Chapter

Cryovolcanism in the Solar System and Beyond: Considerations on Energy Sources, Geological Aspects, and Astrobiological Perspectives

Georg Hildenbrand, Klaus Paschek, Myriam Schäfer and Michael Hausmann

Abstract

Volcanism based on melting rocks (silicate volcanism) is long known on Earth and has also been found on Jupiter's moon Io. Remnants of this type of volcanism have been identified also on other bodies in the solar system. Energy sources powered by accretion and the decay of radioactive isotopes seem to be dominant mainly inside larger bodies, which have enough volume to accumulate and retain this energy in significant amounts. On the other hand, the impact of tidal forces allows even tiny bodies to melt up and pass into the stage of cryovolcanism. The dependence of tidal heating on the size of the object is minor, but the masses of and the distances to accompanying bodies as well as the inner compositions of the heated body are central factors. Even though Io as an example of a body supporting silicate volcanism is striking, the physics of tidal forces might suggest a relatively high probability for cryovolcanism. This chapter aims at considering the parameters known and objects found so far in our solar system to give insights into where in our system and other planetary systems cryovolcanism might be expected.

Keywords: volcanism, cryovolcanism, tidal forces, radioactivity, low-temperature biotopes, black smoker equivalents

1. Introduction

All types of volcanism known until now are in the solar system. All considerations and models for volcanism in other stellar systems are built upon our knowledge from our own system. New types of volcanism still unthought of, might be a challenging research topic but may not be considered here.

The main aim of this chapter is to consider cryovolcanism powered by tidal heating and its potential in exosystems. As an introduction, for reference and to characterize the main features as a base for better comparison, a rough overview of its counterpart silicate volcanism as well as underlying types of energy sources in the solar system are given.

The most prominent objects in our solar system harboring active volcanoes are both an example of what may be named high-temperature range volcanism as rocks are molten and are apparent in the form of glowing liquid lava on Earth and on the moon Io. This is generally better known under silicious-based/silicate volcanism because silicate is the most dominating component in liquid rocks. The known temperatures rise to about 1600 K on Io in the volcanoes on the surface [1], while on Earth about 1000 K to 1550 K temperature in the lava is reached [2] depending on the composition of the rocks. The temperature of magma below the surface may have still higher temperatures.

These two objects already show us also the main energy categories on which volcanism, as we know it, relies on. For the Earth, it is mainly based on the conserved accretion/contraction energy from its formation, decay of radioactive elements pulled into the mantle and center of the planet by gravity-induced differentiation, and also on friction rising from the resulting tectonic activity [3]. For Io, it is mainly based on tidal heating from the huge tidal forces raised by the gas giant it is orbiting in its crust and upper mantle [3]. Both may gain also energy from friction that is arising from the resulting tectonic activity. Some of the following general considerations may also apply to forms of energy resources. The energy retention behavior (and so also the duration of volcanic activity) is among other factors strongly depending on surface-to-volume ratios regardless of energy source. Bigger objects with lower surface-to-volume ratios are tending to stay hotter for a longer period and are able to sustain volcanism longer. For Earth and Moon during the assumed collision of their precursor bodies Theia and Gaia, a transfer of the core of Theia into the forming core of the Earth may have increased also the amount of heavier and so radioactive elements, increasing the power for volcanism on Earth and by this decreasing it on the Moon. Also during this early phase, tidal heating may have played a much bigger role for both objects, as they have been much closer together [4].

Regarding ancient evolution steps in the solar system, it is important stressing that even much tinier impacts than Theia with Gaia were much more common and have played a stronger role in melting parts of a planet, asteroid, or moon, especially during the late heavy bombardment (LHB). As it may be perceived as an external energy source and is now of little relevance, volcanism by bombardment will not be discussed further.

Considering the long-term evolution of heating sources also leads us to inactive silicate volcanism as the bodies considered are too tiny to have been able to sustain volcanism until now, as on the Moon, Mercury [5], Venus, and Mars. They are covered with lava plains and show also volcanoes, for example, the highest of the solar system, Olympus Mons on Mars. Still, for all these objects, signs for stronger or lesser still ongoing or very recent volcanic/tectonic activity have been found or are discussed (Moon: [6–10]; Mercury: [11–13]; Venus: [14–17]; Mars: [18, 19]). On Mars also a connection to a known type of lower temperature volcanism may already be found as the melting of ice and/or its remnants under a volcano may have been found as well [20–23].

In the case of Venus, a relatively young surface [24] and its own type of tectonics [25] may also indicate a presence of modifying influences on silicate volcanism that are not well known until now. If the missing of water or other solvents (on Venus probably mostly after entering into a runaway greenhouse effect) is a cause for a changed plate tectonic and so volcanism [26–28], also availability and abundance of

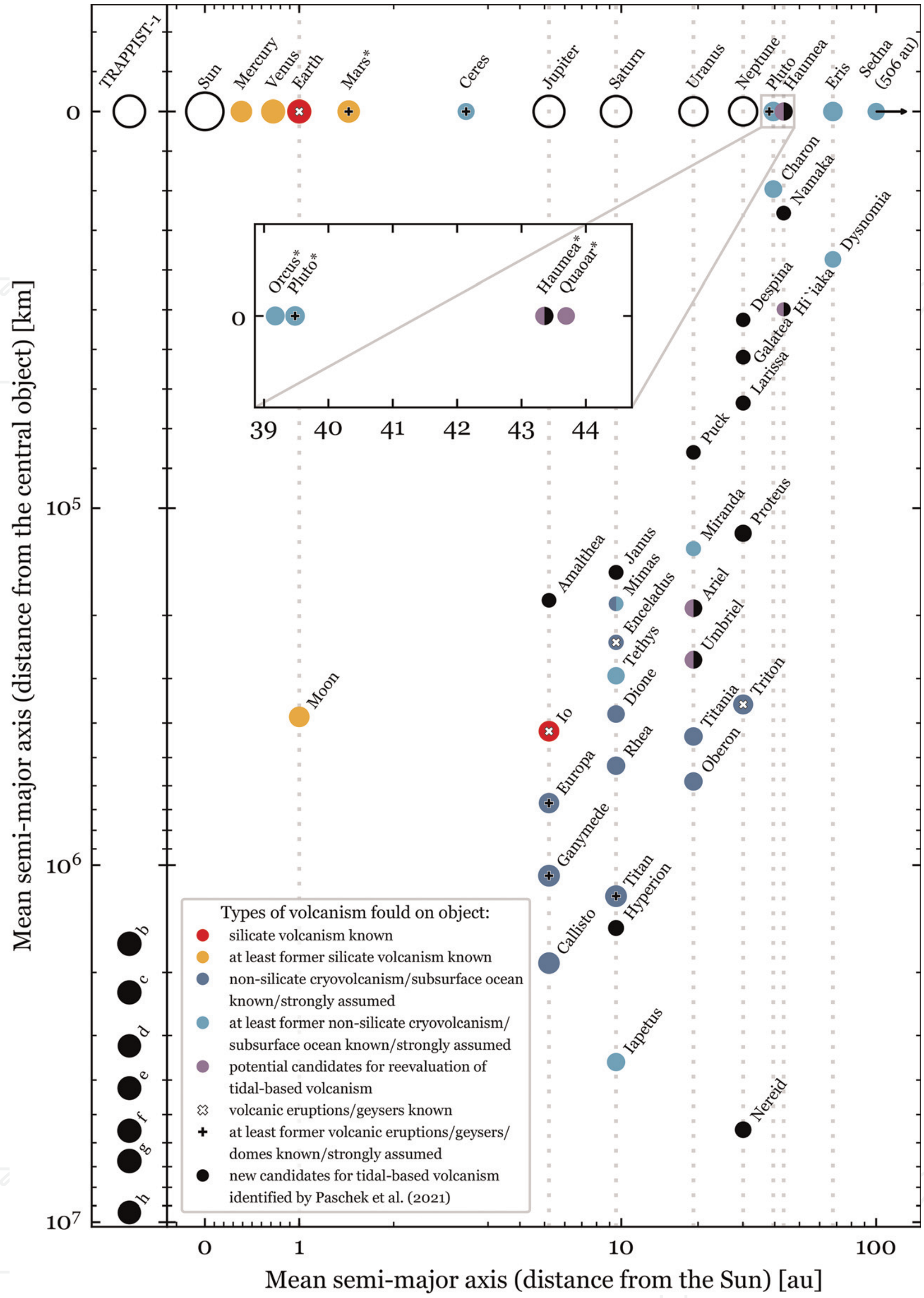

Figure 1.

Overview of types of volcanism identified or assumed on celestial bodies in the solar system (right panel) and the extrasolar planetary system TRAPPIST-1 (left panel). The horizontal axis corresponds to the mean semi-major axis of the orbits as distance to the sun (right panel) and the vertical axis corresponds to the mean semi-major axis of the orbits of moons or exoplanets as the distance from their central object (hosting planet or star TRAPPIST-1) [37–43]. The radii of the circles depicting each object are scaled logarithmically to the actual radii of the celestial bodies [37–39, 41–53]. Please note that close to the dwarf planets Pluto and Haumea the two further dwarf planets Orcus and Quaoar exist. These are shown in the zoomed-in inset panel. Charon is a moon of Pluto, and Namaka and Hi'iaka are moons of Haumea. The dwarf planet Sedna on the right side of the right panel orbits the sun at a mean distance of 506 au, so further away as it is shown here, which is indicated with an arrow. Color-coded is the types of volcanism known or assumed on the objects. ***Table 1*** *Provides an overview of the respective references. The hollow cross marks objects in the solar system for which ongoing volcanic eruptions or geysers are known. The filled plus marks objects in the solar system for which at least former volcanic eruptions, geysers, or domes (remnants of extinct volcanic activity) are known or strongly assumed. Please note that only on Pluto at least former volcanic eruptions are assumed, but not on Orcus. An asterisk (*) at the end of an object's name marks when one or several moons are present but not shown here.*

water, NH_3 or CH_4 have to be considered for modifying silicate volcanism, showing again a link to material and substances beyond rock.

Also, a discussed inhomogeneous distribution of radionuclides as a cause for volcanic activities, for example, on the Moon [6] further highlights a need for deep consideration of how volcanism may be sustained and be modified in behavior.

Moving on outward in the solar system brings us into ranges of asteroids, all of them being tinier than the aforementioned planets and so obviously have cooled and are not maintaining volcanism now. Accretion and radioactive energy seem to be nowadays not important for any type of volcanism in the asteroids. Still, ancient traces of volcanism may be found. The importance of meteorite impacts for melting gets relatively bigger on tinier objects. But also a differing composition of radioactive elements seems to play a bigger role as ^{26}Al [29] and ^{60}Fe [30] seem to have molten these tiny objects and given rise to silicate volcanism. This peroid has made a huge influence on these objects, even though this period may not have been very long, regarding the relatively short half-life of these isotopes.

Entering the realm of the gas giants opens new perspectives. The rocky objects that can show volcanism are now mainly moons, tinier in size but are orbiting much larger gas giants or maybe very close double systems orbiting each other, for example, some TNOs. These conditions open the possibility for tidal heating as the main energy source for volcanoes. Accretion and radioactive energy seem to be nowadays of lesser importance for any type of volcanism in the asteroids, gas giant moons, and beyond in the solar system.

Considering Io as an exception in this range, as we also will show, we encounter two other known examples of volcanism around gas giants that are based on tidal heating, but are now in the lower temperature ranges of cryovolcanism. The moons Enceladus and also Triton have been identified as cryovolcanic worlds [31, 32]. Others show signs of active geology and tectonics, for example, on Europa [33] or Ganymede [34], and are believed to have liquid layers or even oceans of solvents, such as water or NH_3, in their depths and even deeper a basic silicate volcanism.

Regarding this, it becomes easily obvious that a real stable definition of cryovolcanism is not as easy. The aim is mostly trying to focus on volatiles, for example, molten water or methane are thrown out on the surface in an environment colder than their own melting temperature, also even if in greater depths rocks might be quite hot. Earth itself is mostly not being considered as a planet harboring cryovolcanism, even though any volcano under ice known (Iceland) or assumed (Antarctica) and geysers all over the world would fulfill such definitions in winter. Also, mud volcanism (also called "cold" volcanism) being based on mud diapirs and being generally associated with (silicate) volcanism [35, 36], is normally not considered under cryovolcanism.

All these ambiguities in defining cryovolcanism may result from a bias in detecting cryovolcanism on foreign worlds in astronomy or astrophysics. Big eruptions are much easier to observe by optic sensors (on or close to Earth or even on probes) as well as by mass analyzing probes in the proximity of these objects than by constant release of volatiles by tectonics of slowly moving ice shields covering deeper-lying liquids or even silicate volcanism. Also, old remnant structures of previous volcanism may still cover deeper active processes, which is much more problematic to investigate. If we improve our detection capabilities, also our definitions will evolve. Regarding detection and research on cryovolcanic worlds, this all illustrates the strong necessity of modeling based on easier accessible observations, either to understand where we might find such objects with cryovolcanism or what kind of cryovolcanism we might expect. This leads apart from the known active volcanic and cryovolcanic

Object	Primary	Type of volcanism, etc.	Reference
Mercury	Sun	At least former silicate volcanism	[12, 13]
Venus	Sun	At least former silicate volcanism	[15–17]
Earth	Sun	Silicate volcanism; Active volcanic eruptions	
Moon	Earth	At least former silicate volcanism	[9, 10]
Mars	Sun	At least former silicate volcanism; At least former volcanic eruptions/domes	[18, 19]
Ceres	Sun	At least former cryovolcanism; At least former volcanic eruptions/geysers/domes	[54–56]
Io	Jupiter	Silicate volcanism; Active volcanic eruptions	[57]
Europa	Jupiter	Cryovolcanism; At least former volcanic eruptions/geysers/domes	[33, 57–60]
Ganymede	Jupiter	Cryovolcanism; At least former volcanic eruptions/geysers/domes	[34, 57, 61, 62]
Callisto	Jupiter	Cryovolcanism	[57]
Mimas	Saturn	Cryovolcanism/At least former cryovolcanism (debated)	[63–65]
Enceladus	Saturn	Cryovolcanism; Active volcanic eruptions/geysers	[31, 66]
Tethys	Saturn	At least former cryovolcanism	[67–69]
Dione	Saturn	Cryovolcanism	[66]
Rhea	Saturn	Cryovolcanism	[70]
Titan	Saturn	Cryovolcanism; At least former volcanic eruptions/geysers/domes	[71–79]
Iapetus	Saturn	At least former cryovolcanism	[70, 80]
Miranda	Uranus	At least former cryovolcanism	[81–84]
Ariel	Uranus	Potential candidate for at least former cryovolcanism	[81, 82]
Umbriel	Uranus	Potential candidate for at least former cryovolcanism	[81]
Titania	Uranus	Cryovolcanism	[70]
Oberon	Uranus	Cryovolcanism	[70]
Triton	Neptune	Cryovolcanism; Active volcanic eruptions/geysers	[32, 70, 85–89]
Pluto	Sun	At least former cryovolcanism; At least former volcanic eruptions/geysers/domes	[70, 90]
Charon	Pluto	At least former cryovolcanism	[91]
Orcus	Sun	At least former cryovolcanism	[70, 92]
Haumea	Sun	Potential candidate for at least former cryovolcanism	[93]
Hi'iaka	Haumea	Potential candidate for at least former cryovolcanism	[93]
Quaoar	Sun	Potential candidate for at least former cryovolcanism	[94]
Eris	Sun	At least former cryovolcanism	[50, 70]
Dysnomia	Eris	At least former cryovolcanism	[50]
Sedna	Sun	At least former cryovolcanism	[70]

Table 1.
Celestial objects in the solar system on which different types of volcanism are present or strongly assumed. The last column gives the respective references. References given here were also used to categorize the types of volcanism given in ***Figure 1****. For each object, its orbited primary and the types of known or strongly assumed volcanism and eruptions (active or extinct) are listed.*

worlds to a huge list of strongly assumed, mainly cryovolcanic, active as well as inactive worlds (see **Figure 1** and **Table 1**).

All these models are strongly based on energy resources and energy transport. Reconsidering some basic parameters in these models may illuminate some specific aspects of cryovolcanic worlds and offers an insight into basic principles to find general concepts for application in far exoplanetary systems.

2. Volcanism present in the solar system and the extrasolar planetary system TRAPPIST-1

The types of active and inactive volcanism in our own neighborhood are various. **Figure 1** gives an overview of the different types of volcanism found or strongly assumed on celestial objects in the solar system. To classify the different types of (cryo-)volcanism found on objects in the solar system, we distinguish between the case when the respective type of volcanism is active right now and verified (e.g., by measurements of space probes) or strongly assumed due to observations, measurements or theoretical models, and the case when signs of at least former volcanic activity were identified. We also include the (at least former) presence of a liquid subsurface ocean as part of cryovolcanism.

The melting up of a subsurface ocean requires a strong energy source. This is either powered from the interior of the body hinting at the presence of silicate volcanism in its core. Another or even simultaneously occurring energy source can be the deformation by tidal forces of nearby objects, which can liquify silicates or ice and heats up potentially present silicate magma and/or a (subsurface) ocean further. This might result in icy objects in cryovolcanic activity, for example, in the form of geysers penetrating through the ice crust of Saturn's ice-moon Enceladus [31]. By cracking up the ice crust a cryo-form of plate tectonics could be initiated, for example, on Jupiter's ice-moon Europa [33].

In addition, we identify several objects that should be considered as potential candidates for re-evaluation of the potential of tidal-based volcanism based on recent studies. For example, the presence of crystalline water ice and/or ammonia ice on the surface hints at the presence of a mechanism that actively redeposits new material, as crystalline water ice and/or ammonia ice is not stable in the long term in these environments due to destruction by energetic particles (see, e.g., [92–94]).

Domes, which are mountains and bulges in the crust of a celestial object, could be remnants of extinct eruptive volcanoes or could be plumes that do/did not penetrate fully through the crust. We see the identification of domes on the surface of a celestial object as an indicator for at least former eruptive volcanic activity.

Moreover, we included the objects resulting from our recent study [95], which we identified as new and (in the case of the solar system) not yet elsewhere considered candidates for tidal-based volcanism.

3. Considerations on energy from tidal heating

For cryovolcanism, an indispensable prerequisite must be an energy source. In principle, energy could be gained from accretion and contraction during the formation of the planetary object. This process is among other parameters depending on the size of the object (with R being the radius of the object, roughly $\sim R^3$). As radioactive material is incorporated along with this process, equivalent considerations may be done here. Higher volume-to-surface ratios ($\sim R$) minimize cooling effects and allow longer stable heating from inside. Rearrangement of material (e.g., impacts as in LHB, Theia-Gaia events, seeding with ^{26}Al) may change the occurrence, intensity, and also duration of volcanic active phases; inhomogeneities in deposition of material may give rise to local volcanism. The starting composition of radioactive material during formation may differ along with, for example, age of the stellar population. These processes will be complete in the very early phase of a stellar system (roughly 0.5 Gy after formation) and any volcanic activity based on this will evolve based on the then built-up conditions for heating and cooling. Models over several Gys imply significant effects for the heating of liquid volatiles in bigger objects of several hundreds of km radius [96].

This "standard" energy production process might not work in smaller objects where other heating sources are required, for instance, tidal heating, a process occurring in planetary systems with masses closely associated and thus impacting each other. The general principles for tidal heating may be considered as based on many more parameters as for accretion/radioactivity. Aspects of volume-to-surface ratios ($\sim R$) are the same as for accretion and radioactivity, many other parameters differ.

The tidal acceleration A acting on an object's surface is

$$A = \frac{GM}{r^2}\left(\frac{1}{\left(1 \pm \frac{R}{r}\right)^2} - 1\right), \tag{1}$$

G as gravitational constant, M as mass of the influencing object, R as radius of the influenced object, and r as distance between the objects. This can be approximated by a Taylor series expansion to

$$A = \mp 2GM\frac{R}{r^3}. \tag{2}$$

Therefore, the tidal force will go with $\sim R$ (for details and elaborated calculations see [95]). The energy transfer and average dissipation rate gets based on even more parameters and may mostly be assumed by $\sim R^5$ [97–103].

$$\dot{E} = -\frac{21}{2}\frac{k_2}{Q}\frac{n^5R^5}{G^*}e^2, \tag{3}$$

$\dot{E}$ as rate for tidal energy dissipating, G^* as gravitational constant, k_2 as Love number, and Q dissipation function of the satellite. $\frac{k_2}{Q}$ is telling how "effectively"energy is transferred on the satellite and how this leads to heating. Models with k_2 are mainly used, but also models with "higher" Love numbers as k_3, $k_{4,}$ or k_6 may be considered reasonable for special systems [97, 104–106].

Q is in the range from 10 to 500 are found for the terrestrial planets and satellites of the major planets. On the other hand, Q for the major planets is always larger than $6 \cdot 10^4$ [106].

Trying to figure out further principles for tidal heating we may approach this by considering when tidal heating may really be minimized.

A body that is tidally locked on an orbit with eccentricity $e = 0$ will not have any type of tidal energy dissipating. Locking will occur in ranges of

$$t_{\text{lock}} = \frac{\omega a^6 I Q}{3G^* {m_p}^2 R^5 k_2}, \tag{4}$$

G^*, k_2, Q, R as above, ω as initial spin rate, a for the semi-major axis of the orbit of the satellite around the planet/partner, m_s as mass of the satellite, m_p as mass of the planet/partner, and I as momentum of inertia [107] (see pages 169–170 of this article; Formula (9) is quoted here, which comes from ref. [108]), with $I \approx 0.4 m_s R^2$:

$$t_{\text{lock}} \approx \frac{\omega a^6 0.4 m_s R^2 Q}{3G^* {m_p}^2 R^5 k_2} = \frac{0.4\omega}{3G^*} \frac{Q}{k_2} \frac{a^6 m_s}{{m_p}^2 R^3}. \tag{5}$$

With $m_s = \frac{4\pi}{3} \rho R^3$ and ρ as density of the satellite:

$$t_{\text{lock}} \approx \frac{1.6\pi\omega}{9G^*} \frac{Q}{k_2} \rho \frac{a^6}{{m_p}^2}. \tag{6}$$

Apart from ω resulting from the formation process, $\frac{Q}{k_2}$ and ρ, as parameters for interior composition and “behavior” in heating, m_p and especially a seem to strongly influence the period in which tidal heating may be possible.

The moon Io is actually tidally locked and would be on a far bigger orbit with eccentricity $e = 0$ and so no volcanism at all would occur, if its accompanying moons would not have been influencing it and are distracting it from a round orbit [109, 110].

But a may also change over longer periods “on its own” and may so become important regarding the period for tidal heating and so volcanism. This results from an effect of energy transfer by tidal forces beyond heating, yielding a change of orbital velocity because of tidal acceleration or tidal deceleration.

As the energy transfer resulting in heating is not the only effect, tidal acceleration and also tidal deceleration may occur and by changes in velocity, change the orbit of the objects. For tidal acceleration this will bring objects to farther orbits, moving them out of the possible zone for tidal heating, for tidal deceleration, this will lower the orbits and so either crushing the objects when crossing the Roche limit or crashing them on the body which they are orbiting, as it is assumed for Triton [111–113]. These effects have also an impact via changes in the semi-major axis a on t_{lock} . The changes by tidal acceleration/deceleration are still tiny in our system and so changes in t_{lock} maybe on larger scales [111–113].

All these aspects make it obvious how variable volcanism based on tidal heating may be. The discovery of so powered cryovolcanism on the moons Enceladus and also Triton has been quite surprising and many proofs or hints for active or inactive volcanism, of any kind, may have still not been found in the region of the asteroid belt and beyond. A general overview of both silicate volcanism and cryovolcanism is given in **Figure 2**. All sketches of phases given may be powered by both accretion and radioactivity or by tidal heating. Especially if objects are big or young enough, we may also consider overlap of both power types. Known objects in our own system cover only some of these sketches, but still, we do not have proof of volcanism on all objects being considered and, as discussed, some may be cryovolcanic worlds but may have yet not been even put on a list of assumed objects.

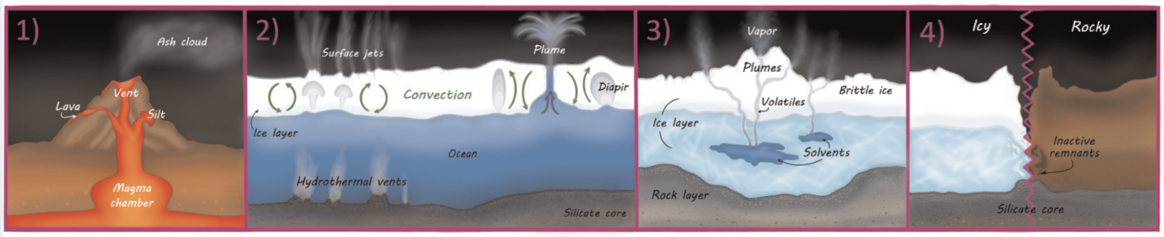

Figure 2.
Schematic overview of general types of volcanism (1–3) and how silicate and cryovolcanism are linked (2). Remnants of both silicate and cryovolcanism as signs of inactive volcanism in (4). Earth is a known example of silicate volcanism powered by accretion and radioactivity, as well as Io is also known example of silicate volcanism powered by tidal heating, may be both sketched in (1). Both known icy moons with cryovolcanism powered by tidal heating, Enceladus, and also triton may be found in (2) or in some parts may be in (3). Inactive remnants (4) as discussed may be found on many objects, for example, Vesta or the moon.

Considering this, we may, when looking out of our own solar system, get aware of how problematic identifications of volcanic worlds may get in these faraway systems. Also, some aspects may get stronger influence. Many systems with close orbits, favoring stronger tidal forces, especially around K- and M-stars, have been found and modeled (e.g., [114–118]). But many parameters of these systems being necessary for modeling are barely known and may need even stronger efforts in measuring and obtaining them. First attempts in reconsidering some constraints of these models have been done (as in e.g., [95]) and first assumptions based on reduced parameter sets for the evaluation of state and kind of volcanic worlds have been made. The approach aims at assessing the potential for volcanic worlds on easier than other observable parameters and has been verified in our own system, yielding all known and many assumed volcanic objects, plus hints for further bodies harboring volcanoes. Thus, it may be considered as a pre-scan before deeper and more intensive modeling. The first application in the system of TRAPPIST-1 gave rise to a higher volcanic potential on all planets, not only by forces of the central star but also by mutual tidal influences of the orbiting bodies [95].

4. Considerations for astrobiology

Regarding the phenomena of silicate and cryovolcanism, all of them may be powered by the energy sources discussed, but conditions for and evolution of these power sources are differing. Considering constraints for life as we know it, new aspects arise. Water in liquid form would be assumed as a requirement, in some alternative chemistry also ammonia or methane are discussed as possible solvents, liquid silicate/rock is less considered as being favorable for life. Also, a longer period of stability of these solvents is seen as favorable.

As accretion/radioactivity powered volcanism is high after formation and presumably gives rise to liquid silicates, it is a narrow gap of parameters depending on the size of the object and seeding of elements, which would allow a long and stable period of solvents as water. Bigger objects (starting already with radii just below 1000 km) might keep the heat over Gys too high, for example, water to rain down on the surface. Objects with sizes of several hundred kilometers and below may cool down very fast, allowing liquid water on the surface or in layers deeper in the crust for short periods of some 10 or 100 Mys [96]. Volcanism by tidal heating seems to be, if special conditions are met, more stable, as may be seen from all moons in our system with known active volcanism or tectonics, for example, Europa, Ganymede, or Enceladus. Even if becoming presumably unstable as Triton, it is after many Gys.

Considering the distribution of stable (e.g., considered from formation until now) volcanism powered by accretion/radioactivity or by tidal heating in our system, only Earth may be considered as accretion/radioactivity powered and many tens of objects powered by tidal heating confirmed or strongly assumed. If not for the power of the sun, habitable biotopes on Earth would be pretty much the same as the assumed ones on the moons discussed, that is, around vents deep in the liquid oceans below an ice crust covering (nearly) the whole surface. If we postulate such black smokers as life forging and maintaining harbors, in general, all over the universe, tidal heating may stably sustain such sources over many Gys, independent of a central stellar object even (and especially) on tiny objects. The requirements for tidal heating to power the cryovolcanism and rendering solvents liquid maybe not easily met, but considering the vast number of tiny objects (in contrast with bigger ones), the overall abundance of the self-powered systems may be seen as relatively high.

5. Conclusions

Silicate and cryovolcanism both occur in a broad spectrum considering the proofs, traces, and remnants in our own system. The constraints and challenges for detecting any volcanic activity beyond our system are huge. Some parameters maybe even far more difficult for measuring than others. Bigger objects with volcanism probably based mainly on accretion energy or radioactivity may still be easier for far distance observation, detection, and measurement. Still, an accompanying approach by modeling, for objects in our own system as well as beyond, based on measurable or other feasible attempts seems reasonable.

Considering the models and also the underlying energy sources and evolution, tidal heating as an energy source can be highly variable. It may have a broader spectrum in occurrence than heating by stored accretion energy or radioactivity. Tinier objects may get energy for significant heating from tidal heating and less from accretion and radioactivity. Objects may start in conditions for tidal heating, move out or in these conditions, and may be stabilized by accompanying partners. The real spectrum of possible sets of moons, asteroids, and planets will be probably even much broader. Considering the fact of much larger amounts of tiny objects, the implications for the probability of worlds with volcanic activity of any kind powered by tidal heating are huge.

Being aware of possible long stable periods for liquid solvents on such volcanic worlds powered by tidal heating and also considering known volcanic structures as deep ocean vents serving as harbors for genesis and maintenance of life, the relevance of tidal heating for cryovolcanism/low-temperature geological activity becomes even more prominent.

By a combination of observational systems and models, by their improvement and mutual influence, description and measurement of volcanic worlds, as well as possible biotopes for life beyond our own system, seems to be achievable.

Author details

Georg Hildenbrand[1*], Klaus Paschek[1,2], Myriam Schäfer[1] and Michael Hausmann[1]

1 Department of Physics and Astronomy, Heidelberg University, Kirchhoff-Institute for Physics, Heidelberg, Germany

2 Max Planck Institute for Astronomy, Heidelberg, Germany

*Address all correspondence to: hilden@kip.uni-heidelberg.de

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