Tuyas: a descriptive genetic classification

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ABSTRACT

We present a descriptive genetic classification scheme and accompanying nomenclature for glacio-volcanic 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.

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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

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);
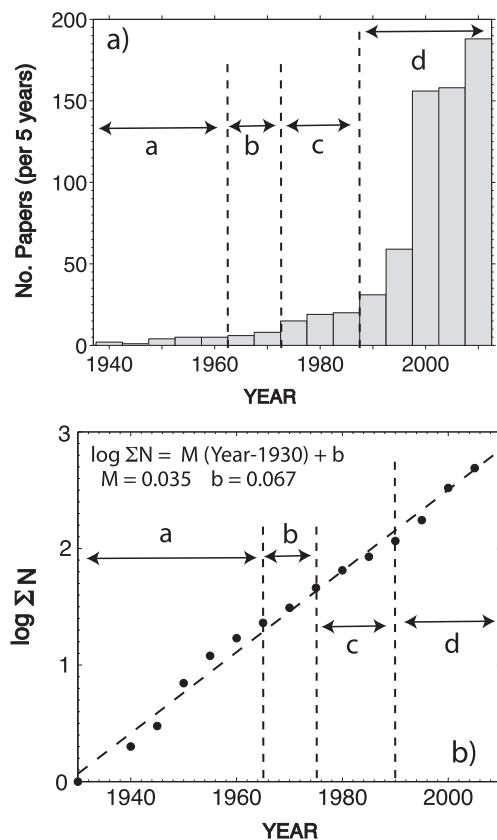
Fig. 1. Compilation of scientific papers published on the topic of glaciovolcanism. (A) Histogram of number of published papers based on the key words: subglacial volcanism, glaciovolcanism, tuya, tindar, stapar and stapi. The data show the increase in the number of publications over the interval 1930- 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.

(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).

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,

Table 1
Compilation of published nomenclature of glaciovolcanic landforms, landform descriptions, and key lithofacies.

Name	Morphology	Key lithofacies (examples)[a]	Source[b]
Stapar/table mountain	Flat-topped, equant	Pillow lava and breccia, hyalotuff, hyaloclastite, capping flat-lying lavas (e.g., Árnessýsla, Herðubreið, Gæsafjöll, IS)	1, 4, 11, 15, 16
Tuya		(e.g., Tuya Butte, BC; Hlöðufell, Hognhoði IS)	2, 3, 9, 23
Flow-dominated tuya		(e.g., The Table, Ring Mtn., Little Ring Mtn., BC)	19
Effusion-dominated tuya		(e.g., Prestahnúkur, IS)	20
Subglacial mound	Conical, equant	Pillow lava and breccia, hyalotuff, hyaloclastite, subaerial lapilli tuff (e.g., Pyramid Mtn., South Tuya, Ash Mtn., BC)	17
Palagonitic cone		(e.g., Krafla, Vindbelgjarfjall, IS)	4
Tephra-dominated tuya	Flat-topped, linear	pillow lava, pillow breccia, hyalotuff, hyaloclastite, capping subhorizontal lava flows (Rauðafossafjöll, Hottur, IS)	20
Hyaloclastite ridge		(e.g., Namafjall-Dalfall, Graddabunga, Brædrafell, Kálfstindar, IS)	4
Tindar	Not flat-topped, linear	Pillow lava, pillow breccia, hyalotuff, hyaloclastite (e.g., Skefilfjall, Kálfstindar, Helgafell, IS; Pillow Ridge, BC)	8, 9, 23, 24
Hyaloclastite ridge		(e.g., Gjálp, IS)	18
Palagonitic ridge		(e.g., Námafjall-Dalfall, IS)	4
Moberg ridge/hryggir		(e.g., Árnessýsla area, IS)	1, 11

[a] BC − British Columbia; IS − Iceland.
[b] Sources: 1 Kjartansson (1943); 2 Mathews (1947); 3 Mathews (1951); 4 van Bremmelen and Rutten (1955); 5 Kjartansson (1960); 6 Jones (1966); 7 Sigvaldason (1968); 8 Jones (1969); 9 Jones (1970); 10 Allen (1979); 11 Allen et al. (1982); 12 Smellie and Skilling (1994); 13 Hickson et al. (1995); 14 Moore et al. (1995); 15 Werner et al. (1996); 16 Werner and Schmincke (1999); 17 Hickson (2000); 18 Guðmundsson et al., 2002; 19 Kelman et al. (2002a); 20 Tuffen et al. (2002); 21 Smellie (2007); 22 McGarvie et al. (2007); 23 Jakobsson and Guðmundsson, 2008; 24 Edwards et al. (2009a).

deduced that erosion could not explain their morphology and geology. Instead, he suggested that they represented individual volcanoes. Mathews (1947) also recognized that these volcanic edifices shared common stratigraphic elements previously described at Icelandic volcanoes (e.g., Peacock, 1926; Nielsen, 1937; Noe-Nygaard, 1940), including: pillow lavas and breccias, massive to bedded deposits of outward dipping fragmented glassy basalt (hyaloclastite), and caps of horizontally-bedded basaltic lava (Table 1; Fig. 2). He proposed the term 'tuya' for these flat-topped, steep sided volcanoes after a local aboriginal term used to name several local geographic features. He interpreted the morphology and attendant volcanic lithofacies (Fig. 2) of these tuyas as indicative of volcanic eruptions from beneath and within late Pleistocene glacial ice sheets. Mathews (1947) also noted similar aged, cone-shaped volcanoes lacking flat tops (Fig. 2) and comprising only pillow basalt, dykes and fragmental deposits. He postulated that these non-flat-topped volcanic edifices were also glaciovolcanic in origin but that they had not breached the surface of the enclosing englacial lake (Fig. 2). Later workers (e.g., Hickson et al., 1995; Hickson, 2000) have referred to these edifices as 'subglacial mounds' (Table 1).

2.2. Iceland

In Iceland, scientists had been struggling with the origins of volcanic deposits and their relationship to glaciation since at least the early 1900's (cf. Jakobsson and Guðmundsson, 2008 for a review). Pjetursson (1900) first recognized evidence that the central part of Iceland had been glaciated multiple times, and that volcanic units were interstratified with glacial sedimentary deposits. Peacock (1926) provided insight on the origins of the 'Palagonite Formation', an extensive suite of volcanic deposits found throughout the central part of Iceland. He deduced that their distinctive properties were a direct result and indication of interactions between volcanism and glaciation (cf. Jakobsson and Guðmundsson, 2008). By the early 1940's, Noe-Nygaard (1940) had identified specific regions where the volcanic deposits had formed subglacially (e.g., Kirkjubæjarheði) and presented one of the first step-wise models for a subglacial eruption sequence. Kjartansson (1943) suggested that ridges of moberg, comprising a variety of lithified volcaniclastic deposits, be referred to as 'hyrggir',

and flat-topped moberg mountains be called 'stapar'. Thus, as Mathews (1947) was working in relative isolation and deducing the origins of Quaternary-aged volcanoes in northern British Columbia, a much larger group of Icelandic and European geoscientists were simultaneously pursuing comparable research on the subglacial origins of Icelandic volcanoes (Fig. 3, Table 1).

The terminology emerging over more than 60 years of published research has become highly varied (Table 1; Fig. 1). In Iceland, the large, flat-topped glaciovolcanoes have been referred to both as 'stapar' and as 'table mountains' - an approximate English translation of stapar (cf. Table 1). Likewise, elongate ridges with glaciovolcanic origins (Table 1) have been referred to 'hryggir' (Kjartansson, 1943), 'tindars' (Jones, 1969, 1970), 'moberg ridges' (Kjartansson, 1943), and 'hyaloclastite ridges' (Chapman et al., 2000). While 'hyaloclastite' is used as a synonym for the Icelandic term 'moberg', the namesake 'Moberg Formation' comprises a diverse array of volcaniclastic rocks (Peacock, 1926; Kjartansson, 1960; Jakobsson and Guðmundsson, 2008). Indeed, few of these volcaniclastic deposits would now be considered hyaloclastite based on modern usage (e.g., deposits dominated by vitric fragments formed by quench fragmentation; Fisher and Schmincke, 1984; Rittmann, 1952).

Other important European contributions to our understanding of glaciovolcanic processes include the wide-ranging studies by van Bremmelen and Rutten (1955) and Jones (1966, 1969, 1970) (Fig. 3). van Bremmelen and Rutten (1955) proposed that Icelandic table mountains formed as a result of eruption from a central vent or a fissure beneath a relatively thick ice sheet (>450 m). They invoked ponding of lava at the base of the edifice against the ice to explain overthickened masses of lava. van Bremmelen and Rutten (1955) also established the importance of meteoric water/magma interaction for eruptive explosivity, and described the multiple sequences of lithofacies that result from the draining and refilling of the englacial lake during ongoing eruption.

Work by Jones (1969, 1970; Fig. 3) in south-central Iceland largely completed the field and stratigraphic foundations for modern glaciovolcanic nomenclature and formation processes. Jones (1969) applied the term 'tuya' to several flat-topped Icelandic volcanoes and proposed the term 'tindar' for more elongate ridges formed during glaciovolcanic eruptions. He deduced that the magma−water interactions resulted from water stored in englacial
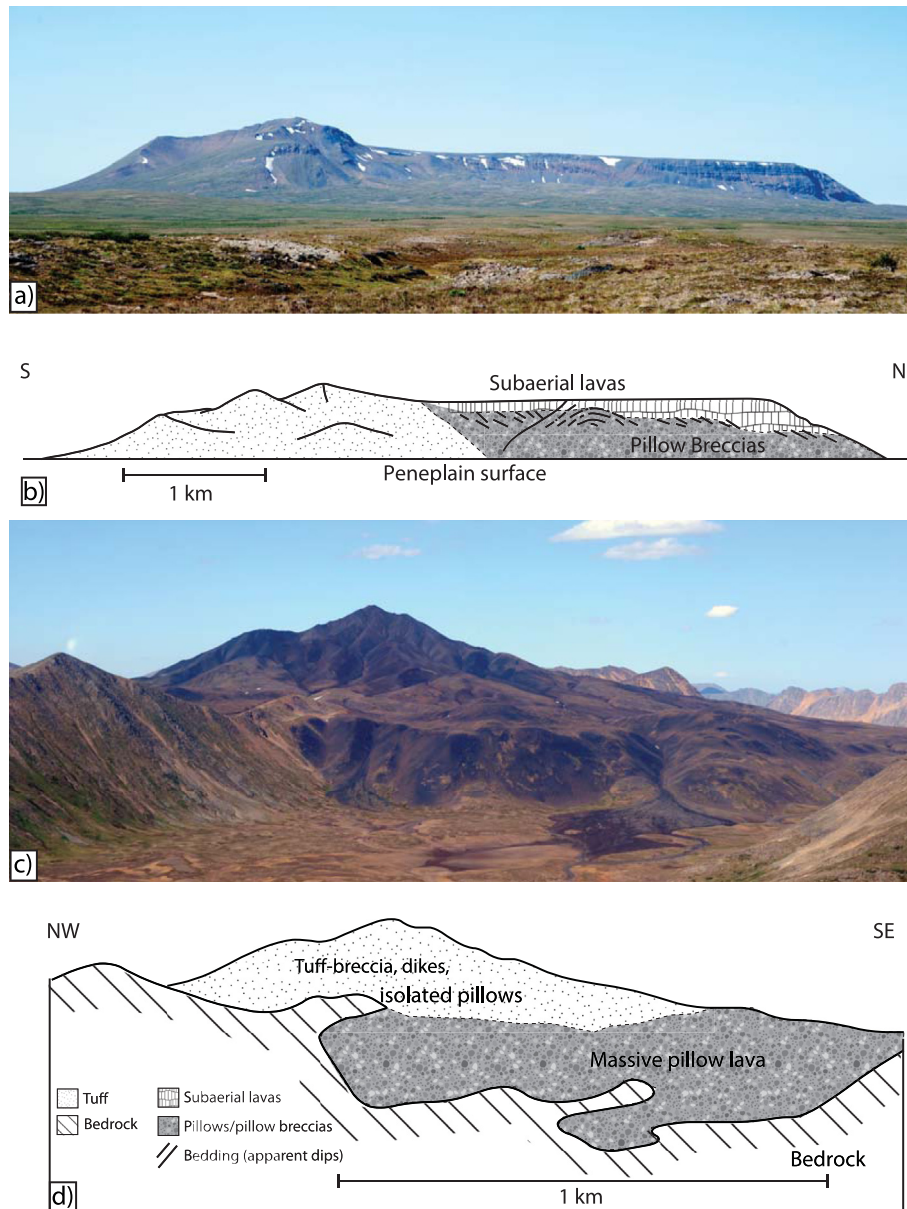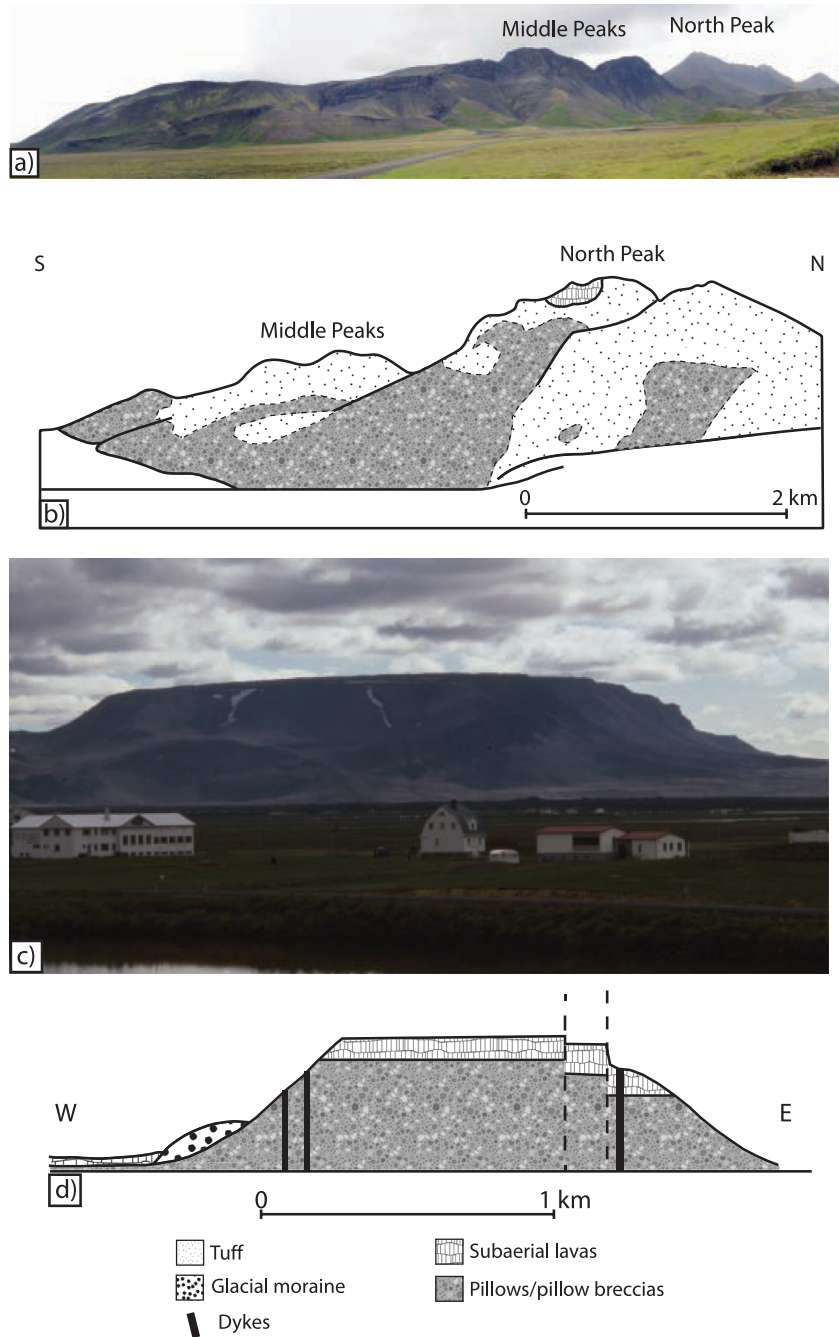
Fig. 2. Field photographs and sketches illustrating early work in Canada by W.H. Mathews on glaciovolcanic edifices and derivative concepts (see Table 1). (A) View of Kima'Kho tuya looking to the west (Ryane et al., 2011; Russell et al., 2013). (B) Modified cross-sectional view of Kima'Kho tuya after Mathews (1947), highlighting the essential components to the tuya including: (i) a tephra cone formed early on in an englacial lake, (ii) lava-fed pillow breccia delta, and iii) capping subaerial lava flows. (C) View of southern flank of Ash Mountain, British Columbia (Mathews, 1947) showing the distinctive broad, flat plateau at the base of the edifice and the capping conical summit. (D) Sketch map of Ash Mountain illustrating the critical elements as discussed by Mathews (1947) including: (i) basal platform of pillow lava, and (ii) upper cone comprising predominantly tephra deposits. Although Mathews (1947) discussed Ash Mountain within the context of his definition of tuya, he was clearly perplexed by examples such as Ash Mountain that did not have flat tops.

lakes derived from melting of the surrounding ice. Building on the work of Mathews (1947), Jones (1970) developed a model comprising an initial phase of subaqueous effusion producing basal pillow basalts and associated hyaloclastite produced by quench fragmentation within an englacial lake. He suggested that, as the volcanic pile approached the surface of the lake, the eruption style could become explosive prior to transitioning to subaerial lava effusion. Critically, Jones (1969) suggested that the mappable transition between the subaerial lavas and the subaqueous deposits, a boundary also tentatively recognized by Mathews (1947), served to demarcate the high stand of the ancient englacial lake. Jones (1969, 1970) ascribed the term 'passage zone' to this surface (cf. Jones and Nelson, 1970). Passage zone surfaces are now one of the signature tools that allow glaciovolcanic deposits to be used as

paleoclimate proxies (e.g., Skilling, 2009; Smellie, 2000, 2001, 2006, 2007; Edwards et al., 2011, 2009b; Russell et al., 2013).

2.3. Subsequent work

Over the past fifteen years three main works have reviewed and discussed the classification and nomenclature of glaciovolcanic edifices and their deposits (Hickson, 2000; Smellie, 2007; Jakobsson and Guðmundsson, 2008). Hickson (2000) presented a brief overview of terms and provided a list of examples mainly from western Canada based on morphological diversity (Table 1). Jakobsson and Guðmundsson (2008) gave a succinct review of glaciovolcanic terms and the Icelandic literature. In particular they advocated a specific geometric criteria (>2:1 length to width ratio)

Fig. 3. Field photographs and sketches illustrating early work in Iceland on glaciovolcanic edifices (see Table 1). (A) Photomosaic showing the eastern side profile of Kalfstindur where Jones (1969, 1970) defined the term 'tindar' as a unique, elongated ridge formed by eruptions beneath ice. (B) Modified cross-sectional view of Kalfstindur after Jones (1969), highlighting the essential components to tindar formation including: (i) eruption onset predominated by effusion of pillow lavas formed in an englacial lake, (ii) later, capping tephra deposits. (C) Photograph showing the western side profile of Burfell, a tablemountain described by van Bremmelen and Rutten (1955). (D) Modified cross-sectional view of Burfell after van Bremmelen and Rutten (1955), highlighting essential components to tablemountain formation including: pillow lavas, associated breccias and flat-lying, subaerial lavas.

to distinguish tindars (glaciovolcanic ridges) from tuyas based on a survey of measurements from Iceland. Using a somewhat expanded dataset, Smellie (2007) proposed a hierarchical classification scheme for subglacial landforms based on morphology and composition using examples from Iceland and the Antarctic. His classification scheme recognized 7 types of glaciovolcanic landforms and he discussed how the different landforms reflected differences in lithofacies, magma properties and the intrinsic properties of the enclosing ice sheet. His morphometric analysis showed that 'mafic' tuyas can have much larger volumes than

'felsic' tuyas, but that 'felsic' tuyas may have higher aspect ratios. He also postulated that lava deltas developed within polar ice sheet regimes would likely be smaller than those emplaced into temperate ice, and that tuyas would be taller if erupted through polar ice. Finally, Smellie (2007) stated that mafic tuyas are 'defined by the presence of lava-fed deltas.

While all three of these works provide important summaries, none has attempted to consolidate the literature with the purpose of establishing a coherent and consistent nomenclature for glaciovolcanoes. Likewise, previous workers have not attempted

to systematically connect glaciovolcanoes and their deposits to the fundamental physical controls imposed upon the volcanic systems by the volumetrically much larger enclosing glacial systems.

3. Definition & classification

The exponential growth of scientific interest in glaciovolcanism on Earth and other planets (Fig. 1) sets up competing forces between a loss of utility for the term tuya *versus* a proliferation of new terms (e.g., hryggir *vs.* tindar *vs.* moberg ridge *vs.* hyaloclastite ridge). Our main goal is to create a unified approach to the nomenclature and classification of glaciovolcanoes that can be easily and accurately used by volcanologists and non-volcanologists alike. Our approach is two-fold. Firstly, we develop a clear, formal definition of 'tuya'. A formal redefinition should take into account, but not be restricted by, the original works that defined the critical terminology (Mathews, 1947; van Bremmelen and Rutten, 1955; Kjartansson, 1960; Jones, 1969, 1970). It should also include the minimum set of criteria needed to identify glaciovolcanoes and their characteristic deposits (Fig. 4) (e.g., Smellie, 2000, 2007). Secondly, we propose a descriptive genetic classification scheme for glaciovolcanic edifices (Fig. 5). The classification uses modifiers to capture variations in: (i) edifice morphology, (ii)
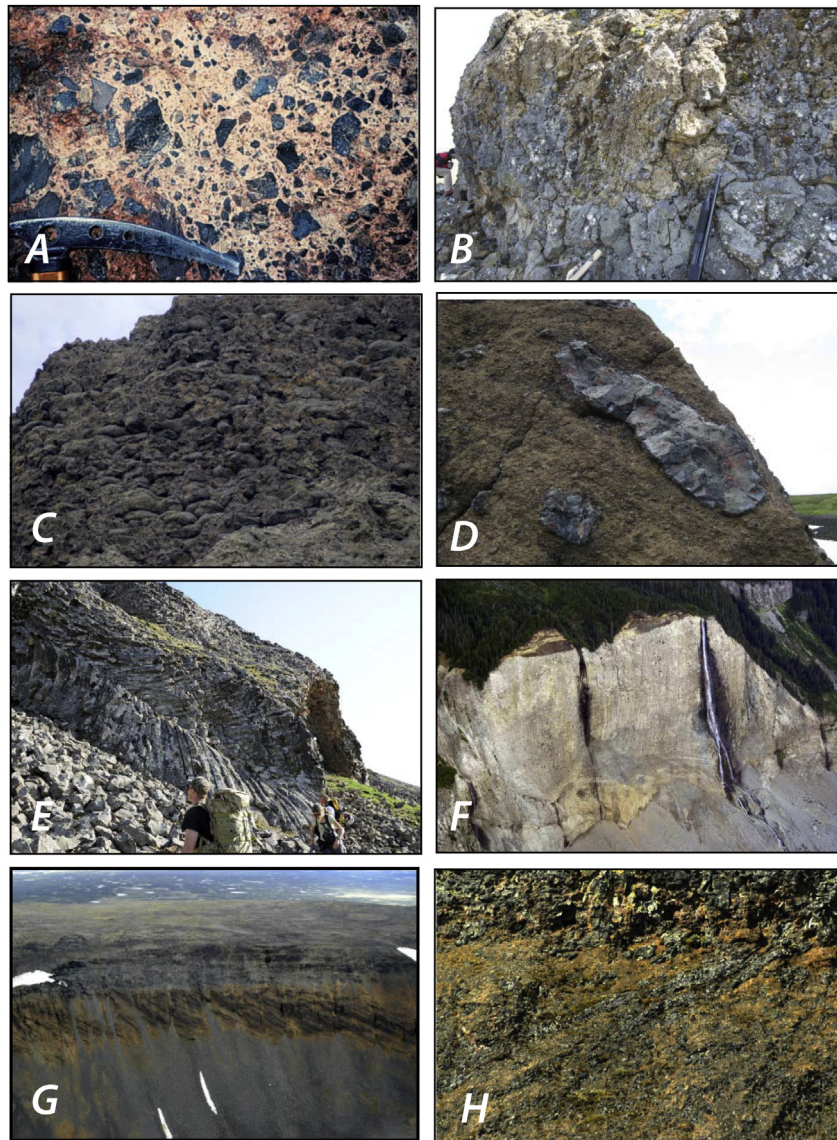
Fig. 4. Field photographs illustrating essential lithofacies/features commonly diagnostic of glaciovolcanism and associated with tuya formation (see text for caveats). (A) Hyaloclastite deposits resulting from quench fragmentation of lavas that have been palagonitized due to sustained interaction between hot, quenched, glassy lava fragments and water from Hoodoo Mountain, British Columbia (Edwards and Russell, 2002; Edwards et al., 2002). (B) Peperitic intrusions at Helgafell, southern Iceland (Schopka et al., 2006) indicating intrusion of basalt into water-saturated, unconsolidated volcaniclastic successions perched at elevations above the surrounding lava plains. (C) Densely stacked pillow lavas at Undirlithur quarry, southern Iceland outcropping at elevations above highstands of Quaternary sea level (Pollock, pers. comm. May, 2013). (D) Isolated lava pillow in crudely bedded, partly palagonitized, tuff-breccia, at Kima'Kho, British Columbia (Ryane et al., 2011). (E) Lobe of radially and horizontally oriented columnar cooling joints indicating high rates of cooling and pronounced variations in cooling direction, Mathews tuya, British Columbia (Edwards et al., 2002). (F) Two hundred meter high cliff comprising an overthickened phonolitic lava at Hoodoo Mountain, British Columbia formed when lava ponded against valley filling glacier; the vertical cliff of lava is characterized by pervasive, horizontally-oriented cooling joints (Edwards and Russell, 2002; Edwards et al., 2002). (G) Steeply dipping beds of pillow breccia and isolated pillow lavas lobes forming a delta sequence at Kima'Kho tuya, British Columbia (Mathews, 1947; Ryane et al., 2011) and overlain by horizontal sheets of lava. (H) Detailed view of an effusive passage zone at Mathews tuya, British Columbia (Edwards et al., 2011) showing the characteristic lithofacies association: crudely bedded tuff-breccia and isolated pillow lavas overlain by virtually penecontemporaneous flat-lying subaerial lava flows.

lithofacies, (iii) magma composition, and (iv) glaciohydraulic conditions (e.g., is only applicable to volcano-ice environments).

3.1. Tuya definition

We define tuyas as: positive-relief volcanoes having a morphology that results from ice confinement during eruption and comprising a set of lithofacies that reflect direct interaction between magma and ice/melt water. Explicitly, our definition implies that a tuya:
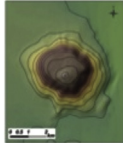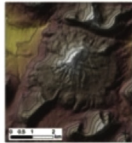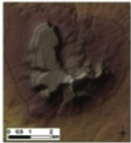
1) is a type of volcano and cannot be applied to distal glaciovolcanic deposits unconnected to any discernible vent (i.e. isolated deposits of lava/tephra; e.g., Harder and Russell, 2007; Mathews, 1958);
2) has positive relief resulting from constructional processes;
3) has a morphology that results from ice confinement rather than erosional processes (e.g., mesas);
4) comprises lithofacies indicative of, or consistent with interactions between magma and ice/melt water (Fig. 4); and
5) can comprise any chemical composition; published descriptions exist for basaltic (e.g., Allen et al., 1982; Moore et al., 1995; Smellie et al., 2008; Edwards et al., 2011), andesitic (Lescinsky and Fink, 2000; Kelman et al., 2002a; Stevenson et al., 2006), rhyolitic (Tuffen et al., 2002; McGarvie et al., 2007; McGarvie, 2009) and trachytic/phonolitic (Edwards and Russell, 2002; Edwards et al., 2002; Le Masurier, 2002) tuyas.

Previous workers have provided detailed descriptions of the lithofacies that, when found together, are diagnostic of glaciovolcanic environments (cf. Jones, 1966; Smellie, 2000; Skilling, 2009; Smellie et al., 2011). In particular, Smellie (2000, 2007) set forth criteria that he considered indicative of a glaciovolcanic origin, including: i) volcaniclastic deposits that are commonly overthickened and contain substantial proportions of angular, vitrophyric clasts resulting from quench fragmentation (Fig. 4a,b), ii) widespread hydrothermal alteration (e.g., palagonitization of basaltic glass) of volcaniclastic deposits (Fig. 4a); iii) pillow lavas indicating subaqueous effusive eruptions (Fig. 4c) with or without enclosing fragmental lithofacies (Fig. 4d); iv) subaerial lavas that are commonly overthickened (Fig. 4f) and feature intense and distinctive patterns of cooling joints (Fig. 4e); and v) larger-scale stratigraphic features indicating significant changes in the eruption/deposition environment (e.g., passage zones; Fig. 4g, h).

The properties and abundances of these lithofacies can reflect the chemical composition of the initial magma. For example, rhyolitic deposits will be more vitric and produce somewhat thicker lava flows. Also, as pointed out by Smellie (2007), no examples of 'felsic' pillow lava deltas have as yet been identified. However, with the exception of the presence/absence of pillow lava, all of the other diagnostic lithofacies can be generated across the spectrum of known lava compositions.

As discussed by Smellie (2000, 2007, 2008), Skilling (2009), and White (2011) most of these lithofacies associations do not uniquely indicate a glaciovolcanic eruption; rather they are only diagnostic of eruption in a subaqueous environment (fluvial, lacustrine, marine, etc.). The surrounding present-day landscape can, however, commonly provide the critical evidence for ascribing a glaciovolcanic origin to these subaqueous volcanic sequences. This indirect evidence includes a lack of obvious impoundment mechanism for sustaining a lacustrine environment, or the distance between the edifice and the sea, or a complete absence of fossils or marine sedimentary sequences. Other evidence, such as the presence of glacial tills and glacial striations coinciding with subaqueous volcaniclastic deposits, can also indicate a probable glaciovolcanic origin.

DESCRIPTIVE CLASSIFICATION of GLACIOVOLCANOES

Geometric Name			
Flat-topped Tuya	Conical Tuya	Linear Tuya or Tindar (L/W > 2)	Complex Tuya
Old term (descriptor)			
Stapei, Tuyas	Mounds	Hryggir, Moberg Ridge, Tindar	(complex form, strat., history)

Sketch morphology

Example maps

Examples (refs)

| Herdubreid [1] | Ash Mountain [2] | Kalfstindar [3] | Kima'Kho Tuya [4] |

[1] van Bremmelen and Rutten (1955); Werner and Schminke (1996)

[2] Mathews (1947); Allen et al. (1982); Moore et al. (1995)

[3] Jones (1969; 1970)

[4] Ryane et al. (2011); Russell et al. (2013)

LITHOFACIES MODIFIERS (e.g.)

Lava-Dominated, Tephra-Dominated, Pillow-Dominated

Fig. 5. Proposed classification of tuyas. The root name of each type of tuya is based of overall form of edifice including: flat-topped, conical or linear tuya (or tindar) as illustrated in the sketch cross-sections and the colorized hillside shaded digital elevation models. We also suggest complex tuya as a term for glaciovolcanic edifices that feature a combination of geometric forms (e.g., Kima'Kho, B.C.), or have been erupted over prolonged periods of geological time (e.g., Hoodoo Mountain, B.C.) or defy a simpler designation (Herdubreid, Iceland). The proposed classification scheme allows for addition of modifiers to the root name that capture the dominant or unique lithofacies: Lava-dominated tuya; Flat-topped lava-dominated tuya; Pillow-dominated conical tuya.

3.2. Tuya classification

Volcanic edifices identified as tuyas based on geometry, lithofacies and other indications of ice presence, can be further characterized using the nomenclature outlined in Fig. 5. This classification serves two purposes. Firstly, it codifies a simple glaciovolcanic terminology thereby improving communication across an increasingly broad spectrum of scientists. Secondly, it facilitates combining the descriptive morphological attributes of the edifice with lithofacies data that may have genetic connotations and implications for the glaciohydraulic conditions extant during eruption.

As with previous work (Smellie, 2007), our classification scheme considers the primary morphologies of the glaciovolcanic edifices and does not consider modifications due to post-eruptive erosion. The classification scheme places all glaciovolcanoes into one of four morphological categories: flat-topped, conical, linear, or complex. The first two categories are self-evident; the only possible caveats here are the possibility that post-eruption erosional processes have created a conical-shaped remnant from an originally 'flat-topped' edifice. While Mathews (1947) was clearly aware of possible post-eruption morphological changes, work in Antarctica clearly demonstrates that subaerial lava caps can survive millions of years of glacial activity (Smellie et al., 2008).

Tuyas that form linear ridges can be referred to as linear tuyas or 'tindars' after Jones (1969). Tindar replaces a plethora of terms that have been applied to linear ridges formed during glaciovolcanic eruptions, most commonly found in Iceland (e.g., Jones, 1969; Chapman et al., 2000; Jakobsson and Guðmundsson, 2008), but also present in British Columbia (Edwards et al., 2008). We adopt the same criteria proposed by Jakobsson and Guðmundsson (2008) to distinguish 'linear' tuyas (i.e. tindar) from 'conical' and 'flat-topped' categories, which is a length to width ratio greater than 2:1.

The final category is complex tuyas and encompasses a subordinate number of tuyas (based on the current literature) that are morphologically or stratigraphically more complicated (Fig. 5). For example, Herdubrieð volcano in north central Iceland has a classic passage zone but, instead of a flat-topped cap of horizontally-bedded lavas, features a post-glacial tephra cone (Werner et al., 1996). Likewise, Kima 'Kho tuya in north central British Columbia (cf. Kawdy Mountain; Mathews, 1947), comprises a cone on its southern end abutted by a flat, lava plateau (Ryane et al., 2011; Russell et al., 2013). The edifice results from a protracted and diverse eruptive history that includes an explosive, cone-building onset followed by lava effusion producing a series of pillow lava deltas, and followed by construction of a 'flat-topped' lava plateau. Thus the 'complex' morphology is a direct reflection of substantial variations in eruption style during what is interpreted as, but need not be, a monogenetic glaciovolcanic eruption. However, 'complex' tuyas also include longer-lived volcanoes, or stratovolcanoes whose history has been dominated by glaciovolcanism (e.g., Hoodoo Mountain; Edwards and Russell, 2002; Mount Haddington; Smellie et al., 2008). Hoodoo Mountain, for example, is a peralkaline volcano featuring a protracted glaciovolcanic eruption history that spanned >100 ky (Edwards et al., 2002).

3.3. Lithofacies modifiers

The tuya classification summarized in Fig. 5 is essentially based on edifice-scale morphologies in addition to combinations of lithofacies diagnostic of glaciovolcanic origins. The root names (e.g., flat-topped tuya) allow for recognition of subtypes on the basis of variations in the proportions of the essential lithofacies and/or magma composition. Descriptive lithofacies modifiers allow for greater discrimination between individual volcanoes with similar morphologies but differing proportions of lithofacies (e.g., pillow-dominated vs. tephra-dominated conical tuya). They also supply additional genetic information that provides a better understanding of the nature of the eruptions (explosive vs. effusive) and the interplay between the erupting magma and the meltwater. Magma composition can be used as a further modifier (e.g., basaltic, pillow-dominated conical tuya vs. rhyolitic, tephra-dominated conical tuya) to fully classify the volcanic edifice. Compositional modifiers provide a useful tool for understanding regional trends in magma chemistry and eruption style, and in helping to predict the likely hazards and associated risks in geologically active, glaciated areas. Below we explore how the combination of edifice morphologies and lithologies can be directly linked to general glaciohydraulic conditions.

4. Discussion & implications

Our tuya definition comprises a lithofacies (Fig. 4) and a geometric (Fig. 5) component. Each of these reflects the interactions between two fundamentally different but mechanistically coupled systems: a volcanic system and a glacial system (Figs. 6 and 7). This explains, in part, the highly variable nature and abundances of associated lithofacies within tuyas. Firstly, lithofacies reflect magmatic parameters (e.g., viscosity, initial volatile content, eruptive flux) that ultimately control the 'style of eruption' (magmatic explosive vs. effusive). Secondly, the development of an ice cauldron by melting and the longevity of the englacial lake during eruption is controlled by glacial parameters such as ice thickness, the basal properties (e.g., wet vs. frozen) of the enclosing glacier (e.g., temperate vs. polar), and the distribution of sub- and within-ice drainage networks (e.g., Smellie and Skilling, 1994; Smellie and Hole, 1997; Smellie, 2001, 2006, 2008; Smellie et al., 2011). Lastly, the presence or absence of water during the eruption, and the magma:water ratio can influence the degree of explosivity (phreatomagmatic vs. effusive) and the subsequent lithofacies (subaqueous vs. subaerial). We have explored the potential consequences, in terms of tuya geometry and lithofacies, arising from these interactions between volcanic and glacial systems (Fig. 6).

Our nine model scenarios consider effusive, transitional and explosive tuya-forming eruptions (columns in Fig. 6) and the predominant, generalized glacio-hydrological conditions of the enclosing ice (closed/sealed, leaky/partly sealed, open/well-drained; rows in Fig. 6). Non-glaciovolcanic eruptions commonly progress from explosive (gas charged) to effusive (gas depleted), with the possible exception of deep marine eruptions (e.g., Head and Wilson, 2003). However, as with deep marine examples, glaciovolcanic eruptions may not always have explosive onsets, so our transitional eruption products are depicted as developing from effusive to explosive, as well as from explosive to effusive. We have chosen these simplified end member scenarios to cover the full range of conditions likely to occur in Nature. A review of the literature on glaciovolcanism shows that 8 of the 9 scenarios are already identified in the field (Fig. 7), and we suspect that the last one (Explosive/Well-drained; Scenario III in Fig. 7) will be discovered and described in the near future.

4.1. Open/well-drained glaciohydraulic conditions

The onset of glaciovolcanic eruptions involves the melting of ice and the production of water and steam (e.g., Allen, 1980). The fate of the water is critical to the environment of eruption and largely dictates the nature and distribution of the resulting glaciovolcanic deposits. Where glacial ice is thin (<200 m) and wet-based/temperate (e.g., Smellie and Skilling, 1994), or basal topographic gradients are steep (Kelman et al., 2002a,b), melting of the overlying ice will be accompanied by relatively rapid drainage of the meltwater (Fig. 6I-III). In this environment, effusive eruptions will mainly produce subaerial lavas or lava domes. If the lavas advance more rapidly than the surrounding ice walls can melt (e.g., basaltic eruptions; Edwards et al., 2012), the lavas will pond in contact with the enclosing ice and will develop intense and variably-oriented jointing patterns. These features can be characteristic of impoundment and anomalously high cooling rates (e.g., Fig. 4e/f). At the very least, continued confinement by ice will prevent extensive lateral spreading of lava flows and will produce a stacked sequence of overthickened lavas (Fig. 7I; Mathews, 1951).

Under well-drained conditions, transitional (explosive to effusive) eruptions are likely to produce an initial tephra mound that is overlain by a stacked sequence of lava (Fig. 6II). This eruption scenario would produce a flat-topped tuya comprising a tephra-dominated base and capping lavas (e.g., flat-topped tephra-lava tuya). A potential example of this tuya type has been described by Tuffen et al. (2002) at Rauðufossafjoll, which is a rhyolitic tuya in south-central Iceland. The eruption is thought to have initiated
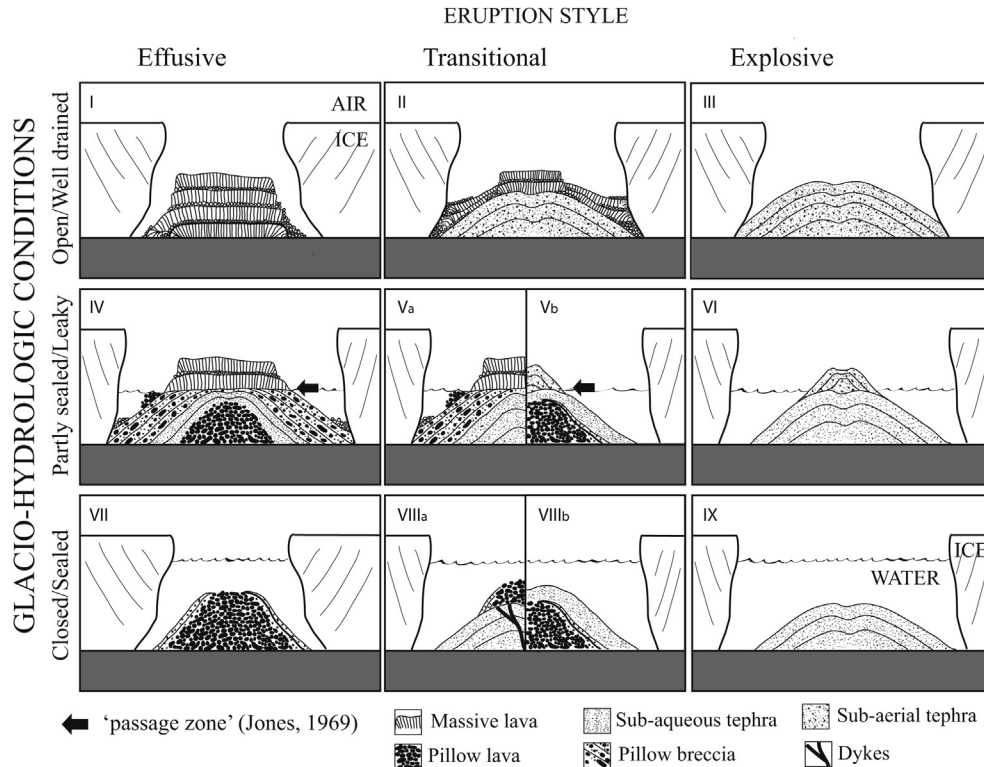
ERUPTION STYLE

Fig. 6. Schematic representation of volcanic lithofacies and lithofacies associations associated with glaciovolcanism and summarized as a function of eruption style (columns) and environment of eruption (rows). Columns denote effusive, transitional and explosive styles of eruption; transitional denotes a change from explosive to effusive or vice versa. The environment of eruption (rows) concerns the glacio-hydrologic conditions and is based on whether the englacial lake is sustained (closed/sealed), transient (leaky), or drained (open). **Subaerial** volcanism (Top Row) occurs in a well-drained environment. The resulting tuyas have a high-aspect ratio and can comprise: I) sub-horizontal lava, II) sub-horizontal lava overlying pyroclastic and polygenetic tephra, III) pyroclastic and polygenetic tephra. **Environmental transitions** (Middle Row) result as the volcano breaches the englacial lake producing a passage zone (Heavy Arrow) separating subaqueous vs. subaerial lithofacies: IV) basal pillow deposits overlain by volcaniclastic deposits resulting from quench fragmentation, capped by sub-horizontal lava and an associated lava-fed pillow delta sequence, V) (a) polygenetic tephra overlain by sub-horizontal lava and associated lava-fed pillow delta sequence or (b) pillow lava overlain by polygenetic tephra capped by pyroclastic tephra, VI) polygenetic tephra overlain by pyroclastic tephra. Multiple passage zones may result if lake level fluctuates significantly throughout the eruption (Jones, 1969; Smellie, 2006). **Subaqueous** volcanism occurs completely within a sustained englacial lake (Lower Row); the lake does not drain on the timescale of the volcanic event resulting in: VII) pillow lava and associated products of quench fragmentation, or VIII) (a) polygenetic tephra overlain by pillow lava or (b) pillow lava overlain by polygenetic tephra, or IX) polygenetic tephra the character of which depends on the explosivity of the system.

explosively beneath thin ice, and subsequently produced lava flows that eventually abutted the enclosing ice (Tuffen et al., 2002). While the volcaniclastic facies is only preserved locally, the morphology and resulting stratigraphic succession are distinctive. Alternatively, if an eruption is explosive throughout, it will produce a tephra cone comprising 'normal' volcanic ejecta (e.g., ash, lapilli, bombs; Fig. 6III). Indicators of ice confinement in this case will be rare but could include anomalously thick tephra deposits resulting from tephra being redeposited and accumulating against an enclosing ice wall (Smellie, 2007; Skilling, 2009). No known examples of this tuya type have been reported in the literature; however, the tephra cone formed at the summit of Eyjafjallajokull during the 2010 eruption is a possible candidate. This eruption style would only produce conical or linear tuyas (e.g., conical tephra-dominated tuya). In general, glaciovolcanic eruptions in well-drained glacio-hydrologic systems may be the most difficult type to identify and to use for constraining paleo-ice conditions, although impounded lava flows and/or anomalously thick tephra beds could be used to place minimal constraints on ice thickness. More importantly, however, during glaciovolcanic eruptions well-drained systems may be more likely to be found near the edges of ice sheets/glaciers, where extensive drainage networks from the interior of the ice are well developed. Thus identification of these deposits might provide key markers for the edges of ice sheets.

4.2. Leaky/partly-sealed glaciohydraulic conditions

Where glacial ice is thicker (>200 m, <500 m), or the glacier is wet-based/temperate, melting of the overlying ice will be accompanied by meltwater leaving the eruption site at varying rates, depending on the capacity of established drainage networks (Fig. 6IV–VI). In this environment, eruptions that are dominantly effusive will initially produce deposits of pillow lavas with minor hyaloclastite. However, if the eruption rate is high or sustained, or meltwater drainage is rapid, the tuya can emerge from the englacial lake leading to subaerial eruption and the potential for formation of lavas and lava-fed deltas (e.g., Skilling, 2002). The boundary between the deltaic deposits, comprising dipping breccias and isolated pillow lobes, and overlying subaerial lava flows will produce a 'classic' passage zone (e.g., Jones, 1969; Jones and Nelson, 1970; Smellie, 2006, Fig. 6IV).

Eruptions that are transitional between effusive and explosive, or vice versa, will produce more variable deposits that might include tephra produced by (phreato-)magmatic fragmentation (Fig. 6Vb) to build a 'pyroclastic passage zone' (Russell et al., 2013). Effusive to explosive transitions can be driven by depressurization resulting from drops in lake level caused by cataclysmic draining of the englacial lake and may produce outburst floods (i.e. jokulhaups; Guðmundsson et al., 1997; Magnússon et al., 2010; Major and Newhall, 1989). If the eruption is explosive throughout, it will

ERUPTION STYLE
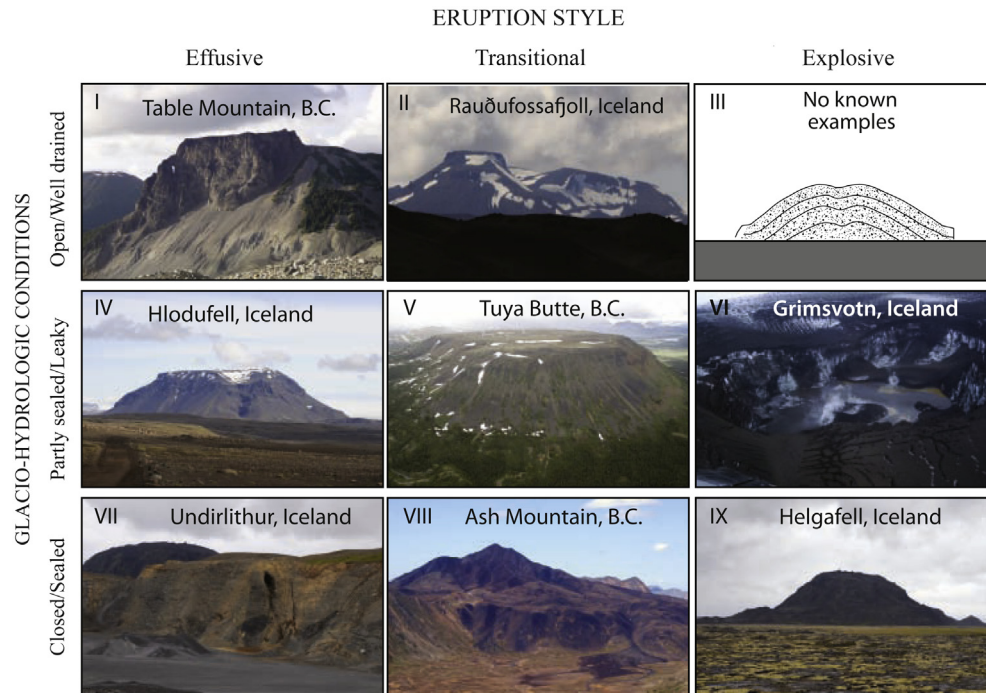
Fig. 7. Photographs of glaciovolcanic edifices (i.e. tuyas) described in the literature and illustrating the model lithofacies or lithofacies associations depicted in Fig. 5. Examples include: **Subaerial** environment (Top Row): I) The Table (Mathews, 1951), II) Rauðufossafjoll (Tuffen et al., 2002), III) no known example. **Transitional** environment (Middle Row): IV) Hludofell, Iceland (Jones, 1969; Skilling, 2009): V) Tuya Butte (Mathews, 1947; Moore et al., 1995), VI) tephra cone produced during the 2004 eruption of Grimsvotn, Iceland (Jude-Eton et al., 2012). **Subaqueous** environment (Lower Row): VII) Undirlithur quarry, Iceland; VIII) Ash Mountain, British Columbia (Mathews, 1947; Moore et al., 1995); IX) Helgafell, Iceland (Schopka et al., 2006).

produce a tephra cone comprising diverse pyroclasts (e.g., a 'Surtseyan eruption') from which a pyroclastic passage zone might also be identified (Russell et al., 2013). Both effusive and one of the two possible transitional eruption scenarios will likely form a flat-topped tuya (Fig. 6IV, Va). The remaining two scenarios (Fig. 6Vb, VI) are more likely to form conical or linear tuyas. Importantly, all of the tuyas produced in 'leaky' glacial systems are likely to produce passage zones, which clearly demarcate the highest elevation of the englacial lake. Because this is the most accurate proxy for the thickness of enclosing ice, eruptions in partly sealed systems are critical to identify, for they represent the most complete records of paleo-glacial information. Examples of each of these subtypes have been identified in the literature (Fig. 7IV–VI).

4.3. Closed/Sealed glaciohydraulic conditions

In glacial environments where ice is very thick (>500 m), or in polar regions where ice is frozen to the bedrock, the meltwater produced during subglacial eruption is unlikely to escape and will pond over the vent to form a sustained, englacial lake (Fig. 6, scenarios VII–IX). If the glaciovolcano does not grow above this sustained lake level then effusive eruptions will primarily produce pillow lava and pillow breccia deposits containing subordinate quantities of inter-pillow hyaloclastite resulting from quench fragmentation of vitric pillow rims (Fig. 6VII). Eruptions that are transitional between effusive and explosive, or vice versa, will produce more variable deposits that include pillow lavas in addition to pyroclastic deposits resulting from magmatic and phreatomagmatic fragmentation processes (Fig. 6-VIIIa/b). The relative stratigraphic positions of the effusive (pillow) and explosive (tephra) units may reflect either changing magmatic conditions (e.g., decreasing gas pressure in the magma) or edifice growth into shallower water (e.g., reducing overall $P_{hydrostatic}$). If the eruption is

explosive throughout, it will produce a tephra cone comprising fragments generated by magmatic, phreatomagmatic, and quench fragmentation (e.g., Surtseyan eruption style). If the edifice does not grow above the englacial lake surface, none of these scenarios will produce a flat-topped tuya and, without draining of the englacial lake, none will develop a passage zone. Tuyas formed in these scenarios are useful for the geochronologic and spatial constraint on ice distribution that they clearly offer. However, the lack of a passage zone defining the specific height of the englacial lake means that they can only fix the minimum height/depth of the englacial lake and hence the minimum thickness of the enclosing ice sheet. Examples of each of these subtypes have been identified in the literature (refer to Fig. 7VII–IX).

4.4. Tuyas as paleoclimate proxies

Although marine records of Quaternary climate change are essentially complete, the terrestrial record for glaciations over the same time period is sparse. Deposits diagnostic of glaciation (e.g., till) commonly have low preservation potential due to erosion between and during subsequent glaciations. Even where preserved, these deposits can be problematic for geochronology. As well, deposits formed during ice retreat will overprint those formed during ice advance. Glaciovolcanic deposits within tuyas have a much higher preservation potential because the deposits are crystalline (e.g., lava flows) or are commonly well lithified by syn- or post-eruption hydrothermal alteration (e.g., palagonitization). Glaciovolcanic eruptions could be sensitive to glacial loading (Edwards and Russell, 2002; Edwards et al., 2002) and record the waxing of glacial cycles, or be related to unloading during the waning stages of glaciation (Grove, 1974; Jellinek et al., 2004; Huybers and Langmuir, 2009; Sigmundsson et al., 2010; Tuffen and Betts, 2010). Whilst the correlations against global oceanic records

remains a challenge (e.g., McGarvie, 2009; Edwards et al., 2011), glaciovolcanic deposits can be directly dated and, thus, potentially allow for recording of ice advance and/or retreat. In this regard, tuyas define the paleoenvironmental conditions extant at the time of eruption and provide critical constraints on continental ice distributions and thicknesses on Earth and eventually on Mars through time (e.g., Smellie, 2000; Edwards et al., 2009b).

5. Conclusion

As with all relatively nascent sciences, growing interest leads to an explosion of diverse terminology. Here, we have proposed a concise and usable definition and classification scheme for 'tuyas' based on geometry and critical diagnostic lithofacies of characteristic of glaciovolcanic eruption environments. The simplified scheme covers a broad range of possible morphologies, and allows for use of specific modifiers to be used in conjunction with 'root' terms with minimal confusion. The combined lithological and morphological criteria can be used to broadly identify fundamentally different glaciohydraulic conditions, strengthening the usefulness of tuyas as paleoclimate proxies on Earth and on Mars. As the resolution of models for predicting global distributions of ice throughout the Quaternary period improve, the spatial and temporal distribution of tuyas will provide key tests of their predictions.

Acknowledgements

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