ARTICLE IN PRESS

Icarus xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Prerequisites for explosive cryovolcanism on dwarf planet-class Kuiper belt objects

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ARTICLE INFO

Article history:
Received 30 December 2013
Revised 21 March 2014
Accepted 25 March 2014
Available online xxxx

Keywords:
Charon
Interiors
Pluto
Satellites, formation
Volcanism

ABSTRACT

Explosive extrusion of cold material from the interior of icy bodies, or cryovolcanism, has been observed on Enceladus and, perhaps, Europa, Triton, and Ceres. It may explain the observed evidence for a young surface on Charon (Pluto's surface is masked by frosts). Here, we evaluate prerequisites for cryovolcanism on dwarf planet-class Kuiper belt objects (KBOs). We first review the likely spatial and temporal extent of subsurface liquid, proposed mechanisms to overcome the negative buoyancy of liquid water in ice, and the volatile inventory of KBOs. We then present a new geochemical equilibrium model for volatile exsolution and its ability to drive upward crack propagation. This novel approach bridges geophysics and geochemistry, and extends geochemical modeling to the seldom-explored realm of liquid water at subzero temperatures. We show that carbon monoxide (CO) is a key volatile for gas-driven fluid ascent; whereas CO_2 and sulfur gases only play a minor role. N_2, CH_4, and H_2 exsolution may also drive explosive cryovolcanism if hydrothermal activity produces these species in large amounts (a few percent with respect to water). Another important control on crack propagation is the internal structure: a hydrated core makes explosive cryovolcanism easier, but an undifferentiated crust does not. We briefly discuss other controls on ascent such as fluid freezing on crack walls, and outline theoretical advances necessary to better understand cryovolcanic processes. Finally, we make testable predictions for the 2015 *New Horizons* flyby of the Pluto-Charon system.

1. Introduction

Cryovolcanism is "*the eruption of liquid or vapor phases (with or without entrained solids) of water or other volatiles that would be frozen solid at the normal temperature of the icy satellites surface*" (Geissler, 2000). It is a clear marker of extant geological activity, and planetary bodies that show evidence for or suggestive of cryovolcanism, such as Europa, Titan, Enceladus, and Triton are the foci of many planetary science and astrobiology investigations. Cryovolcanism could occur by either effusive or explosive processes (e.g. Fagents, 2003). Evidence for past or recent effusive activity has remained inconclusive, because of the difficulty to distinguish cryovolcanic from diapiric surface morphologies (Fagents, 2003; Lopes et al., 2007). Gas-driven activity, on the other hand, has been unmistakably identified in the form of plumes on Triton, Enceladus, and perhaps Europa and Ceres (Kirk et al., 1995; Porco et al., 2006; Roth et al., 2014; Küppers et al., 2014). The upcoming flyby of the Pluto-Charon system by the *New Horizons* spacecraft brings a new opportunity to look for plumes on Pluto and Charon that would imply extensive geophysical and geochemical activity on these icy dwarf planets. The scope of this paper is to evaluate the likelihood of extant cryovolcanism on dwarf planet-class Kuiper belt objects (KBOs) from our current knowledge of explosive cryovolcanic processes, the volatile inventory in the Kuiper belt, and the thermal evolution of KBOs. To this end, we use a novel approach that couples geophysics and geochemistry, and extends predictive geochemical modeling to the domain of liquid water at subzero temperatures. We begin in this introduction by briefly reviewing evidence for explosive cryovolcanism in the outer solar system. In the following section, we review previous theoretical results on gas-driven cryovolcanism, as well as current knowledge of the volatile inventory of KBOs. Building on these results, we then present a new geochemical model for gas exsolution to drive the propagation of fluid-filled cracks to the surface. Next, we discuss other controls on fluid ascent, such as the presence of a primordial ice-rock crust or fluid freezing in the cracks. We conclude by

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http://dx.doi.org/10.1016/j.icarus.2014.03.043
0019-1035/

Please cite this article in press as: Neveu, M., et al. Prerequisites for explosive cryovolcanism on dwarf planet-class Kuiper belt objects. Icarus (2014), http://dx.doi.org/10.1016/j.icarus.2014.03.043

making predictions on the possibility of cryovolcanism on Pluto, Charon, and KBOs of similar size.

1.1. Explosive volcanism and outgassing

Outgassing of volatiles by a planetary body may occur by sublimation of ices close to the surface, as this surface is heated by a source external to the body, such as the Sun or an impact. Alternatively, the volatiles may originate much deeper inside the body, and the cause of their outgassing be rooted in endogenic heating processes. Here, we call the former phenomenon "sublimation" and the latter "explosive cryovolcanism", and we use "outgassing" as a generic term. These processes can all result in observable plumes, and only more detailed analyses (e.g. of their chemical composition or thermal emission) can conclusively determine the cause of outgassing.

For KBOs, the semantics are complicated because two communities have investigated their origins, evolution, and present state. The "large icy satellites" community sees KBOs as mini-worlds with possible geophysical evolution over geological timescales; their viewpoint applies to bodies large enough to be differentiated, with little porosity, and which may have sustained subsurface liquid water. Such bodies may have enough endogenic energy to drive explosive cryovolcanism as understood in the viewpoint of icy satellites (Crawford and Stevenson, 1988; Fagents, 2003; Hansen et al., 2006), although sublimation may also occur. On the other hand, the "small primitive bodies" community sees the Kuiper belt as a reservoir of comet nuclei that have undergone little or no evolution since their formation; their viewpoint applies to smaller (<100 km), undifferentiated bodies, with significant porosity, and no liquid. For these bodies, as for comets, surface manifestations of outgassing are necessarily due to sublimation, except perhaps early in their history (De Sanctis et al., 2001; Choi et al., 2002). Here, we focus on KBOs for which the "large icy satellite" viewpoint applies. These may be referred to as dwarf planet-class KBOs; we call them KBOs for short in the rest of this paper.

1.2. Evidence for cryovolcanism in the outer Solar System

Extant outgassing has been so far conclusively observed in the form of N_2 gas plumes on Triton, assumed to be a KBO captured by Neptune (Smith et al., 1989; Soderblom et al., 1990; Kirk et al., 1995) and H_2O plumes on Enceladus (Hansen et al., 2006; Porco et al., 2006; Matson et al., 2007; Postberg et al., 2009; Waite et al., 2009). An observation of plumes on Europa has also been recently reported (Roth et al., 2014), as well as water emission from Ceres localized in space and time (Küppers et al., 2014). For Triton, although both exogenic and endogenic sources have been suggested to drive the N_2 eruptions, the N_2 may originate in a layer close to the surface (Brown et al., 1990; Ingersoll and Tryka, 1990), but may nonetheless reveal a regime of convection in Triton's icy mantle (Duxbury and Brown, 1997). Triton also experienced an early phase of heating by tidal dissipation during its capture by Neptune (Shock and McKinnon, 1993). On Enceladus, the cryovolcanic interpretation is favored because the plume ejects species such as NaCl and silica; this suggests that the source of the plume contains material leached from Enceladus' rocky core (Postberg et al., 2009; Hsu et al., in preparation; Sekine et al., in preparation). Moreover, the plume activity is synchronized to Enceladus' orbit, with a surge when Enceladus is farthest from Saturn such that South Pole fractures experience tensile tidal stresses (Hedman et al., 2013). *Cassini* observations of Titan suggest that it too is undergoing cryovolcanism, although this remains uncertain (Sotin et al., 2005; Nelson et al., 2009); cryovolcanism could explain the presence of argon-40 and methane in Titan's atmosphere (Tobie et al., 2006). Recently, ground-based observations of an aurora near the south pole of Europa have strongly suggested that it too is experiencing explosive cryovolcanism (Roth et al., 2014). As for Enceladus, plume activity occurs when Europa is farthest from Jupiter, and seems to depend on tidal stresses (Roth et al., 2014). The radii (250–2575 km) and densities of these moons (1.6–3.0 g cm^{-3}) bracket those of the Kuiper belt objects (KBOs) Pluto and Charon [1150 and 600 km; 2.0 and 1.6 g cm^3; Buie et al. (2006)]. This suggests bulk compositions, internal structures, and thermal histories similar to those of the icy satellites, with the notable exception that Pluto and Charon may have experienced little or no tidal heating.

Several observations of KBO surfaces are suggestive of recent cryovolcanic eruptions, whether effusive or explosive. First, short-lived ammonia hydrates have been detected on the surfaces of Charon and, likely, Orcus (Brown and Calvin, 2000; Cook et al., 2007; Merlin et al., 2010; Delsanti et al., 2010). These compounds should be destroyed by solar ultraviolet radiation and galactic cosmic rays on timescales shorter than 1–50 Myr (Jewitt and Luu, 2004; Cook et al., 2007), and no mechanism other than recent localized resurfacing by cryovolcanism has conclusively explained their presence on Charon's surface (Jewitt and Luu, 2004; Cook et al., 2007; McKinnon et al., 2008; Desch et al., 2009; Brown, 2012). The presence of abundant crystalline ice has also been suggested as evidence for resurfacing, because it too should be amorphized on short timescales; however, its presence on KBOs much too small to be geologically active (Brown, 2012) suggests that another process must be at play, such as annealing of amorphous ice by dust impacts (Porter et al., 2010). More generally, cryovolcanism has been invoked to explain the observation of volatile ices other than water (mainly N_2, CH_4, CH_3OH, and NH_3) on KBO surfaces [see recent reviews by McKinnon et al. (2008) and Brown (2012)].

Evidence and mechanisms for effusive volcanism have previously been investigated. For example, Fagents (2003) reviewed a dozen studies that proposed past effusive cryovolcanism to explain morphologies on satellites of Jupiter (Europa and Ganymede), Saturn (Enceladus, Dione, Tethys, and Iapetus), and Uranus (Miranda and Ariel). These morphologies include *"smooth and/or sparsely cratered surfaces, infilled craters and graben, domes, lobate features, ridges, caldera-like features, and low-albedo surfaces"* (Fagents, 2003). Recently, similar morphologies have been studied on Titan using *Cassini* radar and infrared imagery (Lopes et al., 2007; Wall et al., 2009; Le Corre et al., 2009; Soderblom et al., 2009). To assess the possible cryovolcanic origin of these observed morphologies, laboratory experiments and modeling studies have investigated the rheological properties of cryolavas of water-volatile compositions (Schenk, 1991; Kargel et al., 1991; Zhong et al., 2009). Similar effusive morphologies may certainly also occur on KBOs and may well be observed by *New Horizons* at Pluto and Charon. However, as for the icy satellites, it is unlikely that a clear distinction between a cryovolcanic versus diapiric origin of such features will be made. Therefore, for the remainder of this paper, we focus exclusively on predicting the likelihood of *explosive* cryovolcanism on KBOs, which results in outgassing plumes that should be unambiguously detected by *New Horizons* if presently occurring on Pluto or Charon.

2. Ingredients for explosive cryovolcanism

2.1. Liquid persistence

Extant explosive cryovolcanism requires the persistence of fluid to the present day, either as a subsurface ocean layer, as a localized pocket of liquid in the icy mantle (Fagents, 2003; Schmidt et al., 2011), or as volatile molecules trapped in clathrate hydrates which may outgas upon heating. Liquid persistence depends strongly on

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