Title: Foundational exosedimentology: Implications of significant process-response systems on Mars, Venus, the Moon, Io, Europa and Titan

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Abstract

The study of sedimentology on other worlds affords opportunities to test the applicability of earthbound geological theories to other environments with radically different physical and chemical conditions, a field of study termed by the author as “exosedimentology”. From identification of key ways in which these theories incorrectly predict behaviour on other planets, future studies can be undertaken to hopefully refine said theories, thus improving understanding of Earth’s systems in addition to those on other worlds.

The planets and moons selected for a study of their significant process-response systems are Mars, the Moon, Venus, Io, Europa, Titan and to a lesser extent, Earth and Neptune. Some processes such as eolian transport, extrusive processes and meteorite impacts are common throughout the solar system and thus discussed as major themes.

Thermal erosion via extrusive processes is a sedimentological factor found to significantly affect the Moon, Venus and Io. Fluvial processes are contentious for Venus and Titan, but each is discussed in detail as plausible process-response systems.

Further research is required to constrain many of the intricacies of the theories discussed, however a cursory inventory can help direct future efforts. The relationship of particle density to entraining fluid density (be it air, water, methane or lava) may be important, or at least useful in quickly identifying sedimentological regimes on other worlds. The effect of different levels of gravity on sediment entrainment is significant, but very difficult to devise practical empirical testing methods for.

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(A) Introduction

The application of terrestrial sedimentology to other environments in the Solar system is an excellent opportunity to test current theories across a wider range of conditions that aren't normally present on Earth. It also serves to further understanding of various planets and moons and could help direct future planetary exploration efforts. By examining how and why established theories may need to be modified in cases such as Mars, Venus, the Moon, Io, Europa and Titan, it is also hoped that refinement of these theories can in turn lead to a better understanding of terrestrial geology.

While the fundamental laws of physics are constant between planets, there are many different characteristics of planetary environments that are foreign to terrestrial analogues. The most obvious of these are differences in gravity. Among the planets studied in this paper, all have gravity less than that of Earths owing to their lower mass. This alone has serious implications for sediment entrainment theories (Miller and Komar, 1977; Greeley and Leach, 1978; Iversen and White, 1982). An additional consideration for extraterrestrial environments is the density of the mediums involved in sediment transport. Atmospheric pressures range from almost nil (Baker et al., 2004) up to 90,000 kPa (Komatsu, 2007) on the Moon. There are also different fluids and fluid properties involved, including those of methane, water at extremely high and low temperatures and even lava in thermal erosion processes. Since these properties are relatively constant on the worlds they apply to, the author has termed this field of study "exosedimentology", in reference to the application of earthbound sedimentological principles to non-terrestrial environments. Also, the term "planet" is used in this paper interchangeably with "moon" for the sake of nomenclatural convenience even though the Moon, Io, Europa and Titan are technically classified as moons. Broadly, moons are smaller varieties of planets and in different orbital configurations, therefore this simplification is justified.

A secondary objective of this study is to propose hypothetical facies that one might observe if direct observations of sedimentary deposits on these planets were possible. Seeing as on-site observations likely won't be possible for many years to come, this is purely an academic exercise.

The sedimentology of other worlds is a nebulous science, relying upon remote sensing techniques and terrestrial parallels in order to draw conclusions. It is currently impossible to observe many of the processes responsible for the landforms and sedimentation styles observed on other planets, therefore geomorphological analysis must be relied upon as indicators to past process-response mechanisms. On Earth many landforms are formed by fluvial interactions, an inference which made possible because the processes involved can be directly observed (Komatsu, 2007). This luxury isn't afforded to planetary scientists, yet the field of exosedimentology is constantly evolving. As time goes on, planetary scientists will be presented with better data as technology and methodologies improve and as more distant targets are selected for data collection by governments and scientific communities.

In light of this, rocks that are chemically precipitated such as carbonates or evaporites as seen on Earth, are difficult to postulate upon for other worlds. Information such as ambient chemical make-up and key geomorphological indicators for these types of rocks are either unknown or inapplicable to other planets. Additionally, hypothesizing about biologically generated structures and precipitates are ignored in this study, for lack of sufficient evidence of extraterrestrial life.

(B) Overview of process-response factors

Many of the process-response systems evaluated in this study revolve around density or energy differences of fluids and the landforms and deposits that result. Energy in this sense refers to either temperature differences or kinetic energy differences. For example, lava flows, landslides and turbidites are higher energy events than lacustrine processes, and therefore may be responsible for landforms of greater contrast to their surroundings than those that occur over longer time periods, and thus easier to study. That being said, longer period events of lower energy are significant as well, particularly if they occur over a large enough area.

In this paper the author proposes two classes for erosive fluids based on their temperature relative to ambient conditions; low-temperature fluids and high-temperature liquids. Low temperature fluids are typified by gases or liquids that are close to the ambient surface temperature of a planet, and would include things like a planet's atmosphere, its fluvial systems and any hydrological cycles. High-temperature liquids include any higher than ambient temperature liquid that could be involved in thermal erosion and are best classed as lava-like. Since evidence for high-temperature gases involved in mechanical erosion has yet to be found on these planets, the interactions of such gases aren't included in the high-temperature category.

Ashfall is considered to be a potentially important process, particularly on worlds like Venus and Io where volcanism is prevalent (Geissler, 2005). Meteorite impacts are significant on worlds like the Moon and Mars where fewer erosional processes are available, and may lead to compound deposition of ejecta and shock breccia for example.

Table 1 summarizes the proposed origins of noted extraterrestrial channels and valleys in the Solar System as compiled by Komatsu (2007). Note the extreme variation in erosional processes that may be at work on these worlds involving both high and low temperature fluids and the geomorphic responses that result, to be discussed in detail later.

(C) Eolian processes in the Solar System

Eolian activity is very common, and is likely present on any world with a ground-atmosphere interface. There is some overlap in the study of eolian systems among planets; therefore it is prudent to assess certain aspects together in order to better relate them to each other.

Miller and Komar (1977) postulated that there is no theoretical minimum velocity in order to initiate entrainment in extraterrestrial environments, and that entrainment is directly related to the density of the fluid involved. Numerous studies (Iversen et al., 1976; Greeley and Leach, 1978; Iversen and White, 1982) have shown this to not be the case, however, and point to cohesion between particles as significant non-negligible phenomena. Cohesion is a catchall term referring to a variety of interactions such as the effects of moisture, van der Waal's forces, and electrostatic charges on small particles (Iversen and White, 1982). Indeed, the partial effects of such can be seen expressed in a sediment's angle of repose (Iversen and White, 1982). But the fact that small particles will cohere when dry and when subject to a vacuum are indicative that the forces involved in cohesion of particles aren't entirely well known (Iversen et al., 1976), and therefore empirical studies are incredibly valuable for constraining entrainment conditions.

On Earth, most windblown particles are moved by saltation, and creep or suspension of finer particles occurs as a result of impacts from these saltating grains (Greeley and Arvidson, 1990). On planets like Venus, rolling of grains over the bed is the most significant mode of eolian transport (Greeley and Arvidson, 1990), whereas on Mars suspension and saltation dominate (Iversen and White, 1982).

The determining factor for which eolian entrainment processes are important on a particular world is related to the grain sizes available (Iversen and White, 1982). Particle shape, surface texture, fluid and particle density and moisture retension capacity are all secondary due to near identical results Iversen and White (1982) achieved when varying these parameters.

(D) Extrusive processes in the Solar System

While not traditionally referred to in the context of sedimentology, extrusive processes have considerable erosion potential that may open up entrainment pathways for other phenomena (eolian, fluvial, etc) or simply serve as sediment source regions. They are also frequently confused in the planetary realm with fluvial systems, and thus warrant additional investigation in order to be able to distinguish between the two for subsequent studies.

Extrusive processes are generally less common than eolian processes and involve high-temperature liquids as defined above. They play a key role in a process called thermal erosion, whereby high temperature liquids are able to melt, assimilate and plucks substrate particles (Schenk and Williams, 2004) as it moves down a surface gradient. This destructional process has been inferred to have taken place on the Moon in the form of sinuous rilles (Schenk and Williams, 2004; Komatsu, 2007), in some Venusian and Martian lava channels, on Earth among komatiite-hosted sulphide ore deposits and on Io in the form of elemental sulphur extruding atop silicates and sulphur dioxde ice (Schenk and Williams, 2004).

Determining between an extrusive versus fluvial origin can be difficult, however Perron et al. (2006) noted that extrusion events tend to have a single point source, a fairly constant channel width and will often form distributaries down slope. Whereas fluvial systems are noted to have multiple tributaries, widen downstream and coalesce before eventually forming distributaries. Additionally, rafted plates and compressional ridges can sometimes be observed when flow fluxes are greater than 1000 cubic metres per second (Davies, Keszthelyi and Wilson, 2006), which can help distinguish large extrusive distributary complexes from similarly large fluvial complexes.

Planetary environmental conditions can have a significant effect on the style of extrusion events however, which consequently further complicate differentiation between fluvial paleoconditions and extrusive ones (Jones and Pickering, 2003; Wilson and Head, 2005).

(E) Meteor impact processes in the Solar System

Craters are observable on all planetary bodies considered in this study with the possible exception of Titan, and it is generally accepted that the majority of these craters are formed by meteor impacts. There is an overall abundance of volcanic-related craters as well, however they are treated separately since they involve different processes, despite having similar sedimentological responses. Distinguishing between the two usually depends upon identifying secondary geomorphological characteristics such as lava flows, ejecta blankets, and so on.

Schultz, Okubo and Wilkins (2006) detailed the type of deposition expected in impact zones based on their observations of the Albion impactoclastic breccia on Earth. They related what they saw as being similar to very large volcanic debris avalanches, and typified impact-related deposits as brecciated with early turbulent flow sedimentary structures, later conspicuous laminar flow structures and shearing throughout.

Separate process-response events may be related to ejecta-curtain collapse (Shultz, Okubo and Wilkins, 2006), and may involve fallout followed by suspension settling of finer particles.

(F) Earth

Of particular note in reference to the Earth is that surface conditions are very close to the triple point of water, as seen on Figure 1. This means water can exist in any of three phases, solid, liquid or gas on the surface under natural conditions. Other planets have wildly different temperature and pressure ranges, and not all have a hydrological cycle in the terrestrial sense. However, surface conditions on Titan are very close to the triple point of methane, and there is abundant methane present in Titan's atmosphere (Mitri, Lunine and Showman, 2006a) indicating the possibility of a methane-based hydrological cycle.

Other planets aren't as lucky to have similarly accommodating chemistries, however conditions have possibly changed since the early history of each planet, and therefore the possibility of alternative past hydrological cycles cannot be ruled out, to which the Earth can be a suitable analogue. Additional parallels and inferences are made later on as they relate to each planet.

(G) Mars

Mars is one of the easier planets to observe besides the Moon owing to its thin, transparent atmosphere, moderate surface temperature (Table 2) and by being the second closest planet to Earth. These conditions are simple technical challenges to overcome for the engineering of remote sensing probes compared to Venus, for example, which has much harsher temperature, pressure and atmospheric opacity conditions. It is clear from even early scientific imagery (Cupit, 2004), that the geology of Mars is the result of many different processes including eolian, volcanic, fluvial, lacustrine, mass-wasting, glacial, intrusive and even marine processes (Baker et al., 2004). In fact, sedimentary rocks have been observed to be up to 4km thick in places (Malin and Edgett, 2000). Generally, Mars can be divided into two broad hemispherical areas; the northern lowlands typified with relict shorelines and outflow channels, and the southern highlands that have been affected primarily by mountain-building processes (Baker et al., 2004). With Mars' tenable atmosphere, it's possible that significant amounts of eolian sediment can be transported. Indeed, observations of dust storms on Mars has led to further investigations of wind speeds necessary for eolian sediment entrainment on Earth (Iversen and White, 1982), as well as more detailed studies of Martian sediment entrainment theories.

(i) Eolian processes

A mathematical approach by Miller and Komar (1977) determined that the lower Mars gravity makes it easier to entrain sediment for equal flow velocities relative to those on Earth (Fig. 2), based on the Shield's equation. However, they also used the DuBoys equation given by:

tau = rho * g * h * S

From this, the bottom stress required (tau) to entrain sediment was a third of that as on Earth, which they concluded would equate to larger rivers with less erosion. Due to the fact that this relationship is purely a mathematical one, the trend of lower gravity resulting in less entrainment and larger landforms can be applied to other words. Nonetheless, as it applies to Mars, a 0.01cm particle would need a wind velocity of 0.55m/s to be entrained on Earth, whereas an identically sized particle on Mars would need wind speeds of 30-35m/s to reach the same entrainment conditions (Miller and Komar, 1977).

A more empirical study by Iversen and White (1982) was conducted whereby Martian surface conditions were simulated inside an altitude chamber at the NASA Ames Research Center in order to more accurately observe surface eolian processes. Multiple simulations were run with air of either Earth-based or Mars-based composition and particle sizes of either sand or crushed walnut shells. All tests were conducted with an atmospheric pressure of 304-507 Pa. Sediment entrainment was observed by way of a laser beam placed perpendicular to wind direction across the bed and as close to the sediment as possible without obstruction at zero-flow conditions. Any subsequent obstructions recorded by the beam after the simulations started were considered indicative of entrainment by saltation. Figure 3 shows the minimum wind speed velocity required under various Martian conditions in order to initiate entrainment. Note that conditions which favoured higher air densities, namely colder temperatures at higher pressures, resulted in the lowest threshold velocities. However, a particle size of around 115μm was the most easily entrained particle size under all test conditions.

(ii) Fluvial processes

Water is currently present on Mars in polar ice caps and in ground ice (Komatsu, 2007), and modern-day permafrost processes may indeed be taking place (Baker et al., 2004). However, the countless landforms scattered across the globe that appear fluvially generated indicate that the majority of the planet has been subjected to erosional processes that are no longer taking place today. Analyses of these landforms have shown that erosion of the larger valleys and channels are most likely a result of wind action, surface water flow or mass wasting processes (Cupit, 2004). The Valles Marineris is a large, canyon-like erosional feature 4000km long, 80km wide and up to 10km deep, showing evidence that of all these processes have affected canyon development (Cupit, 2004, Komatsu, 2007), some of which have occurred recently (Fig. 4).

If evidence for frozen water present on Mars today is coupled with a fluvial interpretation of many of Mars' surface features, a framework can be established for regional interpretations of sedimentary environments and process-response characteristics. In the case of the Valles Marineris canyon system, outburst floods may be responsible for punctuated sporadic movement of sediment from the canyon system out into the northern basin (Baker et al., 2004; Cupit, 2004). This basin occurs over most of the Martian northern hemisphere (Baker et al., 2004), and an ocean of Noachian age (Fig. 5) is postulated to have existed here. If the outburst flood hypothesis for the Valles Marineris is valid, then it would be reasonable to assume that occasional high energy influxes of fluid and sediment into the northern basin could have occurred, effectively forming turbidity currents. These currents may have had the potential to travel across much of the basin (Baker et al., 2004) due to low Martian gravity and high flow velocities, and therefore sedimentary deposits from this basin may have at least a minimal expression of turbidites.

Complicating matters further, some lava channels on Mars have been modified by water as well, typically occurring on the flanks of larger volcanoes (Komatsu, 2007).

(H) Moon

The Moon has inactive lava channels quite similar to those seen on Earth (Komatsu, 2007) (Fig. 6). These rilles are formed by thermal erosion, leaving their characteristic morphologies in place (Komatsu, 2007). Apart from long dead high-temperature liquid erosion processes though, the only processes active on the moon today are sputtering from solar wind, vaporization from meteorite impacts and outgassing (Baker et al., 2004). Owing to the heavily cratered appearance of the Moon, it can be inferred that much of the stratigraphy may be a result of compound impact breccias and ejecta blankets.

(I) Venus

Relative to Earth, Venus is a planet of extremes. With a surface temperature of 773 K, an atmospheric pressure of 9,000 kPa ,very little water in its atmosphere or on its surface (Baker et al, 2004; Komatsu, 2007), and an almost opaque atmosphere preventing easy observation of the surface, parallels to terrestrial sedimentology rely heavily on theoretical models.

The Magellan spacecraft sent to Venus in the early 1990s used a technique called synthetic aperture radar to penetrate the thick cloud cover of Venus and image the surface. Accuracy was generally no better than 50m vertically and 75m per pixel spatially (Jones and Pickering, 2003), so any landforms identified were of considerable size to begin with, and thus limits the extent of practical sedimentological interpretation. Theoretical models can still be developed however, but they remain speculative until better data exists to validate any hypotheses. Fortunately, some of the Venera probes managed to successfully land on the surface (Greeley and Arvidson, 1990) and create panoramic imagery (Fig. 7) that can be used to help constrain the presence and style of surface processes.

(i) Eolian processes

Radar and surface data suggests that over 95% of Venus' surface is rocky, with minimal soil or sediment present and extending no deeper than 10-40cm (Greeley and Arvidson, 1990). However, this hasn't stopped researchers from examining eolian transport occurring in the thick, hot Venusian atmosphere. Since the gravity on Venus is similar to that on Earth, differences in fluid density and velocity should be more significant to entrainment than gravity, contrary to what was concluded in the case of Mars.

A study by Greeley and Arvidson (1990) was able to determine the theoretical threshold velocities needed for eolian entrainment (Fig. 8). Of particular interest is the observation that the predominant mode of transport is actually through rolling (Fig. 9), whereas on Earth the predominant mode of eolian transport is through saltation, creep and suspension. Wind speeds necessary to generate rolling were 30% less than those needed for fully developed saltation, therefore the average wind speeds needed for eolian processes on Venus are likely lower than estimates from other studies based upon suspension or saltation entrainment as the primary processes. Also worth noting is that because atmospheric pressure, and therefore the fluid density, is lower at higher altitudes, threshold velocities must be higher in order to entrain similar amounts of sediment.

(ii) High temperature versus low temperature fluvial processes

The origin of long, channel-like features on Venus is contentious. While showing some similarity to low temperature fluvial systems on Earth such as meanders, levees, point bars and braided systems, there is also significant evidence these channels are formed by high temperature volcanic processes (Williams-Jones, Williams-Jones and Stix, 1998; Jones and Pickering, 2003;

Komatsu, 2007). These channels exist in low-lying smooth surfaced plains, are up to 6800 km long and also have a nearly constant cross-sectional shape (Jones and Pickering, 2003).

Determining between two possible origins comes down to scrutinizing the finer characteristics of each model. In the case of a low temperature fluvial origin, point bars, levees, floodplain deposits, deltas and cutbacks are typical (Williams-Jones, Williams-Jones and Stix, 1998; Jones and Pickering, 2003). Some researchers have identified close similarities between Venusian channels and terrestrial submarine channels (Table 3) (Jones and Pickering, 2003), particularly in the form of a dendritic outflow pattern (Fig. 10) and narrowing and shallowing of channels downstream. However, characteristics like small-scale tributaries less than tens of metres across are below the resolution of currently available surface imagery (Komatsu, 2007), but unfortunately are of key significance in distinguishing between a distributed low temperature fluvial origin and a single point source high temperature liquid origin.

The best evidence for a high temperature liquid origin of Venusian channels comes from observing modern day conditions on the surface (Jones and Pickering, 2003), and doesn’t require significant climatic changes in the past to fit a fluvial model. By way of thermal erosion, channels can be cut into the substrate (Williams-Jones, Williams-Jones and Stix, 1998; Schenk and Williams, 2004), requiring days to months of consistent lava flow in order to form. While there is much unknown about the chemistry of Venusian lava, the closest parallels on Earth may be high temperature basalts and komatiites (Kargel et al., 1994), or even carbonitite melts (Williams-Jones, Williams-Jones and Stix, 1998; Jones and Pickering, 2003). The viscosity of a lava would need to be low enough to sustain flow from the source area through to the deposition zone. However, crystal formation within a flow would increase viscosity, as would decarbonation of carbonitite lavas.

Additional problems to a high-temperature fluid model for Venusian channels are that these channels are longer than any other lava flow by an order of magnitude observedin the solar system. Not only that, but the amounts of melt needed to create or maintain these channels are similar to those involved in the formation of flood lava plateaux on Earth, on the order of 10^4 – 10^7 km^3 (Jones and Pickering, 2003). As it turns out though, there need be only a slight increase in atmospheric pressure to allow for the existence of liquid water on the surface of Venus (Baker et al., 2004), making a fluid-generated hypothesis worth investigating further. Nonetheless, additional research will be required with improved data sets before more concrete evidence is available to conclude an origin of one type or another, or for an origin that possibly hasn't been considered yet.

(J) Io

Io is a volcanically active moon in orbit around Jupiter with two significant sedimentological processes active today; thermal erosion (from high temperature fluids) and volcanic dust plumes (Showman and Malhotra, 1999; Krueger et al., 2003; Geissler, 2005).
Io is resurfaced relatively quickly due to extensive volcanism caused by tidal heating as a result of Io's close orbit to Jupiter (Showman and Malhotra, 1999; Geissler, 2005; Komatsu, 2007), therefore observations from spacecraft a few months apart can show new landforms, but no active processes. Its surface is mostly silicate volcanics with some massive sulphur volcanic deposits (Showman and Malhotra, 1999). Between these two lava types, an elemental sulphur lava flow would have sufficient low viscosity under conditions experienced on Io in order for thermal erosion to be a significant geomorphological process (Schenk and Williams, 2004). However, erosion rates for both conditions are presented in Figure 11, and show that while

sulphur lavas can erode more deeply more quickly, a silicate lava can erode over longer distances, but to shallower depths.

Very large plumes, up to 100 km high have been observed in Io and are associated with surface volcanic activity (Fig. 12), and more specifically with the vaporization of surficial SO_2 ices induced by said volcanic activity (Geissler, 2005). They are made up of SO_2, S_2, O, K and Na and can be difficult to capture in images due to their punctuated lifespan. These plumes are energetic enough to introduce between 0.001 and 100 kg of dust into the Jovian system per second, with an average contribution of 0.1 – 1.0 kg/s (Krueger et al., 2003). They are typically observed as fountain or umbrella shaped (Fig. 13), and the colour and opacity of plumes can give clues as to grain sizes and dust deposition rates (Geissler, 2005). From these plumes there also exists the possibility of SO_2 snowfall (Geissler, 2005).

Plumes are classified primarily on their size and composition. Larger varieties are often 100 km in height and blue as shown in Figure 13. The smaller plumes are SO_2 rich and are inferred to contribute significantly to resurfacing (Geissler, 2005) since they occur more often and release less material at escape velocity than the giant plumes.

Plume deposits have two classifications corresponding to the two types of plumes. Giant plumes result in red surficial deposits, often ring shaped around the plume source, up to 1000 km in diameter that are poor in SO_2 and rich in S_2 (Geissler, 2005). Smaller plumes make white or yellow rings up to 400 km in diameter, although different colours are inferred to be from by silicate or sulphur contaminants (Geissler, 2005). These ring shapes can also be annular, concentric or irregular (Geissler, 2005). Numerous rings and plumes can be seen in Fig. 12.

A theoretical stratigraphic section from the surface of Io would therefore likely show sulphur lava flows interlayered with abundant erosion resistant silica lava flows, with some residual SO_2 ice and dust layers in between.

(K) Europa

Another one of Jupiter's moons, Europa, is of sedimentological interest due to evidence indicating vast quantities of water in liquid and solid phases (Showman and Malhotra, 1999). The surface temperature of the moon is below the freezing point of water thus resulting in an ice "shell" around the entire moon, however since Europa experiences similar tidal heating effects as Io (Showman and Malhotra, 1999), a liquid ocean of up to 100 km thick could potentially exist underneath this shell, based on data returned from various probes. Gravimetric data has also inferred the existence of a metallic core (Baker et al., 2004), thus radioactive heating may play a role in keeping water in liquid phase as well. In addition, active resurfacing is taking place on Europa resulting in an average surface age of 10 million years (Showman and Malhotra, 1999), but because the surface is mostly ice there are no hardground interactions to speak of, this study focuses on liquid water beneath the ice shell and the interface it shares with an assumed silicate subsurface layer.

Fortunately, oceans on Earth may provide an excellent parallel to underwater conditions on Europa. Continuing the assumption that extraterrestrial life does not exist, the primary sediment sources for an underwater realm like one on Europa therefore may include suspension fallout of sediment accumulated on the surface of the ice shell and transported downward, suspension fallout from volcanic vents, and slope failures around seamounts.

Contamination of the ice shell by various salts such as magnesium sulphate ($MgSO_4$) and sodium carbonate (Na_2CO_3) is known to exist (Showman and Malhotra, 1999; McCord et al., 1998; McCord et al., 1999), and accompanied with sulphur and silicates result in the variety of colours seen on the surface and a potential source of sediment for the ocean below. Some salts appear uniform throughout the surface, thus implying a homogeneous global source (McCord et al., 1998). A salty subsurface ocean with some interaction at the water-ice interface could account for this (McCord et al., 1999), and suggests precipitation of these salts on an underwater hardground if conditions and chemistries were accommodating. Additionally, Europa may receive trace amounts of interplanetary dust ejected into Jovian orbit by plumes on Io, however any amount reaching to Europa may be negligible relative to other sediment sources.

If Europa has underwater volcanism as suggested by the presence of heat sources such as tidal heating and radioactive element decay from a metallic core, then it would be reasonable to expect distribution of volcanic sediments around submarine vents, possibly leading to the formation of seamounts that may one day be detectable through detailed gravity anomaly surveys. Sediments distributed in this manner may include suspension fallout of ash particles, underwater pyroclastics, and slope failures. Particularly, these slope failures may lead to the formation of turbidity currents similar to what occurs from slope failures in the terrestrial submarine realm (Stow, Reading and Collinson, 1996). The extent and scale of these currents is indeterminate given the nature of current data available on Europa, but if conditions allow for the formation of these currents then they can be expected to continue for very long distances relative to the lateral extent of the initial slope failure.

Contour currents on Earth are generated as a result of axial rotation, and are responsible for the slow movement of water over large distances. Because Europa also rotates about an axis, it is possible contour currents are a significant process as well, remobilizing sediments and winnowing unrelated morphologies.

Europa may provide an excellent analogue for terrestrial-like submarine processes taking place on another world, but modern technology is unfortunately limited in its capacity to investigate an environment this distant and shrouded in detail. Further studies into fluid density, temperature gradients and ocean chemistry are required to determine suitable process-response systems on this world. Fortunately, this information may one day arise from more detailed studies of terrestrial systems, which would improve both terrestrial and extraterrestrial sedimentological processes.

(L) Titan

Further out into the solar system from Earth, Titan is one of the larger moons in orbit around Saturn. Its surface temperature is less than 100 kelvin and it has a dense atmosphere of around 150 kPa (Mitri, Lunine and Showman, 2006a; Komatsu, 2007). Its surface consists mostly of hydrocarbon-coated ice (Perron et al., 2006). Of particular note is that surface conditions on Titan are close to conditions required for the triple-point of methane (Perron et al., 2006). In fact, Titan is postulated to have a methane-based hydrologic cycle (Komatsu, 2007), and it has long been argued that liquid methane may exist in lakes, rivers, and precipitating out as rainfall.

From images returned from the January 2005 landing of the Huygens probe on the surface of Titan, a variety of sediment sizes and shapes were seen to exist (Fig. 14), ranging from 3 mm to 150 mm, with a median grain size of 50 mm (Perron et al., 2006). Particles are moderately rounded with a moderate amount of sorting, and therefore flows at one time or another must have been able to mobilize and erode asperities from these particles (Perron et al., 2006). Because of the lower gravity on Titan relative to Earth, flow velocities would usually need to be higher to entrain similarly sized sediment. But because most of the particles involved are composed of ice and thus lower density than the silicate particles common to Earth, entrainment would be easier in that regard. If ethane were present in the transporting fluid, then entrainment effects would be even greater (Perron et al., 2006). Taken together, a complex relationship clearly exists whereby fluid processes on Titan are quite different than as on Earth. However, there are morphological similarities between the two worlds that would suggest that while specific fluid characteristics of each planet may be different, they're acting in similar manners to produce the same response in the environment.

Numerous valleys exist on Titan (Fig. 15) (Perron et al., 2006; Komatsu, 2007), and can be grouped into one of two categories. Short, stubby valleys are suggested by the Huygens science team to have been created by springs. Perron et al. (2006) point out that this process is only possible if the material is poorly consolidated, but make no effort to eliminate this process as a possibility, likely due to lack of data from the surface of Titan. The other valley type is typified by dendritic landforms (Fig.16), which may have been formed through precipitation and subsequent runoff.

It is unlikely that a high-temperature liquid created these valleys, because the model would require a single point source, downstream distributaries and channels of constant width. In a low temperature fluvial system, whereby the fluid is at ambient surface temperature and raining out from the atmosphere, numerous tributaries would be expected, channels would be observed to widen downstream and to coalesce into larger channels (Perron et al., 2006). These fluvial expressions are very similar to what is observed on Titan (Fig. 16).

It is therefore more likely that mechanical erosion from methane precipitation and runoff are responsible for the majority of these valleys. Based on careful calculations and comparisons to terrestrial systems, Perron et al. (2006) predicted that methane precipitation rates of 0.5 – 15 mm/hr would be sufficient to mobilize particle sizes observed at the Huygens probe landing site, a possibility which is further discussed later.

Hydrocarbon lakes were once thought to be commonplace on Titan from Earth-based observations of high methane levels in its atmosphere, however subsequent observations by the Cassini probe showed that lakes are likely not present. Instead though, morphological evidence of past lakes is suggested in some locations (Mitri, Lunine and Showman, 2006a). If these lakes are in any way ephemeral, facilitated by high methane evaporation rates, then lacustrine processes could be playing out intermittently. Additionally, owing to the low relief of Titan's surface, any lakes present could undergo rapid shoreline shifting (Mitri, Lunine and Showman, 2006a), a process which may or may not be expressed in sediments on the surface. Lake surface elevation changes of 20-40m per year are possible and would result in lakes retreating at rates of several kilometres per year, not taking into account additional precipitation (Mitri, Lunine and Showman, 2006a). Given terrestrial ephemeral lake analogues however, it wouldn't be unreasonable to suggest that evaporites are forming within lakes on Titan, and if so, any minerals precipitated out could be used as an indicators for other ephemeral lake locations on Titan. Further investigations into preliminary mineralogical maps of Titan would be required to test this hypothesis, and it is unknown if any of the probes that have visited Titan carried suitable instruments with them to assist in future investigations of this sort.

Clouds observed over Titan have been used as evidence for methane rain (Mitri, Lunine and Showman, 2006a, Perron et al., 2006). Precipitation is likely in liquid form and consisting of methane and ethane, with minor amounts of dissolved oxygen (Mitri, Lunine and Showman, 2006a), and is a plausible surface erosional process. With low infiltration and high runoffs expected for a water ice surface (Perron et al., 2006), the methane hydrological cycle on Titan is likely a very significant sedimentological process.

A more exotic process that may be taking place on Titan is one of cryovolcanism (Mitri et al., 2006b; Perron et al., 2006), so named for the low temperatures of methane and water ice melts involved relative to the many hundreds upon hundreds of degrees kelvin necessary for silicate melts. Since the temperature of these fluids is still above ambient temperature however, for the purposes of this study they are nonetheless classed as high temperature liquids. Because of this temperature difference, thermal erosion once again may be an important contributor to creating erosional landforms. However, sufficient research in thermal erosion has yet to be undertaken on Titan. Figure 17 summarizes many of the possible processes taking place on Titan.

(M) Neptune

As an interesting aside, the planet Neptune is also known to harbor a planet wide ocean under its extensive gaseous atmosphere, and surrounding a rocky nucleus roughly the size of Earth (Baker et al., 2004). Temperature and pressure conditions dictate that water exists here as a liquid at about 5000 kelvin under extreme pressures. Evidence also indicates that this water may be mixed with varying amounts of silicates, methane and ammonia (Baker et al., 2004), derived from both the overlying atmosphere and the underlying hardground. At the moment, this environment is too exotic to postulate upon given the extreme pressure-temperature conditions and dissimilarity to terrestrial environments.

(N) Discussion

It is particularly difficult to empirically test the effects of different forces of gravity on sediment entrainment, due to the infeasibility of escaping Earth's gravity well for the purposes of conducting such tests. In addition, flume experiments are often of considerable size that transporting these apparatuses into space, where prolonged microgravity is present, is impractical. Not to mention the difficulties associated with transporting researchers into space or determining ways to automate flume experiments.

An alternative may be to conduct brief experiments on Earth from a very tall building with a carefully controlled descent platform. Through computerized monitoring and control of decent velocities, it may be possible to simulate gravity less than 9.8 m/s^2 for brief periods of time. Since it would undoubtedly be a disorienting experience for any researcher on the platform during its descent, these would also need to be automated but to a lesser extent than if the equipment were to be sent into space.

If desired, tests could also be run at greater than terrestrial gravity by way of a large centrifuge capable of supporting the weight and volume requirements of a flume experiment. It too would need to be automated, and its relevance to extraterrestrial scenarios is more theoretical at this point. All of the scenarios (with the exception of Neptune) discussed in this paper for example are on worlds with gravities less than that on Earth.

Fortunately, factors such as fluid density, temperature, grain size, and grain density are easily tested in the traditional terrestrial laboratory without resorting to such exotic testing methods.

(O) Future Study

There are a lot of opportunities for new and varied research in the field of exosedimentology, particularly with the flood of images and data returned by each probe periodically sent to investigate other worlds. Based on the results of this study, additional research into the effects of fluid density and temperature over a wide range of conditions and transport styles are recommended. Not only would this help elucidate extraterrestrial scenarios, but it would also improve the accuracy of entrainment modeling on Earth.

It may also be worthwhile investigating the effect of fluid to grain density ratios on sediment entrainment, in order to identify a possible relationship that may be more easily applied to other worlds.

(P) Conclusion

Many physical and chemical differences characterize sedimentary environments on other planets relative to environments on Earth. In many cases, terrestrial analogues may not even exist, or are simply irrelevant.

A complication inherent in the study of planetary geology is the impossibility of visiting these locales in person; therefore the quality of science that can be performed is directly limited by the quality of data and imagery afforded by modern technology. Because governments fund the majority of space-related research, political climates are also to blame for funding research into some areas or programs versus others. However, with limited data and the availability of terrestrial analogues, the study of planetary sedimentology offers excellent opportunities for theoretical geological research that tests many foundational concepts. Any difficulty relating terrestrial theories to extraterrestrial situations can therefore be indicative of needed refinements that could benefit understanding of sedimentology both on Earth and on other words.

(Q) Acknowledgements

The author wishes to thank James MacEachern for his guidance and instruction with advanced sedimentological concepts preceding this paper, and for being supportive of this line of research. Glyn Williams-Jones is thanked for his inspiration and for providing copies of his relevant research. Additionally, Dan Marshall served as an additional source of inspiration that the author wishes to gratefully acknowledge.

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(S) Figures

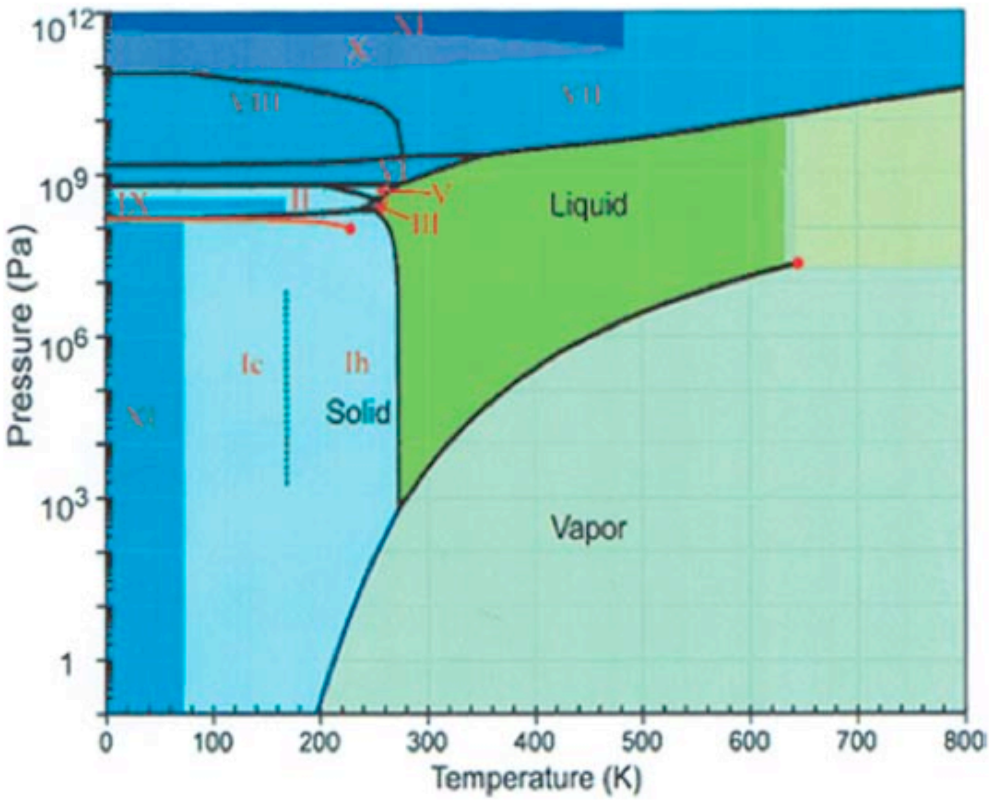


Figure 1: Phase diagram of water (Baker et al., 2004). Note that the solid-liquid-vapor triple point is close to conditions naturally seen on Earth.

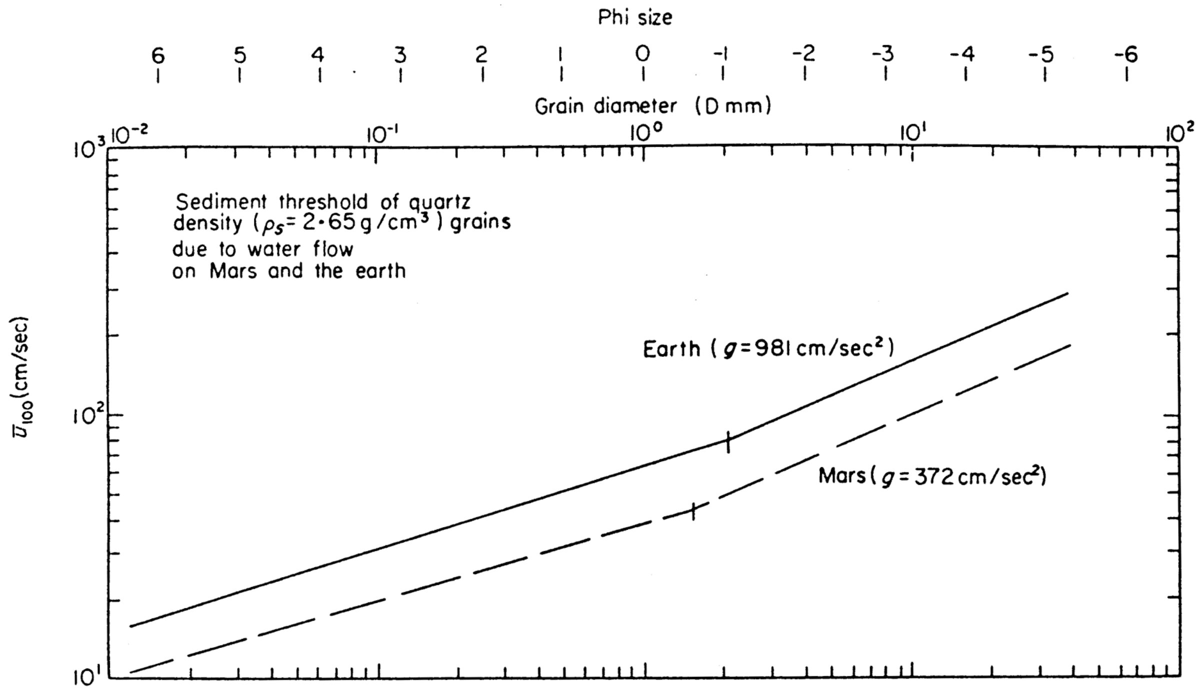


Figure 2: Threshold friction velocity and mean flow velocity curves 1m above the bed for water flows on Earth and Mars. Curves are calculated from the general Shields-type curve of Miller et al. (1977, Fig. 2), and differences between the two curves are related to differing values for g. (Miller and Komar, 1977).

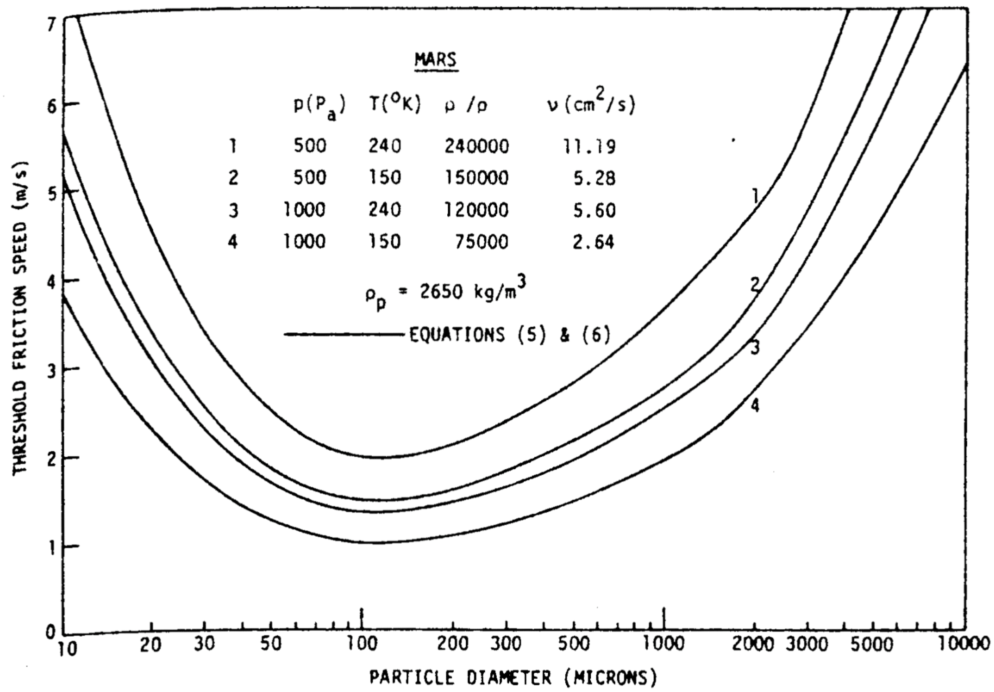


Figure 3: Threshold friction speed predictions for Mars under various pressure and temperature conditions as might be expected on the surface at different lattitudes and elevations. As expected, the highest density conditions at 1000 Pa and 150 kelvin are most easily able to entrain sediment for a given speed (Iversen and White, 1982).

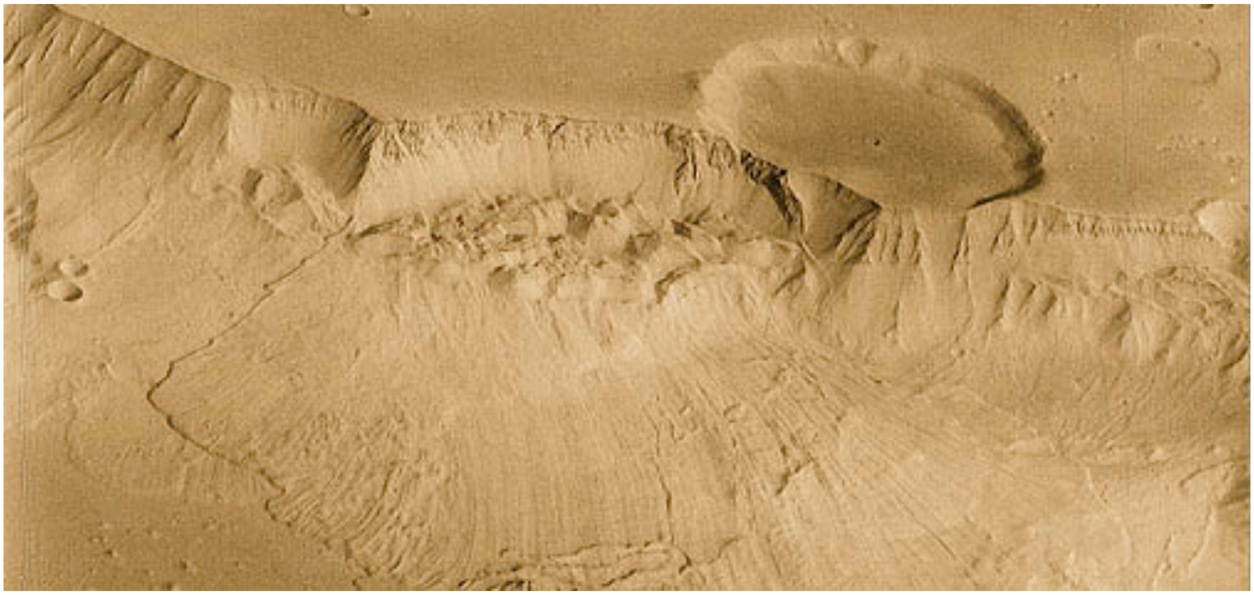


Figure 4: Relatively recent landslide within Valles Marineris canyon system on Mars (Cupit, 2004). Image copyright Calvin J. Hamilton (http://www.solarviews.com/).

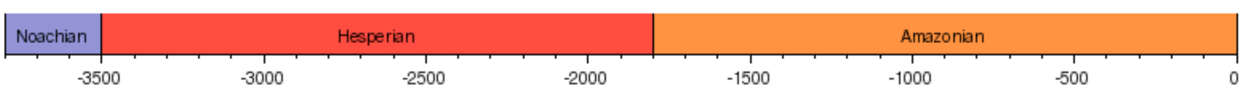


Figure 5: Geological timescale for Mars in thousands of Earth years relative to modern-day (Wikipedia contributors, 2007).

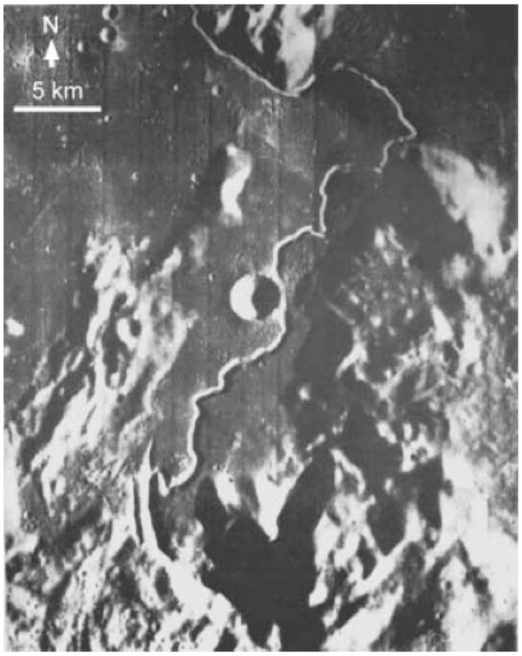
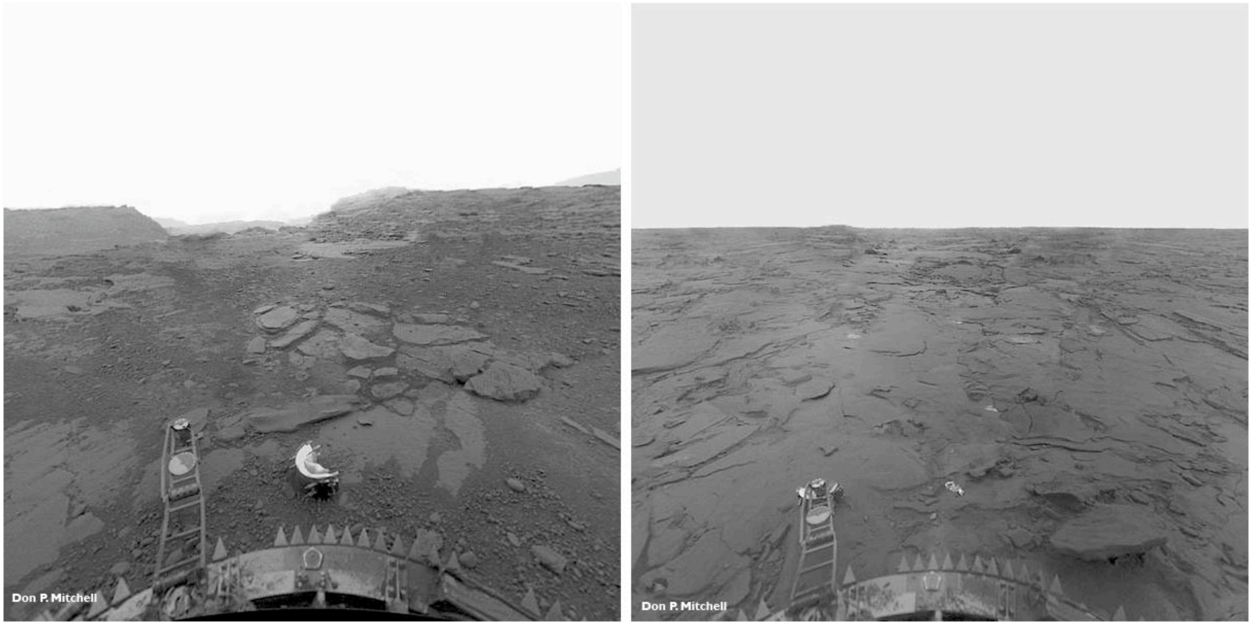


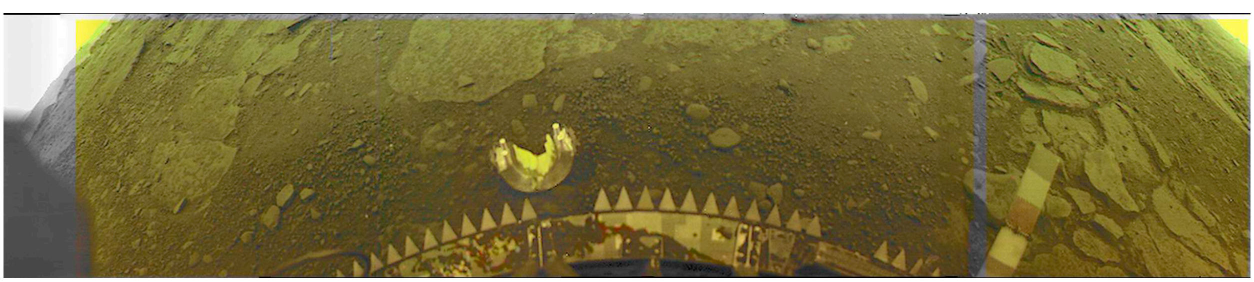
Figure 6: An example of a thermally erosive lunar rille. Photograph is a Lunar Orbiter 5 image (Komatsu, 2007).

7a)

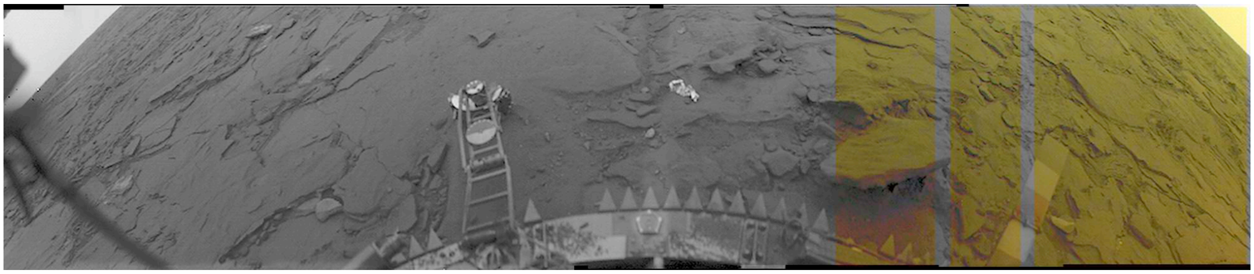


7b)

7c)



7d)



7e)

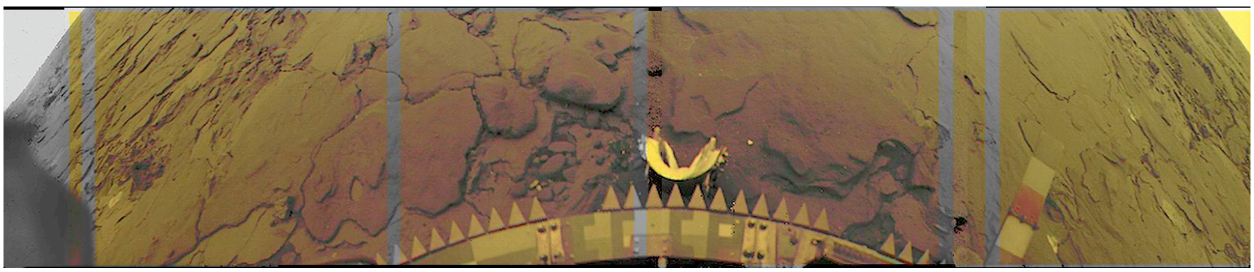


Figure 7: (a) Cylindrical perspective of the surface of Venus, showing rocky volcanic rocks and minimal soil development. Views (b) and (c) are front and back surface images from the Venera 13 probe. Views (e) and (f) are front and back images from the Venera 14 probe. Images remastered by Mitchell (2004). Not all colour information was successfully transmitted back to Earth, however the entirety of the grayscale data was. Colour information is therefore overlain atop grayscale imagery where available.

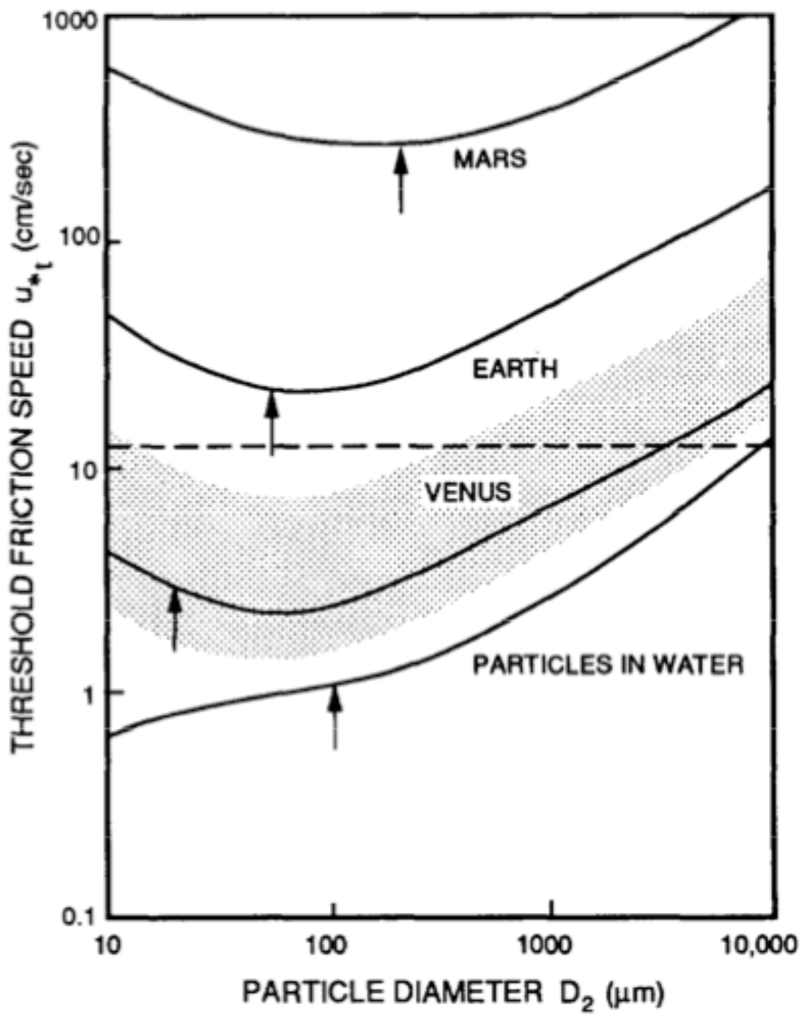


Figure 8: Threshold friction velocity versus particle size for Mars, Earth and Venus in air compared to threshold in water on Earth. Shaded zone represents the range of atmospheric density conditions represented on Venus at high and low elevations. Dashed line represents maximum wind speed velocities measured by the Venera landers. Arrows indicate the transition from suspension to saltation transport styles. (Greeley and Arvidson, 1990)

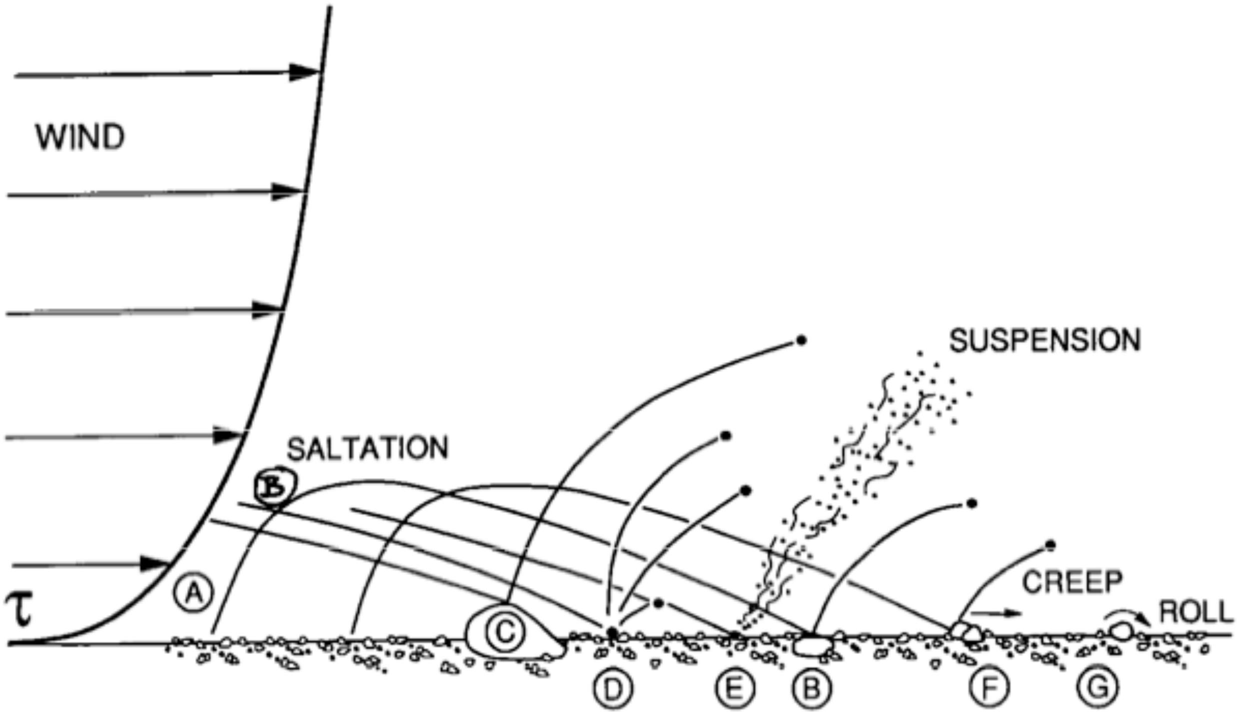


Figure 9: Primary modes of eolian transport for grains on Venus. Surface shear stress imparted by winds cause grains at (a) to be lifted off the bed and subsequently dropped due to inability to keep grain buoyant. Grains can then bounce back into entrainment, a process known as saltation. Grains can hit other grains upon their descent at (c), (d), (e) and (f) causing small scale mechanical erosion, initiation saltation of other particles, knock finer particles into suspension, or impart momentum to larger grains causing them to creep along the surface, respectively. If sufficient shear stress is imparted, grains can roll (g) without being lifted higher up into the wind stream. (Greeley and Arvidson, 1990)

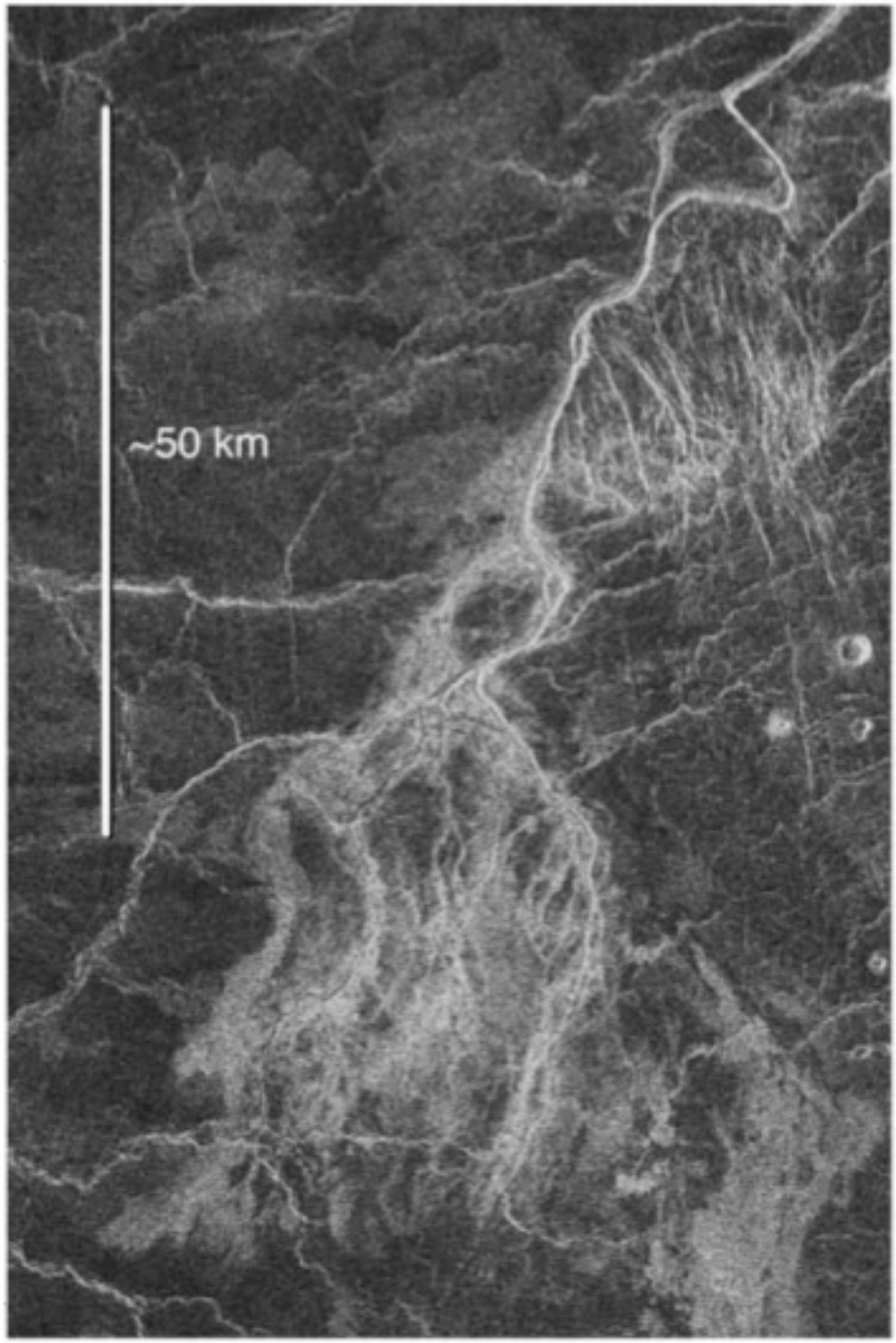


Figure 10: Dendritic outflow pattern at the termination of a Venusian channel (Jones and Pickering, 2003).

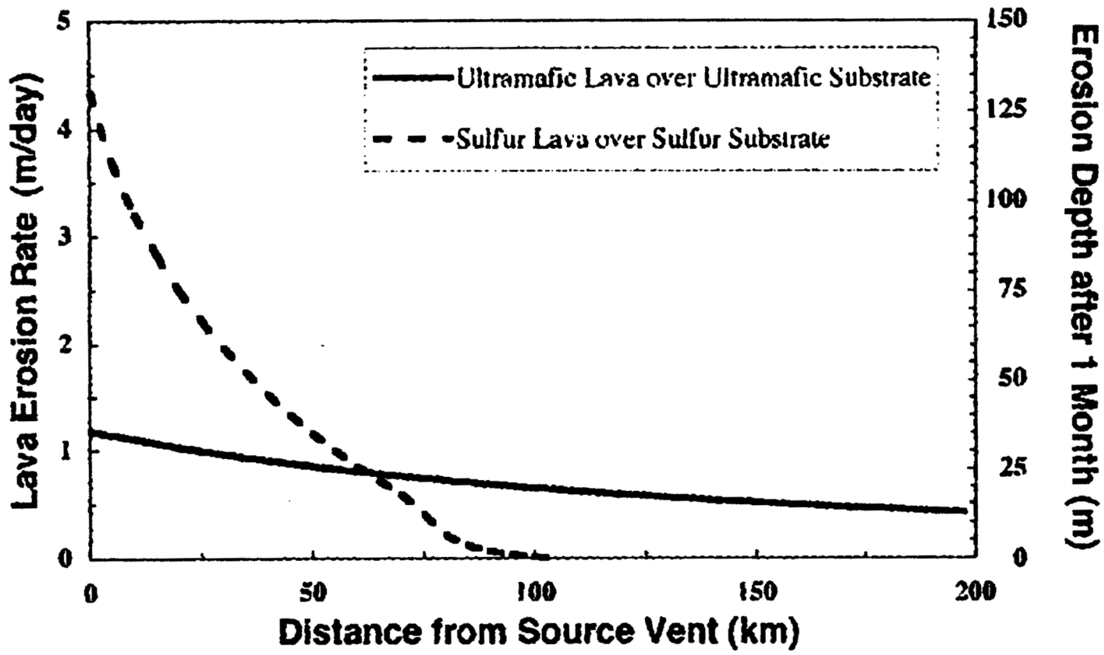


Figure 11: Thermal lava erosion rates and depths for two types of lavas, in relation to their distance from the source vent, as presented by Schenk and Williams (2004). Results assume 10m thick flows at 0.5° slope angles, at 115 kelvin. Eruption temperatures are 1883 kelvin for ultramafic silicate lavas, and 433 kelvin for sulphur lava. Solid sulphur has much lower density, specific heat and heat of fusion than silicate, thus making it easier to erode (Schenk and Williams, 2004).

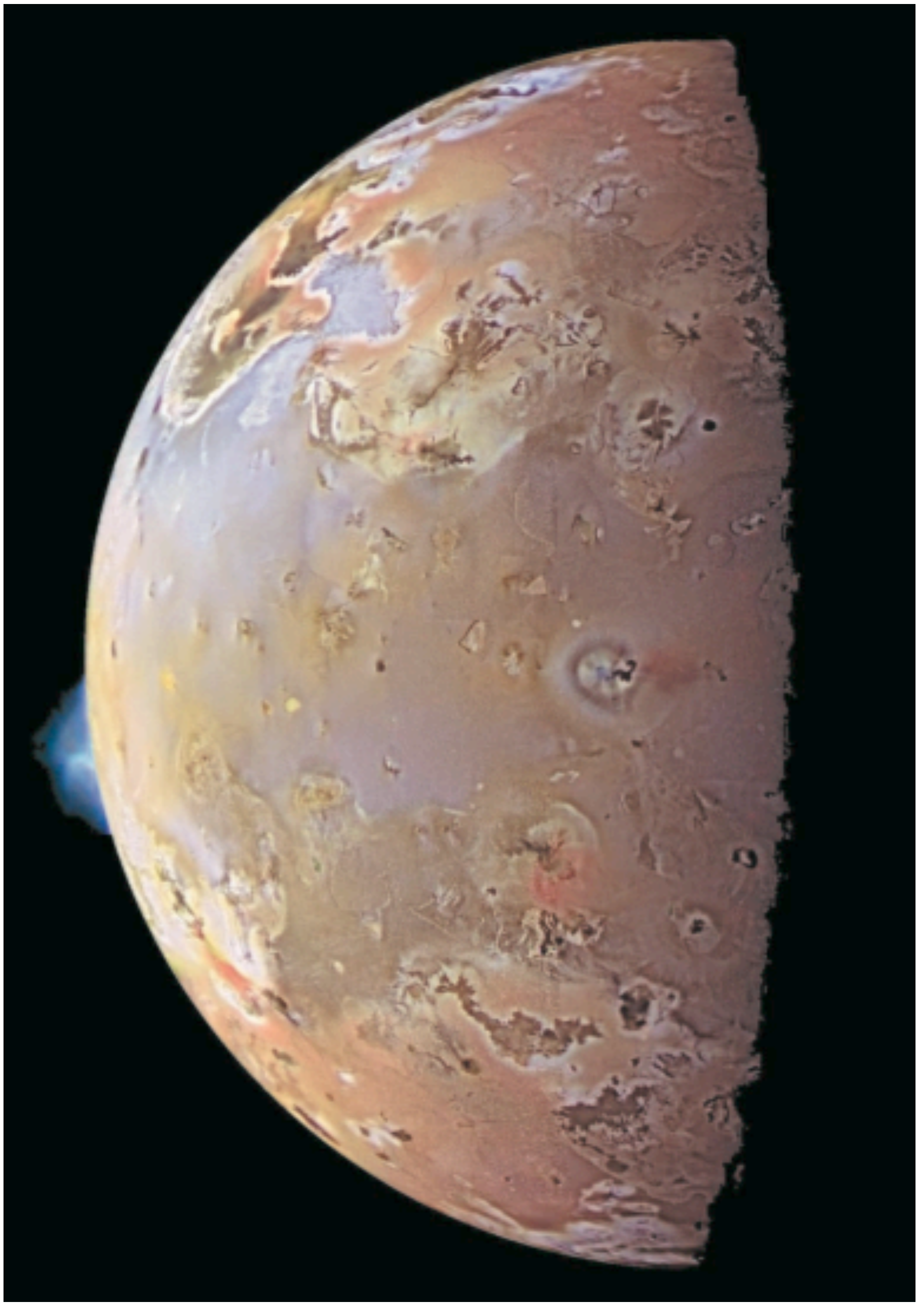


Figure 12: Two active plumes visible on the surface of Io. A blue high-altitude plume is present at the left of image. A smaller reddish plume is visible to the right of centre, extending to the right, with a brown-white plume deposit around it. Image is a composite of data from the Galileo probe. Plumes are a result of vaporization of surface ices and volcanic processes. (Showman and Malhotra, 1999).

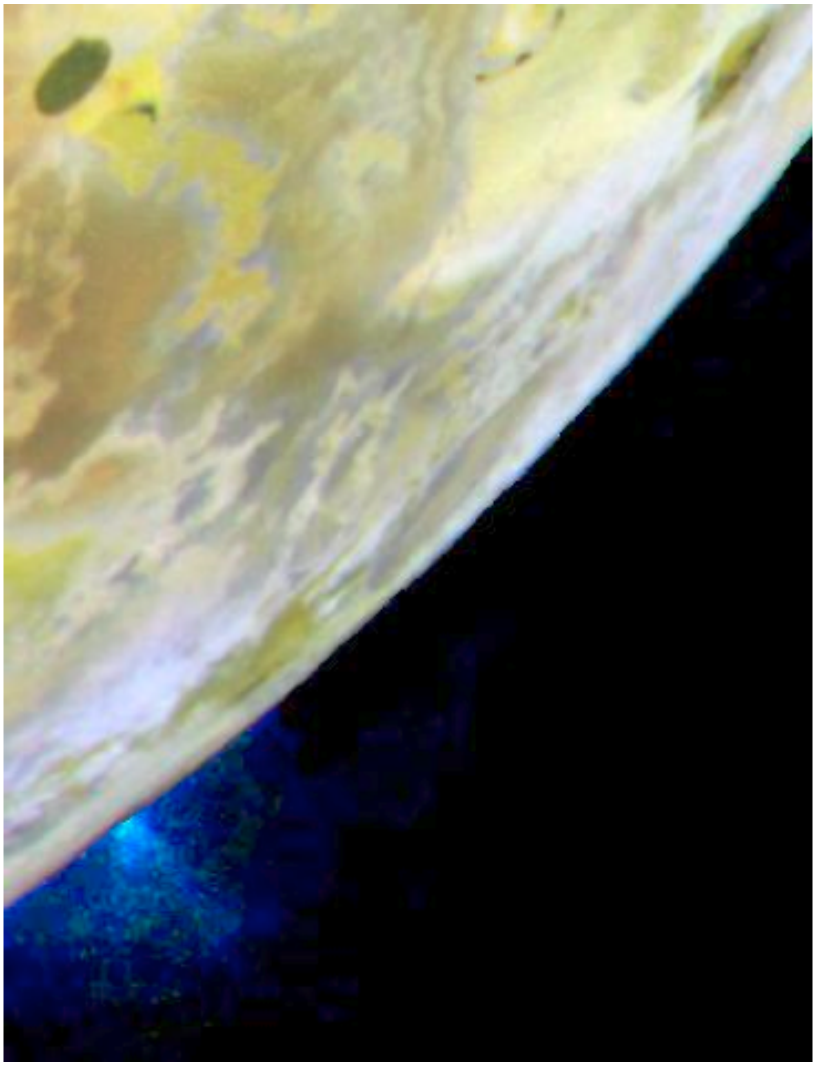


Figure 13: Umbrella shaped plume from the July 1999 eruption of Masubi on the surface of Io, as photographed by the Galileo probe. Dust was lofted neary 100 km. (Geissler, 2005).

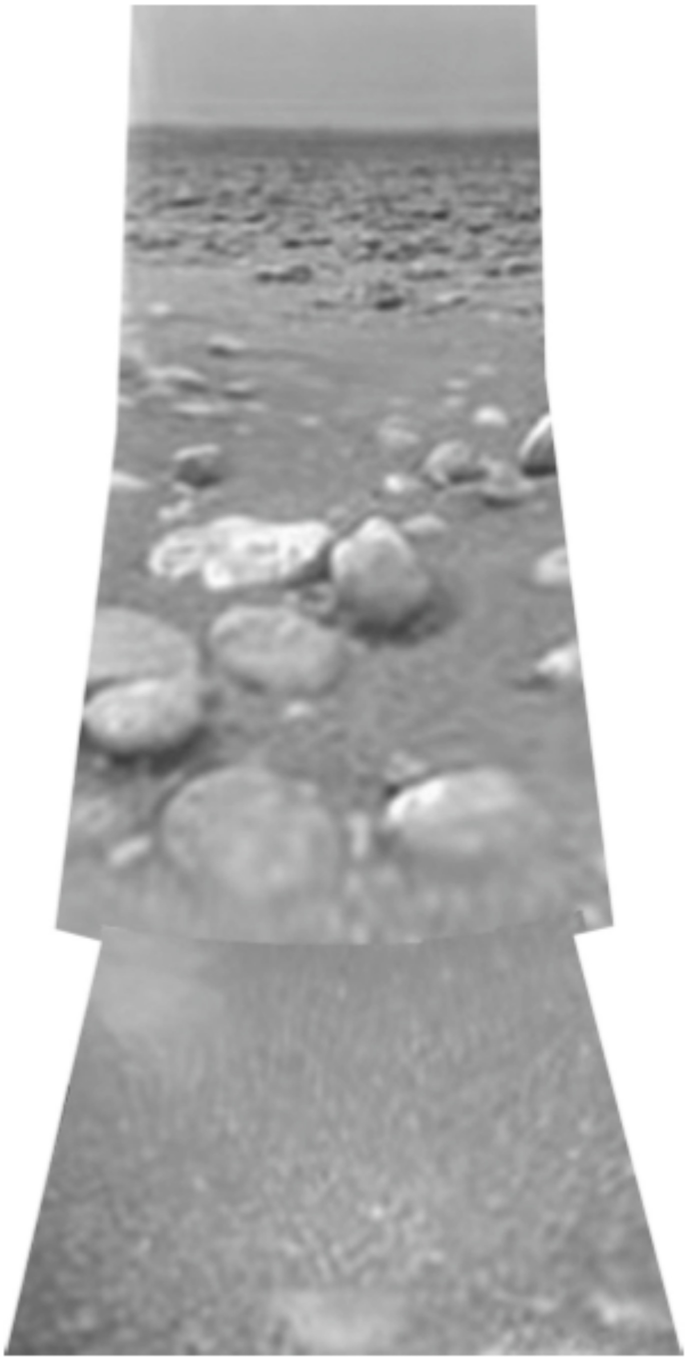


Figure 14: Abundant sediment grains on the surface of Titan as imaged by the Huygens lander in January 2005. The largest grains in the foreground are approximately 15 cm in diameter (Perron et al., 2006). Grains as small as 3mm are resolved in the lower image (Perron et al., 2006).

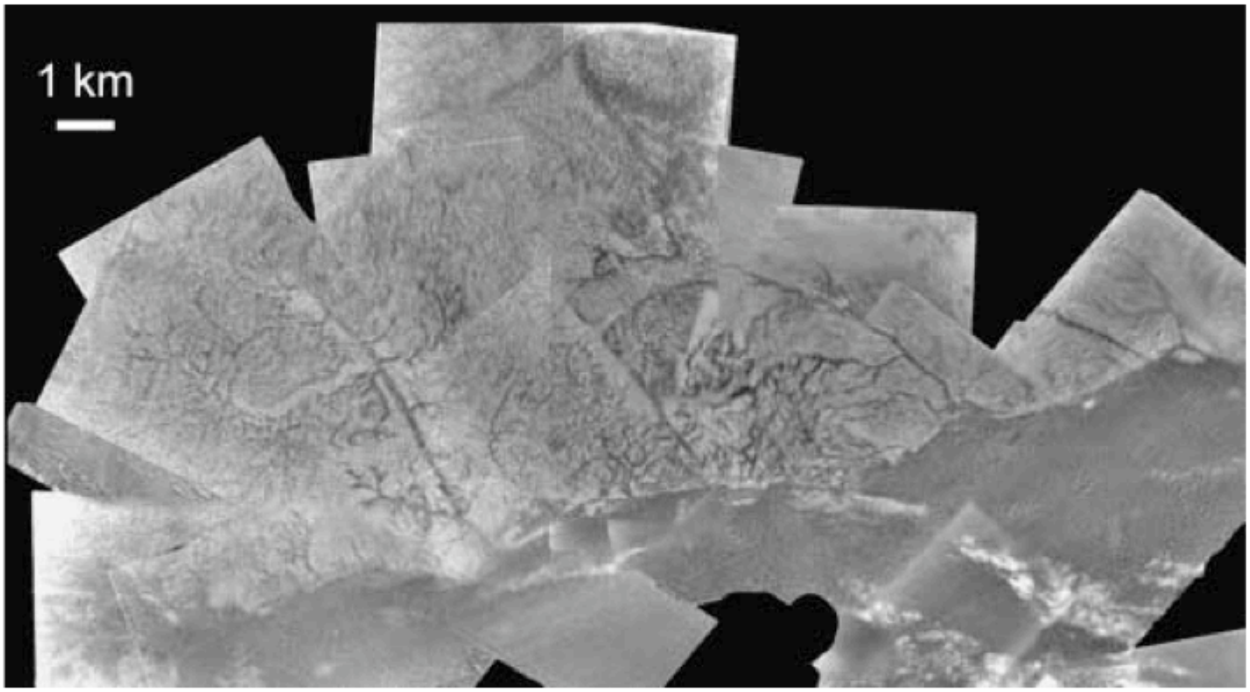


Figure 15: Valleys and channels on Titan imaged during the descent of the Huygens probe (Komatsu, 2007). Image credit ESA/NASA/University of Arizona.

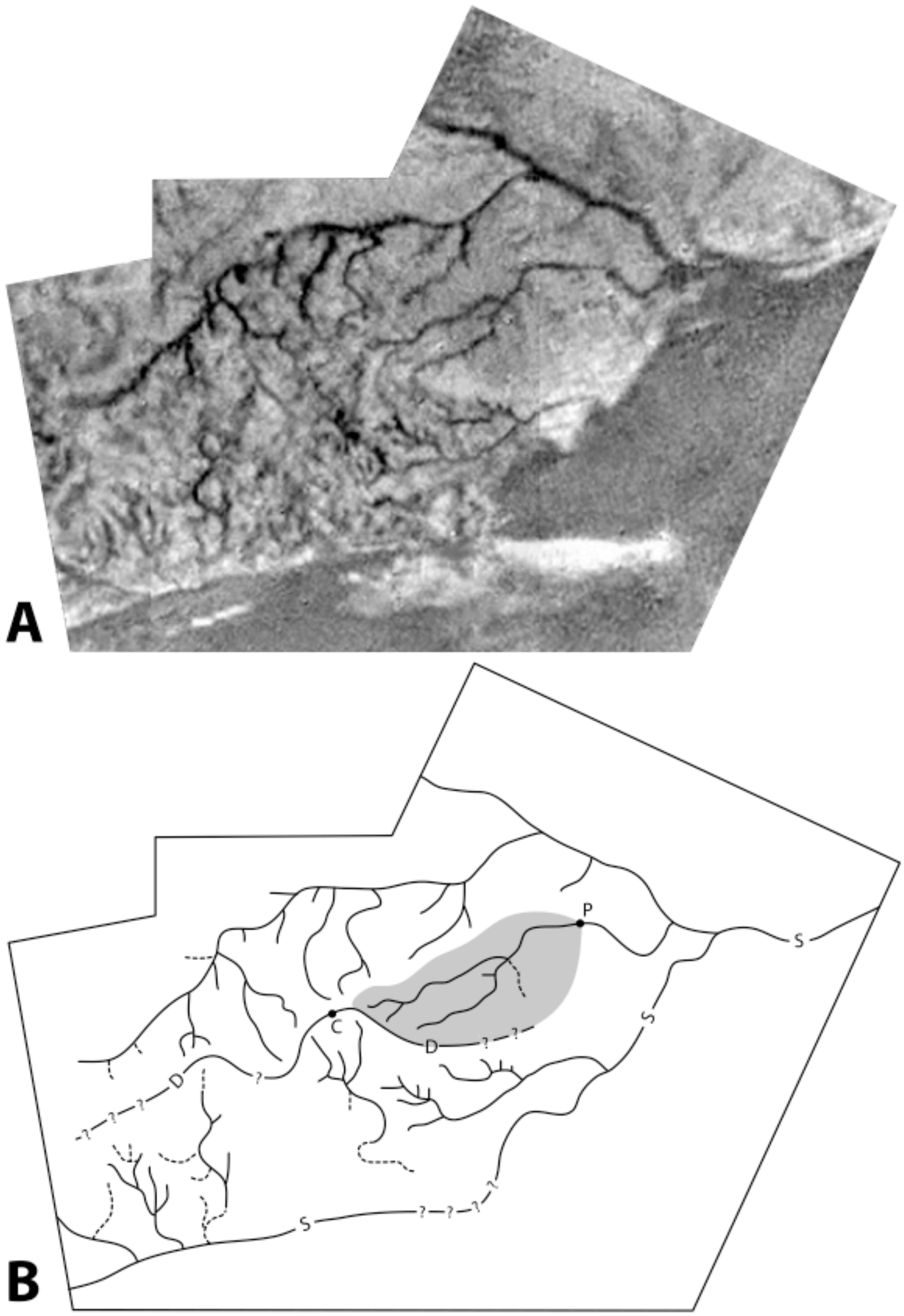


Figure 16: (a) Close-up of valley and channel morphologies during the descent of the Huygens probe. Altitude of probe during this series of images was approximately 16 km. Distance from leftmost to rightmost corners is approximately 6.5 km, and spatial resolution is about 17 m per

pixel. (b) Map of drainage network (Perron et al., 2006) seen in (a). Solid and dotted lines represent known and possible channels, respectively. The lined marked as "S" separates the area of high albedo (above) from low albedo (below). "D" indicates a drainage divide, "C" indicates a point of highest surface elevation, and the shaded area represents a drainage basin flowing past point "P". From Perron et al. (2006).

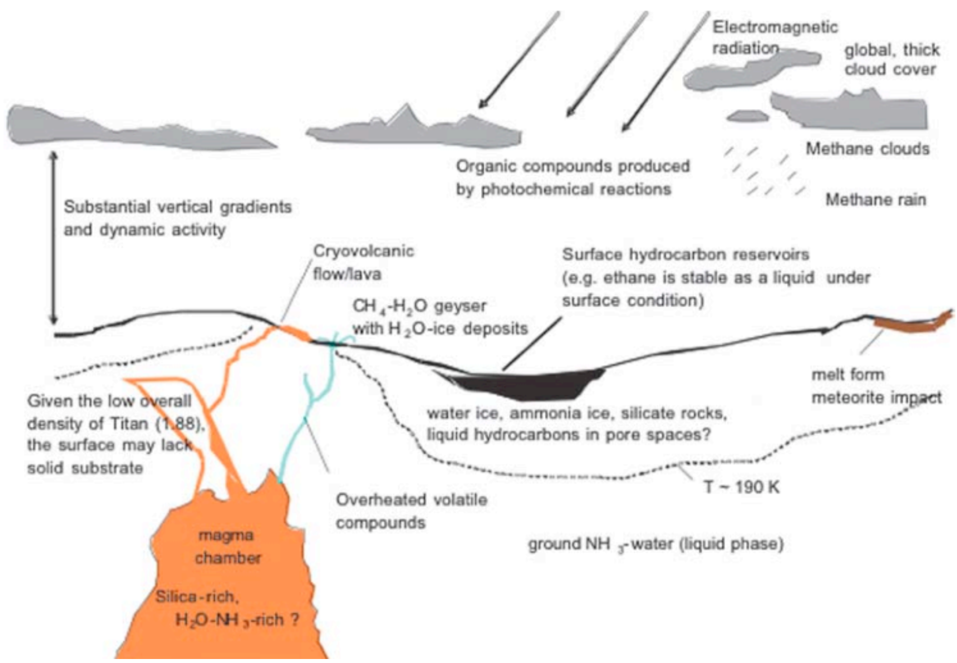


Figure 17: Generalized processes theorized to occur on Titan (Baker et al., 2004).

(T) Tables

Table 1: Summary of processes postulated to be responsible for the creation of various landforms throughout the solar system (Komatsu, 2007).

Planetary body	Landform name	Proposed origins
Moon	Sinuous rilles	Thermal/mechanical erosion by high-temperature, low-viscosity lava flows
Mars	Valley networks	1. Groundwater sapping 2. Surface runoff
	Outflow channels	1. Catastrophic flooding 2. Glaciation 3. Debris flows 4. CO_2-supported debris flows 5. Outpouring of lava
	Gullies	1. Groundwater seepage and subsequent surface runoff 2. Melting of near-surface ground ice 3. Melting of water-rich snow deposits 4. Dry flows of eolian material 5. CO_2-supported debris flows
Venus	Canali	1. Construction by silicate lavas 2. Mechanical erosion by carbonatite or sulfur 3. Aqueous turbidity current
	Kallistos Vallis	Outpouring of lava
	Sinuous rilles	Thermal/mechanical erosion by high-temperature, low-viscosity lava flows
	Valley networks	Low-viscosity lava sapping
Io	Channels	Sulfur and/or silicate lava drainage, thermal erosion
Titan	Valleys or channels	Sapping, precipitation of hydrocarbons

Table 2: Physical properties of Earth and Mars (cold and warm, corresponding to day/night conditions) (Miller and Komar, 1977).

Planet	Gravity g (cm/sec^2)	Grain density, ρ_s (g/cm^3)	Atmospheric density, ρ (g/cm^3)	Kinematic viscosity, ν (cm^2/sec)	Temperature T (°K)	Atmospheric pressure (mb)
Earth	981	2·65	$1\cdot20\times10^{-3}$	0·15	273	1013·0
Mars (cold night)	372	2·65	$2\cdot15\times10^{-5}$	4·35	188	7·65
Mars (warm day)	372	2·65	$1\cdot66\times10^{-5}$	7·23	244	7·65

Table 3: Morphological similarities of channels on Venus compared with submarine channels on Earth. From Jones and Pickering (2003).

	Venus			Earth		
	1, Baltis Vallis	2	3	Cascadia, W USA	Indus, Indian Ocean	Mississippi, Gulf of Mexico
Length (km)	6800	3000	1800	>2000[1]	>1000	600
Width (km)	1–3	1–2	1–2	1.5–5.6	0.5–1.5	1.1–4.1
Depth[2] (m)	<50	n.a	.n.a.	83–285	7–195	6–50
Gradient (m km^{-1})	0.5–2.5 Average 1.0			>1.0 Average 1.0	1.0–2.0	c. 1.0–5.0

n.a., not available

(1) The Cascadia channel merges with a fracture zone system, which extends east-west for hundreds of kilometres.

(2) Elsewhere channel depths are up to 300m (Komatsu and Baker, 1996)