Journal of Volcanology and Geothermal Research 333–334 (2017) 134–144

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Methods for mapping and monitoring global glaciovolcanism

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ARTICLE INFO

Article history:
Received 12 September 2016
Received in revised form 12 January 2017
Accepted 19 January 2017
Available online 24 January 2017

Keywords:
Glaciovolcanism
Remote sensing
Cryosphere
Volcanoes

ABSTRACT

The most deadly (Nevado del Ruiz, 1985) and the most costly (Eyjafjallajökull, 2010) eruptions of the last 100 years were both glaciovolcanic. Considering its great importance to studies of volcanic hazards, global climate, and even astrobiology, the global distribution of glaciovolcanism is insufficiently understood. We present and assess three algorithms for mapping, monitoring, and predicting likely centers of glaciovolcanic activity worldwide. Each algorithm intersects buffer zones representing known Holocene-active volcanic centers with existing datasets of snow, ice, and permafrost. Two detection algorithms, RGGA and PZGA, are simple spatial join operations computed from the Randolph Glacier Inventory and the Permafrost Zonation Index, respectively. The third, MDGA, is an algorithm run on all 15 available years of the MOD10A2 weekly snow cover product from the Terra MODIS satellite radiometer. Shortcomings and advantages of the three methods are discussed, including previously unreported blunders in the MOD10A2 dataset. Comparison of the results leads to an effective approach for integrating the three methods. We show that 20.4% of known Holocene volcanic centers host glaciers or areas of permanent snow. A further 10.9% potentially interact with permafrost.

MDGA and PZGA do not rely on any human input, rendering them useful for investigations of change over time. An intermediate step in MDGA involves estimating the snow-covered area at every Holocene volcanic center. These estimations can be updated weekly with no human intervention. To investigate the feasibility of an automatic ice-loss alert system, we consider three examples of glaciovolcanism in the MDGA weekly dataset. We also discuss the potential use of PZGA to model past and future glaciovolcanism based on global circulation model outputs. Combined, the three algorithms provide an automated system for understanding the geographic and temporal patterns of global glaciovolcanism which should be of use for hazard assessment, the search for extreme microbiomes, climate models, and implementation of ice-cover-based volcano monitoring systems.

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1. Introduction

When volcanic systems interact with the cryosphere, a host of significant outcomes result. Human communities become threatened by phreatomagmatic eruptions, lahars (volcanic mud flows), jökulhlaups (glacial outburst floods), and a range of other hazards (Major and Newhall, 1989). A glaciovolcanic lahar from Nevado del Ruiz volcano killed 23,000 in 1985 (Pierson et al., 1990), and phreatomagmatic plumes from Eyjafjallajökull led to flight cancellations costing airlines as much as 3.3 billion euros (Mazzocchi et al., 2010). Glaciovolcanic processes leave a distinctive geological record containing paleoclimate information (Edwards et al., 2010). Volcanic degassing beneath thin ice also produces a unique set of ephemeral ice landforms, which can support unusual microbiomes (Connell and Staudigel, 2013; Tebo et al., 2015; Soo et al., 2009). Thus, glaciovolcanism provides a library of information, but also presents a danger. To access the former and mitigate the latter, we must learn its global distribution and extent on our planet, and begin to address how that distribution changes over time.

Glaciovolcanism, in the broad sense, includes any process whereby volcanic and geothermal systems contact four types of ice masses: snowfields, glaciers, ice sheets, and permafrost (Smellie and Edwards, 2016). Direct human access to locations of glaciovolcanism is logistically difficult and hazardous, leading to the obscurity of certain important phenomena. Warm gasses leaking from flanks and summits of snow and ice-clad volcanoes can form fumarolic ice caves, fumarolic ice towers, and ice subsidence cauldrons. Such features are rarely studied, but examples at Erebus (Curtis and Kyle, 2011; Curtis, 2015), Melbourne (Keys et al., 1983), Hood, Rainier (Zimbelman et al., 2000), Wrangell, and Baker (Kiver, 1978) suggest such modes of glaciovolcanism may be globally widespread, but largely undiscovered or unreported, leading to apparent rarity. Necessarily sparse, "boots on the ground" investigations of these often ephemeral phenomena should be complemented and targeted using worldwide assessments of glaciovolcanism.

In recent years, rich datasets regarding the distribution of the above four ice types on Earth have become available. The MODIS instrument aboard NASA's Terra satellite provides a record of weekly (8-day) global

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http://dx.doi.org/10.1016/j.jvolgeores.2017.01.017
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snow cover at 500 m spatial resolution extending back to 2000: the MOD10A2 product (Hall et al., 2006). The Randolph Glacier Inventory (RGI), a "globally complete" catalog of glaciers, was compiled by Pfeffer et al. (2014). Ice within the soil is more difficult to map; it is not observable by remote sensing alone. Using elevation data and global air temperature data from general circulation models (GCM), Gruber (2012) was able to create a high-resolution model called the Permafrost Zonation Index (PZI) which provides an estimate of frozen ground extent worldwide. In the Northern Hemisphere, PZI closely matches the commonly used Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 1997), and it was validated for use in the Himalayas by Schmid et al. (2015) and in New Zealand by Sattler et al. (2016). Many decades of field investigation provide good constraints on the locations of volcanic centers active during the Holocene. The best catalog is the Smithsonian Institution's Volcanoes of the World (VOTW) database, which contains entries for 1443 terrestrial volcanoes (and 113 seamounts) (Global Volcanism Program, 2013).

Before these datasets were available, no global map of glaciovolcanism existed, although compilations of case studies such as Major and Newhall (1989) did exist. Curtis (2014) produced a preliminary global map using MOD10A2 data. In 2015 and 2016, worldwide maps were published, but lacked description of the methods used to create them. Fig. 1 of Waitt et al. (2015) cites the use of GLIMS (Global Land Ice Measurements from Space) polygon data, but displays ice-clad volcanoes in areas (e.g. Aleutian Islands) where no GLIMS polygons exist. Presumably, the spatial analysis was manually augmented based on expert knowledge. Smellie and Edwards (2016) include similar maps, but they must be considered illustrative schematics rather than quantitative global surveys as they are presented without a description of input data or cartographic methods. In an effort to produce a systematic global survey, we present and evaluate three glaciovolcanic potential detection algorithms (MDGA, RGGA, PZGA) of potential glaciovolcanism, using the aforementioned global geospatial datasets (MOD10A2, RGI, PZI, VOTW) as input.

In the course of developing methods for observing global glaciovolcanism spatially, we assess to what extent these tools are also useful for volcano monitoring. Several near-real-time volcano monitoring and eruption alert systems are already in operation, based on remote sensing of thermal and gas concentration anomalies. The MODVOLC system leverages thermal sensing to detect molten lava, based on data from the MODIS instrument (which we are also using here for the MDGA system) (Wright et al., 2015). SACS combines data from several satellites to provide automated alerts of SO_2 plumes (Brenot et al., 2014). However, there no system has been developed to detect the loss of ice mass and area associated with glaciovolcanism. Such ice loss was the first observable precursor of the Redoubt eruption in 2009 (Bleick et al., 2013). An autonomous, satellite-based system to detect ice loss induced by volcanic activity would provide an important complement to existing thermal and gas monitoring capabilities.

2. Background

Chapman et al. (2000) provided a useful classification of glaciovolcanism, dividing it into three types: (1) volcanic interaction with snow, firn, and thin ice masses, generally <100 m, (2) volcanic interaction with thick, extensive glaciers and ice sheets, and (3) volcanic interaction with permafrost. Although Chapman et al. primarily referred to eruptions, we combine these categories with a broader definition of glaciovolcanism: processes resulting from interaction between any volcanic emissions (including flank degassing and emissions from hydrothermal systems) and nearby ice. Smellie and Edwards (2016, Ch. 2) provide a regionally grouped review of known glaciovolcanic centers across all three types based on existing literature, extending deeper into geological time than the current Holocene-focused work.

Type 2 glaciovolcanism produces the most recognizable deposits (tuyas, tindars, and associated lithofacies), and are best represented in the literature. Many studied Type 2 deposits date to the Last Glacial Maximum. Type 1 is common at alpine volcanoes but is only rarely recognizable in the geological record. Tuffen and Castro (2009) described the first discovery of an eruption deposit demonstrably formed beneath "thin" ice, "only 35–55 m thick." Eruption into such snowpacks at Fimmvörðuháls and Tolbachick were recently observed in situ by Edwards et al. (2012, 2014). Alpine firn fields and thin glaciers respond not only to eruption of lava, but also undergo significant melting and deformation in response to fumarolic activity and flank degassing. Loss of alpine ice masses in response to increased degassing can be an early indicator of volcanic unrest (Bleick et al., 2013; Kiver, 1978). In some arid environments, galciovolcanism is the only process capable of supplying water to biological communities and for aqueous mineral processes such as weathering. This primarily occurs at Type 1 systems like Mt. Erebus, Antarctica, where fumarolic degassing not only produces liquid water but also melts caves into the summit caldera ice mass. Native microbiological ecosystems with unusual metabolic strategies and molecular machinery have recently been identified in the caves (Connell and Staudigel, 2013; Tebo et al., 2015). Firn caves in the summit crater of Mount Rainier are also likely to host a microbiome. "Warm ground" areas occur when volcanic heating melts holes in the ice cover, supporting patches of moss in the otherwise inhospitable Antarctic (Broady et al., 1987; Soo et al., 2009). These ecosystems depend on the water, consistently warm microclimate, and UV protection in the case of caves, all of which are available due to glaciovolcanism.

The remaining category of glaciovolcanic processes, Type 3, occurs when magma bodies and related hydrothermal and volcanic systems encounter permafrost. This may be the primary glaciovolcanic phenomenon in the geologic history of Mars, where the major water reservoir is known as the cryolithosphere, a permafrost-like layer which is thought to be more than 9 km deep for the majority of the planet (Head and Wilson, 2007). On Earth, Type 3 is particularly well studied in Kamchatka (Abramov et al., 2008).

It is becoming increasingly clear that interactions between the global cryosphere and magma bodies play a role in global climate. Huybers and Langmuir (2009) observed an increase in eruption rate during the last deglaciation and suggested depressurization of magma chambers by the removal of ice overburden as a causative factor. Recent work on submarine volcanism supports this type of process. Midocean ridge eruption frequency appears to increase in response to depressurization from falling sea levels (Conrad, 2015; Tolstoy, 2015). Mapping the distribution of glaciovolcanism is an important precursor to global models of the type of feedback between glaciation and subaerial volcanism.

3. Methods

We created three detection algorithms for locations of glaciovolcanic potential (Fig. 1) by intersecting circular buffers of 10 km diameter drawn around each VOTW volcano coordinate with a satellite snow cover product (MOD10A2), a global inventory of glaciers (RGI), and a global permafrost model (PZI). Most VOTW coordinates correspond to stratovolcano summit locations. VOTW coordinates representing volcanic fields, such as clusters of cinder cones, are generally located near the centroid of the cluster. Large caldera complexes are notable exceptions and glaciovolcanism in those locations may be poorly represented in this study. If a database representing volcanic centers as polygons rather than points becomes available, it could be incorporated into the present work to remove this issue. This buffer zone also accounts for the various errors which VOTW warns is inherent in their coordinates (Smithsonian Institution, 2013).

The MOD10A2 product is computed using a "normalized difference snow index" (NDSI) based on the difference between MODIS bands 4 (0.55 μm) and 6 (1.6 μm). A set of algorithms centered on NDSI are used to classify each pixel as one of several ground cover types including "snow," "cloud," "land," and "lake ice" (Hall et al., 2006). Multiple values obtained during the 8-day period are combined, and if a pixel (roughly

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