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A toolbox for identifying the expression of dome-forming volcanism on exoplanets

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ABSTRACT

The presence of volcanism is often anecdotally used to define a “living planet”. Since dome-building volcanism on Earth occurs primarily at plate boundaries, the identification of such domes could inform on exoplanetary development. Lava domes form when extruded magma is too viscous to flow from a vent, and their morphology on Earth varies from flat, pancake lobes to steep, blocky domes. Identification of lava domes on other terrestrial planets in our Solar System indicates that they likely also exist on rocky exoplanets. Here we show, using particle-based modelling, that the diversity of lava dome morphology in our Solar System is dwarfed by the diversity expected for exoplanets. Specifically, the height-to-diameter ratio of a dome decreases as a function of increasing gravity (i.e., planetary mass and radius). For example, lava domes on high-gravity super-Earths will be extremely wide and flat and a volcanic origin may not be immediately apparent. Creating a toolbox to help identify exoplanetary volcanism will allow us to make initial estimations as to the development and habitability of these alien worlds as images become available.

1. Introduction

The formation of lava domes on Earth requires viscous magma and, as a result, dome-building volcanoes are primarily found at plate boundaries (Cottrell, 2015) where high-silica, high-viscosity magmas form. The morphology of these domes varies depending on factors such as material properties (e.g., viscosity, primarily affected by composition and temperature) and eruptive conditions (e.g., ascent velocity) (Blake, 1990; Fink and Griffiths, 1998; Watts et al., 2002). Although the formative processes (including the existence of plate tectonics) are sometimes unclear, volcanic domes are considered to exist on other planetary bodies in our Solar System (Platz et al., 2014), such as Venus (Aubele and Slyuta, 1990; Bulmer and Guest, 2008; Pavri et al., 1992), Mars (Rampey et al., 2007; Brož et al., 2015), and the Moon (Chevrel et al., 1999; Glotch et al., 2011; Guest and Murray, 2007). The identification of dome-forming volcanism on rocky planets and moons in our Solar System suggests that we should also expect similar volcanic processes on rocky exoplanets. Although the focus of this contribution is rocky exoplanets, we also highlight that dome-like features may also form as a result of cryovolcanism on icy planets and moons (e.g., Ruesch et al., 2016).

At the time of writing, the NASA Exoplanet Archive currently lists over 4000 confirmed planets outside our Solar System. The ongoing hunt for other habitable planets means that the planetary evolution (e.g., geological formation and atmospheric development) of exoplanets is of great scientific interest. Of the planets in the NASA Exoplanet Archive, direct imagery has only been obtained for a handful of exoplanets. Presently, the direct imaging of exoplanets typically involves imaging star systems and measuring the separation, in arcsec or astronomical units (AU), between the planets and their central star (e.g., Traub and Oppenheimer, 2010; Pepe et al., 2014). Although unavailable at present, technological advances and potential future space-based direct imaging missions, such as the Habitable Exoplanet Observatory (HabEx), could provide high-resolution images of exoplanets in the future.

The intriguing question therefore is whether we can interpret future high-resolution images to confidently identify volcanic processes on exoplanets. Since lava domes on Earth are associated with plate tectonics, their identification could inform on the developmental stage (e.g., the presence of plate tectonics; Bercovici and Ricard, 2014) and potential habitability (e.g., subduction-related volcanism has been linked to atmospheric development; Mikhail and Sverjensky, 2014) of an exoplanet.

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However, lava dome morphology is unknown for exoplanets. To better inform those tasked with interpreting geological processes from exoplanet imagery, we present here a toolbox that provides the likely expression of dome-building volcanism on variably sized rocky exoplanets, from dwarf planets to super-Earths. Our toolbox shows how exoplanetary lava domes can differ in morphology to their equivalent Terran counterparts, but indicate processes as we understand them on Earth.

2. Methods

We constructed our toolbox using a discrete element method model, which has been shown to successfully simulate lava dome emplacement (Husain et al., 2014, 2018; 2019; Walter et al., 2019) and subsequent gravitational settlement (Harnett et al., 2018) on Earth. We use Particle Flow Code 5.0 from the Itasca Consulting Group Inc., which employs the discrete element method (Cundall and Strack, 1979). The particle model

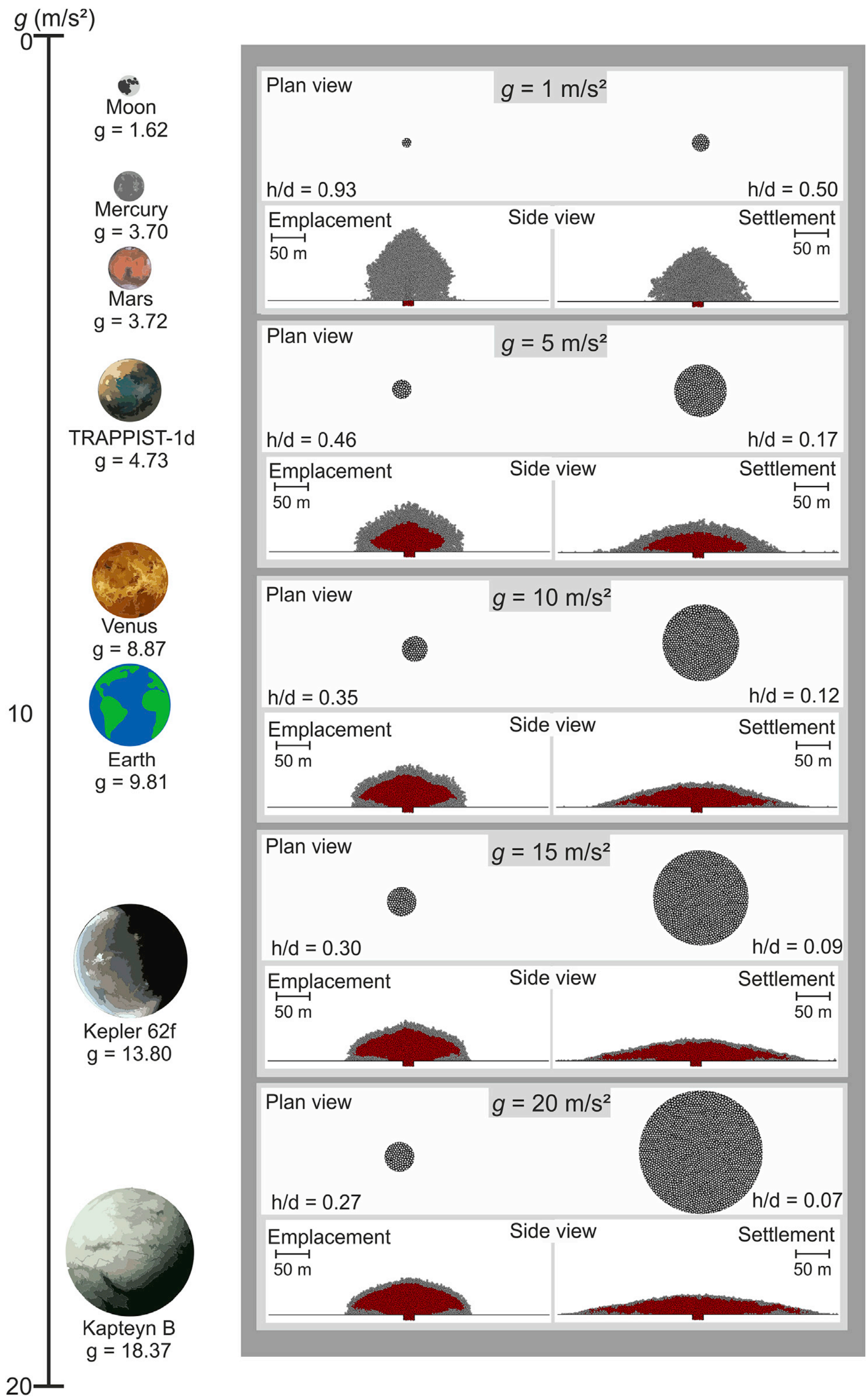

Fig. 1. Exoplanet volcano toolbox. Modelled domes (cross sections) after emplacement and settlement, shown for gravity of 1, 5, 10, 15, and 20 m/s^2 (the vertical scale is the same as the horizontal scale). Red particles within the dome show material behaving as a fluid, and grey particles show material behaving as a solid (see Harnett et al., 2018 for more details). Also shown are illustrative diagrams for the plan view of each dome. Exemplar planets are shown on the left for different gravity values in the range 1–20 m/s^2. Images of TRAPPIST-1d, Kepler 62f, Kapteyn B are based on artist's impressions from the NASA Exoplanet Archive. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

is initialised with a magma-filled conduit, and all particles are given an upwards velocity. We used the same timestep, velocity, and number of cycles as in Harnett et al. (2018), who successfully modelled realistic lava dome morphologies as seen on Earth (which we consider, in the absence of data for exoplanets, as the most appropriate values for our modelling). We note that the model produces domes of equivalent volume. Following the method outlined by Harnett et al. (2018), the modelled material behaves as a viscous magma within the core of the dome and as a solid within the outer shell of the dome. This is to model dome growth as observed on Earth, where a dome is comprised of a fluid magma core that solidifies as its exterior to form a brittle shell (e.g., Iverson, 1990). This transition is controlled by a solidus pressure of 0.4 MPa, as experimentally determined by Couch et al. (2003) for the initial composition at Soufrière Hills volcano (Montserrat), and used in lava dome modelling by previous authors (Hale et al., 2009a, 2009b; Harnett et al., 2018; Husain et al., 2014). The effective model viscosity was taken as 10^5 Pa s, a viscosity shown to reproduce realistic lava dome morphologies as seen on Earth (see Harnett et al., 2018).

All parameters in the model are kept constant as on Earth and we isolate only the effect of acceleration due to gravity (hereafter referred to as gravity) on volcanic dome morphology. Although parameters such as magma viscosity likely differ from exoplanet to exoplanet, our toolbox can be used to give a first order indication of the expression, and therefore presence, of dome-forming volcanism on other worlds. Importantly, the gravity of an exoplanet can be determined for any planet for which the mass and radius are known, both of which are measurable metrics for exoplanets. Our toolbox contains height-to-diameter ratios and images (cross section and plan view) of modelled domes following emplacement, and also following a period of gravitational settlement, to suggest how domes can be recognised long after activity has ceased at a particular volcano. Since there are no planes or zones of weakness in our modelled domes, the gravitational settling process is homogeneous.

3. Results

Our modelling shows that the height-to-diameter ratio of the volcanic domes decreases with increasing gravity (Figs. 1 and 2). Domes emplaced on dwarf planets (very low gravity) will be very narrow with steep sides and domes emplaced on super-Earths (very high gravity) will be very wide and flat (Figs. 1 and 2). This is due to the greater proportion of fluid core material that is maintained in the dome as gravity is increased, which results in dome growth governed by lateral spreading rather than by vertical extension (e.g., Walter et al., 2019). The height-to-diameter ratio decreases following gravitational settling (Figs. 1 and 2). Although the height-to-diameter ratio is greatly decreased following settling for the dome emplaced under $g = 1\ m/s^2$, because steep and brittle structures are inherently unstable, we highlight that there is still a large difference between the morphology of settled domes as a function of increasing gravity (Figs. 1 and 2).

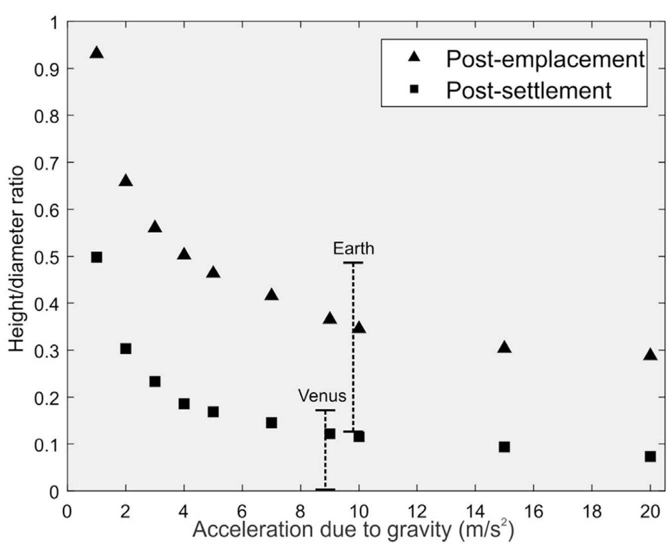

Fig. 2. Height/diameter ratio of a lava dome as a function of acceleration due to gravity for domes post-emplacement (triangles) and post-settlement (squares). Each symbol represents a unique model run. We note that macroscopic dome morphologies of model runs with the same input parameters are essentially identical and that any variability is captured by the symbol size. Height/diameter ratios for Earth and Venus are taken from Fink et al. (1993). Data for Earth is for Mt. St. Helens (USA) and Soufrière Hills volcano (Montserrat). Data for Venus includes "Class 1" and "Class 2" domes. We note that the height/diameter ratio ranges provided for Earth and Venus likely underestimate the true range.

4. Discussion

These results form the first astrophysical toolbox for understanding what volcanic domes could look like on variably sized exoplanets, and therefore show how volcanism could be recognised from first-glimpse images of the surface of exoplanets. Our toolbox will allow astrophysicists to have an idea of the morphology of a dome on any exoplanet for which mass and radius are known, and therefore understand whether the planet is currently, or was, volcanically active. Alternatively, our toolbox could be used to provide supporting evidence in scenarios for which volcanism on a particular exoplanet is hypothesised using other data. Because the persistence of a lava dome (i.e., before it is destroyed or completely eroded) is likely much longer than its emplacement period, we suggest that post-settlement morphology should be considered ahead of the post-emplacement morphology. Indeed, the majority of the dome height/diameter ratio range for Earth (data from Fink et al., 1993) is between the modelled post-emplacement and post-settlement values (Fig. 2). We additionally highlight that, although erosion rates on exoplanets will likely be unknown, flat domes on large exoplanets will likely be less eroded than tall domes on small exoplanets (because tall structures are more susceptible to weathering). To provide an end-member example, we ran an additional simulation to assess the morphology of a lava dome on a high-mass super-Earth with a gravity of $65\ m/s^2$. The settled dome when $g = 65\ m/s^2$ has a very low height/diameter ratio of 0.03 (Fig. 3). The large difference in dome morphology between Earth-like and super-Earth planets, illustrated in Fig. 3, highlights the ease at which such landforms on planets with a different gravity to that on Earth could be misidentified.

Although in this study we isolate the effect of gravity, other factors, such as magma viscosity (determined by composition, temperature, atmospheric pressure, and surface temperature) are likely to play a role in determining exoplanetary dome morphology (Fink and Griffiths, 1998; Watts et al., 2002). Magma viscosity on Earth has been found to vary up to eight orders of magnitude at one volcano (Melnik and Sparks, 2002). The extent to which viscosity could vary on exoplanets is currently unconstrained, but we expect that, like on Earth, a higher viscosity would create a dome that is narrower and taller, effectively pushing the height-to-diameter ratio towards those observed at lower gravities. Indeed, the dome height/diameter ratio range for Earth (data from Fink et al., 1993) exceeds the height/diameter ratio predicted for a planet with an Earth-like gravity (Fig. 2). If magma viscosity is very low, the extrusion of lava is more likely to result in the formation of flows rather than domes. Previous studies also suggest that, in addition to the internal yield strength of the magma, the solidification of the outer layer also increases the effective viscosity of the dome (Fink and Griffiths, 1998; Griffiths and Fink, 1997). The solidification process is therefore crucial to dome morphology. In the model used here this relates to the solidus pressure that controls the transition between fluid and solid, where higher solidus pressures have been shown to increase the rock/fluid fraction (Harnett et al., 2018). Solidification depends primarily on composition (Couch et al., 2003; Melnik and Sparks, 2005), and will also be influenced by surface temperature. Solidification is therefore

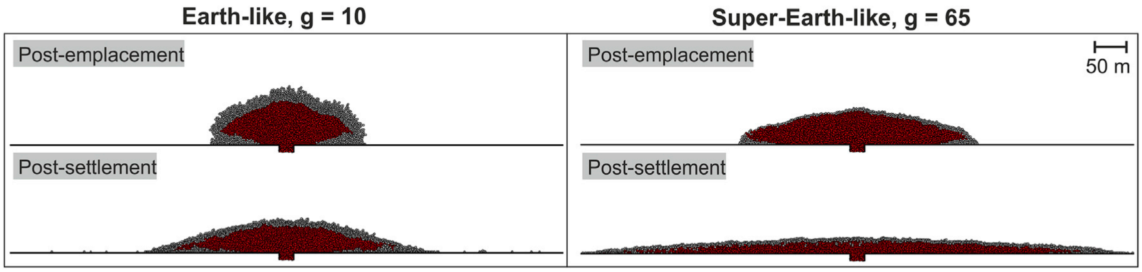

Fig. 3. Cross-sections of modelled domes (post-emplacement and post-settlement) for an Earth-like planet with $g = 10\ m/s^2$, and a Super-Earth-like planet with $g = 65\ m/s^2$.

currently unconstrained for exoplanets, but could be incorporated into future models to indicate detailed morphology on specific exoplanets. The associated rock strength of the solid outer shell of the dome or talus, maintained constant in the simulations presented here, will also influence dome morphology, particularly during settlement. This is because a dome constructed using weaker, perhaps hydrothermally altered (e.g., López and Williams, 1993; Finn et al., 2001), rock is more likely to experience mass wasting.

Surface temperature and atmospheric pressure will also affect the expression of volcanic landforms on exoplanets. The high surface temperature of Venus (467 °C), for example, will contribute to maintaining more of the volcanic material in its fluid state (i.e., preventing solidification). Maintaining more material in its fluid state will have a similar effect to increasing gravity (creating wider and flatter domes), and could explain, amongst other factors, why the domes on Venus have very low height-to-diameter ratios (<0.05; Aubele and Slyuta, 1990). Indeed, we note that the majority of the height/diameter ratio range for Venus (data from Fink et al., 1993) plots below that predicted for a planet with a Venus-like gravity (Fig. 2). Differences in atmospheric pressure will, for example, influence the efficiency of volatile exsolution that, in turn, will impact factors such as magma viscosity (e.g., Wilson and Head, 1983; Head and Wilson, 1986). Although future models that incorporate variations in, for example, magma viscosity, rock strength, and atmospheric pressure and temperature can be performed as and when data are available, our toolbox provides an important first look as to the morphology of lava domes on other worlds using presently constrained parameters (planetary mass and radius).

Although the scientific advances required for the acquisition of high-resolution exoplanet imagery are still to be achieved, it is crucial that we equip ourselves with the tools to interpret the appearance of exoplanets when imagery becomes available. The importance of identifying volcanic landforms on exoplanets therefore cannot be understated. Geoscientists often anecdotally define a "living planet" as one with active volcanism. Since dome-forming volcanoes on Earth are primarily found at plate boundaries, an abundance of lava domes on a given exoplanet, or a curvilinear band of lava domes, could provide evidence for the existence of plate tectonics, informing on the stage of development of a particular exoplanet (Bercovici and Ricard, 2014). Since lava domes are also observed on the surface of Venus, a planet without global-scale plate boundaries, we consider the observation of curvilinear bands of lava domes (as seen on Earth; e.g., Cottrell, 2015) will emerge as the key indicator of plate tectonics on exoplanets using the approach described herein. Volcanism also speaks to the process of volatile degassing and mature atmosphere evolution, and subduction-related volcanism has been linked to the development of the nitrogen-enriched atmosphere required to create a habitable planet (Mikhail and Sverjensky, 2014). The search for habitable planets beyond our Solar System may therefore rest on understanding the expression of volcanism on these alien worlds.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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