Global distribution of volcanic features

Inspection of global mapping by [77Spu] and [78Sco] shows that up to 60% of the Martian surface are covered by volcanic products. Volcanic units are not uniformly distributed across the surface of Mars. The main volcanic provinces are located at the Tharsis and Elysium rises, around the ancient Hellas impact basin, and at Syrtis Major (see Fig. 1 of [00Zim1]). The largest accumulation of volcanoes is found in the Tharsis bulge (Table 12). The youngest lava flows on Mars are exposed in Tharsis and Elysium Planitia. Besides Tharsis and Elysium, several highland volcanoes (see below) are clustered in the circum-Hellas volcanic province [09Wil], in Syrtis Major [04Hie], and in some more isolated locations (e.g., Apollinaris Patera).

Table 12. Morphometric data of large Martian volcanoes (after [04Ple]; P.: Patera, M.: Mons, Th.: Tholus).

Volcano	Geographic location*	Edifice dimension [km]	Relief [km]	Volume [m^3]	Flank slope [°]	Caldera depth [km]	Caldera area [km]
Alba P.	40°N, 251°E	1015 × 1150	5.8	1.8×10^{15}	1.0	1.2	106 × 138
Albor Th.	19°N, 150°E	157 × 164	4.2	2.9×10^{13}	5	3.5	36
Apollinaris P.	8°S, 174 °E	189 × 278	5.4	7.3×10^{13}	5	1.8	73 × 85
Arsia M.	9°S, 240°E	461 × 326	11.7	9.2×10^{14}	5	1.5	108 × 138
Ascraeus M.	11°N, 256°E	375 × 870	14.9	1.1×10^{15}	7	3.7	62 × 67
Biblis P.	2°N, 236°E	128 × 176	3.6	1.8×10^{13}	5	4.6	53 × 59
Ceraunius Th.	24°N, 263°E	98 × 130	6.6	2.4×10^{13}	9	2.2	25
Elysium M.	25°N, 146°E	375	12.6	2.0×10^{14}	7	0.1	14
Hecates Th.	32°N, 150°E	177 × 187	6.6	6.7×10^{13}	6	0.4	13
Jovis Th.	18°N, 243°E	52 × 58	1.0	8.7×10^{11}	3	1.0	27 × 32
Olympus M.	28°N, 227°E	840 × 640	21.9	2.4×10^{15}	5	3.2	72 × 91
Pavonis M.	0°N, 247°E	380 × 535	8.4	3.9×10^{14}	4	4.8	91 × 96
Tharsis Th.	13°N, 269°E	131 × 158	7.4	3.1×10^{13}	10	6.8	43 × 55
Ulysses P.	3°N, 238°E	100	1.5	2.9×10^{12}	4	2.4	60
Uranius P.	26°N, 267°E	242 × 280	3.0	3.5×10^{13}	3	2.4	88 × 115
Uranius Th.	26°N, 262°E	62	2.9	3.4×10^{12}	8	0.3	20
Amphitrites P.	59°S, 61°E	600 - 700	0.5 - 1.5	nc	0.5	0.8	120
Peneus P.	57°S, 53°E	600 - 700	0.5 - 1.5	nc	0.5	0.8	120
Hadriaca P.	30°S, 94°E	330 × 550	1.1	1.6×10^{13}	0.6	0.7	90
Tyrrhena P.	22°S, 97°E	215 × 350	1.5	2.1×10^{13}	1.0	0.6	41 × 55
Meroe P.	7°N, 69°E	1000 × 1400	4	nc	0.25 - 0.5	1.9	71
Nili P.	9°N, 67°E	1000 × 1400	4	nc	0.25 - 0.5	1.3	52

*after [00Zim1]

Volcanic landforms

About 15 huge shield volcanoes are located in Tharsis and Elysium (Fig. 7a,b) (Table 12). They share many physiological characteristics with large terrestrial shields like those of Hawai´i and the Galapagos Islands: Rift zones and nested caldera complexes [96Cru, 07Mou], very low flank slopes (~5°), and numerous large individual lava flows that can be channel-fed or tube-fed [07Ble]. Channelized flows are well known from Mars and may reach enormous lengths of several hundred kilometers [e.g., 07Gar, 08Bal], indicating high volumetric flow rates for extended periods of time. Lava flows of this length are rarely, if ever, observed on the Earth, and it is debated whether their formation on Mars requires some extraordinary conditions that are or have never been met on Earth [08Bal]. The rheology of Martian lava flows, as determined from their morphology and morphometry in remote sensing data, suggests basaltic lavas with low viscosities [e.g., 78Moo, 85Zim, 07Hie, and references therein]. Taken together, these properties indicate basaltic, mainly effusive eruptions fed by relatively shallow (i.e. within the volcanic construct) magma chambers over an extended period of time, perhaps in an episodic pattern [01Wil2]. A distinctly different class of large central edifices is typical for the circum-Hellas province. The flank slopes of these shields are even gentler (≤ 1°), the flanks are dissected by erosional channels, and the shield-building eruptions seem to have stopped much earlier, as indicated by crater counts. The particular morphology suggests that these volcanoes were built by explosive volcanism rather than by the effusive lava flows typical of Tharsis and Elysium, and that erosion could have easily affected the fine-grained material (e.g., volcanic ash) [93Crn, 93Gre]. Besides the relatively few large well-known volcanoes, there are hundreds of much smaller shield volcanoes distributed in clusters within the Tharsis and Elysium provinces (Fig. 7d, e). Their diameters range from several kilometers to tens of kilometers, their heights reach a few hundred meters, and the corresponding flank slopes are extremely shallow (~ 0.5°) [08Hau].

Sets of long and linear grabens radiating from Tharsis have been interpreted as the surface expression of dike swarms analogous to the Mackenzie dike swarm in the Canadian shield (see Section 4.2.3.5.3) [96Mèg1, 02Wil1, 01Ern2], and dikes have been identified elsewhere on Mars [05Gou, 06Hea].

Volcanic plains are found in all volcanic provinces. They are composed of layered material with thicknesses of up to several kilometers, interpreted to be analogous to terrestrial flood basalts [90Ple, 99McE, 00Kes, 04Kes1]. The Medusae Fossae Formation (a large layered deposit in the equatorial region between Tharsis and Elysium), might be the result of pyroclastic eruptions (e.g., ignimbrites [82Sco]).

Since the surface and crust of Mars show many signs of past and present water and ice [e.g., 89Squ, 96Car, 01Bak], it is not surprising that there is a lot of evidence for *volcano-water interaction* or *volcano-ice interactions* [87Squ, 02Sme]. Examples are possible subglacial volcanoes [01Cha], pseudocraters [01Gre, 01Lan], and even the catastrophic release of water confined in pressurized aquifers by warming due to volcanic heat [79Car] or by cracking of the cryosphere [93Cli] by dikes [e.g., 03Hea1].

Chronology of volcanism

Chronological classifications of Martian volcanic surfaces are provided by [79Ple] and [81Neu]. More recently, more standardized crater counts using images of higher spatial resolution together with improvements in the cratering model [01Har] led to a new compilation of volcanic ages [06Wer]. In general, it appears that the oldest volcanic units are roughly 4 to 3.7 Ga old. They are present in Tharsis, Elysium, and the highland volcanoes. The bulk volume of Tharsis might have been already emplaced at the end of the Noachian epoch [01Phi]. Volcanic lowland plains in Tharsis and Elysium were emplaced between ~3.5 Ga and around 2 Ga. Volcanism in the highlands seems to have stopped next, at least ~1 Ga ago. Later, volcanism was limited to central volcanoes in Tharsis and to Elysium Planitia at the southern margin of the Elysium province [00Har1]. Overall, it appears that volcanism was intense in the early history of Mars, with a possible peak in the Noachian and Early Hesperian, and gradually declined over time. This overall decline might have been punctuated by episodic higher intensity [e.g., 01Wil2, 04Neu].

The erupted volumes of volcanic materials are difficult to determine. The most comprehensive analysis was performed using Viking data, i.e. prior to the detailed global topographic information from MOLA. According to this study [91Gre], the total volume of extrusive and intrusive magma generated over the last ~3.8 Ga is about 654×10^6 km^3, or 0.17 km^3 per year (Table 13). This rate is substantially lower than rates for the Earth (26 to 34 km^3 yr^{-1}) or Venus (< 20 km^3 yr^{-1}), but much higher than for the Moon (0.025 km^3 yr^{-1}) [91Gre] (Table 10).

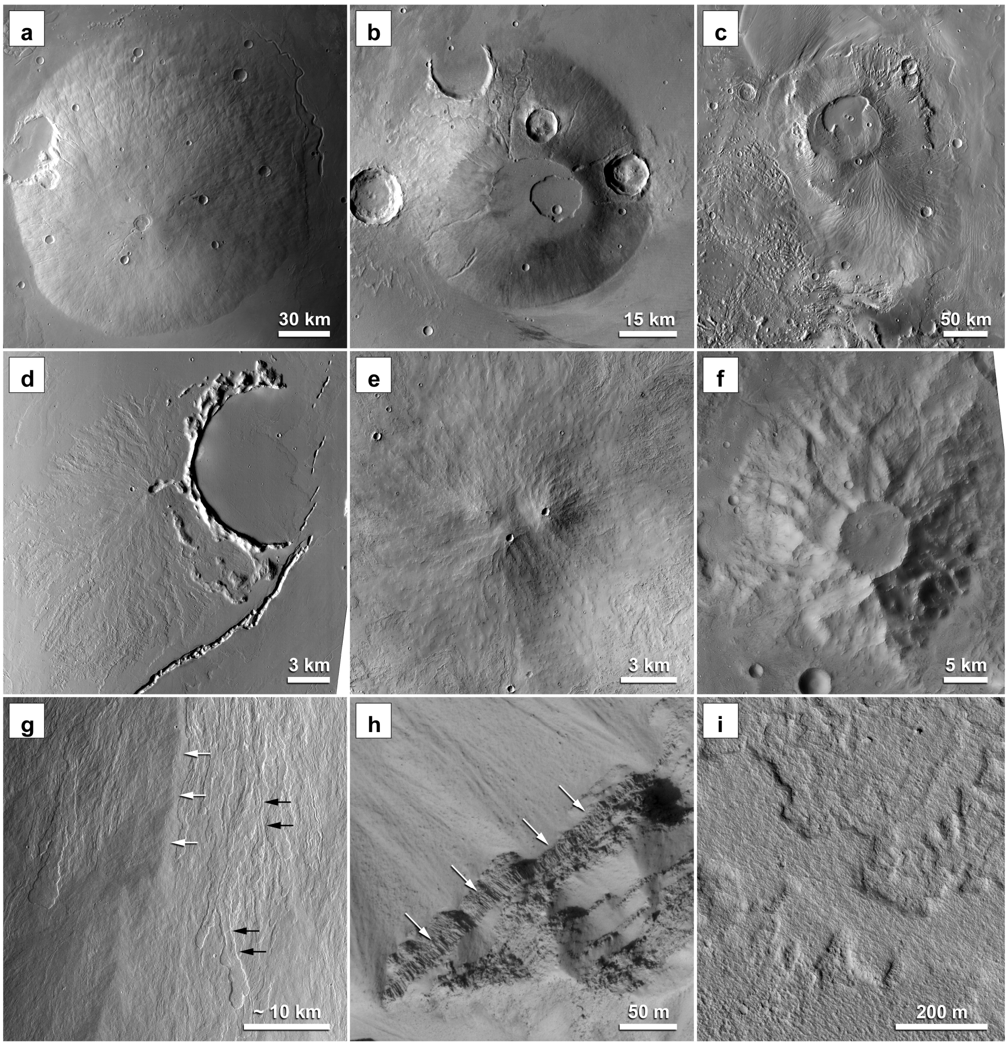


Fig. 7. Examples of volcanic surface features on Mars. (a) One of the large Martian shield volcanoes, Hecates Tholus, in the Elysium volcanic province (31.8°N/150°E). Hecates Tholus was probably built by effusive and explosive eruptions [82Mou, 05Hau]. HRSC image h2907_0008.nd. (b) Uranius Tholus in the Tharsis region, one of the smaller "large" volcanoes on Mars (26.2°N/262.5°E). Many large impact craters attest to the volcano`s old age of 3.9 - 4.0 Ga [06Wer]. HRSC image mosaic. (c) Apollinaris Patera (8°S/174°E), a medium-sized volcano that might have produced large amounts of pyroclastic material. Characteristic features are the caldera and a prominent fan of volcanic material extending southwards from the caldera (THEMIS-IR daylight mosaic). (d) Small low shield in the Ceraunius Fossae region (23.73°N/249.57°E, CTX image P05_002829_2046). (e) Low shields with radial lava flows in Tharsis (2.4°S/252.05°E, CTX image P02_001906_1776). Low shields as shown in (d) and (e) are built by lava flows with low viscosity. (f) Zephyra Patera (21.5°S/173.5°E) has been defined as possible composite cone [78Gre]. It is located in the ancient cratered terrain of Aeolis Mensae. (g) Individual lava flows on the northern flank of Olympus Mons (North is down). Both channelized flows (black arrows) and lava tubes (white arrows) can be identified (HRSC image h6220_0000.nd). (h) Columnar jointing (arrows) could be identified in a large, fresh, unnamed crater near Marte Vallis, centered at 21.52°N/184.35°E [08Mil]. The joints that separate the columns form as the lava contracts and fractures extend perpendicular to the cooling front (HiRISE image PSP_005917_2020). (i) Inflated features in lava flows, well known on Earth, could unambiguously be identified in MOC and HiRISE images [08Kes]. Shown here is a classic example of an inflation plateau at 7.741°N/164.410°E (HiRISE image PSP_003241_1880).

Table 13. Martian magma volumes (values from [91Gre]; Exp.: Exposed; Extr.: Extruded; Topogr.: Topography). The magma volume extruded on plains was estimated assuming that some portion of volcanic plains are covered by non-volcanic units, so the total area of volcanic plains is larger than the exposed area of volcanic plains. The total magma volume assumes a ratio of intrusive to extrusive magma of 8.5:1 (the average ratio for Earth [84Cri]).

Epoch	Area of plains [10^6 km^2]	Exp. plains volume [10^6 km^3]	Thickness of plains [km]	Extr. plains volume [10^6 km^3]	Volume from topogr. [10^6 km^3]	Total extr. volume [10^6 km^3]	Total magma volume [10^6 km^3]
Late Amazonian	1.06	0.29	0.27	0.33	1.78	2.11	20
Middle Amazonian	3.28	1.04	0.32	1.42	7.07	8.49	81
Early Amazonian	7.93	2.22	0.28	3.61	12.15	15.76	150
Late Hesperian	7.63	1.87	0.24	4.54	11.09	15.63	148
Early Hesperian	22.52	3.95	0.18	10.83	6.82	17.65	168
Late Noachian	9.31	1.28	0.14	4.31	3.46	7.77	74
Middle Noachian	2.85	0.47	0.17	1.39	0.00	1.39	13
Early Noachian	?	?	?	?	?	?	?
Total	54.57	11.12	0.20	26.43	42.37	68.80	654

Magmatism and tectonic style

Mars does not show any evidence for plate tectonics in the observable geologic record. Volcanism on Mars shares many similarities with terrestrial intraplate volcanism. The huge (diameters > 100 km) shield volcanoes in Tharsis resemble volcanoes in island chains like Hawai´i or Galapagos, plains volcanism on Mars [81Ple] is similar to plains volcanism on Earth like in the Snake River Plains [82Gre], and huge, topographically flat lava flow fields (e.g., in Elysium Planitia) resemble flood basalts like those in the Columbia River plateau or the Deccan traps in India. There is evidence for limited volcanism at rifts [01Hau, 05Gro1, 07Kro], but these rifts accomodate very moderate extension and are not seen as evidence for plate tectonics. No volcanism on Mars that would be related to plate tectonics is known in the observable geologic record. One possible explanation for the focussing of the volcanism in a few provinces only is the existence of few long-lived mantle plumes [e.g., 96Har, 98Har, 98Bre, 07Li], and indeed some researchers, e.g., [97Hea1], considered Tharsis to be the equivalent to a terrestrial large igneous province (LIP) [94Cof, 97Mah, 05Ern]. Since it is actually larger than terrestrial LIP (at terrestrial standards, each of the individual large Tharsis shields could be considered an individual LIP), it was even compared to terrestrial superswells, which are huge geoid anomalies [98McN], or to plume clusters [04Scu, 07Ern] (for the case of Mars, see, e.g., [98Bre]). Mantle plumes could certainly explain some of the main volcanic characteristics of Tharsis and Elysium, including the existence of giant dike swarms [96Mèg1, 02Wil1, 01Ern1]. However, the physical plausibility of the long-term stability of mantle plumes rising from the core-mantle boundary has been questioned by [06Sch1, 06Sch2], who doubt that the heat flow from the core could have supported the sustained plume action for sufficiently long periods. Instead, [06Sch1,06Sch2, 07Sch1] suggest that the insulating effect of a thickened crust in Tharsis and Elysium might have created a deep-seated (~ 300 km) zone of partial melt, which might have been responsible for the recent volcanism on Mars.

Venus

Venus is the second-largest terrestrial planet, with a diameter only ~ 330 km less than that of Earth. The intensity of volcanism on a planet should scale with its mass, and so it is not surprising that Venus has the second largest number of volcanoes in the Solar System. Moreover, erosion is low on the dry surface of Venus. Therefore, the planet displays an extraordinary inventory of diverse and well-preserved volcanic landforms. Magellan radar images are the most valuable source for geologic interpretations of volcanic (and other) surface features. Previous to Magellan, the Soviet Venera missions had delivered the first radar images that showed the diversity of the Venusian surface [e.g., 86Bar], and Venera landers survived the harsh environment on Venus` surface long enough to transmit a few images and geochemical measurements [77Flo, 85Bas]. A list of all missions that observed Venus is contained in a review on the Venusian surface [03Bas], and an overview of the Soviet-era scientific results is given by [92Bar1]. Summaries of Magellan results are provided by [97Bou], [94Cat], and in a special issue of the Journal of Geophysical Research, published in 1992. Several reviews cover mainly the morphology and distribution of volcanic features on Venus [92Hea2, 97Cru, 00Cru].

Magma composition
Volcanism on Venus is predominantly mafic, but a wide range of magmatic compositions seems possible from the observations. The Venera landers acquired gamma-ray and X-ray fluorescence spectra, which showed that the contents of potassium, thorium and uranium (Table 14) as well as other petrogenic elements (Table 15) are similar to those of terrestrial mafic rocks (alkali basalts and tholeiitic basalts, depending on the landing sites) [e.g., 92Bar2, 97Sur], although other lithologies can not be excluded. Significant variations in K and U contents have been reported [97Sur, 99Nik]. Additional evidence for basaltic volcanism comes from the investigation of volcanic landforms, which show the morphologic characteristics of terrestrial basalt landforms. It has to be noted, however, that some volcanic edifices have relatively steep flanks, suggesting to some researchers [99Iva, 92Pav] more viscous material with a possibly more evolved composition than the extensive lava flows and flow fields with the associated channels (see below for details). Similarly, some festooned lava flows have been cited as evidence for silicic, perhaps rhyolitic compositions [93Man]. In summary, volcanism on Venus shows many characteristics of basaltic products, but other compositions might well be present and reflected in the wide variety of landforms (see below; and see the discussion in [07Elk]).

Table 14. Abundances of primary mineral-forming and radiogenic elements. Values are taken from [93Kar, 07Smr, 07Tre]. The abundances for each element are interpretations of the most likely minerals on the Venusian surface [07Smr].

Lander	U [ppm]	Th [ppm]	K [ppm]
Venera 8	2.2 ± 0.7	6.5 ± 0.2	40000 ± 12000
Venera 9	0.6 ± 0.16	3.65 ± 0.42	4700 ± 800
Venera 10	0.46 ± 0.26	0.7 ± 0.34	3000 ± 1600
Vega 1	0.64 ± 0.47	1.5 ± 1.2	4500 ± 2500
Vega 2	0.68 ± 0.38	2.0 ± 1.0	4000 ± 2000

Table 15. Oxide abundance measured by Venera 13 and 14 (V13, V14), and Vega 2 (V2). Values are in weight-%, and element abundance was converted into likely chemical combinations (values from [07Smr]).

	SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	TiO_2	MnO	S	Cl
V13	45.1±3.0	15.8±3.0	9.3±2.2	11.4±6.2	7.1±0.96	4.0±0.63	1.59±0.45	0.2±0.1	0.65±0.4	<0.3
V14	48.7±3.6	17.9±2.6	8.8±1.8	8.1±3.3	10.3±1.2	0.2±0.07	1.25±0.41	0.16±0.08	0.35±0.31	<0.4
V2	45.6±3.2	16.0±1.8	7.74±1.1	11.5±3.7	7.5±0.7	0.1±0.08	0.2±10.1	0.14±0.12	1.9±0.6	<0.3

Global distribution of volcanic features
The distribution of volcanoes and volcanic centers on Venus (Fig. 8) can provide clues to the global tectonics (see below). Volcanic features are very wide-spread and occur almost everywhere. There are several databases listing the different volcanic features on Venus. The most comprehensive one is that of [00Cru]. Other catalogues are available for radiating graben systems perhaps being the surface expression of dike swarms [94Gro], coronae [01Sto, for modifications see 02Gla], and coronae, arachnoids, and

novae [01Kos]. An overview of these databases with graphical maps of volcanic feature distributions is provided by [04Ern].

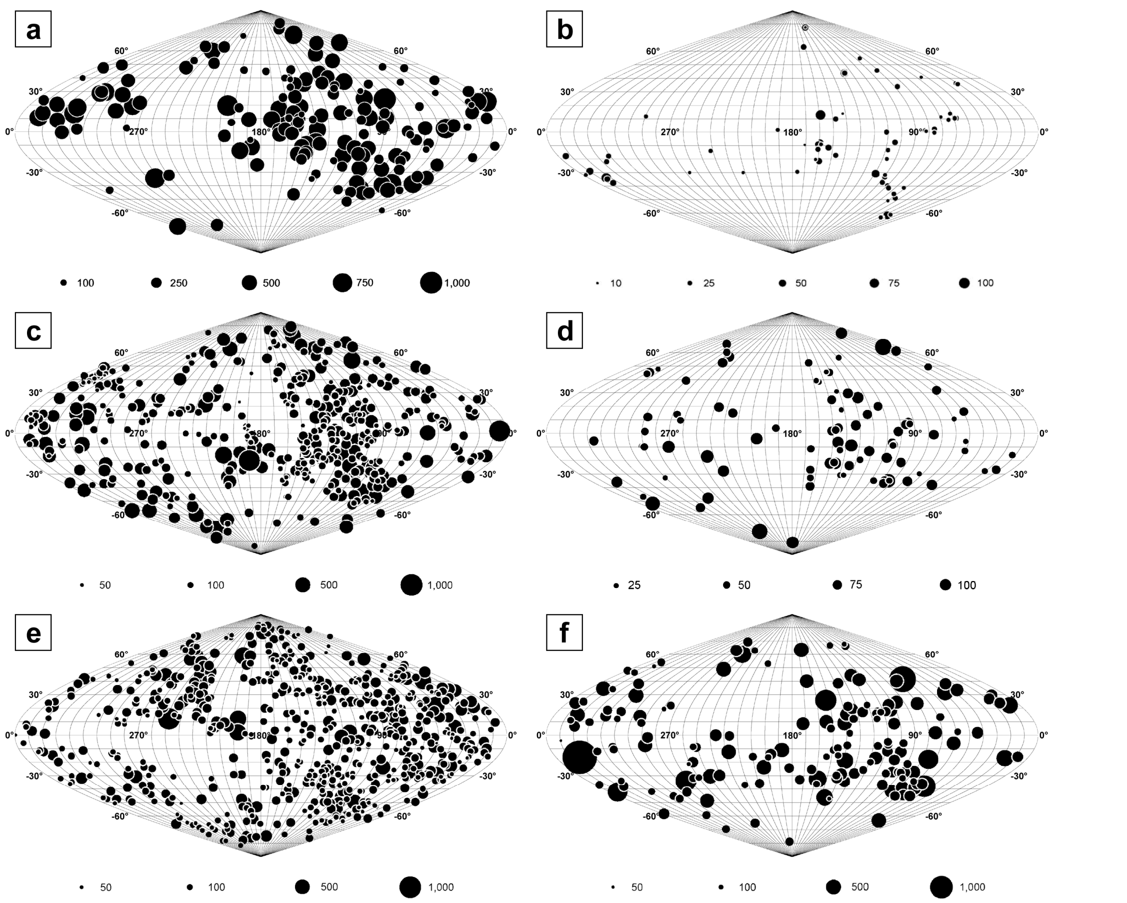


Fig. 8. Distribution of selected volcanic features on Venus (modified after [Ern04]), plotted in sinusoidal projection with center meridian at 180°. **(a)** Large volcanoes after [Cru00]. Symbol size indicates diameter in km. Note that here and in all other panels of this figure, the symbol sizes do not correspond to actual size of volcanoes in this map projection (to allow a greater dynamic range in symbol size, so as to better display the range in feature size). **(b)** Intermediate-sized volcanoes [Cru00]. Symbol size indicates diameter in km. **(c)** Coronae and Arachnoids after [Kos01, Ait02]. Symbol size indicates diameter in km. **(d)** Calderae after [Cru00]. Symbol size indicates diameter in km. **(e)** Fields of small shield volcanoes after [Cru00]. Symbol size indicates diameter in km. **(f)** Radiating graben-fissure systems after [Gro94]. Symbol size indicates radius in km.

Volcanic landforms

Volcanic landforms on Venus (Fig. 9) have been categorized into four main classes: 1) volcanoes, 2) volcanic fields, 3) lava fields and plains, and 4) magmatic centers [00Cru]. Volcanoes on Venus have a large range of sizes: Small shields may have a diameter of less than 1 km, while large edifices or volcanic centers can reach diameters of more than 1000 km. A large part of the Venusian surface (50 - 60%) is covered by regional plains [00Bas]. Lava flows are obvious in many images and occur as radar-dark (i.e. smooth) lava plains and as lava flow fields that can reach lengths of > 1000 km and can cover very large areas [e.g., 91Hea1, 92Hea2, 01Mag]. A unique feature within Venusian lava plains are linear to sinuous channels, which can reach extreme lengths of > 6800 km (Nile river: ~ 6500 km) [92Bak, 97Bak]. It requires lavas with extremely low viscosities to build channels of such lengths, and basaltic lavas typically do not have such low viscosities. Other compositions like ultramafic komatiites, high-Ti lunar-type basalts, and carbonatites or sulphur flows [94Kar] might be candidate alternatives.

Magmatic centers are described by [00Cru] as large volcano-tectonic features on Venus that do not have direct terrestrial counterparts. In many cases, they are characterized more by structural features indicating surface deformation than by magmatic features like volcanic edifices or lava flows. This class of features includes coronae, arachnoids, and radial fracture centers, or novae.

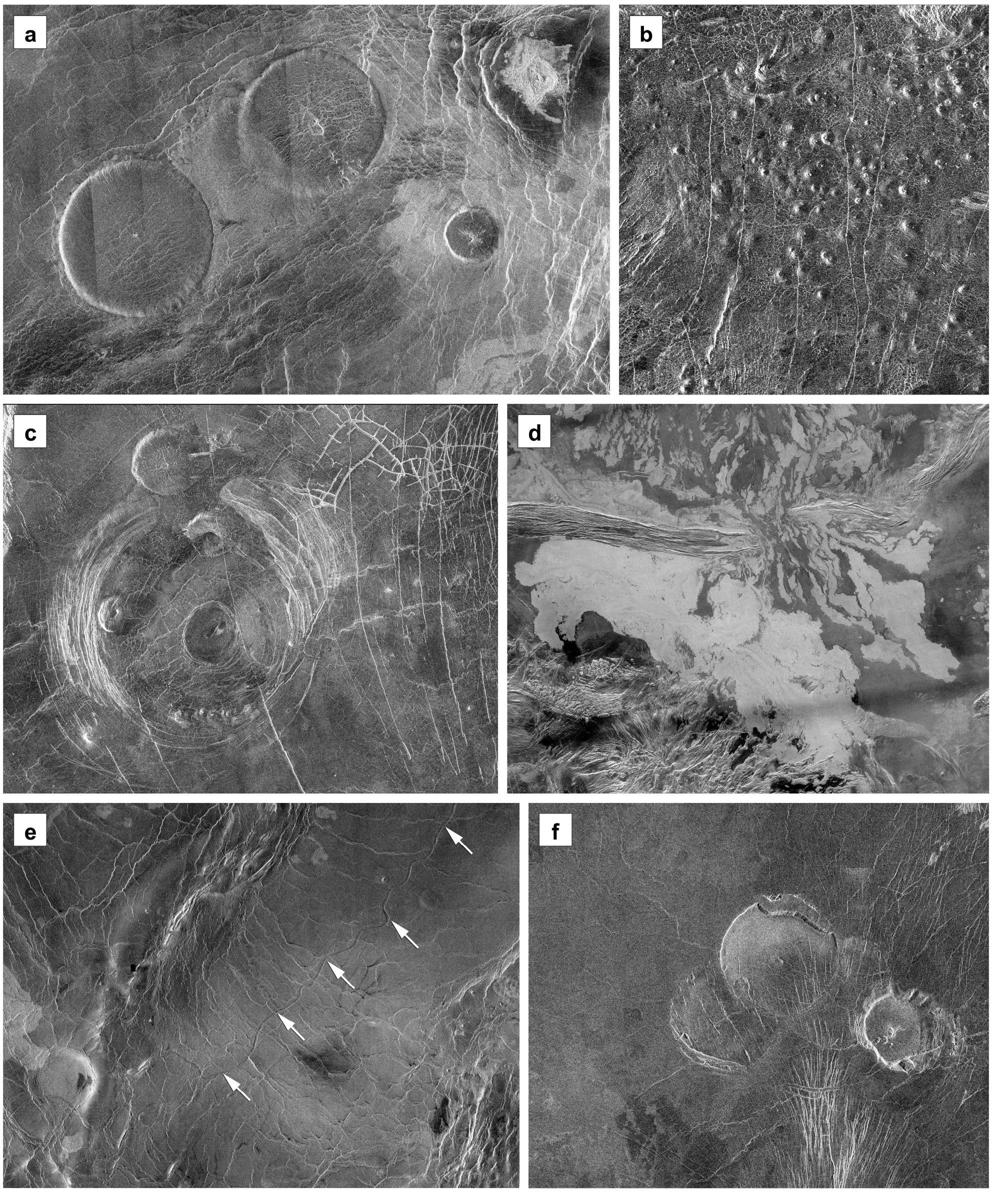


Fig. 9. Examples of volcanic surface features on Venus. **(a)** Volcanic domes in Eistla Regio with diameters of 65 km, steep flanks and broad, flat tops less than 1 km in height (so-called 'pancake' domes). These domes represent a unique category of volcanic extrusions on Venus formed from viscous lava (12.3°N/8.3°E, image width ~250 km; image: NASA/JPL). **(b)** Field of small shield volcanoes, ranging in diameter from 2 to 12 km (64°N/110°E). These small shield-type volcanoes are the most abundant geologic feature on the surface of Venus, believed to number in the hundreds of thousands, perhaps millions. They are probably constructed mainly from eruptions of fluid lava flows similar to those that produce the Hawaiian Islands and sea floor volcanoes (illumination from the west; image: NASA/JPL). **(c)** Aine Corona, a volcano-tectonic structure south of Aphrodite Terra (59°S/164°E). The corona is outlined by a concentric set of fractures, and associated with several volcanic edifices: Just north of Aine Corona is a

pancake dome with about 35 km diameter. Another pancake dome is located inside the western parts of the annulus of the corona fractures. Other volcanic features associated with Aine Corona include a set of small domes, each < 10 km across, located along the southern portion of the annulus of fractures, and a smooth, flat region in the center of the corona, probably a relatively young lava flow. The range of volcanic features associated with coronae suggests that volcanism plays a significant role in their formation (image width ~ 300 km). **(d)** Radar-bright and -dark lava flows encountering and breaching a north-trending ridge belt in Lada Regio (47°S/25°E, North is to the right, image width 630 km). **(e)** Lava channels are common on Venusian plains. Shown here is a 600 km-long segment of the longest channel discovered on Venus to date, formed by lava which may have melted or thermally eroded a path over the plains' surface (arrows). It is approximately 1.8 km wide (49°N/165°E, image width ~ 345 km). **(f)** Three unusual volcanoes in Guinevere Planitia. The northern rim of this center volcano has a steep scarp, probably the result of material that has slid away from the volcano and subsequently has been covered by lava flows. This volcano overlaps another feature to the southwest that is about 45 km in diameter and disrupted by many fractures. The southeastern volcano (25 km in diameter) displays scalloped edges, which are perhaps the result of multiple material slides along the volcano margin. All images: NASA/JPL.

Chronology of volcanism

The distribution of impact craters on the surface of Venus is random, and traditional methods of dating planetary surface units by analysis of the crater size-frequency distribution are not applicable. Previous attempts to use crater counts to date geological units by the combination of morphologically similar units into large composite regions [e.g., 94Nam, 94Pri, 96Pri] were questioned by [99Cam] who argued that determining the relative ages of separate areas lacks statistical validity because of the small number of craters available.

Many researchers agree that the crater distribution can best be explained by global resurfacing, originally believed to have happened sometimes between 500 Ma to 300 Ma ago [e.g., 92Sch, 94Str, 94Her1, 94Her2 96Pri], but the exact timing of this event is under debate. A new determination of the mean surface age is about 750 Ma [97McK, 02Bas2], but it could be as old as 1 Ga and as young as 300 Ma [97McK]. The duration of the resurfacing event, often called catastrophic resurfacing, was once considered to be extremely short (10 Ma, [94Str]), but is now thought to have lasted considerably longer. In the most extreme case (oldest mean surface age, largest uncertainties for the deviations from this mean age), the period between the formation of the oldest terrains (tessera) and the youngest structures (rifts) might have spanned from almost 2 Ga to the present. Even for less extreme cases, the resurfacing time is still from 1.1 Ga to 200 Ma and thus more than the originally proposed 300 - 500 Ma. In any case, however, it is dramatically short compared with global terrestrial resurfacing rates [04Ern]. Within that time, 80 - 85% of the surface, including the vast regional volcanic plains, were resurfaced in a rather short time span, and the remaining area was resurfaced in a period that was an order of magnitude longer. Tectonism in that long and less active time was restricted to young rifts, and volcanism to lobate flows forming both volcanic constructs and plain-like lava fields, and smooth local lava fields. It seems that the volcanic and tectonic activity peaked early in the time covered by the observable geologic record, and that it was followed by a relatively quit time with low rates of volcanism that extends until now [03Bas]. The volcanic flux in that late period was probably lower than the terrestrial intraplate volcanism rate, and similar to the average lunar rate of volcanism during mare volcanism [03Bas].

Magmatism and tectonic style

There is no evidence for plate tectonics on Venus in the geological record spanning the observable time since the global resurfacing event (see Section 4.2.3.5.3). Instead, Venus is thought to be a one-plate planet, and in agreement with this hypothesis, volcanism on Venus displays many similarities to intraplate volcanism on Earth. The global or large-scale surface expressions of volcanism are generally ascribed to mantle upwellings or plumes.

On Earth, plumes are thought to be responsible for the formation of large igneous provinces or LIP [e.g., 94Cof], which are marked by huge voluminous basaltic lava flows (flood basalts). Several volcanic or volcano-tectonic surface features on Venus have previously been compared to LIP [e.g., 97Hea1, 04Ern]: volcanic rises, large coronae, crustal plateaus, and regional plains. The most unambiguous examples of surface signatures of mantle plumes are the volcanic rises, and some (particularly some of the larger) coronae [07Han]. Coronae are widely agreed to be the result of buoyant mantle material impinging on the lithosphere [e.g., 97Sto, 06Gri]. Compositional diapirs, thermal diapirs, or a combination of both might be the driving forces behind coronae formation, and coronae probably have significantly contributed to heat loss on Venus [97Smra, 03Han, 03Joh].

Large *volcanic rises* were classified by [95Sto] into rift-dominated volcanic rises, corona-dominated rises, and volcano-dominated rises. They are typically characterized by broad domical topography with ~ 1300 - 2300 km diameter and ~ 1 - 3 km height, local radial lava flows, and deep apparent depths of compensation, which is thought to be evidence of thermal support within the mantle [07Han]. Volcanic rises are interpreted as mantle upwellings comparable to terrestrial hotspots on Earth [e.g., 81Phi, 91Phi, 94McG, 94Phi, 97Han, 98Phi, 99Smr, 98Nim, 05Sto], because the combination of a topographic rise, a geoid high, sometimes triple junction rifting, and large-scale magmatism (comparable to LIP) most closely matches the criteria to recognize terrestrial hotspots or plumes [73Bur, 01Sen, 01Ern2, 03Ern]. The broad consensus that volcanic rises on Venus are due to plumes is, therefore, supported by different data sets, including both geological and geophysical observations: size, topography, gravity-topography ratios (admittance), deep apparent depths of compensation, and wide spread evidence of volcanism [07Han].

Finally, major concentrations of volcanic centers are located between the Beta, Atla, and Themis regions, which are also characterized by surface features indicative of rifting and mantle upwelling [93Cru]. The plains around these accumulations of volcanic centers show evidence for crustal shortening. [93Cru] interpret this combination of volcanic and tectonic observations as large-scale patterns of mantle circulation, resembling those attributed to intraplate volcanism on Earth, and [04Ern] compare these concentrated activity to plume clusters (or "superplumes") on Earth.

Databases
Venus: Tabulated Magellan Venus Volcanic Feature Catalog [00Cru]:
http://www.planetary.brown.edu/planetary/databases/venus_cat.html
Venus: Venus Coronae with Volcanic Flow Fields [93Mag]:
http://www.planetary.brown.edu/planetary/bin/flows.xls
Venus: Steep-sided domes [99Iva]:
http://www.planetary.brown.edu/planetary/steep/
Venus: Venus Radial Dike Swarms [94Gro]:
http://www.planetary.brown.edu/planetary/bin/dikeswarms.xls
Venus: Venus Crater Database [97Her]:
http://www.lpi.usra.edu/resources/vc/vchome.shtml

Volcanism on the Jovian satellites

Io

Despite its relatively small size (radius 1821.6 km), the Jovian satellite Io is the volcanically most active body in the Solar System. The mechanism that produces the internal heat is widely agreed to be dissipation of tidal energy from interaction with Jupiter, induced by the orbital resonance of 4 : 2 :1 between Io, Europa and Ganymede that maintains an elliptical orbit of Io. This dynamical relationship, first discovered by Galileo, was found to be stable on long timescales by Laplace in 1805, but it was not until the work of [79Peal] that the implications for the internal activity were fully understood. Peale and his colleagues predicted "widespread and recurrent volcanism". Somewhat earlier, several other studies had reported measurements that already pointed towards volcanism. Infrared measurements showed high brightness temperatures [e.g., 72Mor], but the authors did not associate them with volcanic activity. The spectral detection of sulphur by [78Nel] was interpreted as fumarolic or hot spring activity, and [79Wit] showed again that the surface of Io displayed high brightness temperatures. Only a few days after the theoretical study of [79Peal] was published, its predictions were dramatically confirmed by images taken during the encounter of the Voyager spacecraft with Io. They showed a faint plume against the background of space, rising 200 km above the surface [79Mor]. This was the first unambiguous evidence for currently active extraterrestrial volcanism. Subsequently, a number of other plumes has been found (Table 16). SO_2 gas was also identified in infrared spectra [79Pear]. Since then, a large number of publications reported on many aspects of Ionian volcanism, including several reviews of, e.g., [96Spe], [03Gei], [00Lop], [05Lop], [00McE], [07Lop1], [07Lop4], and [07Dav].

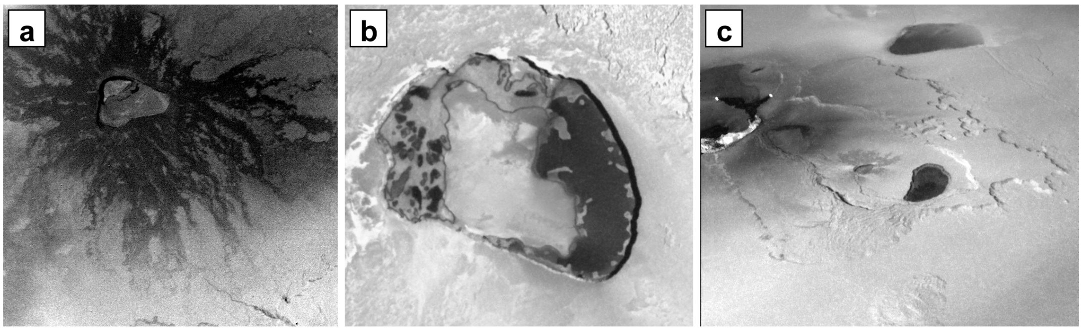


Fig. 10. Examples of volcanic surface features on the Jovian moon Io. **(a)** Irregularly shaped caldera (~ 50 km diameter) with dark flows radiating from its rim. The flows are probably low viscosity lavas, possibly of basaltic composition. Some of them are over 100 km long and 15 km wide (image: NASA/JPL). **(b)** Paterae are saucershaped, shallow volcanic constructs that often have a central caldera [00Lop]. Tupan Patera is a volcanic depression, about 75 km across, surrounded by ~ 900 m-high cliffs. The floor is covered with a pattern of dark black, green, red, and yellow materials (as determined in colour images). The dark material is recent, still-warm lava. This image exhibits the best evidence to date of chemical reactions taking place between molten sulfur and molten rock on Io (image: NASA/JPL/University of Arizona). **(c)** Tvashtar Catena is a chain of giant volcanic calderas, which was the location of an energetic eruption caught in action in November 1999 (image width ~ 250 km, North on top, illumination from the left; NASA/JPL/University of Arizona).

Table 16. Hot spots on Io (from [00McE], after [99Lop]).

Hot spot	% observations detected*	Latitude [°]	Plume?
Pele	100	–18	yes
Mulungu	100	+17	no
Marduk	100	–27	yes
Isum	100	+31	no
Amirani	100	+25	yes
Hi`iaka	100	–2	no
Kanehekili	100	–16	yes
Pillan	89	10	yes
Loki	88	+11	yes
Malik	88	–35	no
Prometheus	88	–2	yes
Janus	83	–4	no
Zal	83	+41	no
Tupan	75	–18	no
Culann	75	–19	probably
Altjirra	56	–35	no
Zamana	56	+18	yes
Aidne	56	–1	no
Gish Bar	44	+17	no
Sigurd	44	–5	no
Monan	44	+19	no
Shamash	38	–34	no

* Percentage of observations covering each region in which the hop spot was detected [99Lop].

The Voyager and Galileo missions returned a wealth of data on Io, and today it is recognized that the surface of Io is dominated by volcanic features. Most of the volcanoes are so-called paterae, caldera-like collapse depressions (Fig. 10). More than 400 calderas have been mapped. Only few topographic edifices like shield- or stratovolcanoes could be identified. Large lava flows have been observed, and the 300 km-long Amirani lava flow field is the largest active flow field known in the Solar System. The global distribution of volcanic features is bimodal, with peaks at lower latitudes and 155° and 355° longitudes, respectively [01Rad]. This pattern is in agreement with expected heat flow patterns from tidal heating [90Ros] and the simulated pattern of mantle convection [01Tac].

A major debate after the Voyager encounter concerned the nature of the volcanism: Was it sulphur or silicate volcanism? Spectral data seemed to favour sulphur [e.g., 79Fan, 79Smy], while Io`s bulk density (3500 km m^{-3}) and the topography of some surface features [80Clo, 86Moo] could be more easily reconciled with the concept of silicate volcanism. Since the melting temperature of sulphur is lower than that of basaltic silicates (sulphur ponds and flows are expected to have temperatures of 400 - 600 K), the measurement of eruption temperatures in excess of 800 K was strong evidence for silicate volcanism [e.g., 88Joh]. Today it is believed that silicate volcanism is dominant at hot spots (defined by enhanced thermal emission), while secondary sulphur volcanism may be important at places [05Lop, 07Jes] and is responsible for the dominance of SO_2 in Io`s atmosphere. The very high temperatures of > 1800 K as reported by some researchers [e.g., 01Dav] exceed that of typical basaltic lavas. This was explained by three hypotheses: Ultramafic (komatiite-like) compositions [98McE], superheating of basaltic lavas by rapid ascent from a deep high-pressure source (where the melting temperature is higher than at surface pressure) [98McE], and "ceramic" volcanism [03Kar]. Most researchers prefer the ultramafic hypothesis, since the other mechanisms are either not known from Earth or poorly investigated. Recently, the extremely high temperatures of > 1800 K have been questioned by [07Kes], who put lower limits of ~ 1600 K to the magma temperature of the volcano Pele.

Eruptions on Io (Table 8) can be classified into three categories [05Lop]: Promethean eruptions are the source of large compound lava flow fields that originate at paterae or fissures [01Kes]. They are long-lived and steady (a single eruption can last up to several years) and resemble the flows fields of Kilauea in Hawaii, which are characterized by slow emplacement and inflation features. The lava flows of Promethean eruptions may remobilize surface volatiles and initiate "Promethean" plumes. "Pele"-type plumes, on the other hand, result from direct eruption of gas from a central vent (Pele is the name of a prominent volcano on Io). Pillanian eruptions also originate at paterae and fissures [01Kes]. They are short-lived and display high eruption rates, producing dark lava flows and dark pyroclastic deposits. Pillanian eruptions can be associated with large plumes (> 200 km high), which are created by the interaction of silicate magmas with sulfurous volatiles. Plumes contain S_2 as well as SO_2. While temperatures at Promethean eruptions correlate with terrestrial basaltic volcanism, those of Pillanian eruptions correlate with ultramafic volcanism. Lokian eruptions only occur within paterae and involve lava lakes with or without plumes [04Lop]. One and the same hotspot can display several eruption styles over time [07Lop1].

No impact craters are seen on the surface of Io, so the resurfacing rates must be high. Indeed, a comparison between Galileo and Voyager images showed significant local changes of the surface, although 90% of the surface remained unchanged. The combination of intense volcanism and ultramafic eruption products is a paradox: A body as active as Io should have experienced a high degree of differentiation [97Kes], and, at the current rate, a volume of magma 140 times the volume of Io should have been produced over the age of the Solar System [04Kes2]. How can this be reconciled with ultramafic volcanism, which is considered to be typical of a primitive and undifferentiated mantle? A major unknown is the age of the orbital resonance which is necessary to maintain tidal heating in Io. Estimates from dynamical models suggest an age of the resonance of a few Ga with a lower bound of the order of a few hundreds of Ma [79Yod, 81Yod, 99Pea]. Based on the coupling of thermal and orbital models it has also been suggested that Io's activity could be oscillatory during its evolution in resonance [90Fis]. An alternative explanation would be that differentiation was prevented by some unknown response of the lithosphere and mantle to tidal heating [04Kes2].

Europa

Cryovolcanism is defined as the effusion or eruption of fluid H_2O and/or aqueous solutions of components such as NH_3, CH_4, N_2 etc. on icy satellites (including dwarf planets and objects beyond the orbit of Neptune) [89Kar, 98Kar], in contrast to silicate volcanism on the terrestrial planets. Also, volatile materials can be pyroclastically erupted or ejected in solid state.

Europa's surface which can be subdivided into plains and mottled terrain in Voyager images [79Smi1, 79Smi2, 82Luc] was thought to have undergone cryovolcanic resurfacing in its recent past, but the comparably low Voyager image resolution did not allow to clearly identify cryovolcanic landforms [04Gre, and ref.'s therein].

Galileo SSI images confirmed that cryovolcanism occurred in the past [04Gre, and ref.'s therein]. Putative cryovolcanic features (e.g. flow lobes) in several localities infer a wide range in viscosities of the source materials, possibly a water/ice slush or slurry [98Gre1]. Locally, ridged plains appear to have been flooded by low-viscosity materials [98Gre1] (Fig. 11 (top)). Active cryovolcanism is believed to occur at present time but could not be detected in Galileo SSI images because of the following two reasons [00Phi]: Either cryovolcanism takes place at a scale not distinguishable in SSI data, or this activity is episodic rather than continuous.

Europa's surface also shows indication for intrusive processes. Linear ridges which are the most widespread landform on Europa possibly formed by intrusion of melt into fractures [98Tur]. Another explanation for double ridges is diapirism of warm ice into linear fractures [99Hea]. Cryovolcanism and/or intrusions (including diapirism) also could have caused the formation of pits, domes, and spots commonly termed lenticulae [04Gre].

Ganymede

Ganymede's surface is subdivided into dark, densely cratered ancient plains covering about 1/3 of its total surface and bright, less densely cratered, heavily tectonized, grooved terrain on 2/3 of its total area [79Smi1, 79Smi2, 04Pap] (see Section 4.2.3.5.3).

In dark terrain, smooth units which embay other surface units such as crater rims, in some parts less densely cratered, where thought to represent cryovolcanic flows, extruded as icy slushes or slurries with darker, rockier components incorporated [98Sch2, 04Pap, and ref.'s therein]. High-resolution Galileo SSI images revealed that dark, smooth units originated from mass wasting processes along slopes rather than cryovolcanism [98Pro].

In the bright terrain, regional- and high-resolution scale images of the Galileo SSI camera revealed that intense tectonism was the dominant process to create and shape Ganymede's bright terrain (see Section 4.2.3.5.3) while cryovolcanism played a comparably minor role [04Pap, and ref's therein].

Several caldera-like, scalloped depressions termed paterae found in the bright terrain represent volcanic vents according to several authors [04Pap, and ref.'s therein] (Fig. 11 (bottom)). Ridged deposits in one of the largest of such paterae were interpreted as cryovolcanic flows [98Hea].

Stereo images (Galileo SSI as well as Voyager) showed that the smoothest units found in a number of localities in bright terrain could have been created by extrusion of low-viscosity cryomagmatic materials [01Gie, 01Sch1]. At highest resolution (10 - 15 m/pxl), also the smoothest units exhibit some degree of tectonicsm, inferring that cryovolcanism and tectonic deformation are closely linked [02Hea].

Callisto

Neither Voyager nor Galileo SSI high-resolution camera data could provide unequivocal evidence for cryovolcanism in the old, densely cratered plains on Callisto [95Sch, 00Gre1, 04Moo2]. Bright, at Voyager resolution smooth possibly cryovolcanic plains in one specific locality could be interpreted as a degraded palimpsest at higher SSI resolution [00Gre1].

Material in dark smooth patches was created by sublimation and degradation processes (see Section 4.2.3.5.4) rather than by cryovolcanism [00Gre1, 04Moo2]. However, the still incomplete image coverage at high resolution leaves cryovolcanism on Callisto as an open issue [00Gre1].

Volcanism on the Saturnian satellites

Mid-sized icy satellites

Smooth plains, possibly indicating cryovolcanic processes involving H_2O-NH_3 melts, active either in the past or even in recent times, were identified on Saturn's mid-sized icy satellites Enceladus, Tethys, Dione, and, less conclusively, on Rhea [81Smi, 82Smi, 83Moo, 83Ple, 84Moo, 85Moo].

Higher-resolution images returned by the Cassini ISS cameras since 2004 demonstrated that the smooth plains observed on these satellites are not of cryovolcanic origin [05Wag, 06Wag, 07Wag1, 07Moo]. No flow fronts or other features indicative of flows or source vents could be detected.

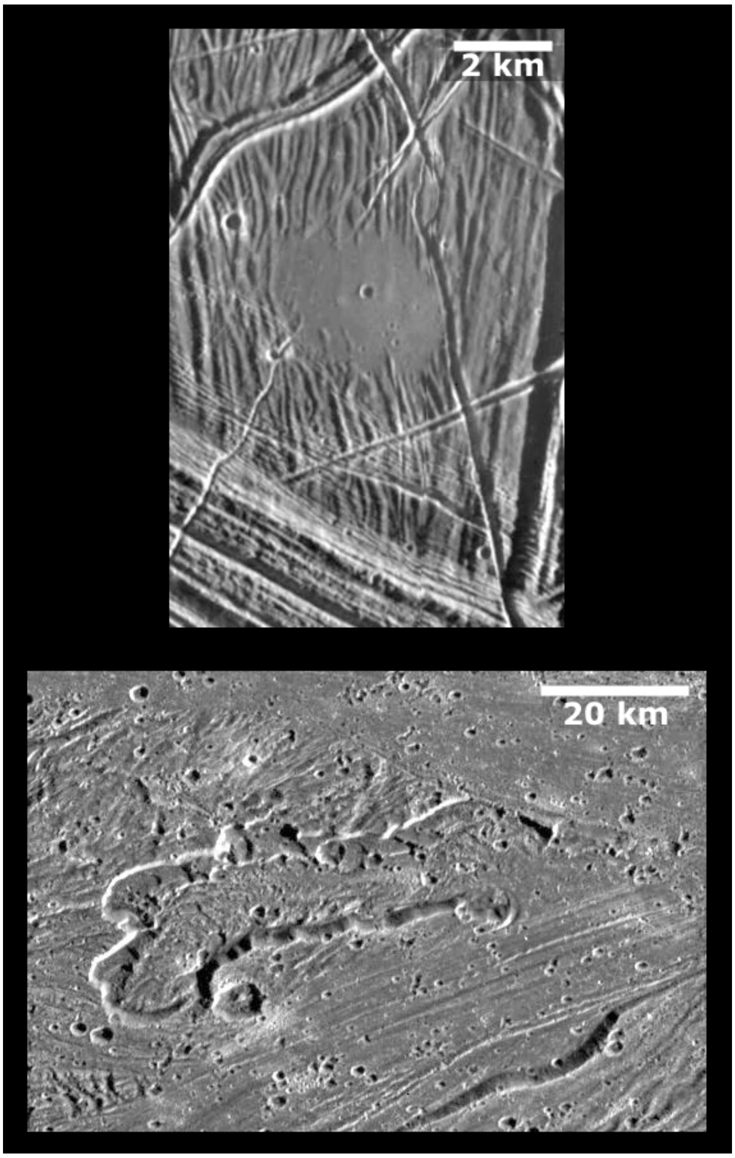


Fig. 11. Landforms indicating possible cryovolcanism on the two icy Jovian satellites Europa and Ganymede. Top: Smooth unit in ridged plains on Europa which could have been created by a low-viscosity flow, possibly by material preferentially consisting of water or of a water-rich solution [98Gre1]. Alternatively, this feature could also have been formed by melting due to a heat source in the sub-surface without extrusive processes [98Gre1]. Part of a Galileo SSI frame with 26 m/pxl resolution, centered at lat. 5.9° N, 326.8° W. Bottom: A caldera-like, scalloped depression (patera) with flow-like features possibly created by cryovolcanism in the Sippar Sulcus area on Ganymede [98Hea]. Part of a Galileo SSI frame with 172 m/pxl resolution, centered at lat. 31° S, long. 189° W. Image source: http://photojournal.jpl.nasa.gov, image ID PIA00592 (top), PIA01614 (bottom). North is pointing toward the top in both images.

Data from the instruments CIRS (used for temperature measurements), ISS and VIMS aboard Cassini verified that (1) Enceladus is volcanically active and that (2) material ejected from this satellite is constantly feeding the E ring [06Por, 06Spe]. The active region is near the south pole in heavily tectonized terrain, with linear source vents termed “tiger stripes” [06Por] (Fig. 12). ISS was able to capture bright jets against the unlit surface of Enceladus for the first time in late 2005 [06Por]. Similar eruptions were observed repeatedly ever since. The south polar terrain of Enceladus is a hotspot region with temperatures several 10s of K higher than in the surrounding terrain [06Por, 06Spe].

Responsible for the present-day volcanic activity of Enceladus may be [06Por]: (1) The higher rock-to-ice ratio in Enceladus, compared to the other icy satellites, (2) tidal heating due to its orbital eccentricity forced by a resonance with Dione, and (3) possibly a so-far undetected measured concentration of ammonia.

Water ice particle sizes across Enceladus's surface were investigated with VIMS data and were found to be more or less correlated with surface age: the younger the age, the larger the particles [08Jau]. The largest particle sizes are abundant in the volcanically active areas.

Titan

With a diameter of 5150 km the second-largest satellite in the Solar System Titan is speculated to be large enough to have been cryovolcanically active [e.g. 96Lor].

Data obtained with the Radar instrument aboard Cassini revealed landforms which provide evidence that effusive cryovolcanism may have shaped the landscape of Titan. A large, circular feature 180 km in diameter, Ganesa Macula, was interpreted as a volcanic dome or shield volcano [07Lop2]. Deposits with lobate boundaries are morphologically similar to volcanic flow features on Earth or Venus and therefore could represent cryovolcanic flows [07Lop2].

Caldera-like features, reminescent of those seen in Galileo SSI data on Ganymede (Fig. 11 (bottom)), were detected in the Cassini Radar data [07Lop2]. Flows emanate from the calderas which supports a cryvolcanic origin. Small circular features could be either impacts or cryovolcanic calderas [08Lun1].

Volcanism on the Uranian satellites

Smooth plains on the major satellites of Uranus, Miranda, Ariel, Umbriel, Titania and Oberon, were interpreted as units created by extrusion of fluid cryovolcanic materials [98Sch2]. On Oberon, crater floors (e.g. craters Hamlet and Othello) are covered by very dark, smooth material. Possibly triggered by the impacts which created these craters, fluid materials extruded on the crater floors, either originally dark, or darkening with time [86Smi, 91Cro]. One possible explanation for the global dark coating on Umbriel is explosive eruption of material from the interior, driven by methane [84Ste, 86Smi]. A smooth bright unit on the floor of crater Wunda on Umbriel also was interpreted as cryovolcanic in origin [91Cro].

Cryocolvanic extrusion of liquid material on canyon floors (e.g. in Kewpie Chasma) and outside the canyons at high latitudes on Ariel was inferred for the origin of smooth units seen in these areas [86Smi, 91Cro]. Repeated extrusions of highly viscous material – either explained by a (1) axial-eruption model [86Smi] or by a (2) lava-tube eruption model [88Jan] – and/or subsequent faulting caused the formation of medial grooves and ridges [86Smi]. Similar smooth plains units were reported from canyons on Uranus' largest satellite Titania (e.g. Messina Chasmata) [86Smi, 91Cro]. Cryovolcanism is also most likely associated with the features termed coronae on Miranda [91Cro, 91Grn].

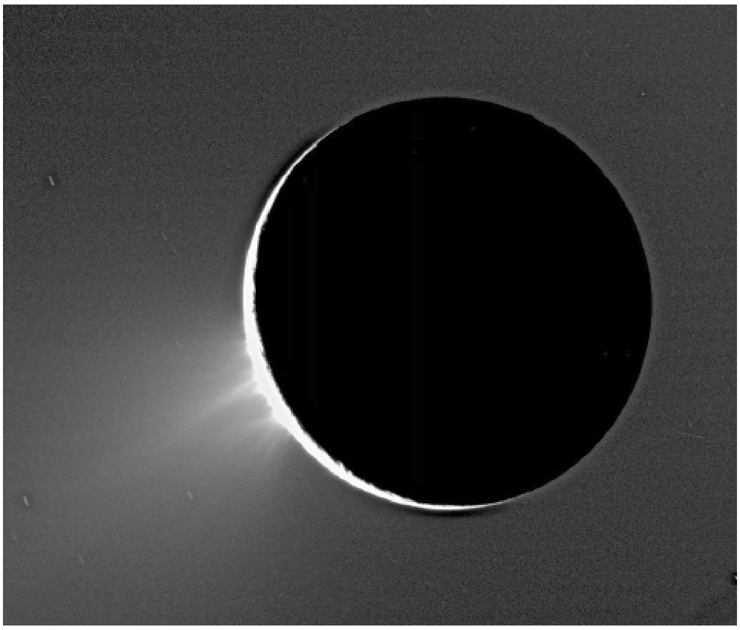
The most likely candidates for fluids creating these features on the cold Uranian satellite surfaces are mixtures or assemblages of water ice and ammonia with varying concentrations of each species, e.g. ammonia dihydrate (~ 32% NH_3) [86Smi, 98Kar].

Volcanism on the Neptunian satellites

Extensive plains on Triton support an origin by cryovolcanic activity. A smooth to undulating plains unit extends over several hundred kilometers, originating at an 80-km wide caldera-like structure (Leviathian Patera) [89Smi, 95Cro]. Plains units are also found in several up to 200 km large lake-like depressions bounded by terraced scarps [89Smi, 95Cro] (Fig. 13). Clusters of pits near the centers of these plains could represent source vents where liquid material extruded.

Some authors reported flow fronts, small domes, ridges and hummocky plains to be indications for cryovolcanism on Triton's surface, but a volcanic origin of these features is equivocal [e.g. 95Cro, 98Sch2, and ref.'s therein]. A cryovolcanic origin of the so-called cantaloupe terrain in connection with subsequent modification by erosion and degradation (Ref. 4.2.3.5.4) was discussed by e.g. [89Smi].

That Triton, like Earth, Io and Enceladus, is a volcanically active body at present times could be verified during the Voyager-2 encounter in 1989. High-emission angle views of the satellite limb at high southern latitudes revealed active dark plumes suggestive of geyser-like activity [89Smi]. Originating from a dark spot on the surface, a dark stem rises more or less vertically up to an altitude of about 8 km and then extends horizontally over a distance of 150 km an more. Possibly an inversion exists at a level of 8 km causing the abrupt change from vertical to horizontal movement of the plume material.



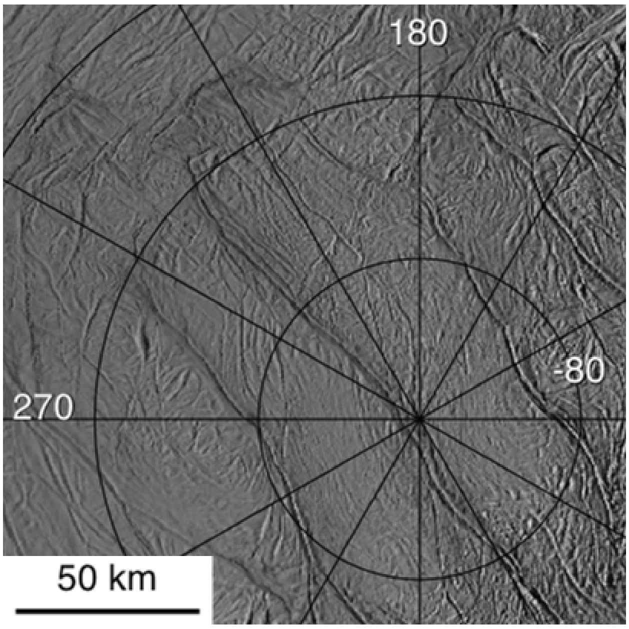


Fig. 12 Present-day cryovolcanism on Saturn's satellite Enceladus. **Top:** Jets of H_2O particles ejected by pyroclastic eruptions originating in the south polar terrain (SPT) of the satellite, captured by the Cassini ISS narrow angle camera [06Por] (Pic. ID: PIA07758). The particles feed Saturn's E ring. **Bottom**: Detail of the highly tectonized south polar terrain (SPT) of Enceladus with dark fractures or gooves (termed *sulci* [08Roa1]) which were identified to be the source vents of the pyroclastic eruptions (Pic. ID: PIA10360 (part); longitudes in degrees West).
Image source: http://photojournal.jpl.nasa.gov.

Emplacement of viscous material composed mostly of water-ice and ammonia, similar to the eruption styles observed on the Uranian satellites, is believed to have formed the cryovolcanic units on Triton [e.g. 89Smi]. Nitrogen and/or methane were discussed as major gas materials driving the geyser-like plumes, entraining fine dark particles up to an altitude of 8 km which eventually are transported downstream by winds in Triton's atmosphere. Non-volcanic origins for the plumes where also discussed, such as solar insolation and sublimation, or sublimation due to intrusion of liquid material into volatile-rich material in the upper crust [e.g. 89Smi].

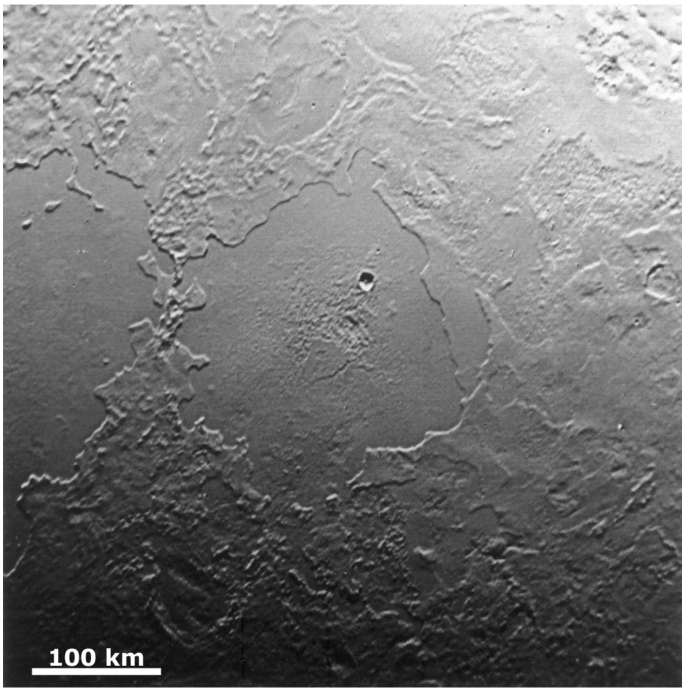


Fig. 13. Landforms on Triton indicative of past cryovolcanic activity, seen in Voyager-2 images obtained during its August 1989 flyby. The image scene is dominated by two lake-like, scarp-bounded and terraced structures, possibly former calderas where fluid material was emplaced. Clusters of pits, superimposed by a single, approximately 10 km large, fresh impact crater, may represent source vents. The low freqency of impact craters is an indication of a young surface age. Image source: Planetary photojournal (http://photojournal.jpl.nasa.gov, image ID: PIA05138, North is pointing upward).

4.2.3.5.3 Tectonics

Tectonic structures are known from the surfaces of all terrestrial planets and the Moon. They reflect the deformation of the crust by internal forces and, therefore, put important constraints on models of the interior evolution of planetary bodies. Here we first introduce the basic fault types and the most important styles of tectonism, before we give short overviews of the structural geologic inventory of Mercury, Venus, the Moon, and Mars. A full discussion of the tectonics of these bodies is beyond the scope of this paper, and instead the reader is referred to the literature cited.

Fault types

The deformation of planetary lithospheres by mechanical stresses produces tectonic structures like faults and folds. The style and levels of tectonism provide important constraints on models of the interior of a planet or moon, since they are intimately linked to the heat transport and are indicative of the vigor of internal processes (see Section 4.2.3.4). Tectonic features are observed on all terrestrial planets and the Moon, although in different relative importance [e.g., 81Hea, 94Gre]. The basic fracture types are the same on all planets and Moons: mode I fractures are opening fractures, where the relative motion is normal to the fault plane (e.g., joints). Mode II fractures (sliding mode; shear fractures) are characterized by relative displacement parallel to the fault plane, and mode III fractures (tearing mode) display motion parallel to the tip line of the fault. Joints are usually too small for observation in orbital imagery, although they are known to control the preferred orientation of large-scale erosional structures. Very high-resolution images of Mars (25 cm/pixel) allowed the first-ever direct identification of jointing in sedimentary rocks [07Oku]. Most recognized faults on planets and moons, however, are shear fractures: Normal faults, reverse faults, and strike-slip faults (for a modern text on structural geology see [05Pol]). Examples of the various appearances of planetary tectonic faults are shown in Fig. 14. Extensional features include normal faults, grabens and halfgrabens [07Sch2], and more complex and larger structures like rifts. While normal faults and (half)grabens are found on all terrestrial planets, the Moon, and on several icy satellites, rifts are restricted to the larger bodies Earth, Venus, and Mars. It has to be noted, however, that some moons of the outer satellites, like Tethys and Dione, also display rift-like features in their icy crusts [e.g., 07Gie1]. Contractional features are reverse faults as well as folds. On larger scales, they can form fold-and-thrust belts, which are only known on Earth and Venus [92Sup]. The terminology of some other planetary contractional tectonic features is more descriptive than genetic: Lobate scarps are asymmetric positive topographic features, which are linear or arcuate in plan view, with a steeply sloping scarp face and a gently sloping back scarp [e.g., 98Wat]. They are thought to be surface-breaking thrust faults (thrust faults are reverse faults with very low-angle fault planes). Wrinkle ridges are also positive topographic structures, characterized by a broad arch with a superposed “wrinkle” structure. There are several structural interpretations, most of them involving a combination of folding and contractional faulting (fault-propagation folds, i.e. folds in a layered sequence like sediments or a stack of lava flows over a blind thrust fault; e.g., [93McG], [01Gol], [00Sch2]). Strike-slip faults (sometimes also called wrench faults) are relatively rare on terrestrial planets, with the exception of Earth. The only other terrestrial planetary bodies showing evidence for them are Venus and Mars [e.g., 89Sch, 98Koe], and some icy moons in the outer solar system. This limited presence on these planets is not very surprising, since strike-slip faulting is a characteristic tectonic signature of plate tectonics, which is currently operating only on Earth (see below). Their existence on Venus and Mars, in the absence of plate tectonics, might be explained by perturbations of mantle convective stress fields due to structural heterogeneities in the crust [e.g., 98Koe]. A perspective of modern structural geology and possible new applications to planetary science is given by [99Sch].

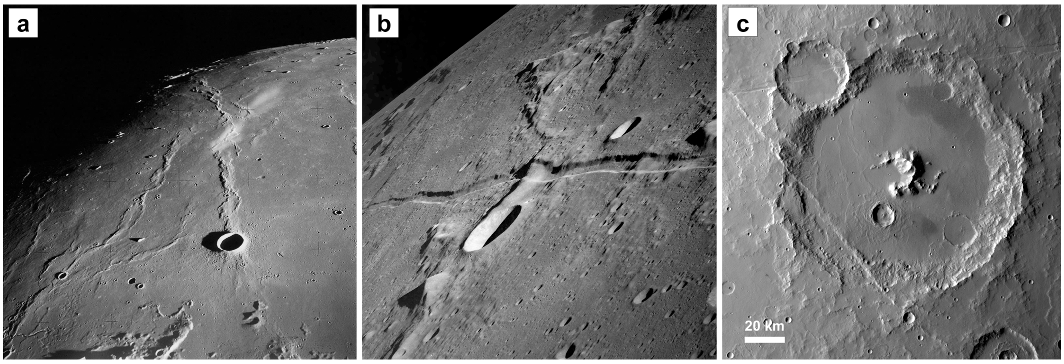


Fig. 14. Surface appearance of major fault types on planetary surfaces. **(a)** Wrinkle ridges in lunar mare basalts (image: NASA). **(b)** Linear graben bounded by two parallel normal faults, cutting the lunar surface. A review of the nomenclature of normal faults is given by [00Pea] (image: NASA). **(c)** The diagonal surface feature cutting the impact crater on Mars is interpreted as a strike-slip fault by [08And3] (HRSC image mosaic).

Styles of tectonism

While the local and regional deformations and associated faulting patterns on the bodies of the inner Solar System are quite similar, the global styles of geodynamic processes and their associated structural geologic features are unique for each body. As an example, vertical tectonic movements due to lithospheric loading or uplift can be encountered on all terrestrial bodies. They are controlled by the thickness and rheology of the lithosphere [81Hea]. On the other hand, the global tectonic style is controlled by the internal dynamics. Two tectonic end-member regimes are related to mantle convection [07ONe]: Active-lid convection involves the foundering and stirring of cold lithosphere into the mantle [e.g., 98Mor, 04Sol1, 04Sol2]. The only known example of this tectonic regime in the Solar System is plate tectonics on Earth. The other end-member, applying for most terrestrial planets and moons, is the stagnant lid regime. It is characterized by mantle convection beneath a strong, intact and immobile lithosphere [91Oga, 95Mor, 97Sol, 00Sol], which is why such bodies are called “one-plate planets”. An intermediate regime was envisaged by [98Mor], in which convection occurs as catastrophic overturns of the stagnant lid followed by a period of quiescence, thereby oscillating between the active and stagnant modes.

The mineralogy and internal dynamics of terrestrial planets are functions mainly of the mass of a body and its capability to retain light elements like water, and of the distance to the sun [07Alb]. Earth is the only planet with significant amount of water in the lithosphere and atmosphere. Even small amounts of water can dramatically reduce the strength of rocks, allowing the lithosphere to break into plates. Cold crust sinks into the mantle, rehydrates it and thereby lowers its viscosity by several orders of magnitude [96Hir]. The lithosphere can bend, the mantle can yield, and in this way the mantle hydration might mark the onset of plate tectonics [07Alb]. The resulting global topographic signature of plate tectonics is a two-peaked or bimodal hypsometric curve, representing continents and ocean floors. Venus, while almost identical in size, does not exhibit signs of this tectonic style. The main explanation seems to be the lack of water in the lithosphere and atmosphere, causing a high relative stiffness, which acts against subduction [98Nim]. Consequently, the hypsometric curve is characterized by one peak only, which corresponds to the vast volcanic plains with elevations close to the mean planetary radius [94Ros]. The opposite end-member of the terrestrial bodies, compared to the water-rich Earth, is the small Moon, which lost its volatile content early due to its low gravity. After the cooling of a magma ocean [e.g., 70Woo, 73Sol, 06She], the mantle had probably been consolidated early (3.8 Ga), documented by high relief differences in the lunar highlands. A similar scenario is plausible for Mercury. Only limited evidence for tectonic activity is visible on the Moon and Mercury, mainly caused by contraction due to global cooling, local loading by volcanic basin fillings, and impact tectonics [05Koe]. Mars is intermediate between the Earth and the Moon. Mars had a more active volatile cycle in the past than today, including water, but the nature and the duration are not very well constrained [e.g., 01Jak]. It is not clear whether plate tectonics ever operated on Mars (see below). The preserved tectonic record points to the response of an elastic lithosphere to loading processes (e.g., by plume-induced volcanism) and to global contraction. Plume- and basin-related tectonism seems to be the main tectonic style. The concept of plume tectonics was developed [e.g., 94Mar] following the recognition that plate tectonics fails to account for all aspects of terrestrial tectonics. It should be mentioned here that the plume model [71Mor], after it was almost universally accepted for a long time, was recently criticized by several authors. A discussion of this "plume debate" is beyond the scope of this text. Instead, the reader is referred to recent collections of papers that are available in favour of plumes (see [07Cam] and papers discussed therein) and in opposition to plumes [05Fou].

Moon and Mercury

The smaller bodies like the Moon and Mercury are thought to have experienced an earlier decrease of significant internal heat production, as compared to Earth or Venus. The internal heat production drives the endogenic processes volcanism and tectonism. Consequently, the structural geology of the small terrestrial planets Moon and Mercury is characterized by relatively few and old features. Moon and Mercury are considered to be one-plate planets, i.e. their lithosphere is made up of a single spherical shell.

Most lunar faults are associated with volcanic loads (e.g., in basins), which bend the elastic lithosphere downwards and lead to the generation of concentric extensional features (normal faults or grabens) at the edges of the basins and to contractional features in the interior of the basins [80Sol, 87Wil]. More globally distributed faulting would be expected from global expansion and contraction due to heating and cooling, respectively. The lack of such globally distributed tectonic features on the Moon suggests that there were no significant changes in the radius of the Moon since the formation of the presently observed surface, which is about 3.9 Ga old [93Gol]. A modern review of the lunar surface geology, which includes a section on tectonic processes, is given by [06Hie].

The lithosphere of Mercury has experienced both tensional and compressional stresses [88Mel, 88Tho, 07Hea2]. Extensional features are rare, however, and have so far been observed only in the interior of the 1550-km-diameter multiring basin Caloris. They are interpreted to be the result of the flow of a thick crust towards the basin center and the associated uplift and extension of the basin floor [05Wat], a model that was recently questioned by [08Ken] who tested a range of models of lithospheric structure and surface loading by finite element modelling. Recently, new images from the MESSENGER mission have revealed a (so far) unique tectonic feature, which is a set of grabens radiating outwards from a common center, at or near of which is an impact crater located. The origin of this pattern is unknown. Far more important than extensional features are contractional features on Mercury. Three types are known: Wrinkle ridges, lobate scarps, and high-relief ridges (symmetrical positive topography, thought to be the surface expression of high-angle reverse faults). While wrinkle ridges are confined to the interior of the large, 1550-km-diameter multiring Caloris basin, lobate scarps are more widespread [e.g., 08Wat] (Fig. 15). It has been suggested that lobate scarps reflect crustal shortening due to internal cooling and global planetary contraction. Recent mapping of lobate scarps on the part of Mercury that was imaged by the Mariner 10 spacecraft revealed that lobate scarps are not uniformly distributed and that the direction of the dip of the fault planes is also not random. A possible explanation is that lobate scarps formed by a combination of regional-scale compressional stresses and of stresses from global thermal contraction [04Wat]. The source of regional stresses on a small planet like Mercury is not known, but mantle convection under a stagnant lid regime might have invoked stresses that could have deformed a thin elastic lithosphere (25 - 30 km). Alternatively, gravitational Rayleigh-Taylor instabilities might have transmitted shear stresses to the base of the crust, causing crustal thickening [04Wat]. The first images of the MESSENGER mission seem to indicate that lobate scarps are also widely distributed on the previously unseen hemisphere. Contrary to previous estimates, at least some lobate scarps seem to be embayed by Caloris ejecta (Caloris is the largest known impact basin on Mercury and formed about at the end of the heavy bombardement), and are therefore older [08Sol]. Further evidence for an older than previously assumed age of lobate scarps comes from the new observation that some large impact craters overprint lobate scarps [08Wat, 08Sol].

In summary, faulting on the smallest terrestrial bodies is dominated by local loading, mainly from impacts, and global contraction due to secular cooling [77Sol]. Recently, however, numerical simulations suggested that an ancient pattern of Hermean mantle convection might have contributed to the formation of lobate sarps [08Kin], so the tectonic history of Mercury might have been more complex than previously thought.

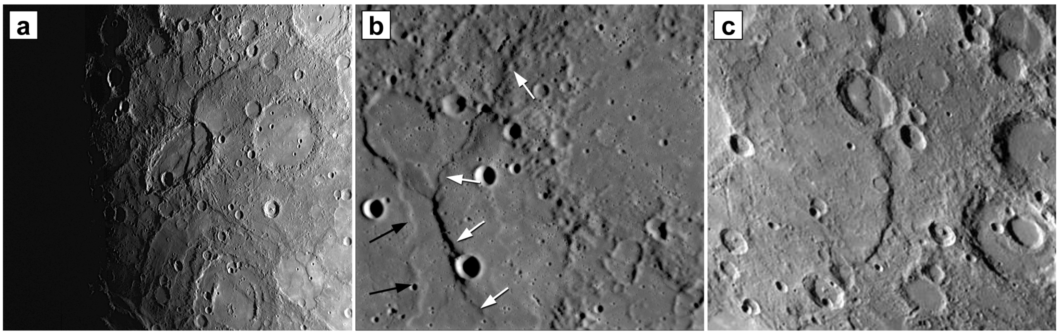


Fig. 15. Examples of tectonic surface features on Mercury. **(a)** Beagle Rupes is more than 600 km long and one of the largest fault scarps on Mercury. Here it crosscuts Sveinsdóttir crater (image center; diameter 120 km × 220 km) and uplifted the easternmost (right) portion of the crater floor by almost one kilometer, indicating post-impact tectonic activity. Image: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington. **(b)** A classic lobate scarp (black arrows) crosses the crater floor, the crater rim, and continues off the top edge of the picture. In contrast, several wrinkle ridges (white arrows) are restricted to the crater floor. Image: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington. **(c)** Discovery Rupes, one of the most prominent lobate scarps on Mercury, as seen in Mariner 10 images. Image: NASA.

Mars

Besides widespread evidence for volcanism, intense tectonic deformation of the lithosphere attests to the vigorous endogenic activity of Mars. Both contractional and extensional structures can be observed globally, although the overwhelming majority of extensional structures in particular are associated with the Tharsis bulge. Strike-slip faults are rare, but a few examples have been described in Tharsis. A comprehensive review of Martian tectonic structures is provided by [92Ban].

Mars, like the Moon or Mercury, is a one-plate planet. There is no morphological signature of plate tectonics, and the conceptual plate tectonics-scenario of [94Sle] has not gained wide acceptance. However, a very early phase of plate tectonics could explain the dynamo activity [00Nim] and would have avoided early massive melting on Mars [02Hau]. Its morphological traces might have been overprinted by later resurfacing processes. Currently, such a scenario can not be ruled out [04Len], although it is difficult to reconcile with thermal evolution models [03Bre] (see Section 4.2.3.4).

The single largest tectonic feature on Mars is the global dichotomy, which separates the southern highlands from the northern lowlands [07Wat, 08Kie]. It was long thought that the northern lowlands, showing an apparently younger (i.e. less cratered) surface in images, were created much later than the southern heavily cratered highlands. When highly accurate topographic data from laser altimetry became available, it became obvious that many large craters in the northern lowlands have a very subdued topographic expression, obscuring their visibility in imaging data. If these craters are considered, the crust in the northern lowlands seems to be as old as in the southern highlands [02Fre, 06Fre]. The origin of the dichotomy is unknown. Two main models exist: A formation by a giant impact [84Wil2], and endogenic processes related to mantle convection, e.g., convective overturn of the interior [79Wis] or degree-1 convection [01Zho, 06Rob]. Recently, several studies revived the impact theory [08And2, 08Nim, 08Mar], which had been rejected after the first analyses of the MOLA topographic dataset [99Smi, 01Smi].

Except for the dichotomy, the Tharsis rise in the western hemisphere and the formation of Isidis Planitia and the Elysium rise in the eastern hemisphere clearly dominate the tectonic map of Mars (Fig. 16) on a global scale [08And1]. The most striking large-scale tectonic feature in the Tharsis-dominated western hemisphere is a pattern of extensional features, mostly long and narrow simple grabens, radiating outwards from several centers within Tharsis [01And]. These grabens are interpreted to have an “hourglass” subsurface structure and to indicate thick-skinned tectonics [07Schu2]. Several studies suggest that volcanic dikes may underlie the long, linear grabens [e.g., 96Mèg1, 02Wil1], and that the radiating graben sets are the surface expression of giant radiating dike swarms [01Ern1]. It has to be noted, however, that this interpretation is not universally accepted and that separate local dike swarms might be associated with single graben segments [03Mèg].

Contractional features are wide spread on Mars (for a review, see [04Mue]). In the western hemisphere, most wrinkle ridges are arranged in a concentric pattern around Tharsis. The concentric pattern of contractional features formed as a result of Tharsis and an additional horizontally compressive stress field, which was caused by global contraction [e.g., 93Wat, 01Gol, 07And]. The idea that there was a single and global origin of the compressional deformation on Mars [00Man] has recently been questioned by [07Nah], who analyzed the fault data set by [06Kna] and found that there is no significant episode of compression from global contraction of Mars. Topographic data of wrinkle ridges suggest that the deformation of the lithosphere reaches down to tens of kilometers, again indicating thick-skinned tectonics [95Zub1, 01Gol], rather than previously proposed thin-skinned folding [91Wat]. High-resolution topographic and gravity data show that the geometric pattern of radiating extensional features and concentric contractional features can best be explained by flexural loading stresses, induced by loading of Tharsis volcanics and the membrane-flexural support of the rise [00Ban2]. Tharsis, which is the key to the tectonic evolution of Mars, is often considered to be the possible expression of a hot spot or mantle plume. The Tharsis-related fracture sets are, therefore, often ascribed to plume tectonics [e.g., 96Mèg2, 07Bak].

About five large and complex rift structures, which are similar in dimension and structural architecture to terrestrial continental rifts [e.g., 01Hau], are also located at the periphery of Tharsis. It is not clear whether they are associated with the same stresses that caused the radiating grabens, since some of these rifts have an along-trend orientation which is not radial, but rather tangential to Tharsis. One possibility is that they are related to stresses caused by gravitational potential energy in combination with weak lithospheric zones associated with volcanism [06Dim, 07Gro].

The different fault sets on Mars have different ages. The tectonic evolution is often subdivided into five stages [01And], ranging in age from the end of the Noachian to the Amazonian epoch. A comprehensive catalogue of Martian faults together with their maximum ages is described by [06Kna]. As for the volcanism, tectonic activity seems to have peaked early and has gradually waned with time (see Section 4.2.3.3), although punctuated by episodes of higher and lower intensity. Minor centers of tectonic activity seem to be associated with ancient impact basins (e.g., Utopia) or other volcanic provinces (e.g., Elysium, Hesperia Planum). In general, the tectonic deformation seems to be mainly associated with impact basins and large volcanic provinces. Vertical deformation is dominant, and no evidence for plate tectonics is visible.

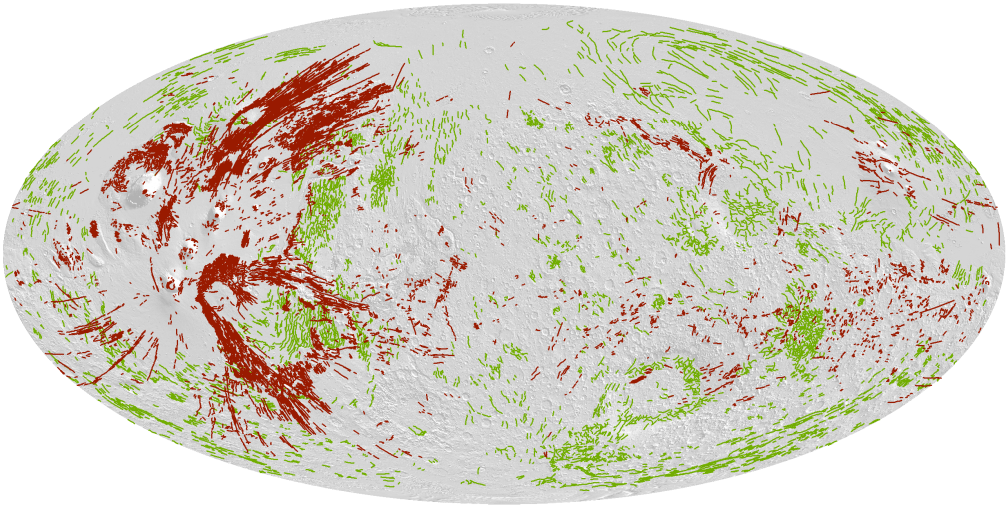


Fig. 16. (see also color-picture part, page 621) Global tectonic map of Mars (Mollweide projection centered at 0° longitude) [06Kna]. Red lines mark extensional faults (normal faults, grabens, rifts), green lines mark contractional features (thrust faults, wrinkle ridges). The majority of faults are associated with the largest volcano-tectonic province on Mars, Tharsis, in the western hemisphere.

Venus

Venus is the planet with the most numerous and diverse tectonic structures next to the Earth (Fig. 17). The most striking characteristics of Venus` surface and tectonism is the apparent lack of plate tectonics. A lack of plate tectonics is indicated by the globally random distribution of impact craters, which would not be expected on a planet with plate tectonic-style resurfacing. A lack of Earth-like plate tectonics is also indicated by the general absence of linear alignments of volcanoes, as it is common on Earth along plate boundaries. The spatial pattern of magmatic structures is mostly more indicative of blistering of the crust by magma diapers than by plate tectonics, suggesting that vertical deformation prevails over horizontal deformation [93Han]. The lack of tectonic deformation of circular structures like coronae and impact craters, which display a pristine appearance, suggests that there is no plate tectonics working on Venus since the global resurfacing event (see Section 4.2.3.5.2). Evidence against plate tectonics also comes from global topography, which does not display an interconnected network of linear trenches or mountain chains [07Smr], the hallmarks of terrestrial plate tectonics. Instead, the topography is characterized by many circular or elongated discrete features, which are attributed to uplift or subsidence. Finally, the unimodal distribution of the Venusian surface elevations [94Ros] is markedly different from Earth`s bimodal hypsometry, caused by the existence of old continents and younger ocean floors as a consequence of sea-floor spreading. In contrast to Earth, the surface of Venus can be subdivided into three major domains: Volcanic plains form the largest part of the surface, intensely deformed tessera form upland plateaus, and broad topographic rises are associated with volcanoes and converging rifts [e.g., 03Bas].

Numerous reviews discuss the tectonic history of Venus [e.g., 84Phi, 91Phi, 92Sol, 94Phi, 98Nim]. A major debate concerns the sequence of tectonic events on the Venusian surface. In contrast to the other terrestrial bodies in the inner Solar System, the unique crater inventory largely prevents the dating of surface units on Venus by conventional crater statistics (see Section 4.2.3.5.1). The spatial distribution of the only known ~ 940 impact craters can not be distinguished from a random one [e.g., 92Sch], a fact which has often been interpreted as the result of a global resurfacing event in the last 300 Ma to 1 Ga [97McK]. It should be noted, however, that a partly non-random distribution seems to be possible [98Hau]. The more or less random crater distribution and the problem of dating have led to fundamentally different views of the global evolution of Venus. One school of thought proposes that the evolution of Venus was directional, i.e. that major geological events on Venus did not only produce the same global stratigraphy everywhere on Venus [e.g., 98Bas, 00Bas], but that these events also occurred simultaneously all over the globe. The other end-member opinion considers the observed sequence of units to be the result of a specific sequence of volcano-tectonic regimes occurring in different areas of the planet at different times [e.g., 99Gue]. These two hypotheses correspondingly represent synchronous and diachronous interpretations of the geologic history [see 02Bas2]. A major criticism of the concept of a global Venusian stratigraphy comes from the recognition that it is problematic to map secondary (i.e. tectonic) structures as primary (i.e. material) units [00Han1]. On the other hand, [07Bas1] point out that tectonic fracturing can be so pervasive that no reliable interpretation of primary material properties is possible, so that in some cases the delineation of tectonically deformed zones can be useful. For a more in-depth discussion of this debate, the reader is referred to the recent review of Venusian surface evolution by [07Bas1].

Contractional tectonic features on Venus are widespread and include wrinkle ridges as well as larger-scale ridge belts. Many wrinkle ridges can be observed all over Venus, affecting more than 40% of all plains surfaces [e.g., 99Bil]. They are concentrated in low elevations and are associated with negative geoid anomalies. Ridge belts are 200 - 2000 km-long and relatively narrow (30 - 400 km) areas with a slightly elevated topography above the adjacent regional plains. Individual ridges are less than ~ 500 m high, 5 - 20 km wide, and up to 100 - 200 km long with a spacing of about 25 km [07Smr]. It is thought that large ridge belts formed as contractional features as a consequence of convective mantle downwelling, characterized by topographic subsidence followed by tectonic thickening of the crust [e.g., 90Zub]. Fold-and-thrust belts accommodate large-scale horizontal crustal convergence and form mountain ranges surrounding the volcanic plateau Lakshmi Planum in the Ishtar Terra region [e.g., 92Sup, 94Kee]. They are considered to be the result of thick-skinned deformation, involving horizontal shortening of a laterally heterogeneous lithosphere [95Zub2].

Extensional tectonic features are also widespread and consist of relatively simple fractures and grabens, often grouped in fracture belts, as well as more complex rift structures. Fracture belts are highly fractured zones that can be embayed by regional plains lavas, and, on the other hand, can fracture regional plains. Therefore, it seems possible that the relatively old process creating fracture belts was more extensive than what can be observed from their present-day distribution [07Bas1]. Within the fracture belts, fracturing is more homogeneous than in rift zones, and the fracture trends are less sinuous.

Rift zones on Venus are characterized by complex extensional faulting, central rift valleys, and uplifted rift flank topography [e.g., 89Stf]. The remarkable similarity of Venusian and terrestrial rifts, e.g., the East African Rift System, were recognized by many researchers [81McG, 82Schb, 84Cam, 96Fos]. Rift systems, called chasmata (singular: chasma), can reach lengths of up to 4000 km, widths of 150 - 300 km, and depths of 5 km [92Sen]. Individiual normal faults may be as long as 100 km [96Fos]. A spectacular confirmation of significant crustal extension at Venusian rift zones comes from the observation of an impact crater located in the rift between Rhea and Theia Montes in Beta Regio (Fig. 17a). A total extension of ~ 20 km has been determined for Devana Chasma, one of the most prominent rift systems on Venus [06Kie]. An extension of this magnitude is comparable to continental rift systems on Earth. Venusian rift zones are often located on domal topographic highs, which might have formed in response to mantle heterogeneities, i.e. plumes [89Stf, 05Sto, 07Bas2].

Strike-slip faults do occur on Venus [e.g., 95Bro, 98Koe, 03Tuc], although they are of lesser importance than on Earth, where they are characteristic of horizontal motions of the tectonic plates which constitute the terrestrial lithosphere. On one-plate planets, the dominant deformation is vertically oriented (e.g., [81Hea], for the case of Venus, see [91Phi]). The question is, then, what tectonic forces are responsible for the observed strike-slip faulting on Venus? One explanation, put forward by [98Koe], might be that during mantle downwelling [92Bin] a perturbation of the mantle convective stress field might have led to horizontal compressive stresses in the lithosphere, which is coupled to the mantle stress field. Usually, this situation leads to the formation of deformation belts [e.g., 92Squ, 95Zub2]. If the maximum compressive stress is slightly rotated away from belt normal, this may induce lateral shear across the belt and initiate secondary fractures.

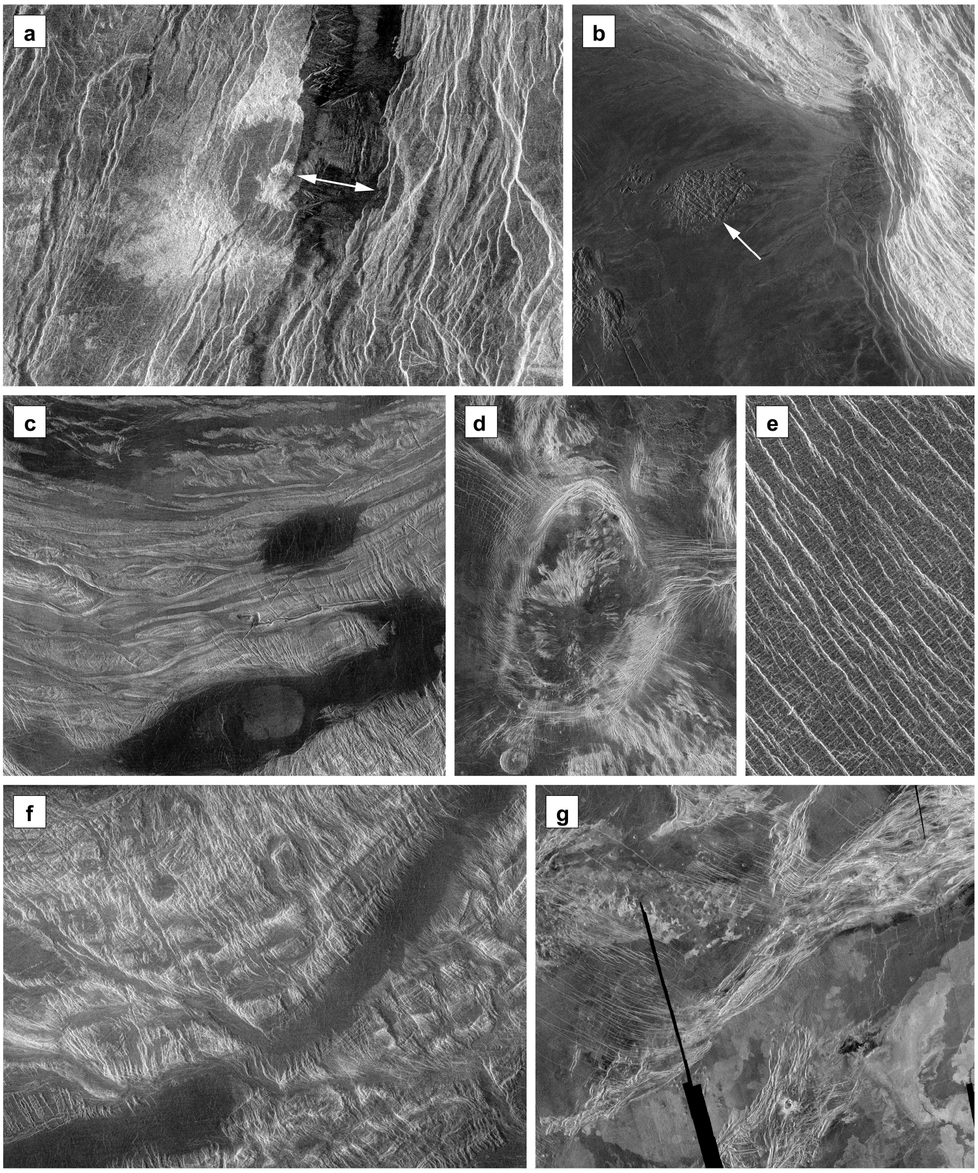


Fig. 17. Examples of tectonic surface features on Venus. **(a)** An example of rifting on Venus: A large crater in the image center with 37 km diameter (29.9°N/282.9°E) is destroyed during the formation of a 20 km-wide rift valley (white arrow). The easternmost part of the crater rim is just visible to the right of the dark rift valley [92Sol]. **(b)** Mountain belts: Smooth, radar-dark lava flows of Lakshmi Planum (65°N/0°E) embay isolated tessera terrain (arrow), made up of intersecting 1 to 2 km-wide grabens. Maxwell Montes, the highest mountain on the planet, rises to an elevation of 11.5 km and is part of a series of mountain belts surrounding Lakshmi Planum. It is interpreted to have formed by compressional tectonics (image width 300 km). **(c)** Ovda Regio is one of the large highlands ringing the equator of Venus. Low-relief, rounded linear ridges, 8 - 15 km wide and 30 - 60 km long, have locally been cut at right angles by extension fractures. The curvilinear, banded nature of these ridges suggests that crustal shortening, roughly oriented north-south, is largely responsible for their formation (1°N/81°E). Image height is ~ 225 km. **(d)** Coronae are volcano-tectonic features that are probably unique to Venus. Shown here is Bahet corona (230 km × 150 km; at 49°N/2°E), surrounded by a ring of ridges and troughs, which in places cut more radially-oriented fractures. The center also contains radial fractures as well as volcanic domes and flows. Coronae are thought to form due to the upwelling of hot material from deep in the interior of Venus. Note the small ‘pancake’ dome just to the southwest of Bahet. **(e)** Cross-cutting faults at 30°N/333.3°E. The fainter lineations are spaced at regular intervals of about 1 km. Their width is at the resolution limit of Magellan images. The brighter, more dominant lineations are less

regular and, in places, appear to begin and end where they intersect the fainter lineations. It is not clear whether the two sets of lineations are faults or fractures, but in other Magellan images, these bright lineations are associated with pit craters and volcanic features. This type of terrain has not been seen on Venus nor on other planets. Image width is ~37 km. **(f)** Tessera terrain: Several tectonic events formed this complex fractured terrain in Ovda Regio. An underlying fabric of ridges and valleys strikes NE-SW. The ridges are spaced 10 - 20 km apart and may have been caused by crustal shortening. They are cut by extension fractures trending NW-SE, suggesting a later episode of NE-SW extension. Lastly, the largest valleys, particularly the 20 km-wide one extending across the image, were probably filled with lava. The complex internal fabric of Ovda Regio attests to a long history of tectonic deformation (1°S/81°E, image width ~ 225 km). **(g)** Compression and strike-slip faulting: A ridge belt (the bright area running from the upper right to the lower left) is embayed by radar dark (and thus presumably) smoother lavas (50°S/345°E). NW-trending secondary fractures may have been formed during ridge belt-parallel strike-slip motion [98Koe]. All images: NASA/JPL.

Regional volcanic plains, whose surface lies close to the mean planetary radius (MPR = 6051.5 km above the planet's centre of mass), cover about 80% of the surface [03Bas]. Low and broad ridge belts extend for thousands of kilometres across the plains and suggest gentle folding and shortening. Complicated networks of wrinkle ridges are observed on the surfaces of the majority of the plains and are further evidence for compressional deformation.

The oldest and most intensely deformed areas on Venus are the so-called tessera terrains. The name comes from the Latin (and originally Greek) word for tile (tessera), because the appearance of the first identified example of this type of terrain resembled a tile roof in the Venera radar images [86Bar]. Tessera are characterized by both contractional and extensional tectonic structures, and the term has been used to describe regions of deformed crust displaying two or more intersecting sets of structural elements. However, tessera includes terrains of several types [96Han], formed by a variety of spatially and temporally discrete tectonic processes [98Han]. Their chemical composition is unknown. They might be basaltic, but some studies suggest that they consist of more feldspathic material, somewhat resembling anorthosites on the Moon or granites on Earth [92Nik].

Tessera terrain comprises isolated areas that stand elevated above the surrounding regional plains, and are mostly exposed within crustal plateaus. This is perhaps due to a thicker crust, though there is no consensus whether this is due to upwelling and magmatism [91Gri, 94Phi, 00Han2] or downwelling and compression [90Bin, 91Len, 92Bin, 98Gil].

Large volcanic rises on Venus have been categorized into three classes: rift-dominated rises, corona-dominated rises, and volcano-dominated rises [95Sto]. In general, the rises are thought to be formed by mantle plumes, although there may be differences with respect to the sizes and the source depths of the plumes. [99Smr] suggest that the main difference between corona-dominated rises and other large volcanic rises may be attributed to different sources for the mantle upwellings: Plumes at other rises might originate from the core-mantle boundary, while smaller plumes from shallower depths form the corona-dominated rises [99Smr].

Plumes on Venus might also be indicated by the observation of radiating fracture patterns, which can reach lengths of more than 2000 km [95Ern]. On Earth, one of the most famous giant dike swarms is the Mackenzie dike swarm in the Canadian Shield. It has been recognized that dike swarms are important to unravel major magmatic events, which are often associated with mantle plumes (for a review on mafic dike swarms see [87Hal]). More than 118 radiating dike swarms have been mapped on Venus [01Ern1].

How do these combined observations fit into a model of the global tectonics of Venus? One possible scenario is decribed by [91Phi]: Venusian tectonics may be dominated by plumes, which rise from the mantle and impinge on the lithosphere, thereby creating hot spots. There is no sea-floor spreading, but mantle flow fields might be coupled to the lithosphere and lead to regional-scale deformation. A hot-spot may evolve in several steps, involving a broad domal uplift resulting from a rising mantle plume, subsequent massive partial melting in the plume head, generation of a thickened crust or crustal plateau, the collapse of dynamic topography, and lateral creep spreading away of the crustal plateau. Crustal material is generated by gradual vertical differentiation, rather than by the horizontal creation and consumption (as it is characteristic of terrestrial sea-floor spreading). It has to be noted that a plume-dominated tectonic evolution of Venus over the observable part of its history is not unambiguously accepted. As plumes are criticized for the case of Earth (see above), some researchers also question the validity of the plume concept for Venus [05Ham].

The tectonic evolution of Venus, as it is known today, raises many questions. Although the planet is very similar to Earth in terms of its size and overall density, the present day level of geologic activity on Venus is low. This is indicated by the impact crater record, which is statistically uniform over the entire surface of the planet and gives a mean production age of 300 - 600 Ma. A very small percentage of craters (≤ 10%) is volcanically embayed from the outside or deformed by tectonism [92Phi, 94Her1, 94Str, 97McK]. This uniformity could be a result of gradual resurfacing [92Phi]. Most researchers, however, favour a global resurfacing event that ended at 300 - 600 Ma, with only minor resurfacing thereafter [e.g., 92Sch, 93Bul, 94Str]. An alternative view has been proposed recently by [07Han], who consider it likely that the surface of Venus preserves a much more ancient geologic record, a hypothesis that does not require massive resurfacing in a relatively short time.

It follows from the above observations that a central question in studies of Venusian tectonics concerns the mechanism which allows a planet with a bulk density, mantle composition, and thus radioactive heat production similar to Earth, to lose its heat without currently active large-scale resurfacing [99Smr]. Why is the tectonic style so different on Earth and Venus (plate tectonics versus plume-dominated tectonics)? The absence of water on present-day Venus might explain some of these differences. The lack of plate tectonics may be due to strong faults, because the presence of water can reduce fault strength through pore fluid pressure. For a more in-depth discussion of the extremely important role of water, see [98Nim], who emphasize that most of the differences between Earth and Venus processes can be explained by the absence of water on Venus.

Databases

Mars: Interactive Global Database of Martian Faults [06Kna]:
http://europlanet.dlr.de/index.php?id=26

Tectonics on the Jovian satellites

Io

143 mountains are identified on Io [03Jae]. They are rugged and isolated peaks with a random distribution across the surface [98Car1]. Their heights range between a few kilometers and ~ 18 kilometers [01Sch2]. These large heights suggest dominantly silicate structures, rather than sulfur-rich edifices, which should not support steep topography in excess of 1 km [80Clo]. Mountains are often spatially associated with pateras (calderas) [79Mas]. While a few moutains may be volcanoes [e.g., 86Moo], most are interpreted to be tectonic massifs [82Scha, 86Nas, 89McE]. Their formation is not well understood. The rapid volcanic resurfacing of Io (see Section 4.2.3.5.2) might generate horizontal lithospheric compressive stress that might be sufficient to induce thrust faulting and uplift the mountains [98Sch1]. Alternatively, lithospheric heating associated with a secular trend of decreasing volcanic activity on all scales could induce large compressive stresses at the base of the lithosphere. As resurfacing rates vary, the fluctuating thermally induced stress could create alternating episodes of compressive and tensile faulting [01Sch2].

Europa

The two major geologic units on Europa identified in Voyager and Galileo images are (1) bright, in color images bluish plains, and (2) darker, brownish mottled units which superpose the older plains [79Smi1, 79Smi2, 82Luc, 98Gre1, 04Gre] (Fig. 18, top). Europa is dominated by tectonic features on all scales, documented by numerous linear or arcuate features which crisscross the surface [82Luc]. Several types of linear or curved markings, generally termed lineae, with widths up to several tens of kilometers and lengths up to 1000 km and more were identified in Voyager images [82Luc, 98Gre1, 04Gre]:

1. triple bands
2. ridges
3. dark, wedge-shaped bands
4. gray bands
5. dark bands

During the Galileo Mission at Jupiter (1995 - 2003), these features were observed at various spatial resolutions. Ridges and fractures have been shown to be ubiquituos tectonic landforms on Europa

[98Gre1, 04Gre] (Fig. 18, middle). The bright plains consist of a network of parallel ridges and troughs, similar to grooved terrain on Ganymede.

Ridges are predominantly double ridges with a medial groove or trough [98Gre1, 04Gre]. In some places complex ridges occur, characterized by a central trough flanked by subparallel linear features [98Grb, 98Pap2] (see e.g. Fig. 11, top, Section 4.2.3.5.2). Heights of double ridges measured e.g. with Galileo stereo image data are several hundred meters high [99Gie]. Features previously termed triple bands are actually double or complex ridges with dark flanks at either side [98Gre1].

Depending on the depth of a liquid water layer underneath, several models of ridge formation are in discussion, involving compressional tectonism, diurnal tidal stresses, cryovolcanic and/or intrusive processes [04Gre, and ref.'s therein].

Dark wedge-shaped bands and dark bands occur all across Europa's surface. In a region near the anti-Jovian point termed "pull-apart terrain" they are the dominant landform [98Gre1] (Fig. 18, middle). Bright plains are separated by dark bands. The morphology of this terrain type is a possible indication of crustal spreading, with brittle plates moving on a warmer, mobile substrate [e.g. 98Sul, 02Pro]. An analogy with sea ice in the arctic has been inferred for pull-apart bands in this area [96Pap, 98Gre2].

Morphology, albedo and color of linear features such as ridges and bands changes with time [98Gei1]. For example, older bands are brighter than younger ones. Formation of linear features may even be going on today [98Gei1].

Mottled terrain consists of smooth plains, the so-called chaos regions, and features termed lenticulae (domes, pits and spots) [98Car2, 98Pap, 04Gre] (see Section 4.2.3.5.2). Chaos regions, such as Conamara Chaos (Fig. 18, bottom) are characterized by broken plates of pre-existing terrain, such as ridged plains, which were translated, rotated and tilted in a matrix of predominantly hummocky terrain which in turn could represent converted pre-existing terrain [98Spa]. Individual plates either moved on a substrate of warm, mobile ice [e.g. 98Spa] or like icebergs on liquid water at some shallow depth, possibly a subsurface ocean [98Car2, 98Grb].

Several stress origins are in discussion to account for the abundance of tectonic features identified on Europa [98Gre1]: (1) phase changes, causing global expansion [81Fin]; (2) global cooling, causing global contraction [83Hel]; (3) polar wander [89Oja]; (4) tidal stresses caused by Europa's eccentricity in the Laplace resonance with Io and Ganymede [83Hel, 86Mce, 98Grb]. A possible non-synchronous rotation of Europa with a lower limit of 10,000 years with respect to its orbit about Jupiter could provide an additional source of stress [98Gei2].

Ganymede

The surface of Ganymede consists of two major geologic units (Fig. 19, top): older, densely cratered dark material, and younger, less densely cratered bright material [79Smi1, 79Smi2, 82Sho2]. Dark material covers about 1/3 of the total surface [04Pap]. The geologic boundary between the two major units is tectonically controlled [79Smi1, 79Smi2, 82Sho2].

Tectonic landforms in the dark terrain units are 6 - 20 km wide linear or curved troughs and furrows termed *fossae*. Furrows are characterized by flat floors and raised rims with a maximum vertical distance of 1400 m between rim and floor [88Mur, 98Gie, 98Pro]. Most of the furrows are arranged in concentric sets with more or less regular spacing of ~ 50 km between individual furrows [82Sho2].

Two models of formation for the concentric furrow systems were discussed: (1) extensional tectonism caused by convection of mantle material [84Cas], or (2) deformation by huge, basin-forming impacts into a thin lithosphere early in Ganymede's history, as observed in ring structures (e.g. Valhalla) on Callisto [82Sho2, 87Sce]. The latter model is now favored [04Pap]. Later endogenic events could have reactivated these zones of weakness [90Mur].

Bright terrain occurs in two thirds of the total surface area. Bright terrain separates the dark units in broad, up to several hundred kilometers wide, linear or curved bands termed sulci. At higher resolution, these bright bands were shown to consist of numerous parallel, closely spaced grooves [79Smi1, 79Smi2, 82Sho2]. Furthermore, parallel grooves of this so-called bright grooved terrain are combined in so-called structural cells or domains characterized by similar trends of individual grooves within one cell, while the general trends of the cells differ greatly from one another which reflects a complex stress and strain history [80Luc, 82Sho2, 86Mur].

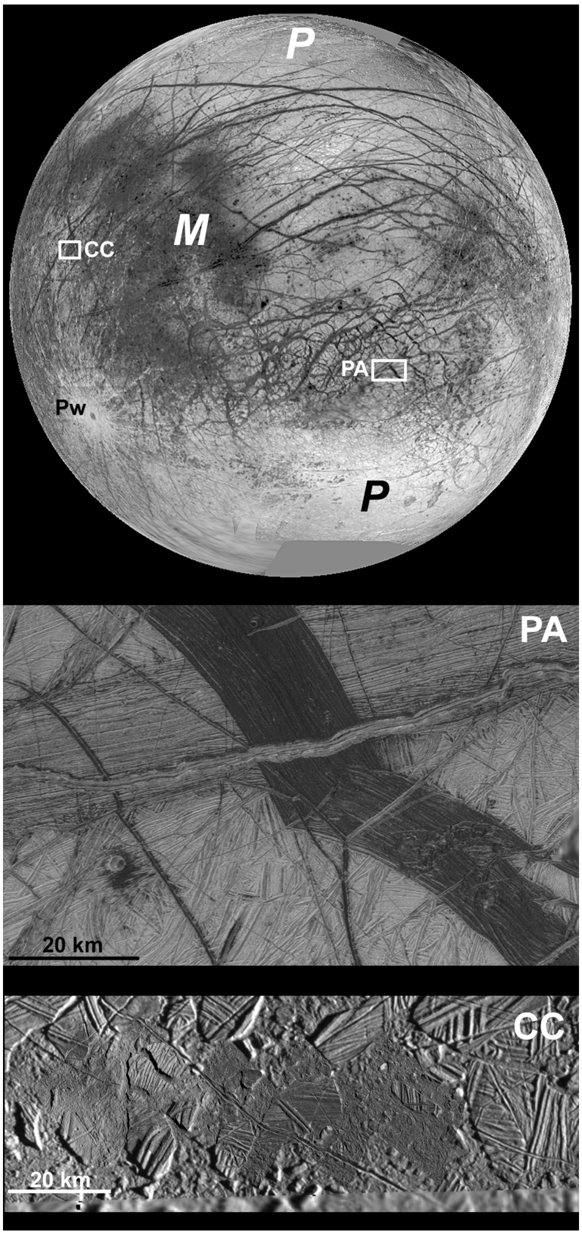


Fig. 18. Geological and tectonic features on Europa (Voyager and Galileo SSI data). **Top:** global mosaic of Europa showing the two major terrain types: (1) bright plains (P) and (2) mottled terrain (M) [82Luc, 98Gre1, 04Gre]. The two rectangles indicate the location of the two detailed views. Pw indicates the 25-km ray crater Pwyll. **Middle**: Ridged plains separated by dark wedge in the "pull-apart terrain" (PA). A prominent double ridge transects the scene about from west to east (left to right). **Bottom**: Detail of one of the chaos regions (Conamara Chaos, CC). Broken plates of ridged plains were "rafted" in hummocky matrix material. Further explanation in text. In both detailed views, north is pointing upward.

Prior to the Galileo mission, the formation of grooved terrain was believed to take place in a combination of tectonic and cryovolcanic processes [e.g. 81Gol, 82Sho2, 04Pap] but Galileo SSI images enforced a substantial revision of this view. Apparently, cryovolcanism has played a minor role in creating grooved terrain [04Pap]. The bright terrain units formed predominantly at the expense of dark terrain through a process termed tectonic resurfacing, causing the partial or total transformation of dark terrain into bright terrain by pervasive tectonism [97Hea2]. Generally, grooved terrain represents rifts created by extensional stress [04Pap].

At high resolution, aided by digital terrain models (DTMs) derived from stereo images, grooved terrain consists of smaller-scale grooves and ridges indicative of (a) horst and graben and (b) listric faulting [98Pap1]. Topography is on the order of 500 m up to 1 km [98Gie]. Also, high-resolution and stereo imaging showed two wavelengths in the topography of grooved terrain [98Gie, 98Pap1, 04Pap]: smaller-scale ridges and troughs with a wavelength of 1 - 2 km (not resolved in Voyager images) are superimposed on larger-scale ridges and troughs with a wavelength of ~ 8 km.

Strike-slip faults created by shear stress have been observed in both Voyager and Galileo data. Lateral movement can be up to several hundreds of kilometers [88Mur, 02Hea]. There is much less evidence for compressional features [04Pap].

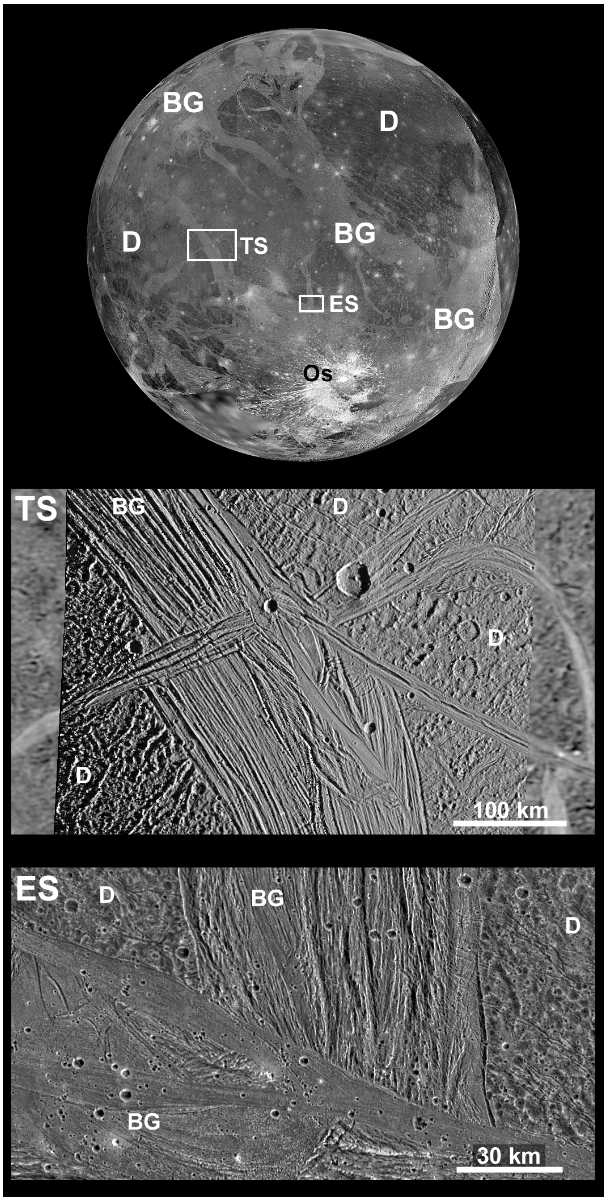


Fig. 19. Geological and tectonic features on Ganymede. **Top:** Global Galileo SSI mosaic of Ganymede, centered on lat. 0°N, long. 180°W (anti-Jovian hemisphere), showing the two major surface units: older dark terrain (D), and younger tectonically altered bright terrain (BG). Osiris (Os) is a large, bright ray crater. Location of the two detailed views Tiamat Sulcus (TS) and Erech Sulcus (ES) are shown. **Middle**: Detail of bright grooved terrain (BG) in *Tiamat Sulcus* (Galileo SSI in Voyager context) showing extensional deformation and right-lateral shear. Tiamat Sulcus transects older dark terain (D). **Bottom:** Bright grooved terrain (BG) in North-South-trending *Erech Sulcus* is cut by younger West-East-trending sets of bright grooved and smooth terrain units. The bright terrain units formed at the expense of older dark terrain (D). North is pointing upwards in both detailed views.

Callisto

Callisto is devoid of prominent tectonic features. Furrows reminescent of those in Ganymede's dark terrain, as well as ridges and scarps are impact-related and were created in basin-forming impact events, such as Valhalla or Asgard [95Sch, 04Moo2].

Albedo lineaments were identified and mapped in the cratered plains, with preferential NW-SE, NE-SW, NNW-SSE, or ENE-WSW trends [85Tho, 91Wag, 04Moo2, 07Wag2]. These features could result from an early period of tidal despinning which were possibly reactivated in later times, but their origin remains an open question [04Moo2]. The same lineament trends could be found in Galileo SSI high-resolution images. It could be shown that surface degradation on Callisto followed these pre-existing zones of weakness [07Wag2].

Tectonics on the Saturnian satellites

Mid-sized icy satellites

Tectonic landforms are found on seven of the nine major Saturnian satellites, including Titan. Mimas is characterized by old, densely cratered plains with little geologic diversity but displays a set of parallel lineaments, scarps, ridges and grooves [89Sto1]. These features are rather faint compared to the other satellites. They were interpreted to be related to large impact events, such as the formation of the 110-km diameter crater Herschel [89Sto1].

A large, almost satellite-encircling rift system named Ithaca Chasma occurs in the old, densely cratered plains on Tethys [81Smi, 82Smi, 83Moo]. It is (a) a ~ 100 km wide trough which encircles ~ 3/4 of the satellite circumference, (b) consists of at least two narrower branches towards the south and (c) has terraces [81Smi, 82Smi, 83Moo, 86Mor, 89Sto2]. Stereo models created with Cassini ISS data showed flexural uplift along the flanks of the trough and a total vertical topography of approximately 10 km [07Gie1]. Two modes of origin for Ithaca Chasma are in dicussion [82Smi, 83Moo, 04Moo1, 07Gie1]: (1) Expansion due to freezing of a liquid water interior, or (2) deformation by the large impact which formed Odysseus.

The first close flyby of Cassini at Iapetus in December 2004 has revealed an enigmatic ridge which encircles the satellite equatorially along about half of its circumference [05Por1]. The feature bisects the dark terrain of Cassini Regio symmetrically. Digital terrain models (DTMs) with Cassini ISS data have yielded a ridge height of 13 km and width of 70 km within the DTM [08Gie]. In a more recent Cassini flyby at Iapetus in September 2007, the ridge was imaged at much higher resolution [08Den].

Currently, two models exist to explain the origin of the ridge: (1) an endogenic model which is related to shape and/or spin state changes of Iapetus [05Por1], and (2) an exogenic model in which the ridge accumulated from ring material remnant from the formation of proto-Iapetus [06Ip] (see also Ref. 4.2.3.5.4).

Dione and Rhea show higher geologic and tectonic diversity than the preceding three satellites [81Smi, 82Smi]. Dione is known for a variety of tectonic features, such as troughs, ridges, scarps and lineaments seen in Voyager images [83Ple, 84Moo]. Ridges, scarps and lineaments were also observed in the old, densely cratered plains on Rhea [85Moo].

One common feature of both satellites are bright wispy markings abundant on their trailing hemispheres [81Smi, 82Smi]. Cryovolcanism, possibly pyroclastic eruptions, was offered as a likely process. A possible tectonic origin has also been inferred [e.g. 84Moo, 02Sto]. With higher-resolution images by Cassini ISS, the true nature of these wispy markings on both satellites as preferentially tectonic instead of cryovolcanic could be verified [05Wag, 06Wag, 07Moo, 07Wag1, 07Wag3, 08Wag].

The region on Rhea dominated by tectonism has not yet been imaged at high resolution. On Dione, detailed imaging of the fractured cratered plains revealed a variety of horsts, graben, scarps and ridges indicative of extensional, compressional and shear tectonism [05Wag, 06Wag, 07Moo]. The nomenclature of Dione has been updated recently to account for the tectonic nature of the bright wispy markings, using terms such as chasmata and fossae (troughs and graben) instead of the previous term linea [08Roa2].

Since the two Voyager flybys, Enceladus was known as the satellite with the highest geologic diversity, implying an intense cryovolcanic and tectonic activity which could even persist until present times [81Smi, 82Smi, 95Kar].

Several very close flybys of Cassini at Enceladus have revealed a wide variety of geologic units which are predominantly tectonic and cryovolcanic (see Section 4.2.3.5.2) in origin [05Hel]. Tectonism is pervasive and also affected old densely cratered plains. Tectonic forms include (1) sets of horsts and graben, (2) rifts, (3) folded ridges, and (4) ridged and grooved plains reminescent of those on the Galilean satellites Europa and Ganymede [05Hel]. Various trends indicate a complex stress and strain history involving extension, compression, and shear.

Linear grooves or sets of grooves have been known since Voyager and termed sulci (or sulcus for a single groove) [81Smi, 82Smi, 95Kar]. The south polar terrain is surrounded by sinuous scarps and ridges and displays several narrow individual grooves unofficially nicknamed “tiger stripes” [06Por]. Recently, these features were assigned names [08Roa1]. In late 2005, the south polar terrain and the “tiger stripes” were observed to be a cryovolcanically active region [06Por] (see Section 4.2.3.5.2).

Titan

Prior to the Cassini Mission, the surface of Saturn's largest satellite Titan was unknown due to the dense N_2-atmosphere opaque at visible wavelengths [e.g. 81Smi, 82Smi]. Based on thermodynamic and energetic considerations, tectonic landforms were expected to be present on Titan ([05Lor]).

Since 2004, the Cassini VIMS and Radar instruments have revealed Titan's surface at sufficiently high resolution. Bright lineated material and linear hills seen in Radar data from one of the first Titan flybys were attributed to tectonic processes [06Sto, 07Rad, 08Lun1]. Linear ridges up to 2000 m in height were interpreted as tectonic features originating from compressional as well as extensional stresses, but other scenarios of origin (such as impact ejecta blocks) were also offered as possible explanation [07Rad].

VIMS and Radar data obtained in further flybys during the Cassini Prime Mission have revealed linear mountain ranges up to 1000 km in length and several hundreds of meters high which appear to be unequivocally tectonic in origin [07Bro; http://photojournal.jpl.nasa.gov, image PIA10654].

Tectonics on the Uranian satellites

Landforms of tectonic origin occur on all five major satellites of Uranus, Miranda, Ariel, Umbriel, Titania and Oberon.

Umbriel and Oberon have the oldest and tectonically least altered surfaces [86Smi]. Lineaments, canyons, ridges and mesas were observed and mapped on Umbriel [91Cro]. Canyons are 10 to 25 km wide. Mesas are somewhat indistinct because of the low image resolution, are rectangular in shape and on the order of 30 - 50 km wide and 100 - 150 km long. Topographic relief is a few kilometers. Canyons and mesas appear to represent horsts and graben created by extensional stress. Tectonic features on Umbriel are old and may date back to an early period of heavy meteorite bombardment [91Cro].

Lineaments and canyons also occur on the surface of Oberon [91Cro]. Older and younger systems can be distinguished, based on their preservation states. Older canyons are generally wider (order of 70 - 80 km) than younger canyons (~ 20 km). Relief is also on the order of a few kilometers. Canyons on Oberon were created by extensional stresses which were active at an early period of heavy bombardment but may have acted for a longer time than on Umbriel because younger canyons cut bright rayed craters [91Cro].

Titania is mostly densely cratered but displays prominent tectonic landforms, such as lineaments, canyons, scarps and ridges [86Smi, 91Cro]. Extensional tectonism has created extensive canyon systems and trough-like lineaments such as Messina Chasmata which can be traced up to a length of 1500 km in the imaged area. Graben in these canyons are on the order of 50 to 100 km wide. Ridges (termed Rupes in planetary nomenclature) up to several hundreds of kilometers long also occur on Titania.

Three modes of origin are discussed [91Cro, and ref.'s therein]: (1) compressional tectonism, (2) cryovolcanism, (3) or they represent rims of heavily degraded large impact structures. Vertical relief between the canyons and the ridges is ~ 8 km. Tectonic stresses also deformed the surface at an early period of heavy bombardment but the time of tectonic activity was more extended compared to Umbriel and Oberon.

Ariel shows a completely different surface indicating a much more intense geologic evolution [86Smi, 91Cro]. Ariel's surface was extensively resurfaced by tectonism and cryovolcanism (see Section 4.2.3.5.2) [91Cro]. Based on the state of preservation and superimposed impact crater frequencies, a time-stratigraphic sequency of extensional graben-like canyons and scarps has been established. Canyon widths are from 10 to 100 km, with the oldest canyons being the widest structural features [91Cro]. Canyons depths are ~ 3 - 4 km [88Thm]. The canyons are associated with landforms indicative both of cryovolcanism (see Section 4.2.3.5.2) as well as erosion and degradation (see Section 4.2.3.5.4).

Ridges are also found on Ariel but their origin – either compressional tectonism or cryovolcanism – is uncertain [91Cro]. The system of canyons and scarps on Ariel is believed to have been created by global expansion which started during an early intense meteorite bombardment and most likely continued into a period where the heavy bombardment had ceased [86Smi].

An even more dramatic geologic history is recorded in the surface of Miranda, the smallest and innermost of the five major Uranian satellites. Densely cratered plains are abundant, but these old terrains are cut by a series of complex tectonic zones including (1) canyons and fault scarps, and (2) features termed coronae [86Smi].

Canyons can be subdivided by their widths into four different groups (1 - 2 km, 15 - 20 km, ~ 35 km, and ~ 80 km) [91Cro]. In the two larger groups, the inward-facing scarps on either side of the canyon show asymmetries in height, with one scarp being significantly higher than the opposing scarp. The wider canyons are on the order of 6 - 8 km deep. Terraces are also observed in some of these canyons [91Cro].

The coronae are characterized by (1) a sharp geologic contact with the densely cratered plains, (2) a much lower crater frequency and (3) a smoother topography than in the cratered plains, and (4) by parallel, linear or curved ridges, troughs and bands [86Smi, 91Cro, 91Grn]. There are differences in morphology and albedo between the three areas termed coronae [86Smi, 91Cro, 91Grn]. Two of them, Arden and Elsinore Corona, are ovoid-shaped but in turn differ from one another in structural zones [91Grn]. Inverness Corona is trapezoid-shaped and differs from the the two other coronae by e.g. a much less pronounced curvature of the bands [95Cro].

It is believed that tectonism and cryovolcanism were reponsible to create the coronae but what caused these geologic activities is not yet fully understood [91Cro, 91Grn]. The coronae formed subsequent to an early heavy bombardment which created the densely cratered plains. Several modes of coronae origin are in discussion [86Smi, 91Cro, 91Grn]: (1) An exotic scenario such as disruption and reassembling of a small satellite was suggested after the Voyager flyby [86Smi]. Other scenarios offered are (2) “sinkers” involving high-density material sinking through a viscous asthenosphere or (3), alternatively, diapirs of low-density material [87Joh]. A thorough description of the various models and the complex geologic history of this small satellite is found in [91Cro] and [91Grn].

Tectonics on the Neptunian satellites

Neptune's largest satellite Triton shows a network of lineaments, graben, scarps and ridges [89Smi, 95Cro].

Linear and sinuous ridges are reminescent of similar tectonic features on the Jovian satellite Europa. A variety in ridge morphology (e.g. single broad ridges, double and multiple ridges) can be observed [95Cro]. Widths of ridges range from 10 to 25 km, lengths can amount up to 1000 km and more. Ridge heights are on the order of 200 m. Ridges and lobate scarps are interpreted as compressional features, but extension may also be involved, especially in complex ridges [89Smi, 95Cro]. Troughs are interpreted as graben created by extensional stress [95Cro]. Locally, strike-slip movements could also have occured [89Smi]. Locally, both graben and ridges were modified by cryovolcanism.

It is assumed that Triton is an object captured by Neptune [95Mck2]. The major trends of the tectonic forms mappable on Triton suggest stresses created by tidal interaction involved with the satellite approaching its primary [93Cro, 95Cro]. Other, e.g. concentric and radial trends may have been caused by large impacts [90Boy] or rising mantle plumes [93Cro].

Cryovolcanism and erosion/degradation are the dominant processes on Triton (see Sections 4.2.3.5.2, 4.2.3.5.4) which locally obliterated tectonic forms. Ridges formed subsequent to a global cryovolcanic resurfacing event which created the so-called cantaloupe terrain and possibly destroyed the old densely cratered surface [95Cro]. The characteristic processes in the following periods are events of cryovolcanism and tectonism (e.g. formation of extensional graben). At some unknown time in the past, endogenic activity has more or less ceased. Until present time, formation of impact craters, erosion, degradation and deposition are the major geologic processes on Triton [95Cro] (see Section 4.2.3.5.4).

4.2.3.5.4 Erosion, transport and sedimentation

Erosion on the terrestrial planets

The surfaces of all terrestrial planets show evidence for the transport and displacement of material. Naturally, the intensity of these is much stronger on planets with an atmosphere than on those lacking it. Since Mercury and the Moon do not have atmospheres, erosion by ice, water or wind is absent. The only remaining transport processes on Mercury and the Moon are, therefore, related to impact processes and to mass wasting, i.e. the downslope movement of material due to gravitational forces.

The planet with the most widespread and significant erosion, transport, and sedimentation processes is Earth. Its surface is shaped by their traces at all scales, from microscopic structures to continent-sized ancient erosion surfaces (e.g., ancient cratons). Earth`s dynamic atmosphere, hydrosphere, and biosphere all favour the decomposition or weathering of rocks by physical, chemical, and biological weathering. Some of the weathering products, like rock and mineral particles, can be mobilized by fluid or liquid media like air (solid particles suspended by wind), ice, or water. Over sufficiently large time intervals, even huge mountain chains can be eroded on Earth. Erosion rates on Earth are highly variable (Fig. 20) and depend on substrate (lithology), climate, and precipitation. In general, they are several orders of magnitude higher than those on the next active planets, Mars and Venus. Often they are referred to as denudation rates, i.e. the lowering of the Earth`s surface measured in mm ka^{-1} (mm per 1000 years). Terrestrial denudation rates, sometimes subdivided into chemical and mechanical denudation rates, typically range between tens and hundreds of mm ka^{-1} (Table 17). It seems that extreme events (e.g., flooding events) account for a proportionally large fraction of the erosion, which might explain why erosion rates measured over short timescales (10^0 - 10^2 years; without such events) are often smaller than those determined for long timescales (10^4 - 10^7 years) [07Tom].

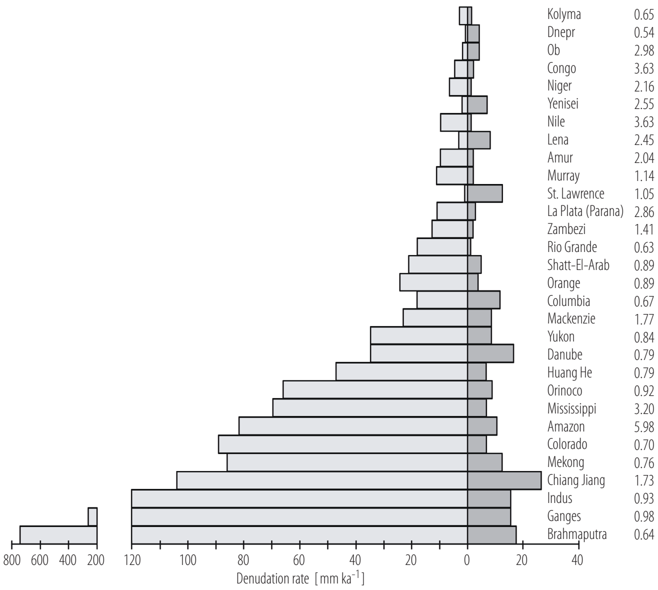


Fig. 20. Denudation rates of major terrestrial drainage areas (slightly modified from [94Sum]). Rates for mechanical erosion are shown on the left, rates for chemical erosion are shown on the right.

Erosion on Mars occurred in the past by virtually all mechanisms known from the Earth, although at different rates. Fluvial erosion was widespread in the early history, before about 3.5 Ga ago, as evidenced by numerous valleys [82Bak, 96Car]. Surprisingly, recent high-resolution images revealed the existence of small, kilometer-sized gullies, which exactly resemble landforms produced by the runoff of liquid water on Earth. These are often arranged in dendritic patterns, typical for terrestrial drainage networks. Glacial erosion is less evident, but growing evidence for glacial processes on Mars [e.g., 03Hea2] indirectly imply a significant role for them as well. Aeolian erosion (i.e. erosion by wind) is indicated by the presence of ventifacts (wind-abraded clasts or rock surfaces), seen in lander images, and yardangs (wind-moulded landforms in drylands). Erosion rates on Mars are highly variable over time. When the young Mars still had a denser atmosphere and a more vigorous hydrological activity at its surface, which involved significant fluvial incision, erosion rates were comparable to slow continental denudation rates on Earth that are dominated by liquid water. After Mars had become cold and dry (about 3.8 Ga ago), erosion rates dropped dramatically. It is estimated that long-term erosion rates since then are as low as 0.01 to 10 nm/year, which is 2 - 5 orders of magnitude lower than on early Mars (Table 17) and are 2 - 3 orders of magnitude lower than the slowest erosion rates on Earth.

Venus has a thick atmosphere, so wind as a geological agent is expected to have shaped the surface. Indeed, yardangs on Venus attest to some aeolian erosion on Venus [97Gre]. However, Venus is completely shrouded in clouds and the surface temperature varies only slightly as a function of latitude. Therefore, winds are only gentle and wind as an erosional agent is not effective (Table 17).

Erosion is also an important geological process on the Saturnian moon Titan, as documented by Radar images from the Cassini and Huygens missions, which show fluvial channels that were probably formed by liquid methane [e.g., 05Tom, 08Lor]. Titan is unique in the sense that methane seems to play the role in exogenic processes that water plays on Earth [08Lun2]. Methane clouds in the atmosphere, and the dendritic fluvial features suggest methane rainfall, and even lakes of liquid methane have been reported recently [07Sto]. The area on Titan that is affected by fluvial channel formation is unknown, but extrapolation of the analyzed portion to the entire surface indicates a very small percentage (~ 0.1%) covered by river channels [08Lor].

Table 17. Typical erosion rates on the terrestrial planets. Terrestrial values modified and simplified from [83Sau], values for Mars from [07Gol], values for Venus from [93Str] and [97Bas], values for the Moon from [00Cra].

Climate	Relief	Typical range for rate of denudation [mm ka^{-1}]
Earth		
Temperate continental	Normal	10 - 100
Rain forest	Normal	10 - 100
	Steep	100 - 1000
Arid	Variable	10 - ?
Semiarid	Normal	100 - 1000
Polar/mountainous	Steep	10 - 1000
Glacial, ice sheet	Normal	50 - 200
Glacial, valley glaciers	Steep	1000 - 5000
Any climate	Badlands	1000 - 1,000,000
Mars		
Early Mars (> 3.8 Ga)	Any	1 - 10
~ 3.8 Ga until today	Any	0.00001 - 0.01
Venus		
~ 1 Ga to 300 Ma until today (large uncertainties!)	any	0.003 - 0.2 (0.21 m/Ma to 0.003 m/Ma)
Moon		
~ 3 Ga until today (average)	Any	0.0002 (2×10^{-7} mm/a)

Transport of eroded material on Earth can occur over distances of all scales. Wind-blown material can be transported across continents (e.g., sand derived from the Sahara is often deposited in Europe, and dust storms on Mars can affect the atmosphere on global scales), and rivers can be thousands of kilometers long (e.g., Nile and Amazon on Earth: > 6,000 km; outflow channels on Mars: thousands of kilometers). Material transport by wind is in the form of creep, saltation (bouncing or leaping movement of rock particles carried by wind or water currents) or suspension (e.g., the classical paper by [41Bag]; see also [85Gre]). The minimum wind speeds needed for aeolian transport of particles depend on the density of the atmosphere and the gravitational acceleration (Fig. 21). Fluvial transport, i.e. transport by liquid water in rivers and streams, includes the suspension of particles in the water current (washload and suspended load), and the sliding, rolling, and saltating of particles on or very near the river bed (bed load) [e.g., 64Leo]. A recent review on flow discharge and sediment transport models is given by [05Kle]. In addition to these transport processes of clastic particles, material can be transported in solution. A comparison of flow velocities required to move clastic particles on Earth, Mars, and Titan is shown in Fig. 21.

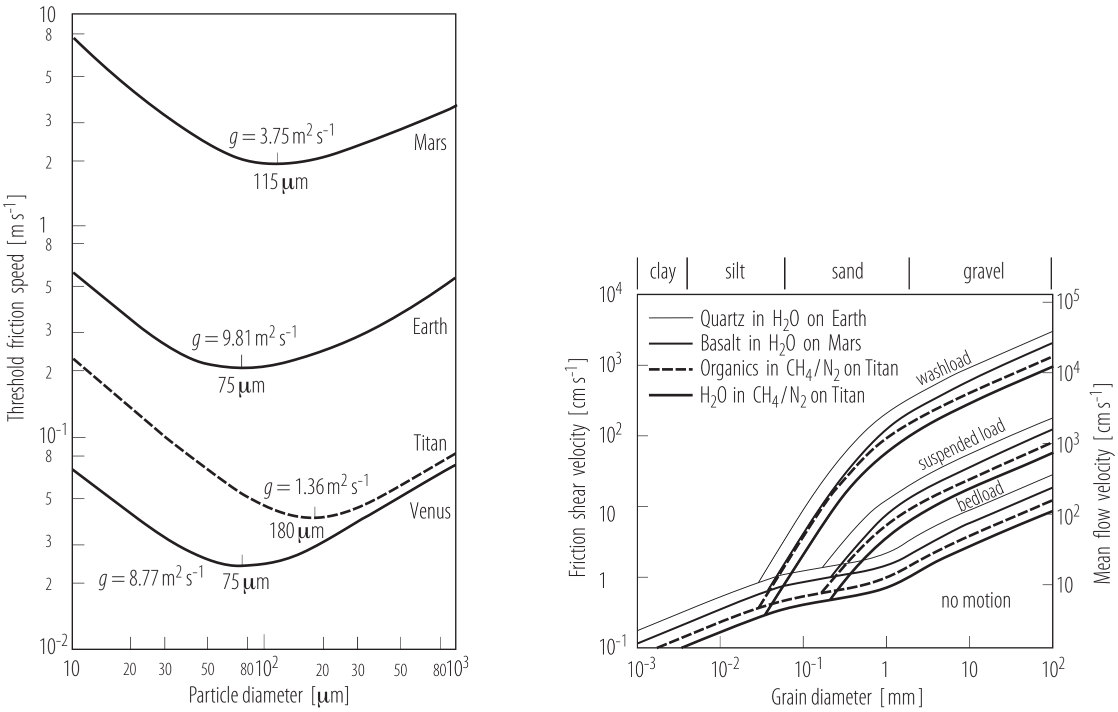


Fig. 21. Velocities in wind and water currents required to transport clastic particles. **Left:** Threshold friction speed predictions for Venus, Titan, Earth, and Mars. Particle densities for Venus, Earth, and Mars were chosen to be 2.65 g cm^{-3}, representative for silicate material, and 1.9 g cm^{-3} for Titan, corresponding to the average density for the satellite [partly redrawn and simplified from [85Gre]. **Right:** Fields of transport categories on Earth, Mars, and Titan (slightly modified from [06Bur]).

Glaciers transport material as particles distributed in the glacier-ice matrix itself (rock glaciers; note that there is a debate whether rock glaciers are glacial or periglacial phenomena, which will not be addressed here), as moraine material (e.g., medial moraines), or as a mantle covering the glacier (debris-covered glaciers). Virtually all of these transport processes also act or acted on Mars, although at different intensity in different periods of Mars` history. It also has to be noted that periglacial processes, which are known on Earth and are thought to be important on Mars, involve material transport, e.g., by sorting mechanisms like frost heaving. The transport distances, however, are usually minor, and we will not further consider periglacial processes here.

Erosion and transport imply sedimentation. Sedimentary structures and landforms are particularly widespread on Earth, the planet with the most active volatile cycle. Major sources and sinks for sediments are not randomly distributed on Earth, but are controlled by geodynamic processes. Examples are passive continental margins, where stacks of sediments with thicknesses of tens of kilometers can be encountered. The sedimentation itself is the result of the interplay between the sediment supply, its reworking and modification by physical, chemical, and biological processes, and the accommodation space, i.e. the space that is available for sedimentation [e.g., 96Rea]. Factors controlling the sedimentary rock record include the sediment supply, climatic conditions, tectonic displacements, sea-level changes, orbital forcing (e.g., Milankovitch cycles), water chemistry, volcanism, and others.

The only other solar system body with a variety of sedimentary deposits other than Earth is Mars, although the volume of known sediments on Mars is minor in comparison to Earth. Eolian sedimentation is ubiquitous, both as dust (grain sizes of about 1 - 2 microns) and sand-sized particles [92Gre]. Dust deposition is part of the dynamic dust cycle and regularly affects the surface. Recent measurements by rovers allowed dust deposition rates to be measured in situ. They are estimated to be in the order of 1 grain diameter per 100 Martian days [07Kin]. Sand dunes are evident in most high-resolution images [e.g., 07Hay]. Some of the largest occurrences of dunes are found around the North Pole, where they form a continuous sand sea. All dune forms known from Earth have also been observed on Mars, and recent time-resolved observations showed that at least some dunes are currently active [08Bou].

Delta and fan deposits are found at several locations on Mars and are clear evidence for the deposition of clastic sediments by fluvial and lacustrine processes [e.g., 03Moo, 03Mal]. It seems that their formation could have taken place over geologically short timescales, and that the discharge in the fluvial channels feeding the deposits are characterized by short flooding events [e.g., 08Kra]. Other morphologically important large-scale sedimentary materials on Mars are layered deposits of considerable horizontal (hundreds of kilometers) and vertical (several thousand meters) dimensions, which are found within some large topographic depressions like Valles Marineris or several craters. Despite decades of research, their origin is still unclear. An origin as eolian, lacustrine, and volcaniclastic sediments as well as spring deposits or salts have all been invoked to explain their characteristics. Layered sedimentary materials are also important in Meridiani Planum, the region where the Mars Exploration Rover, Opportunity, found mineralogical, geochemical and morphological evidence for past liquid water on the Martian surface.

An important process on Mars that shall be shortly discussed here in the context of sedimentation is aqueous alteration. Recently it was found that the layered deposits in Valles Marineris, in some craters, and in Meridiani Planum are often, but not always, associated with hydrated sulfates [05Bib, 05Gen]. Their formation must, therefore, probably have involved liquid water. Another alteration process, again associated with layered deposits, produced phyllosilicates [05Bib, 05Pou]. Since both sulfates and phyllosilicates point to aqueous alteration, but in different environments, their identification puts extremely important constraints on the reconstruction of the Martian paleoclimate. While the phyllosilicate-bearing layers may have formed in situ by the aqueous alteration of basalt more than ~ 4 Ga ago, the sulfate-bearing layers are younger and formed in a more acidic environment. In their case, the original nature of the layers is unclear. A third major class of hydrated phases that was recently identified on Mars is sedimentary silica-rich material.

The in situ investigation of Martian terrain has recently revealed a great amount of information on sedimentary environments on Mars. In particular, the Mars Exploration Rover, Opportunity, identified the geochemical, mineralogical, and morphological signatures of sedimentary processes in Meridiani Planum [e.g., 04Squ, 05Tos, 05Gro2, 06Gro].

Sedimentary deposits on Venus are observed in the form of wind-deposited materials and finely layered material seen at the landing sites. Eolian features occur as radar-dark (i.e. smooth) mantlings, wind streaks, and dunes. The mantling materials were probably formed by fine debris derived from impact events. Wind streaks are the most abundant eolian features and formed as the result of accumulation and/or erosion of loose surface material due to turbulence behind topographic obstacles. Sand dunes are found as two dune fields [97Gre]. The finely layered rocks seen in the Venera lander images are easily crushable and porous. One hypothesis interprets them as ejecta from upwind craters that were deposited from the atmosphere.

Sediments on Titan are documented as large fields of sand dunes, which can reach heights of 100 - 150 m [06Lor] and cover as much as 20% of the total surface [08Rad]. The limited extent of river channels (see above) can not account for this large volume of sediments, and the large-scale sediment transport processes on Titan remain an enigma [08Lor].

Erosion, transport and sedimentation on the Jovian satellites

Io

Erosion is limited on Io. Long scarps on Io (hundreds of kilometers long, hundreds of meters high) can have an irregular or fretted appearance, which might be the result of sapping (backward erosion induced by groundwater or other volatile seepage) involving liquid SO_2 [79McC]. Ions and electrons in the Jovian magnetospheric plasma bombard the surface, and can erode SO_2 ice with rates of 10^{-5} m a^{-1} [82Mel, 84Joh].

Europa

Galileo SSI images do not show widespread abundance of erosional or degradational features on Europa, compared to features on Ganymede and Callisto [99Moo] (see below). Smooth units near the bases of tectonic ridges were created by downslope movements of fine-grained material and represent talus deposits. Such features are only discernable in high-resolution images (< 30 m/pxl) [99Moo].

Ganymede

The two major terrain types on Ganymede, older, dark terrain, and younger, bright grooved terrain, show unique surface features of degradation and deposition [79Smi1, 79Smi2, 04Pap].

Widely abundant processes of mass wasting in the dark terrain are documented in high-resolution Galileo SSI images [98Pro, 99Moo]. Low-albedo streaks on bright slopes are clear indications of such processes. Dark, loose material accumulated on floors of furrows, craters, or other topographic lows [98Pro, 99Obe]. Dry slumping or sliding along steep slopes was discussed to be responsible for these features [99Moo].

High-resolution views of the dark terrains on Ganymed also revealed a strong heterogeneity between very dark and very bright landforms within these regions [98Pro]. Sublimation of volatiles, e.g. H_2O, has been inferred to be the major process to create such features [98Pro, 99Moo, 04Pap]. In some of the dark areas, a combination of sublimation of volatile materials and scarp retreat has created a dark lag, embaying and partly covering high-standing landforms such as crater rims [99Moo, 04Pap].

Downslope movements indicating mass wasting processes are also observed in the bright grooved terrain [99Moo, 04Pap]. Dark streaks occur on steep slopes in bright terrain and dark material is accumulated in topographic lows, induced by sublimation processes and segregation from the bright host material [98Spe, 99Obe, 04Pap].

The degree of landform degradation was used to map three classes of impact crater forms on Ganymede on medium-resolution Voyager images (1-2 km/pxl) [84Luc]: Class c_3 represents young, fresh, more or less pristine impact craters, in many cases with an extended system of bright or dark rays. In class c_2, crater rims are more degraded, and ejecta are partially removed. Generally, these crater forms are older than those in type c_3. Class c_1 comprises forms almost entirely eroded or degraded, with crater rims partially or almost completely removed (crater ruins), or covered by younger units. This class represents the oldest impact crater forms.

Callisto

Impact cratering (see Section 4.2.3.5.1), erosion and landform degradation, preferentially by sublimation, are the dominant geological processes on Callisto. These processes are revealed in detail by high-resolution images returned by the SSI camera aboard the Galileo Orbiter [95Car, 96Moo, 99Moo, 04Moo2, 07Wag2]. Callisto is unique in this respect and features the most heavily degraded surface of the four Galilean satellites [99Moo].

Sublimation degradation of bright, topographically high-standing landforms, e.g. crater rims, is mainly caused by (a) solar insolation changing over each diurnal cycle (16.689 Earth days), (b) compositional differences in the icy crust, and (c) zones of weaknesses created by early tectonism (see Section 4.2.3.5.3) [96Moo, 99Moo, 04Moo2, 07Wag2]. Temperature variations during one Callisto day range from a maximum of > 165 K at noon to a minimum of 80 K at predawn at the equator [99Moo].

In addition, sublimation degradation may be triggered by a substantial amount of a species more volatile than H_2O-ice, most likely CO_2, in the icy crust of Callisto [96Moo, 99Moo]. That CO_2 is an abundant component in the icy crust can be inferred from the discovery of a tenuous CO_2 atmosphere created by outgassing [99Car].

Sublimation degradation created two characteristic landforms: bright massifs, or groups of massifs, with a geometric albedo of ~ 0.8, and a globally abundant layer of smooth or gently undulating, in some parts hummocky, dark material (geometric albedo ~ 0.2) [96Moo, 99Moo, 04Moo2, 07Wag2]. This characteristic distribution of dark and bright material is illustrated in a Galileo SSI high-resolution image in Fig. 22.

Landslides several kilometers wide with a range in morphology from lobate and blocky to slump-like can be found on crater floors [00Chu, 04Moo2]. Such mass movements are believed to have been triggered by seismic energy released upon large impact events several hundreds of kilometers away [00Chu].

Currently it is not known exactly at which rate sublimation degradation occured because the (average) thickness of the layer, its thermal inertia, particle sizes and composition are not known exactly [99Moo]. Crater counts in the dark, smooth material yielded highly divergent model ages, depending which cratering chronology model is used [e.g. 04Moo2, 07Wag2].

As is the case for Ganymede, crater forms on Callisto can be subdivided into three erosional classes of different ages [97Ben, 00Gre1, 07Wag2].

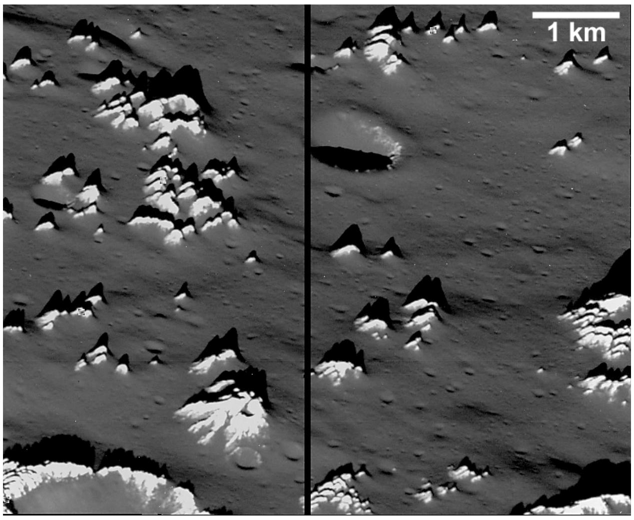


Fig. 22. Landforms indicating erosion and degradation on Callisto. Part of Galileo SSI picture 30C0004. During the final closest flyby at Callisto (Galileo orbit C30), the SSI camera was able to return the highest-resolution images of the surface. Spatial resolution of this frame is 9 m/pxl (in horizontal direction). The dark vertical bar is a permanent data gap. The figure shows the two major surface units of Callisto [04Moo2]: (1) bright, topographically high-standing material, and (2) dark, smooth material. Some craters are degraded but their circular rims are still preserved. Other massifs represent the remnants of former, now heavily degraded craters. Shadow lengths were used to measure the heights of the massifs implying an average height of about 200 - 300 m [02Bas1, 07Wag2].

Erosion, transport and sedimentation on the Saturnian satellites

Mid-sized icy satellites

Several of the mid-sized icy satellites of Saturn show landforms indicating mass wasting in the higher-resolution Cassini ISS images. These forms include landslides on the steep inner walls of crater rims, on central peaks, or on scarps within tectonic forms.

Deposits indicative of mass wasting processes were reported from Dione [06Wag], Rhea [08Wag], and Iapetus [08Sch]. On the small, low-gravity satellite Phoebe material slumped down from steep crater walls, accumulating a hummocky deposit on the floor and exposing a bright, ice-rich surface on crater wall interiors beneath a darker coating [05Por1].

Iapetus is known for an anomalous dichotomy in albedo, with a factor of 10 difference between the leading (about 0.05) and trailing hemisphere (about 0.5, comparable to other icy bodies), a fact which was known since the time when Iapetus was discovered by G.D. Cassini in 1671 [82Smi, 86Mor]. For this dark area on the leading hemisphere which is also distributed symmetrically around the apex point of orbital motion (lat. 0°N, long. 90°W), the name Cassini Regio was assigned in planetary cartography.

Cassini ISS data from the first close flyby (Dec. 31, 2004) revealed that Cassini Regio is an old and heavily cratered dark unit, shows evidence of mass wasting (landslides in craters), and displays an enigmatic almost satellite-encircling equatorial ridge up to 15 km high (see Section 4.2.3.5.3) [05Por1].

The origin of the dark material in Cassini Regio is not well understood. Two sets of theories exist which try to explain the origin of the unusual albedo feature: (1) In one set of theories, the dark material in Cassini Regio is a deposit created by exogenic processes. (2) Other theories suggest endogenic processes (e.g. cryovolcanism).

The exogenic origin theories invoked primarily impact-related processes (summaries and references given by [01Den1, 01Den2] and [05Por1]). Possible sources of deposited dark material are (a) dust ejected from other Saturnian satellites due to impacts (e.g. Phoebe, Hyperion), or (b) material created by cataclysmically disrupted satellites.

Endogenic origins (volcanism) have also been discussed but seem less likely [82Smi, 01Den2, 05Por1]. High-resolution data from a flyby in Sep. 2007 show that the dark material deposit is only a few meters thick [08Den, 08Sch]. These new image data also favor a primarily exogenic origin by thermal segregation processes which create a dark lag on preferentially icy material [08Den, and ref.'s therein].

Titan

Titan has a substantial N_2-atmosphere and is the only natural satellite in the Solar System which shows a morphologic record of fluvial, lacustrine, and eolian processes. The dense atmosphere can be penetrated only at infrared wavelengths by ISS and VIMS [05Por2, 06Mcc] and by the Cassini Titan Radar Mapper [07Pag]. The surface could be investigated in detail by the Huygens landing probe on Jan. 14, 2005 [08Kel, and ref.'s therein].

The presence of a hydrological cycle on Titan has been assumed, with methane or methane-ethane being the working fluids analogous to water on Earth or early Mars [e.g. 05Lor]. Landforms inferring fluvial and lacustrine processes were captured by the DISR camera during descent of the Huygens probe to the ground [05Tom]. Images show a dendritic drainage system of dark channels carving into the brighter highlands, similar to terrestrial river systems (Fig. 23). The dendritic network terminates in a dark lake basin. The channels and the lake basin did not seem to contain fluids at present since Huygens landed on a solid surface. Images from the landing site showed a number of rounded pebbles which conclusively indicate transportation and deposition by fluid material (Fig. 23) [08Kel].

Channels and lakes inferring fluvial and lacustrine processes were also revealed in the Cassini Titan Radar Mapper data [06Sto]. Lakes are abundant in the high latitudes [07Lop3]. Some of these lakes are several 100 kilometers across. Radar images showed that some of them could be filled with fluid hydrocarbons, as derived from the smoothness at a Radar wavelength at 2.2 cm [07Lop3, 07Mit]. It was verified with VIMS data that one of the major lakes is filled with a liquid, most likely ethane in solution with e.g. methane or other hydrocarbons [08Bro].

Eolian processes are indicated by the presence of thousands of dark, longitudinal dunes within 30° latitudes of the equator in the Radar data [06Ela]. These features represent deposits of particulate materials, possibly consisting of hydrocarbons, and were transported by a global wind system to the equator where desert-like conditions occur [08Rad]. These materials are then shaped into dunes by East-West-oriented winds, inferred from their preferential East-West orientation [08Rad].

Erosion, transport and sedimentation on the Uranian satellites

Landforms indicative of erosion and degradation are not easily discerned on the five major satellites of Uranus, Miranda, Ariel, Umbriel, Titania and Oberon. The comparably low resolution of Voyager images (on the order of several kilometers per pixel) obtained at Umbriel, Titania and Oberon during the Voyager-2 flyby impedes the detailed analyses of erosional and degradational features on these two satellites. Voyager returned higher-resolution images (< 1 km/pxl) only of the two innermost major satellites Miranda and Ariel [86Smi].

Craters on these satellites except Miranda were subdivided into at least three degradational classes: (1) old, degraded craters, (2) fresh craters, and (3) relatively young bright ray craters [86Smi, 91Cro]. On Miranda, only two preservation states of craters were found: (a) fresh craters and (b) mantled craters [91Cro]. Degradation of craters is a result of obliteration by subsequent impacts and/or by tectonicsm. Bright rays in the younger craters could date back to 3 - 4 Ga indicating that erosion and degradation might have played a minor role in shaping the surfaces of these bodies.

Bright fresh deposits at the base of tectonic features (canyons and scarps) are interpreted as talus deposits implying mass wasting processes [86Smi, 91Cro]. These features are found on Oberon, Titania, and Miranda. The interior of the canyons on Ariel, especially in those at the margins of cratered plains plateaus, display landslides which were interpreted as stratigraphically young geologic units [91Cro].

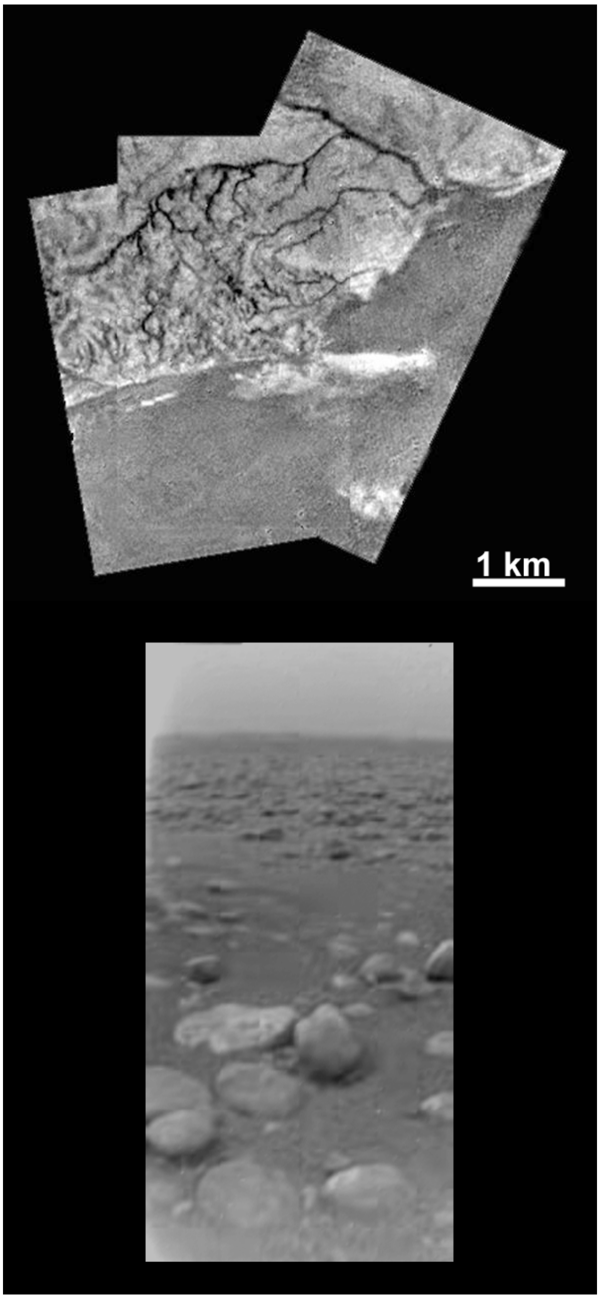


Fig. 23. Landforms indicative of fluvial and lacustrine processes, seen in image data of the DISR camera aboard the Huygens probe. **Top:** Dendritic drainage system of dark channels and a dark (at the time of Huygens landing) dry lakebed, seen from an altitude of about 8 km (http://photojournal.jpl.nasa.gov, image ID: PIA07236). **Bottom:** Image taken on the dry lakebed at the Huygens landing site during the 70-minute lifetime of the probe after landing. Rounded pebbles indicate transport and deposition by a fluid. Sizes of pebbles are on the order of 15 - 20 cm.

Neptunian satellites

The southern hemisphere of Neptune's largest satellite Triton is covered by a seasonal bright, reddish ice cap probably composed of N_2-ice mixed with organic compounds reponsible for the reddish hue [89Smi, 89Stn]. Darker patches are abundant within the polar cap probably exposing material beneath the bright ice deposit. The lack of clear morphologic boundaries between the bright material and the darker patches in the cap is an indication for a relatively thin veneer of ice. Generally, all surface features on Triton appear to be covered by a thin frost-like veneer of N_2- and CH_4-ices [89Stn].

The surface of Triton also shows evidence of erosion, transport and deposition by wind. Triton's atmosphere is dominated by N_2, with traces of other compounds such as CH_4 at low altitudes near the surface [89Stn]. Dark streaks are abundant in the south polar ice cap [89Smi, 89Stn]. The streaks extend over several 10's of kilometers up to 100 km. They are concentrated between 10° and 30° south latitude and are preferentially oriented southwest-northeast indicative of a dominant wind direction [89Smi].

A surface unit unique to Triton is termed cantaloupe terrain and is composed of pits and dimples, with a spatial extent of several kilometers up to 25 km across [89Smi, 89Stn]. Collaps and degradation by extensive sublimation of surface materials has been invoked as a likely process which created these landforms [89Smi]. Sublimation of matrix-forming materials also may have caused mechanical weakening of material exposed in scarps which caused the recession of these scarps with time [90Moo].

Voyager image resolution is not sufficient to observe surface features indicative of erosion, transport and sedimentation on the smaller Neptunian satellites.

4.2.3.5.5 Nomenclature

JUDIT JÄNCHEN AND MARITA WÄHLISCH

4.2.3.5.5.1 IAU rules

IAU composed several rules and conventions over the past years that can be found on the webpage http://planetarynames.wr.usgs.gov/, which is the official IAU Gazetteer of Planetary Nomenclature homepage. The following lists in Sections 4.2.3.5.5.2 - 4.2.3.5.5.3 contain the descriptor terms as well as categories for naming features on celestial bodies. These terms and categories, including the definitions are to be found on the same webpage http://planetarynames.wr.usgs.gov/.[1]

4.2.3.5.5.2 Descriptor terms as defined by IAU

Albedo Feature	Geographic area distinguished by amount of reflected light
Arcus, arcūs	Arc-shaped feature
Astrum, astra	Radial-patterned features on Venus
Catena, catenae	Chain of craters
Cavus, cavi	Hollows, irregular steep-sided depressions usually in arrays or clusters
Chaos	Distinctive area of broken terrain
Chasma, chasmata	A deep, elongated, steep-sided depression
Colles	Small hills or knobs
Corona, coronae	Ovoid-shaped feature
Crater, craters	A circular depression
Dorsum, dorsa	Ridge
Eruptive center	Active volcanic centers on Io
Facula, faculae	Bright spot
Farrum, farra	Pancake-like structure, or a row of such structures
Flexus, flexūs	A very low curvilinear ridge with a scalloped pattern
Fluctus, fluctūs	Flow terrain
Flumen, flumina	Channel on Titan that might carry liquid
Fossa, fossae	Long, narrow depression
Insula, insulae	Island (islands), an isolated land area (or group of such areas) surrounded by, or nearly surrounded by, a liquid area (sea or lake).
Labes, labēs	Landslide
Labyrinthus, labyrinthi	Complex of intersecting valleys or ridges.
Lacus	"Lake" or small plain; on Titan, a "lake" or small, dark plain with discrete, sharp boundaries

[1]) [USG]

Landing site name	Lunar features at or near Apollo landing sites
Large ringed feature	Cryptic ringed features
Lenticula, lenticulae	Small dark spots on Europa
Linea, lineae	A dark or bright elongate marking, may be curved or straight
Lingula, lingulae	Extension of plateau having rounded lobate or tongue-like boundaries
Macula, maculae	Dark spot, may be irregular
Mare, maria	"Sea"; large circular plain; on Titan, large expanses of dark materials thought to be liquid hydrocarbons
Mensa, mensae	A flat-topped prominence with cliff-like edges
Mons, montes	Mountain
Oceanus	A very large dark area on the moon
Palus, paludes	"Swamp"; small plain
Patera, paterae	An irregular crater, or a complex one with scalloped edges
Planitia, planitiae	Low plain
Planum, plana	Plateau or high plain
Plume	Cryo-volcanic features on Triton
Promontorium, promontoria	"Cape"; headland promontoria
Regio, regiones	A large area marked by reflectivity or color distinctions from adjacent areas, or a broad geographic region
Reticulum, reticula	reticular (netlike) pattern on Venus
Rima, rimae	Fissure
Rupes, rupēs	Scarp
Satellite Feature	A feature that shares the name of an associated feature. For example, on the Moon the craters referred to as "Lettered Craters" are classified in the gazetteer as "Satellite Features".
Scopulus, scopuli	Lobate or irregular scarp
Sinus, sinūs	"Bay"; small plain
Sulcus, sulci	Subparallel furrows and ridges
Terra, terrae	Extensive land mass
Tessera, tesserae	Tile-like, polygonal terrain
Tholus, tholi	Small domical mountain or hill
Undae	Dunes
Vallis, valles	Valley
Vastitas, vastitates	Extensive plain
Virga, virgae	A streak or stripe of color

4.2.3.5.5.3 Categories for naming features on celestial bodies as defined by IAU

The Moon

Craters Deceased scientists, scholars, artists and explorers who have made outstanding or fundamental contributions to their field. Deceased Russian cosmonauts are commemorated by craters in and around Mare Moscoviense. Deceased American astronauts are commemorated by craters in and around the crater Apollo. Appropriate locations will be provided in the future for other space-faring nations should they also suffer fatalities; e.g. Schliemann.

Lacūs, Maria, Paludes, Sinūs Latin terms describing weather, other abstract concepts; e.g. Lacus Mortis

Montes Terrestrial mountain ranges or nearby craters; e.g. Mons Bradley

Rupēs Name of nearby mountain ranges (terrestrial names); e.g. Rupes Kelvin

Valles Named from nearby features; e.g. Vallis Alpes

Other features (catenae, dorsa, rimae) Named from nearby craters; e.g. Catena Humboldt

Mercury
Craters Deceased artists, musicians, painters, and authors who have made outstanding or fundamental contributions to their field and have been recognized as art historically significant figures for more than 50 years; e.g. Homer
Dorsa Deceased scientists who have contributed to the study of Mercury; e.g. Antoniadi Dorsum
Fossae Significant works of architecture; Pantheon Fossae
Montes Caloris, from Latin word for "hot"; Caloris Montes
Planitiae Names for Mercury (either the planet or the god) in various languages; e.g. Budh Planitia
Rupēs Ships of discovery or scientific expeditions; e.g. Pourqoui-Pas Rupes
Valles Radio telescope facilities; e.g. Goldstone Vallis

Venus
Astra Goddesses, miscellaneous
Chasmata Goddesses of hunt; moon goddesses; e.g. Seo-Ne Chasma
Colles Sea goddesses; e.g. Ruad Colles
Coronae Fertility and earth goddesses; e.g. Xilonen Corona
Craters Deceased women who have made outstanding or fundamental contributions to their field (over 20 km); Common female first names (under 20 km); e.g. Judith
Dorsa Sky goddesses; e.g. Dyan-Mu Dorsa
Farra Water goddesses; e.g. Seoritsu Farra
Fluctūs Goddesses, miscellaneous; e.g. Eriu Fluctus
Fossae Goddesses of war; e.g. Nike Fossae
Labyrinthi Goddesses, miscellaneous; Radunitsa Labyrinthus
Lineae Goddesses of war; e.g. Kara Linea
Montes Goddesses, miscellaneous (also one physicist); e.g. Gula Mons
Paterae Famous women; e.g. Wilde Patera
Planitiae Mythological heroines; e.g. Helen Planitia
Plana Goddesses of prosperity; e.g. Lakshmi Planum
Regiones Giantesses and Titanesses (also two Greek alphanumeric); e.g. Alpha Regio
Rupēs Goddesses of hearth and home; e.g. Ut Rupes
Terrae Goddesses of love; e.g. Ishtar Terra
Tesserae Goddesses of fate and fortune; e.g. Tyche Tessera
Tholi Goddesses, miscellaneous; e.g. Justitia Tholus
Undae Desert goddesses; e.g. Menat Undae
Valles Word for planet Venus in various world languages (400 km and longer); River goddesses (less than 400 km in length); e.g. Lo Shen Valles

Mars and moons
Albedo Features Names from classical mythology assigned by Schiaparelli and Antoniadi
Large craters (approximately 60 km and larger) Deceased scientists who have contributed to the study of Mars; writers and others who have contributed to the lore of Mars
Small craters (approximately 60 km and smaller) Small towns and villages of the world with populations of approximately 100,000 or less
Large valles Name for Mars/star in various languages
Small valles Classical or modern names of rivers
Other features From a nearby named albedo feature on Schiaparelli or Antoniadi maps

Moon Deimos Authors who wrote about martian satellites
Moon Phobos Scientists involved with the discovery, dynamics, or properties of the martian satellites, and people and places from Jonathan Swift's "Gulliver's Travels"

Moons of Jupiter
Moon Amalthea (crater, facula) People and places associated with the Amalthea myth; e.g. Pan

Moon Thebe (crater) People and places associated with the Thebe myth; Zethus

Moon Io
Active eruptive centers Fire, sun, thunder, and volcano gods and heroes; e.g. Prometheus
Catenae Sun gods
Fluctūs Name derived from nearby named feature, or fire, sun, thunder, volcano gods, goddesses and heroes, or mythical blacksmiths; e.g. Acala Fluctus
Mensae People associated with Io myth, derived from nearby feature, or people from Dante's Inferno; e.g. Hermes Mensa
Montes Places associated with Io myth, derived from nearby feature, or places from Dante's Inferno; e.g. Nile Montes
Paterae Fire, sun, thunder, volcano gods, heroes, goddesses, mythical blacksmiths, including names from the associated eruptive center; e.g. Tung Yo Patera
Plana Places associated with Io myth, derived from nearby feature, or places from Dante's Inferno; e.g. Nemea Planum
Regiones Places associated with Io myth, derived from nearby feature, or places from Dante's Inferno; e.g. Lerna Regio
Tholi Places associated with Io myth, derived from nearby feature, or places from Dante's Inferno; e.g. Apis Tholus
Valles Names derived from nearby named feature; Tawhaki Vallis

Moon Europa
Chaos Places associated with Celtic myths; e.g. Arran Chaos
Craters Celtic gods and heroes; e.g. Balor
Flexūs Places associated with the Europa myth, or Celtic stone rows; e.g. Delphi Flexus
Large ringed features Celtic stone circles; e.g. Tyre
Lenticulae Celtic gods and heroes
Lineae People associated with the Europa myth, or Celtic stone rows; e.g. Corick Linea
Maculae Places associated with the Europa myth; e.g. Thera Macula
Regiones Places associated with Celtic myths; e.g. Tara Regio

Moon Ganymede
Catenae Gods and heroes of ancient Fertile Crescent people[2]; e.g. Enki Catena
Craters Gods and heroes of ancient Fertile Crescent people; e.g. Kadi
Faculae Places associated with Egyptian myths; e.g. Thebes Facula
Fossae Gods (or principals) of ancient Fertile Crescent people; e.g. Zu Fossae
Paterae Dry wadis (channels) of the Fertile Crescent region
Regiones Astronomers who discovered Jovian satellites; e.g. Galileo Regio
Sulci Places associated with myths of ancient people; e.g. Ur Sulcus

Moon Callisto Names are drawn from myths and folktales of cultures of the Far North such as Norse, Chukchi, Inuit, Sami, etc.
Catenae Rivers, valleys, and ravines from myths and folktales of cultures of the Far North; e.g. Sid Catena
Craters Characters from myths and folktales of cultures of the Far North; e.g. Keelut
Faculae Gods and characters of frost, snow, cold, and sleet from myths and folktales of cultures of the Far North; Kol Facula
Large ringed features Places (other than rivers, valleys and ravines) from myths and folktales of cultures of the Far North; e.g. Valhalla

Moons of Saturn
Moon Janus (craters) People from myth of Castor and Pollux (twins); e.g. Castor

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[2]) Region of ancient Egypt and Mesopotamia; it is named after its crescent moon-shape and its rich soil.

Moon Epimetheus (craters) People from myth of Castor and Pollux (twins); e.g. Pollux
Moon Mimas (craters, chasmata) People and places from Malory's Le Morte Darthur legends (Baines translation); Arthur
Moon Enceladus (Craters, Dorsa, Fossae, Planitiae, Sulci) People and places from Burton's Arabian Nights; e.g. Sindbad
Moon Tethys (chasmata, craters, montes) People and places from Homer's Odyssey; e.g. Ajax
Moon Dione (catenae, chasmata, craters, dorsa, fossae) People and places from Virgil's Aeneid; e.g. Dido
Moon Rhea (chasmata, craters) People and places from creation myths (with Asian emphasis); e.g. Pu Chou Chasma, Yu-Ti

Moon Titan
Albedo features Sacred or enchanted places, paradise, or celestial realms from legends, myths, stories, and poems of cultures from around the world; e.g. Ching-tu
Craters and large ringed features Gods and goddesses of wisdom; e.g. Sinlap, Nath
Facula and Faculae Facula: Names of islands on Earth that are not politically independent Faculae: Names of archipelagos; e.g. Santorini Facula
Fluctūs Gods and goddesses of beauty; e.g. Ara Fluctus
Flumina Names of mythical or imaginary rivers; Elivagar Flumina
Insulae Names of islands from legends and myths; Mayda Insula
Lacūs Lakes on Earth, preferably with a shape similar to the lacus on Titan; e.g. Waikare Lacus
Maria Sea creatures from myth and literature; e.g. Kraken Mare
Other features (maculae, regiones, arcūs) Deities of happiness, peace, and harmony from world cultures; e.g. Eir Macula
Undae Gods and goddesses of wind
Virgae Gods and goddesses of rain; e.g. Kalseru Virga

Moon Hyperion (craters, dorsa) Sun and Moon deities; e.g. Helios, Bond-Lassell Dorsum
Moon Iapetus (craters, montes, regiones, terrae) People and places from Sayers' translation of Chanson de Roland; e.g. Basile, Seville Mons, Cassini Regio, Saragossa Terra
Moon Phoebe
Craters People associated with Phoebe, people from the Argonautica by Apollonius Rhodius and Valerius Flaccus; e.g. Mopsus
Other features Places from the Argonautica

Moons of Uranus
Puck (craters) Mischievous (Pucklike) spirits (class), Bogle
Miranda (coronae, craters, regiones, rupēs, sulci) Characters, places from Shakespeare's plays; e.g. Ferdinand
Ariel (chasmata, craters, valles) Light spirits (individual and class); e.g. Sprite Vallis
Umbriel (craters) Dark spirits (individual); e.g. Minepa
Titania (chasmata. craters, rupēs) Female Shakespearean characters, places; e.g. Belmont Chasma
Oberon (chasmata, craters) Shakespearean tragic heroes and places; e.g. Mommur Chasma, Hamlet
Small Satellites Heroines from Shakespeare and Pope

Moons of Neptune
Proteus (craters) Water-related spirits, gods, goddesses (excluding Greek and Roman names); Pharos
Triton (catenae, cavi, craters, dorsa, fossae, maculae, paterae, planitiae, plana, plume, regiones, sulci) Aquatic names, excluding Roman and Greek. Possible categories include worldwide aquatic spirits, terrestrial fountains or fountain locations, terrestrial aquatic features, terrestrial geysers or geyser locations, terrestrial islands; e.g. Set Catena
Nereid Individual nereids
Small Satellites Gods and goddesses associated with Neptune/Poseidon mythology or generic mythological aquatic beings

Pluto Underworld deities

4.2.3.5.6 References for 4.2.3.5

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