Quaternary Science Reviews 87 (2014) 70–81

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Tuyas: a descriptive genetic classification☆

J.K. Russell [a,*], B.R. Edwards [b], Lucy Porritt [a,c], C. Ryane [a]

[a] Volcanology & Petrology Laboratory, Department of Earth, Ocean & Atmospheric Sciences, University of British Columbia, Vancouver V6T 1Z4, Canada
[b] Department of Earth Sciences, Dickinson College, Carlisle, PA 17013, USA
[c] School of Earth Sciences, University of Bristol, Bristol, UK

ARTICLE INFO

Article history:
Received 23 June 2013
Received in revised form
23 December 2013
Accepted 3 January 2014
Available online 31 January 2014

Keywords:
Glaciovolcanism
Tuya
Tindar
Subglacial volcanoes
Pillow lava
Passage zone
Paleo-environment
Classification
Glacialhydraulics
Physical volcanology
Iceland
Canada

ABSTRACT

We present a descriptive genetic classification scheme and accompanying nomenclature for glaciovolcanic edifices herein defined as tuyas: *positive-relief volcanoes having a morphology resulting from ice confinement during eruption and comprising a set of lithofacies reflecting direct interaction between magma and ice/melt water*. The combinations of lithofacies within tuyas record the interplay between volcanic eruption and the attending glaciohydraulic conditions. Although tuyas can range in composition from basaltic to rhyolitic, many of the characteristics diagnostic of glaciovolcanic environments are largely independent of lava composition (e.g., edifice morphology, columnar jointing patterns, glass distributions, pyroclast shapes). Our classification consolidates the diverse nomenclature resulting from early, isolated contributions of geoscientists working mainly in Iceland and Canada and the nomenclature that has developed subsequently over the past 30 years. Tuya subtypes are first recognized on the basis of variations in edifice-scale morphologies (e.g., flat-topped tuya) then, on the proportions of the essential lithofacies (e.g., lava-dominated flat-topped tuya), and lastly on magma composition (e.g., basaltic, lava-dominated, flat-topped tuya). These descriptive modifiers potentially supply additional genetic information and we show how the combination of edifice morphologies and lithofacies can be directly linked to general glaciohydraulic conditions. We identify nine distinct glaciovolcanic model edifices that potentially result from the interplay between volcanism and glaciohydrology. Detailed studies of tuya types are critical for recovering paleo-environmental information through geological time, including: ice sheet locations, extents, thicknesses, and glaciohydraulics. Such paleo-environmental information represents a new, innovative, underutilized resource for constraining global paleoclimate models.

1. Introduction

Glaciovolcanism is formally defined as encompassing 'volcano interactions with ice in all its forms (including snow and firn) and, by implication, any meltwater created by volcanic heating of that ice' (Edwards et al., 2009b; Kelman et al., 2002a,b; Smellie, 2006, 2007). Glaciovolcanic edifices have morphologies and lithofacies that reflect their contact with, or impoundment by, ice (Noe-Nygaard, 1940; Kjartansson, 1943; Watson and Mathews, 1944; Mathews, 1947; Edwards and Russell, 2002; Skilling, 2009) and, thus, provide important paleoenvironmental information (e.g., ice thicknesses, englacial lake depths; Edwards et al., 2002; Smellie, 2000, 2001; Smellie et al., 2008; Smellie and Skilling, 1994; Tuffen et al., 2002, 2010).

Modern research on glaciovolcanism has expanded to include all aspects of these ice-magma-water interactions. Recent advances in glaciovolcanic research include: understanding the physics of eruption within and under ice (Hoskuldsson and Sparks, 1997; Guðmundsson, 2003; Tuffen, 2007), assessing volcanic hazards resulting from enhanced ash production due to increased intensity (i.e. phreatomagmatic) of explosive eruptions (Belousov et al., 2011; Taddeucci et al., 2011; Petersen et al., 2012), the generation of flood events (i.e. jökulhlaups) due to rapid melting of ice (Major and Newhall, 1989; Guðmundsson et al., 1997; Jarosch and Guðmundsson, 2012; Magnússon et al., 2012), and the recovering of paleoenvironmental information for the purposes of constraining global paleoclimate models (McGarvie et al., 2007; Smellie et al., 2008; Huybers and Langmuir, 2009; Edwards et al., 2009b, 2011; Smellie et al., 2011).

Constraining the distribution and thickness of ancient terrestrial ice masses throughout space and time is a challenge. Erosional

* Corresponding author. Tel.: +1 778 995 7710.
E-mail address: krussell@eos.ubc.ca (J.K. Russell).

0277-3791/$ – see front matter © 2014 The Authors. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.quascirev.2014.01.001

features formed by ice movement are difficult to date directly, and can derive from multiple periods of glaciation that are essentially impossible to distinguish (e.g., Pjetursson, 1900; Geirsdottir et al., 2007). Most deposits resulting from direct deposition by ice action are unconsolidated (e.g., till) and are highly susceptible to erosion. Commonly, where such deposits are preserved, their depositional ages can only be constrained in a relative sense. In this regard, the mapping and precise age-dating of glaciovolcanic edifices (tuyas) represents a powerful resource as the volcanic deposits themselves record direct interaction between volcanism and ice masses (e.g., Mathews, 1947; Grove, 1974; Smellie et al., 1993; Edwards and Russell, 2002; Smellie et al., 2008; McGarvie, 2009; Edwards et al., 2009a; Smellie et al., 2011). Such information is critical for research efforts to constrain the paleoclimates of Earth (e.g., Mathews, 1947; Smellie and Skilling, 1994; Smellie et al., 2008; Huybers and Langmuir, 2009) and Mars (e.g., Allen, 1979; Ghatan and Head, 2002; Chapman and Smellie, 2007; Smellie, 2009).

The literature on volcano-ice-snow interactions has grown exponentially over the past two decades (Fig. 1). This growth in glaciovolcanic research (Fig. 1; Edwards et al., 2009b) has been driven by: (1) studies of modern glaciovolcanic eruptions and their hazards as observed in Iceland (e.g., Nielsen, 1937; Guðmundsson et al., 1997, 2004; Taddeucci et al., 2011; Jude-Eton et al., 2012; Magnússon et al., 2012), Alaska (e.g., Yount et al., 1985) and the western Antarctic ice sheet (e.g., Smellie, 2000, 2001, 2006, 2007); (2) the recognition of glaciovolcanic edifices as terrestrial-based proxies for paleoclimate (e.g., presence, absence and thickness of ice sheets) (Smellie and Skilling, 1994; Werner et al., 1996; Smellie and Hole, 1997; Smellie, 2000; Edwards et al., 2002; Smellie et al., 2008; Edwards et al., 2009b; Tuffen et al., 2010; Edwards et al., 2011; Smellie et al., 2011); (3) investigations of the temporal and causal linkages between waxing and waning of continental ice sheets and volcanism (Grove, 1974; Jellinek et al., 2004; Huybers and Langmuir, 2009; Sigmundsson et al., 2010; Tuffen and Betts, 2010); and by (4) the need for terrestrial analogues to constrain interpretations of landforms on other planetary surfaces (e.g., Mars; Allen, 1979; Chapman and Tanaka, 2001; Head and Pratt, 2001; Ghatan and Head, 2002; Chapman and Smellie, 2007; Smellie, 2009).

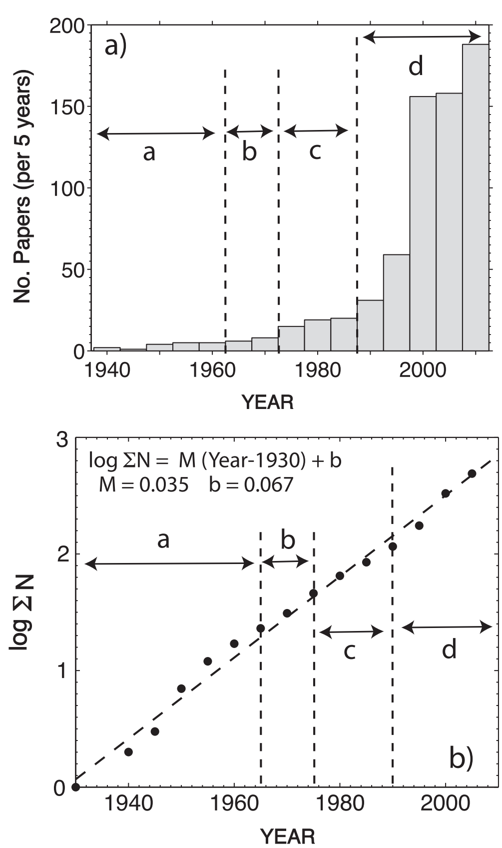

Fig. 1. Compilation of scientific papers published on the topic of glaciovolcanism. (A) Histogram of number of published papers based on the key words: subglacial volcanism, glaciovolcanism, tuya, tindar, stapar and stapi. The data show the increase in the number of publications over the interval 1930- present day and are divided into four categories of interest: a) pre-1965: curiosity-based or opportunistic study, b) 1965–1975: a relatively small group of focused researchers, c) 1975–1990: emergence as a legitimate subdiscipline of volcanology, and d) post 1990: exponential growth characteristic of rapidly maturing subdiscipline. (B) Plot of cumulative data over the past 70 years following a power law relationship and demonstrating an exponential increase in the number of publications.

Several consequences result from this recent and increasing surge of interest in glaciovolcanism (Fig. 1). Firstly, the community of scientists working on glaciovolcanic landforms has diversified to include growing numbers of geomorphologists, climatologists, and planetary scientists, all of whom use different descriptive nomenclature. Secondly, the number and variety of landforms uniquely ascribed to glaciovolcanic eruptions is growing rapidly, resulting in a proliferation of terms (cf. Table 1). As the science of glaciovolcanism expands, it seems appropriate to establish a clearly defined terminology for describing edifice-scale features formed during glaciovolcanic eruptions. This is especially important for studies of volcanic landforms on other planets (e.g., Mars), where interpretations of eruptive environments can be heavily weighted towards edifice morphology (e.g., Allen, 1979; Chapman et al., 2000; Ghatan and Head, 2002).

To address these issues, we offer a brief historical review of the development of volcano-ice science as context for a clear, formal (re-) definition of '*tuya*' that can be used easily and accurately by all scientists. We also include a brief synopsis of key elements for identifying glaciovolcanic eruptive environments. We then propose a descriptive genetic classification based on morphological and lithological features that builds upon and unifies past work (e.g., Kjartansson, 1943; Mathews, 1947; van Bremmelen and Rutten, 1955; Jones, 1969; Hickson, 2000; Smellie, 2000; Jakobsson and Guðmundsson, 2008). Lastly, we show how the combination of morphological and lithological characteristics places first order constraints on glaciohydraulic conditions extant during edifice construction.

2. Historical perspective: two solitudes

2.1. Canada

Seventy years ago, W.H. Matthews published two landmark papers describing the stratigraphy and morphology of a series of steep-sided and flat-topped basaltic volcanoes in the Tuya-Teslin region of northwestern British Columbia (Watson and Mathews, 1944; Mathews, 1947). There, Watson and Mathews (1944) encountered numerous, small, apparently young, volcanic hills hosting a variety of enigmatic features (Fig. 2):

> "....... *flat-topped volcanic mountains of somewhat circular plan. The lower parts of these mountains are composed essentially of beds of black basaltic agglomerate and tuff having dips, probably initial, of 15 to 30 degrees. In some mountains these rocks dip radially outward from the centre, suggesting that they form the flanks of a cone. Near the tops of most of these mountains the beds of agglomerate and tuff are truncated by remarkably level surfaces, presumably formed by erosion, and are capped with flat-lying lavas which commonly reach 300–400 feet in thickness.*"

Mathews (1947) observed that the lavas capping the summits of these mountains did not correlate with each other and, thus,