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Volcanic Destabilisation of Methane Clathrate Hydrate on Titan: the Mechanism for Resupplying Atmospheric NH_3?

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1. Introduction

As previously noted [1-3], Titan may have an upper crust rich in methane clathrates which would have formed early in Titan's history [2, 3]. With an estimated mass of ~2 x 10^{17} kg, methane is a major component of Titan's atmosphere. The abundance of methane, which photo-dissociates under the influence of solar UV, and the presence of ^{40}Ar require replenishment of these atmospheric components over geologic timescales. One possibility is that volcanic processes release these gases from Titan's interior, although so far there is no conclusive evidence of on-going volcanic activity: no "smoking gun" has been observed. Still, some process has recently supplied a considerable amount of methane to Titan's atmosphere. We have been investigating the emplacement of proposed "cryolavas" of varying composition to, firstly, examine how such a volcanic process behaves thermally in order to determine event detectability via remote sensing, and, secondly, to model the penetration of the thermal wave into a methane-rich substrate. Destabilisation of clathrates would release methane into the atmosphere and liberate trapped argon.

1.1 Modelling

We previously adapted models of solidification and heat loss from lava flows to determine not only the rate of cooling of a cryolava or impact melt on Titan [4] but also the expected thermal signature and its temporal evolution from "cryolava" emplacement [5]. These calculations modelled the surface temperature as a function of time as an upper crust formed and thickened, and included the atmospheric control of heat removal. We have now incorporated into the model the calculations of the formation of the crust at the flow base and the penetration of a thermal wave into the flow substrate (adapting methods described in [6]). Table 1 shows solidification and cooling times as a function of flow thickness. Figure 1 shows the evolution of the post-solidification temperature profile for a 3.1-m-thick flow and the penetration of the thermal wave into the substrate. Also shown in Figure 1 is the destabilisation isotherm. It takes ≈40 days for this flow to reach total solidification, with a top crust thickness of 1.52 m and a base thickness of 1.58 m. The surface temperature has fallen to 101 K from the eruption temperature of 251 K. The environment temperature is 93.7 K [6].

Table 1: Solidification as function of flow thickness

Total solidifica-tion time	Top crust thickness	Base crust thickness	Total thickness	Surface temp at solidific -ation
hours	m	m	m	K
~2	0.04	0.06	0.1	212.2
30	0.23	0.27	0.5	142.0
110	0.47	0.53	1.0	118.3
2470	2.48	2.55	5.0	98.0
9400	4.88	4.96	9.8	95.6
23200	7.70	7.79	15.5	94.9
39000	9.99	10.09	20.1	94.3
88000	15.01	15.13	30.1	94.1
113000	17.06	17.19	34.2	93.5

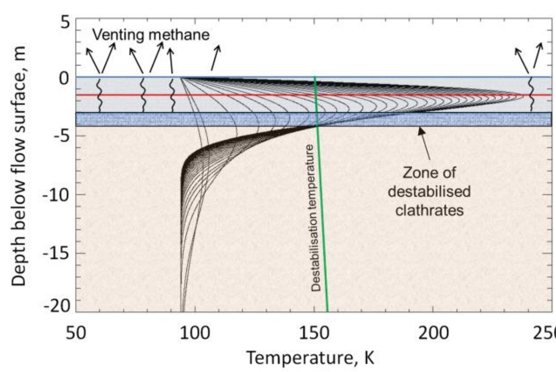

Figure 1. Post-flow solidification cooling curves for 3.1-m-thick cryolava flow [7]. The solid line at ≈150 K is the methane clathrate destabilization curve. Blue lines = flow top and base surfaces. Red = centre line.

1.2 Destabilisation of MCH

The destabilisation temperature of methane clathrates varies as a function of pressure and temperature [e.g., 1]. It is not the absolute lithostatic pressure that is the controlling factor, but the methane partial pressure: at the surface, this is about 5% of atmospheric pressure. In the MCH substrate, the destabilisation temperature is ≈150 K, if cracks form in the overlying solidified flow connecting the surface to the destabilised MCH [7]. If no cracks form, then the destabilisation temperature is ~200 K, and no MCH reaches the destabilisation temperature. [7]. The depth of penetration of the 150-K isotherm is roughly 40% of the thickness of the cryolava flow. This allows us to calculate the volume of methane mobilized by a lava flow, and the extent of lava flows needed to resupply atmospheric methane.

1.3 Methane release

A 10-m-thick cryolava covering 100 km^2 would raise 3 x 10^8 m^3 of substrate methane clathrates to the destabilization temperature in ~10^8 s. With a density of 920 kg/m^3, and about 13% of the mass being methane, the mass of methane released is 4 x 10^{10} kg. This is an impressive amount, but it would take 5 million similar events to yield the current total mass of atmospheric methane. Of greater import is the fact that the area covered is six times that of Titan. If all the flows were, instead, ~60 m thick, then Titan only needs to be completely resurfaced once! The idea of initially supplying all of Titan's atmospheric methane through the destabilization of clathrates by flow substrate heating seems unlikely. However, the potential reservoir of methane clathrates is sufficient to meet the resupply rate of atmospheric methane (~210 kg/s), requiring only one 10-m-thick flow event covering 100 km^2, occurring ~40% of the time, to do so. The average methane release from such an event is 550 kg/s for 2.3 years. Other processes (e.g., impacts) are capable of additional atmospheric methane replenishment through MCH destabilisation. Other styles of volcanic activity may also contribute. For example, the thermal wave propagation from turbulent flows, with mechanical erosion into the substrate, would release more methane than the laminar flows modelled above. Intrusive events are also considered. With a sill-like intrusion, the volume of clathrates that is potentially destabilized is approximately twice that mobilised by a surface flow of the same thickness: methane is mobilised both above and below an intrusion, so long as a pathway opens to the surface. The burial of activity also reduces the chances of detection: on Earth, a rule-of-thumb for the ratio of intrusive to extrusive volcanic activity is ~10:1.

Conclusions

We have modelled the thermal destabilisation of methane clathrate hydrates as a result of cryovolcanism. Meeting Titan's current global methane replenishment rate is feasible through the thermal interaction between cryolavas and MCH deposits, but only (1) after the flow has solidified; (2) if cracks form, connecting surface to substrate; and (3) the cracks form while the temperature of the clathrates is greater than the destabilisation temperature.

Acknowledgements

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