.8 Diagram showing plan view morphologies exhibited by alluvial channels.

Channels with high suspended load and more regular discharge tend to form meandering channels, as displayed on Earth by the lower Mississippi, Amazon, and Nile rivers. These rivers have relatively deep and narrow cross-sections, with stabilized banks. This terrestrial bank stabilization was greatly enhanced ~0.5 billion years ago by the rise of vascular (rooted) plants, before which time, the terrestrial rock record shows less evidence for meandering rivers. However, the discovery of inferred meandering river deposits on Mars (e.g., Figure 14.9) indicates that meandering rivers are not uniquely associated with plants and that other mechanisms can provide the necessary bank stability. The best current hypothesis for the source of cohesion for non-vegetated meandering rivers on Mars is cohesive clays, although permafrost and geochemical cements are also possibilities. Meandering rivers have also been claimed for Titan, but the image resolution is not yet sufficient to distinguish the smaller river channel from the river valley, so that claim awaits testing with higher-resolution images.

On Earth, combinations of these braided and meandering morphologies are possible, providing evidence of a mixed type of sediment load and/or of a mixed fluvial

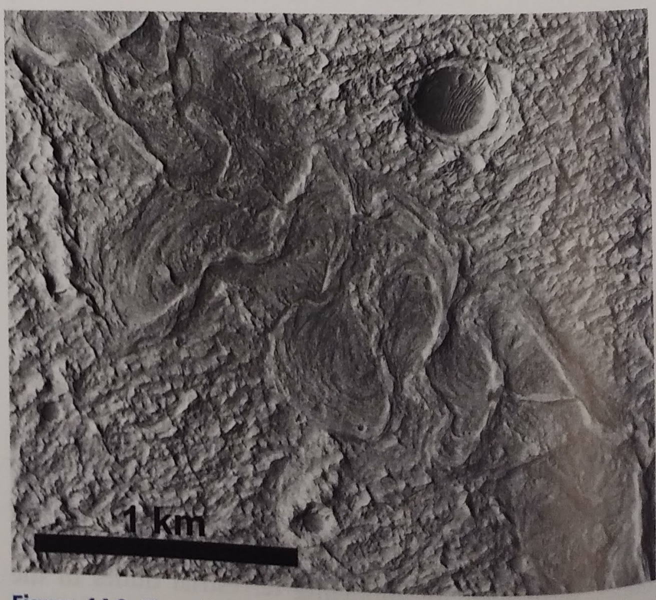

Figure 14.9 Fluvial deposits (oriented upper left to lower right across image) left by ancient meandering rivers on Mars. NASA image.

history. However, the identification of such combined morphologies on Mars or Titan awaits better imaging data.

Channelized flow over bedrock produces channels whose behavior is controlled by the rate of erosion. Because this erosion – by abrasion or, in jointed rock, by plucking – is generally slower than entrainment of grains in alluvial rivers, the rate of migration and incision is often slow, although tectonic uplift or a large supply of sediment accelerates it. Because of the lack of sedimentary banks and floodplains, the morphology of rivers in bedrock is generally simpler than that of rivers in alluvium, and may include straight segments, particularly when flowing over bedrock with fractures or fissures.

14.4.2 Channel Drainage Networks

As channels intersect and grow, they form drainage networks that reflect the controls on overland flow, such as the rate and timing of water delivery to the surface and the land surface over or through which the water flows. Thus, quantitatively characterizing networks provides both relative and absolute information on a variety of drainage controls. Networks can be characterized by the number of branches or links in the network. The number of links in the network reflects the amount of runoff and, because more porous terrain generates less runoff, provides insight into the behavior of rain on the surrounding land surface.

Drainage networks can also be characterized by their planview morphology or pattern (Figure 14.10). Each pattern forms under a different range of circumstances and so has different implications for the controls on overland flow (Table 14.3). The canonical and perhaps most common drainage pattern on Earth is dendritic, in which streams intersect at moderate angles, reflective of a moderate surface slope without significant pre-existing weaknesses. Drainages with lower-angle junctions include parallel networks, which form when the land surface slope is steeper or when elongate landforms, such as longitudinal dunes (Section 13.5) affect the direction of flow. Drainages with higher-angle junctions include rectangular networks, which form over a landscape with near-right-angle joints or faults, and trellis networks, which form most commonly over dipping or folded rocks, as in the Valley and Ridge terrain of the Appalachian Mountains.

Because the broad river valleys that form drainage networks may be visible even in low-resolution data, drainage network morphology can often be characterized when channel morphology cannot. Thus, drainage networks provide early insights into regional land surface features, history, and controls on runoff. For example, the characterization of drainage networks on Titan revealed that over half of the drainages are rectangular in morphology, indicating that – beneath the mantle of atmospherically derived aerosols, aeolian sediments, and other surface veneers – the crust of Titan is tectonically fractured.

Table 14.3 Planview drainage patterns and the geologic implications of each

Drainage pattern	Geologic implications
Dendritic	Uniformly resistant rocks, gentle/moderate regional slope at time of drainage inception
Parallel	Moderate to steep regional slopes and/or parallel, elongate landforms
Rectangular	Joints and/or faults at near-right angles
Trellis	Dipping and/or folded sedimentary, volcanic, or low-grade metasedimentary rocks with contrasting resistance to erosion

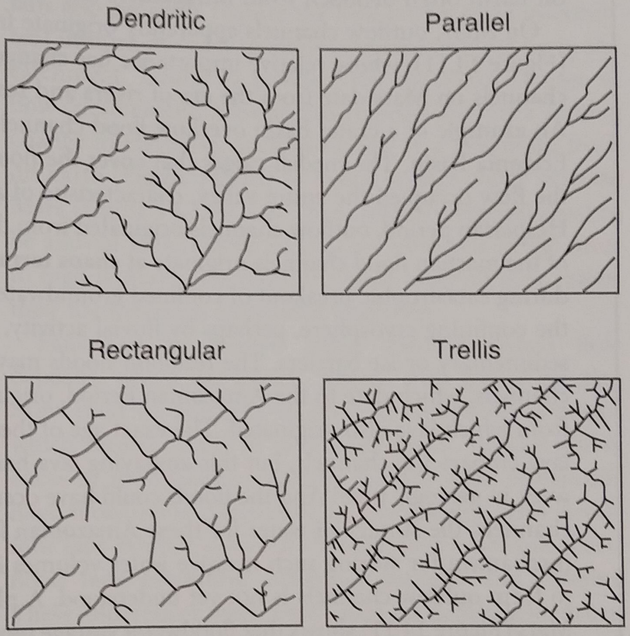

Figure 14.10 Drainage network patterns. Table 14.3 lists the implications of each pattern. Modified from Burr et al. (2013b).

14.5 Deposition from Channelized Flow

The landscape results of channelized liquid flow are not only in the channels and networks that transport the flowing liquid and sediment, but also in depositional features, as seen on Earth, Mars, and Titan.

14.5.1 Subaerial Deposition: Fans and Bajadas

The channelized flow and its sediment may be deposited either in a body of water or on land, i.e., subaerially. Landscape-scale subaerial landforms deposited by channelized running water include both individual fans and coalesced fans or bajadas.

BOX 14.1 CATACLYSMIC FLOODING

In contrast to river valleys, which result from continuous or at least frequent flow, **outflow channels** are produced by sudden and massive deluges of liquid. Whereas river valleys form tributary networks, outflow channels form giant scars across the landscape of interconnected gorges that are hundreds of meters deep, tens of kilometers wide, and orders of magnitude greater in length. On Earth, outflow channels are associated with glaciation, which provides a means for storing the massive amounts of water that are necessary. This storage occurs commonly in pro- or subglacial lakes as a product of the melting of the basal ice of the glacier. Floating or bursting of the ice dam releases this stored water as a sudden flood. The largest outflow channels on Earth are in the Altai Mountains of Siberia, Russia, and in the Channeled Scabland in eastern Washington State, USA, both of which resulted from the damming and sudden release of glacial meltwater. Because glaciers often form on volcanoes, whose heat then melts these ice caps, outflow channels on Earth often debouch from intracaldera lakes, such as in Iceland or New Zealand.

On Mars, outflow channels apparently originate from three different sources or types of water storage (Figure 14.11), whose relative importance has changed over geologic time. The oldest (Noachian) outflow channels on Mars date from the era of rivers and resulted from overflow of **crater basin lakes** fed by runoff. An example of a crater basin overflow flood channel is Ma'adim Vallis, which originates full width from the Eridania Basin. The medial ridges that cover the floor of the Vallis suggest that, at least in some locations, the flow occupied the entire valley, characteristic of a flood, instead of a smaller inset channel. In the Hesperian period, outflow channels originated from the Valles Marineris canyons (Figure 14.11). These largest of the martian flood channels originate at **chaos terrain**, areas of large jumbled blocks inferred to have formed during catastrophic breakout of confined groundwater. The trigger for breakout is suggested to be thinning of the confining cryosphere, perhaps by fluvial activity, or drainage of canyon lakes following collapse of sedimentary or ice barriers. The resultant floods may have fed a vast northern ocean. The youngest outflow channels, which date to the Amazonian Period, originate at volcano-tectonic fissures (Figure 14.11), fractures from which lava also originated. The exact age of these youngest water floods is open to question because the lava embays the channels, but this embaying lava has been dated to just a few million years in age – just last week in geologic time! And the floods could have occurred around the same time. As with the Hesperian-aged channels, the storage of water for these Amazonian floods apparently occurred in the subsurface, but the mechanism for storing such massive water volumes in the subsurface and releasing them suddenly enough to form outflow channels is not yet understood. A plot of the change in flood-generating mechanisms on Mars (Figure 14.11) shows that floodwater storage moved from the surface to the subsurface over geologic time.

Thus, geologically extreme aqueous flooding on Earth and Mars is a function of the ability of water to assume the solid phase. The operative volatile on Titan, which is methane, cannot as easily assume the solid phase under current conditions. On Mars, the largest floods result from subsurface water storage, followed by some mechanism of tectonic or fissure-fed release, or from water storage in crater lakes. Fissures have not been detected on Titan, and craters are sparse, perhaps due to screening by the episodically thick atmosphere. However, precipitation has been inferred on Titan. Thus, extreme precipitation events, which have produced smaller but more frequent floods on Earth, are likely to be the most important flood generators on Titan in the recent past.

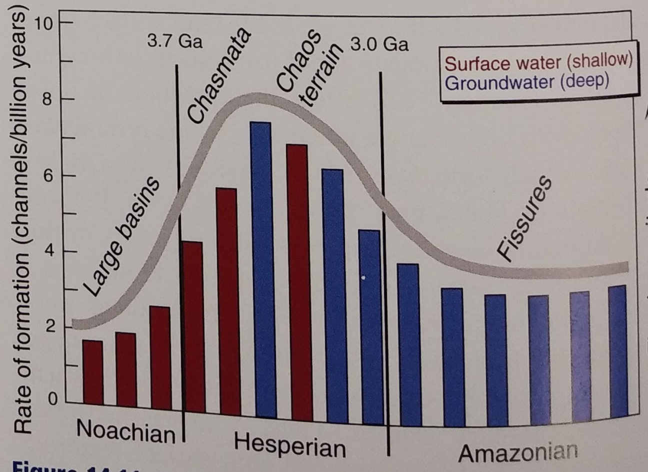

Figure 14.11 Causes of outflow channels over geologic time on Mars. Adapted from Burr (2010).

Alluvial fans (Figure 14.12) are sedimentary landforms that develop at the mouths of upland canyons that contain significant transportable sediment. During high-discharge precipitation events, the channelized flow emerges from the canyon, where it changes from confined to unconfined flow, resulting in an abruptly decreased flow depth. The decrease in flow depth, in turn, results in an abrupt decrease in shear stress (see Equation 14.2), causing deposition of the sediment load (alluvium) at the canyon mouth. Over time, repeated events result in the natural construction of a wedge- or fan-shaped deposit between the canyon mouth and the floor of adjacent plains. In addition to a long-term hydrological cycle, fans also generally require the flow events to be intermittent in time, in order to allow alluvium to build up in the catchment. Lastly, to produce the necessary change in flow confinement, alluvial fans require relief or a sudden change in elevation, such as occurs at a mountain front on Earth (Figure 14.12a) or inside impact crater rims on Mars (Figure 14.12b). On Titan, features hypothesized to be alluvial fans (Figure 14.12c) are observed in the mid- to high latitudes, although the poor imaging data makes their identification somewhat uncertain.

Fans can be formed either through debris flow deposits, which are poorly sorted, with grains ranging from mud to boulders in size, or sheetflood deposits, which consist largely of sand-sized grains. Besides differences in grain size and sorting, the two types of deposits have measurable differences in topography, with debris flow fans exhibiting leveed channels and lobes and sheetflood fans exhibiting smoother surfaces and termini. These differences have been used to distinguish debris flow and sheetflood fans on both Mars and Titan.

A **bajada** develops where multiple alluvial fans coalesce. The lateral spreading is often a function of repeated side-to-side shifting of the contributing streams. Like fans, bajadas can form either in arid climates where flash floods produce repeated sediment depositional events, or in wetter climates where streams deposit sediment more continuously. These broad deposits occur along mountain fronts on Earth and have been documented within impact craters on Mars.

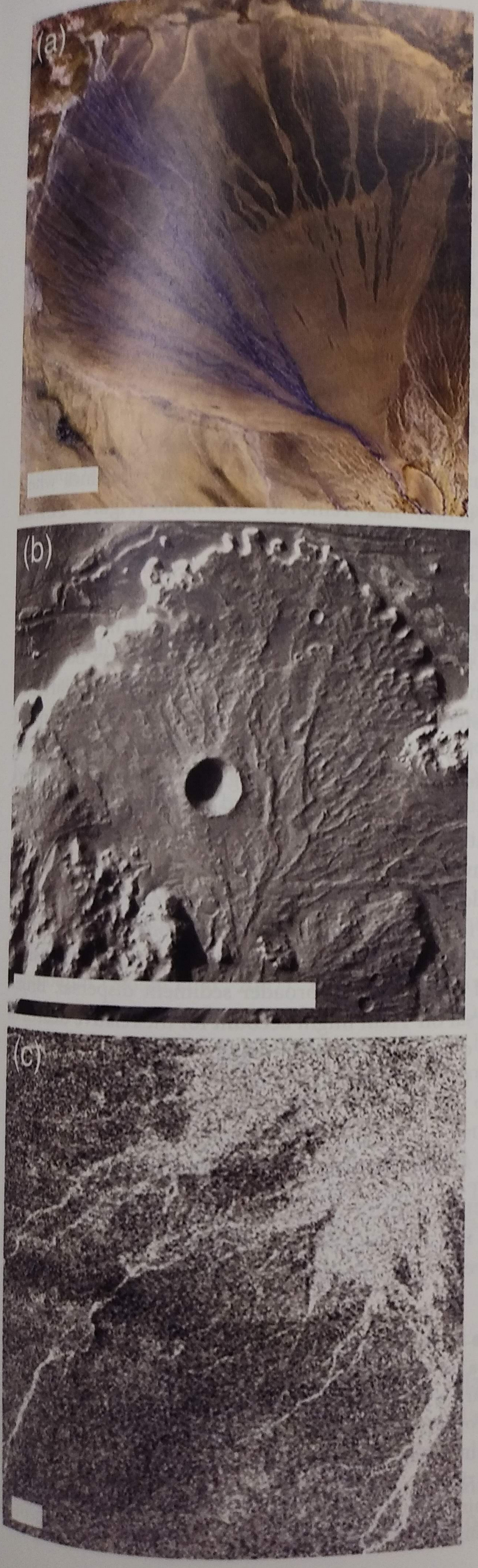

Figure 14.12 Images of alluvial fans. (a) Alluvial fan, Taklimakan Desert, China. The false-color blue on the left side of the fan indicates water currently flowing. (b) Alluvial fan on Mars in Holden Crater, with the part of the inner crater rim visible in the lower left. (c) Elivagar Flumina on Titan, interpreted as a compilation of alluvial fans, which are fed by flow sourced from an impact crater off the image to the left. In all images, flow is toward the top of the page and scale bars are ~10 km. NASA images.

14.5.2 Subaqueous Deposition: Deltas

Deltas (Figure 14.13) derive their moniker from the triangular-shaped deposit of land at the mouth of the Nile River, which the Greeks understood correctly to look from the air like a capital "D" or "delta." Study since that time has shown that deposits of sediment at the mouth of rivers emptying into lakes, seas, or ocean have a range of shapes, which reflect the dominant control. River-dominated deltas, such as the Mississippi River delta, form a digitate shape (sometimes referred to as a "bird's foot" shape) as the river switches course over time. Tidally dominated deltas, such as the Ganges/Brahmaputra delta in the Bay of Bengal or the Fly River delta in Papua New Guinea, show more disaggregated form with lobes or islands perpendicular to the shoreline and separated by tidal flats or channels. Wave-dominated deltas, of which the Nile delta is the classic example, tend to have smooth shorelines where wave action has removed sediment (Figure 14.13a). A fourth kind of delta, named after the geomorphologist G. K. Gilbert, has a distinctive, coarse-grained, sedimentology, such as results from steep mountain streams.

Deltas on Mars also span a range of morphologies. Bird's foot (Figure 14.13b) and Gilbert deltas have been hypothesized, along with other more exotic varieties. Consistent with Mars' small moons, no tidally dominated deltas have been suggested. The observation of deltas on Mars is perhaps a bit surprising. The low gravity on Mars would cause sediment to disperse farther in the basin than it would on Earth, so to be recognizable as deltas the fluvial transport and sediment deposition would take considerably longer on Mars. An increased timescale for delta formation should be even more true for Titan, where both lower gravity and lower sediment densities would result in even broader sediment dispersal. Broad dispersal on Titan might account for the relative dearth of deltas observed to date, although a few suspects have been noted (Figure 14.13c).

14.6 Large Bodies of Standing Liquids

The end result of channelized flowing liquid and sediment is a standing body of liquid. Such standing liquids are seen on Earth and Titan, and have been inferred for

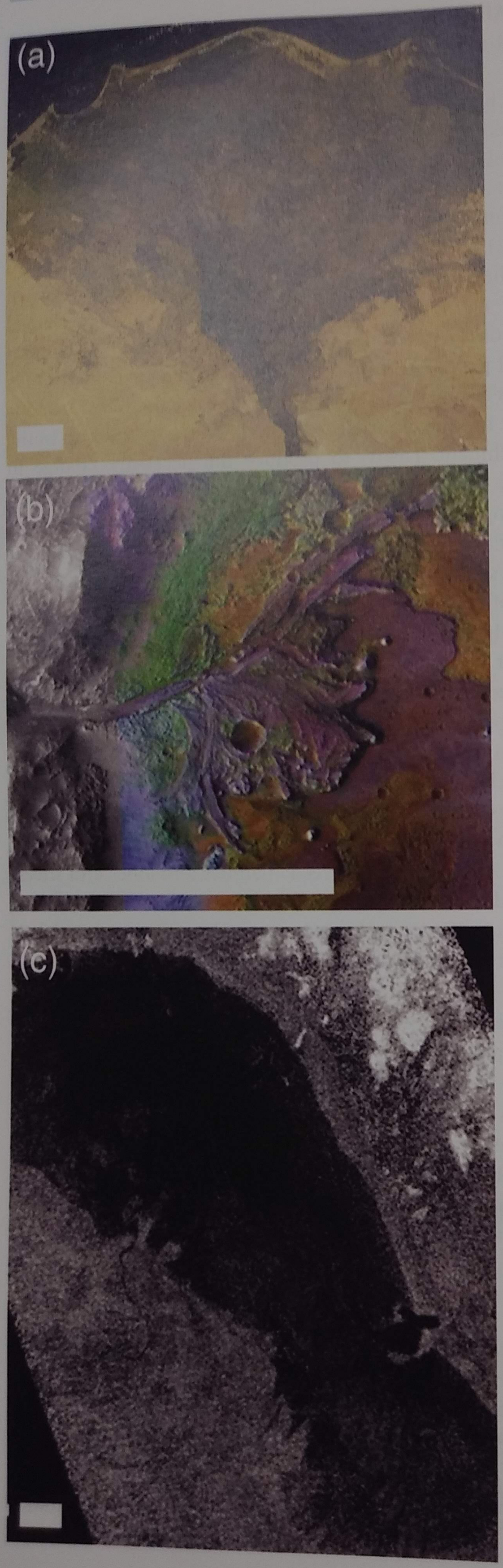

Figure 14.13 Examples of the three types of delta. (a) Nile River delta, a wave-dominated delta on Earth. (b) Jezero Crater delta on Mars, a bird's food delta (colors indicate different types of clay) formed by river channel switching. (c) Possible deltas on Titan in Ontario Lacus (two on the left shoreline, one on the lower right shoreline) inferred to have resulted from channel switching and/or wave modification. In all images, scale bars are ~10 km. NASA images.

Mars. Their existence provides singular evidence for volatile collection and cycling.

14.6.1 Marine and Lacustrine Morphologies on Mars

In addition to the geochemical evidence for oceans and lakes in our Solar System (discussed in Section 12.3), we can also point to geomorphic evidence for standing bodies of water. The low elevation and flat topography suggest that the northern lowlands of Mars once hosted an ancient ocean of water, as illustrated in Figure 14.14a (Baker et al., 1991). Valley networks terminate in the lowlands, as rivers do into the ocean basins on Earth, and a number of deltaic features occur at nearly the same elevation around the lowland margins. Putative remnants of ancient shorelines have been recognized; their elevations, which vary considerably, are inconsistent with standing liquid in equilibrium but may be consistent with geophysical changes on Mars "after the fact." Tsunami "run-up" deposits have also been inferred around the lowland margins.

Mars clearly hosted smaller bodies of water (Cabrol and Grin, 2010). The geomorphic evidence for lakes includes deltaic deposits in impact crater basins that are closed except for an inflow channel. Other crater basins were open (or overflow) lakes, having both inflow and outflow channels. Overflow of some of these crater lake basins produced considerable floods (see Box 14.1). Sedimentology investigated by the Curiosity rover in Gale crater suggests subsurface standing water (Section 12.3).

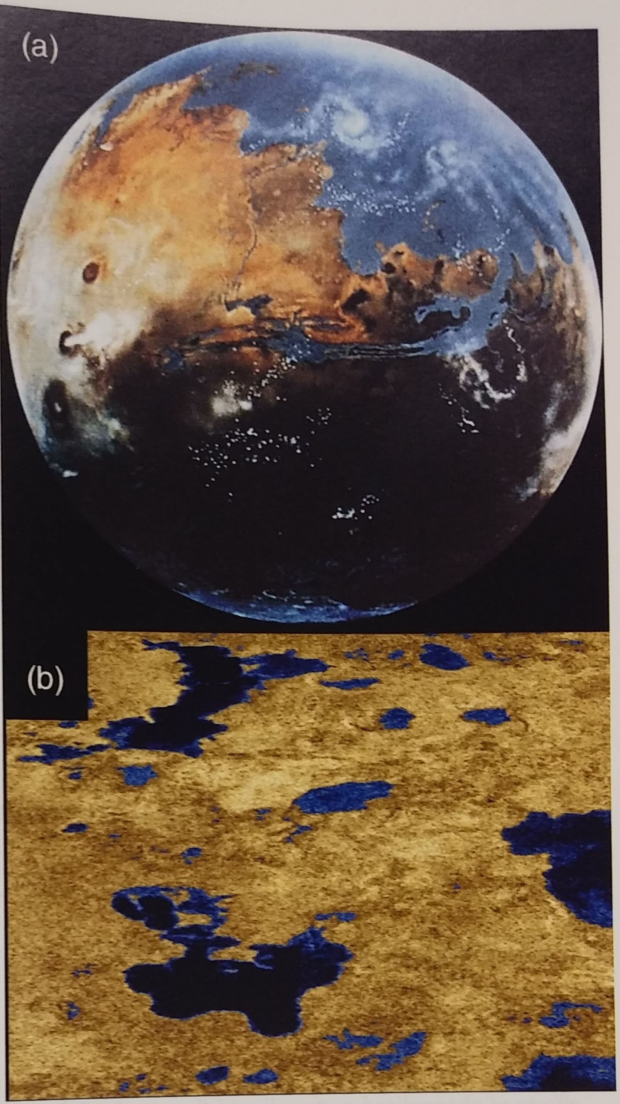

Figure 14.14 Oceans and lakes on other worlds. (a) Artist's rendition of a Noachian ocean in the northern plains of Mars. (b) Colorized radar image of hydrocarbon lakes on Titan. Image is 205 km across. NASA images.

14.6.2 Hydrocarbon Lakes and Seas on Titan

Cassini orbiter radar images found that Titan is dotted with standing bodies (Figure 14.14b) of liquid organic compounds (Stofan et al., 2007). The lakes give no radar return, as appropriate for smooth surfaces, and Ontario Lacus, in the southern polar region, appears to host a delta. One lake has a measured depth of ~180 m, but many more have depths of just a few meters; empty basins, interpreted as dried lakes, have also been detected. These lakes and seas are clustered in the north polar region, apparently a result of orbital control on Titan's volatile cycle. An estimate of the combined volumes of all the extant lakes is 300 times that of Earth's proven oil reserves. A Titan "boat" – a spacecraft mission that would float on a Titan sea, taking data of wind, waves, and composition – is under discussion.

Summary

Liquids on other bodies, though unusual in our Solar System, are diagnostic of atmospheric conditions and hugely influential modifiers of planetary surfaces. Rivers, lakes, and their geomorphic results provide critical clues to understanding planetary geologic processes. River discharges provide constraints on atmospheric models, whereas river networks and associated depositional landforms constrain factors that control the flow and serve as data on the material transport over the surface. Shorelines, deltas, and other lacustrine byproducts point to the locations and extents of standing bodies of liquid. Because water is necessary for life as we know it on Earth, "follow the water" has been a mantra for exploration of Mars with a focus on discovering past habitable environments. On Titan, hydrocarbon liquids provide a medium for facilitating organic processes that might echo prebiotic processes on Earth. Thus, the study of fluvial and lacustrine landforms is a significant source of information relevant to the fields of planetary geology, sedimentology, and astrobiology. Although this chapter has focused on remotely detected evidence of fluvial processes, *in situ* data – such as geochemical analyses or observation of rounded cobbles – support the remote inference of fluvial sediment transport on these two bodies. Continued exploration of such extraterrestrial data, along with improved understanding of fluvial deposits on our own planet, will further deepen our understanding of fluvial processes elsewhere.

Review Questions

1. What conditions are necessary for fluvial landscapes? Does your answer to this question differ between erosional and depositional landscapes? For different planets?
2. What information do fluvial landscapes provide? How does the type of information that can be derived from fluvial landscapes vary with resolution?
3. How can fluvial landscapes be used to constrain atmospheric models?
4. What is surprising about the appearance of meandering fluvial deposits on Mars?
5. Compare and contrast fluvial processes on Earth, Mars, and Titan.
6. Compare and contrast lakes, seas, and oceans on Earth, Mars, and Titan (e.g., composition, size, locations).
7. Why might we expect lacustrine deposits on Earth, Mars, and Titan to be similar? Why might we expect them to be different?

SUGGESTIONS FOR FURTHER READING

Baker, V. R., Hamilton, C., Burr, D. M., et al. (2015) Fluvial geomorphology of Earth-like planetary surfaces: a review. *Geomorphology*, **245**, 149–182. A nice overview of the effects of channelized surface liquid flow in the Solar System.

Burr, D. M. (2010) Palaeoflood-generating mechanisms on Earth, Mars, and Titan. *Global and Planetary Change*, **70**, 5–13. A synthesis of liquid floods on the three bodies in the Solar System with present or past volatile cycling.

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