1
Introduction

1.1 What is glaciovolcanism?

This book is about a class of volcanoes, active and formerly active, that erupt in association with ice in a glacierised setting. They are collectively known as glaciovolcanic centres and their distinctive eruption style is called glaciovolcanism. Glaciovolcanic eruptions are also often referred to as 'subglacial'. The terms glaciovolcanism and subglacial volcanism are commonly used interchangeably, but the inclusion of volcanic features such as subaerial lavas that simply banked and chilled against ice and were not truly erupted subglacially suggests that, of the two, glaciovolcanism is etymologically the more correct. However, we recognise that many scientists have favourite terms that they are loathe to give up, and geologists are no exception. Indeed, one of the respondents involved in the review of the proposal for this book criticised our original title that used glaciovolcanism in preference, arguing that subglacial was more obviously descriptive, more commonly used and therefore more acceptable. Both words will be used in this book interchangeably, but with a preference for glaciovolcanism.

Glaciovolcanism describes *the interactions between magma and ice in all its forms, including snow, firn, ice and any meltwater* (Smellie, 2006). The interaction may occur under ice (subglacial; Fig. 1.1a), above ice (supraglacial; Fig. 1.1b) and/or proximal to ice (ice-constrained, ice-impounded or ice-contact; Fig. 1.1c). The cryosphere (from Greek, *cryos*, 'cold') is the term that is used to describe glaciers, snow cover, floating ice and permafrost, although glaciers are the most visible component. It comprises those areas of the Earth's surface where water occurs in solid form. Today, glaciers (a catch-all term that includes ice sheets and ice caps; Neuendorf et al., 2011) cover about 15.9 million square kilometres of the Earth's land surface, equivalent to slightly less than the size of South America and about 1.5 times the size of Australia. Most of that ice is stored as ice sheets in Antarctica and in Greenland, which comprise c. 96% of all of the Earth's glacier areas and 99.4% of glacier volume, but glaciers are present on all of the continents today except Australia. Similarly, active volcanoes occur on all continents except Australia. For example, Europe has Mt Etna and Stromboli; Russia has Shiveluch and Klyuchevskoy; North and South America have their Pacific coast sections of the Ring of Fire with many active volcanoes (e.g. Mt Redoubt, Alaska; Villarrica, Chile); Africa has Mt Nyiragongo in the

Cambridge University Press & Assessment
978-1-107-03739-7 — Glaciovolcanism on Earth and Mars
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Excerpt
More Information

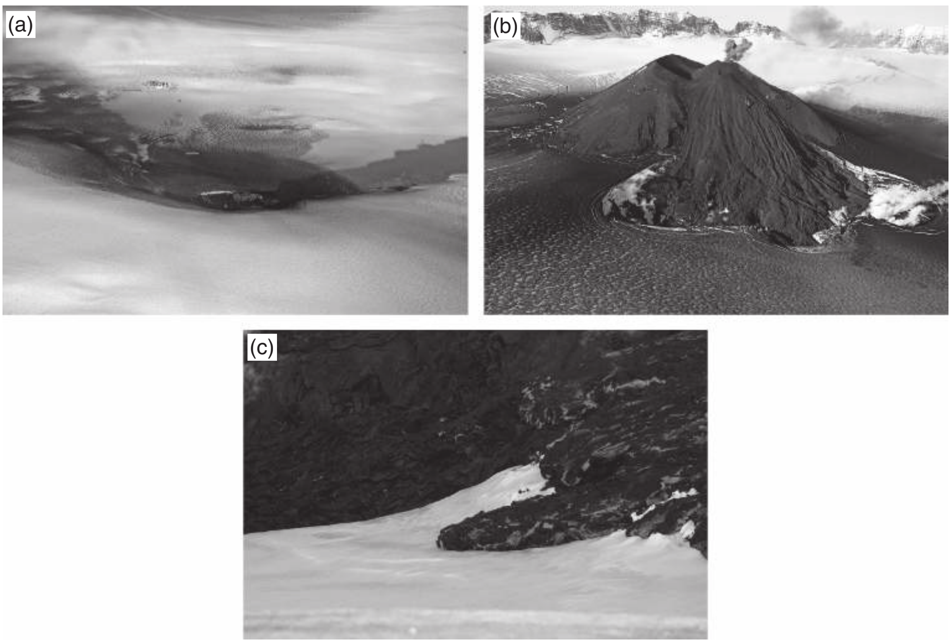

Fig. 1.1 Examples of recent glaciovolcanic eruptions. (a) Aerial view of a crater formed during the 2004 Grimsvötn eruption within the Vatnajökull ice cap, Iceland. The ice cauldron is c. 0.7 km in diameter and is flanked by ash formed during explosive activity. (b) Aerial view of the southern flank of the intracaldera cone during the 2013 eruption of Mt Veniaminof, Alaska. This is a large stratovolcano with a subaerial tephra cone situated within its ice-filled summit caldera, whose margin is visible in the background. The tephra cone protrudes above the surrounding ice and it emitted several ʻaʻā lavas that flowed downslope until they abutted against and/or flowed on top of the surrounding ice, but rates of melting and drainage were such that no lake formed, unlike in 1983–4. The cone is c. 300 m high. (c) Sheet lava flowing over snowpack during the 2013 Tolbachik eruption, Kamchatka. The foreground lava lobe is c. 5 m wide. Note how minimal snow melting has occurred below the moving lava and the lava (with a temperature of over 1000 °C) is flowing over the snow surface. (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

East African Rift; even Antarctica contains a prominently active volcano, Mt Erebus, within a major volcanic province largely contained in the West Antarctic Rift System. The likelihood, therefore, of future interactions between volcanism and ice on Earth is high (Fig. 1.2).

The term ‘glaciovolcanism’ was first used by Kelman et al. (2002), but was only formally defined in 2006 (Smellie, 2006). It is a young science topic and involves multiple scientific fields, including volcanology in its various forms, sedimentology, glaciology, geomorphology, geochemistry, biology (including exobiology), climatology and planetary science. It is thus truly multidisciplinary. Its history extends back only about a hundred years, to early descriptions of subglacially erupted volcanic edifices in Iceland and, later, in British

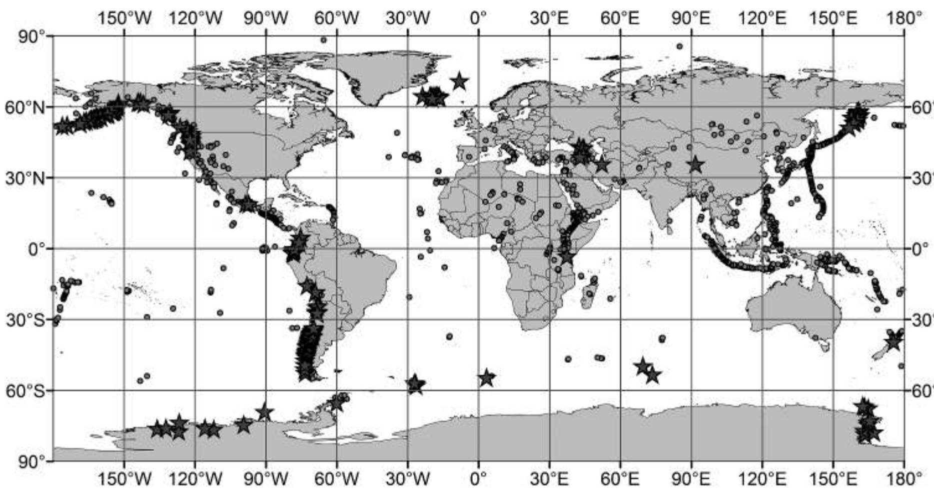

Fig. 1.2 Global map showing the distribution of ice-clad (stars) and ice-free (dots) volcanoes on Earth.

Columbia (see Section 1.3, below). Published accounts were few throughout much of the twentieth century and the early research was undertaken by only a handful of workers until the late 1990s. That was all set to change when the first meeting was convened in Reykjavik in 2000 to consider volcano–ice interaction as a topic in its own right. The meeting attracted 120 participants, indicative of the growing recognition of the increasing importance of major discoveries on planets such as Mars of evidence for past surficial water that could have hosted life. The meeting deliberately targeted terrestrial and planetary researchers and it was the first formal coming-together of the two communities. Following a meeting of interested parties at the IAVCEI (International Association of Volcanology and Chemistry of the Earth's Interior) General Assembly in Pucón in 2004, the establishment of a working group on volcano–ice interactions was proposed to IAVCEI in 2005 and accepted that year. It subsequently became a Joint Commission with the IACS (International Association of Cryospheric Sciences) and it hosts its own very well illustrated and informative website (http://volcanoes.dickinson.edu/iavcei_iacs_viic/index.html). A series of 'Volcano–Ice Interactions' meetings have followed: Reykjavik in 2006 (hosted by the International Glaciological Society); Vancouver in 2007; and Anchorage in 2012. In addition to abstract compilations, three thematic volumes from the meetings have been published thus far: Smellie and Chapman (2002); Clarke and Smellie (2007); and Edwards et al. (2009a).

Our understanding of subglacial eruption dynamics has several significant shortfalls. Because of generally insurmountable difficulties of access and minimal monitoring, subglacial eruptions are far less well understood than their subaerial and submarine counterparts. Many details of glaciovolcanic eruptions are seldom or never observed. This particularly applies to the outset, when the eruptions are often obscured by hundreds of metres of ice. Their products are impossible to observe and sample until the edifice builds up above the surrounding ice surface. With rare exceptions such as well-monitored eruptions at Grimsvötn and Eyjafjallajökull in Iceland (e.g. Gudmundsson et al., 1997, 2012a; Jude-Eton et al., 2012; Magnusson et al., 2012), our understanding of glaciovolcanic processes relies heavily on interpretations from ancient landforms together with detailed analysis of their eroded lithofacies exposed after their associated ice sheets have long since melted away. Our starting point for this book, therefore, is that descriptions of the lithofacies and interpretations of the volcanic processes involved in their formation, in concert with observations of modern and historical eruptions, are vital for a holistic understanding of glaciovolcanism. The knowledge gained will improve our abilities to understand past climate changes (Chapter 13), identify volcano–climate links (Chapter 14), and mitigate associated glaciovolcanic hazards (Chapter 15). It will also significantly improve our ability to interpret past environmental conditions in order to constrain planetary climate histories and to accurately assess the water inventory not just on Earth but on other planetary bodies (Chapter 16).

1.2 The importance of glaciovolcanism

Research on glaciovolcanism has grown extensively in recent years for several reasons. (1) The 2010 eruption of Eyjafjallajökull highlighted the combination of at least two hazards that are uniquely prominent in glaciovolcanism: local massive flooding by meltwater and associated tephra production capable of disrupting regional travel (Chapter 15). Airborne ash from the comparatively small eruption grounded more than 100 000 flights across wide swathes of Europe for a period of a few weeks and caused substantial costs to the airline industry estimated at c. 1.3 billion euros (£1.1 billion, US$1.7 billion). (2) The geological history of many parts of the planet, particularly Iceland, British Columbia and Antarctica, cannot be fully understood without taking into account the increasingly important role glaciovolcanism has in shaping landscape and its pivotal importance in preserving evidence of critical parameters of palaeo-ice sheets (Chapter 13). (3) The simple presence of an ice cover and variations in its thickness over geological time, especially during glacial cycles, can significantly modulate processes of mantle melting and rates of eruption. The resultant sudden increase in atmospheric CO_2 during rapid deglaciation has been cited as a possible positive feedback loop that strengthens global warming, causing further ice melting and triggering more eruptions (Chapter 14). (4) Research on the geology of Mars using various remote sensing techniques has called for improved understanding of terrestrial analogues, including observed glaciovolcanic eruptions and associated deposits (Chapter 16). Finally, (5) the combination of high heat flow and water together with nutrient-rich volcanic glass that are characteristic of glaciovolcanic environments also means that glaciovolcanic environments can likely support ‘extreme-life’, not only on Earth but also possibly on Mars and other planetary bodies. Subglacially active volcanoes may also have played a pivotal role in biological evolution by providing warm, wet ice-free areas sustained by very long-lived geothermal systems. The volcanic refugia thus created may have re-established terrestrial biodiversity in Earth's polar regions, permitting life to survive through multiple glaciations, and the same may be true of other planets (Fraser et al., 2014).

1.3 History of glaciovolcanic research

1.3.1 Iceland

Scientists in Iceland were the first to attempt to interpret the origins of widespread, distinctive volcanic deposits and their relationships to glaciation (see Jakobsson and Guðmundsson, 2008 for a review). Pjetursson (1900) recognised evidence that central Iceland had been glaciated multiple times, and that volcanic units were interstratified with glacial sedimentary deposits. Peacock (1926) discussed the origins of the Palagonite Formation, an extensive suite of volcanic deposits covering much of central Iceland, and he deduced that their distinctive properties were a direct result and indication of interactions between volcanism and glaciation. By the early 1940s, Noe-Nygaard (1940) had identified specific regions where the volcanic deposits had formed subglacially (e.g. Kirkjubæjarheiði) and he presented one of the first step-wise models for a subglacial eruption sequence. Kjartansson (1943) suggested that ridges of móberg, comprising a variety of lithified volcaniclastic deposits, should be referred to as 'hryggir', and flat-topped móberg mountains be called 'stapar'. While a large group of Icelandic and European geoscientists were investigating the subglacial origins of Icelandic volcanoes, similar research was being conducted simultaneously and independently by Mathews (1947) in Canada, deducing the origins of Quaternary volcanoes in northern British Columbia (Section 1.3.2). A terminology of glaciovolcanism emerged mainly based on the studies in Iceland (Table 1.1; also Chapter 8). The large, flat-topped subglacially erupted volcanoes in Iceland were referred to as stapar and table mountains – an approximate English translation of stapar. Likewise, elongate ridges with glaciovolcanic origins were referred to as hryggir (Kjartansson, 1943), tindars (Jones, 1969b, 1970), móberg ridges (Kjartansson, 1943), and hyaloclastite ridges (Chapman et al., 2001; see Glossary). While hyaloclastite (*sensu lato*) was used as a synonym for the Icelandic term móberg, the namesake Móberg Formation comprises a diverse array of volcaniclastic rocks (Peacock, 1926; Kjartansson, 1959; Jakobsson and Guðmundsson, 2008). Indeed, few of these volcaniclastic deposits would now be considered hyaloclastite based on modern usage (e.g. deposits formed during effusive volcanism and dominated by vitric fragments formed by quenching and mechanical fragmentation of the flowing lava; cf. Rittmann, 1952; Fisher and Schmincke, 1984; White and Houghton, 2006; see Glossary and Chapter 9).

Other important European contributions to Icelandic glaciovolcanism include the wide-ranging studies by van Bemmelen and Rutten (1955) and, particularly, Jones (1966, 1969a, b, 1970). Van Bemmelen and Rutten (1955) proposed that the table mountains formed as a result of eruptions from central vents or fissures beneath a relatively thick ice sheet (>450 m). They invoked ponding of lava against the enclosing ice to explain over-thickened

Table 1.1 *Varied nomenclature used to describe glaciovolcanic landforms (modified from Russell et al., 2014)*

Terms	Morphology	Sources[a]
stapi/stapar	equant and flat-topped	1, 4, 11, 15, 16
table mountain		4, 5
tuya		2, 3, 9, 21, 23, 26, 31
flow-dominated tuya		19, 21, 26
effusion-dominated tuya		20
flat-topped tuya		25
subglacial mound	equant and conical	17, 26
palagonitic cone		4
conical tuya		25
tephra-dominated tuya	linear and flat-topped	20, 21, 26
hyaloclastite ridge		4
tindar	linear but not flat-topped	8, 9, 21, 23, 24, 26, 31
hyaloclastite ridge		18
palagonitic ridge		4
hryggir		1
móberg ridge		1, 11
linear tuya		25
sheet-like sequence	thin sheet or sinuous ribbon	26, 27
sheet-flow sequence palagonite		28
breccia mass		29
hyaloclastite flow móberg sheet		30
		31
pillow mound/ridge pillow sheet	low oblate smooth mound	21, 26
		21, 26, 31, 32
subglacial dome/lobe	tall steep-sided dome or lobe	19, 21, 26

[a] 1 Kjartansson (1943); 2 Mathews (1947); 3 Mathews (1951); 4 van Bemmelen and Rutten (1955); 5 Kjartansson, (1959); 6 Jones (1966); 8 Jones (1969b); 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 Gudmundsson et al. (2002); 19 Kelman et al. (2002); 20 Tuffen et al. (2002a); 21 Smellie (2007, 2013); 22 McGarvie et al. (2007); 23 Jakobsson and Gudmundsson (2008); 24 Edwards et al. (2009a); 25 Russell et al. (2014); 26 Smellie (2009); 27 Smellie (2008); 28 Smellie (2001); 29 Walker and Blake (1966); 30 Bergh and Sigvaldason (1991); 31 Jakobsson and Gudmundsson (2008); 32 Snorrason and Vilmundardóttir (2000)

masses of lava. Van Bemmelen 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 associated englacial lakes during ongoing eruptions.

Jones (1969b, 1970), working in south-central Iceland, was largely responsible for erecting the 'standard model' for mafic tuya construction (Section 1.5). Jones' work remains one of the most influential of all glaciovolcanic studies and his model has been used extensively by practically all subsequent workers. Jones (1969b) applied the term tuya to several flat-topped Icelandic volcanoes and proposed the term tindar for ridges formed during glaciovolcanic eruptions. He deduced that the magma–water interactions resulted from water stored in englacial lakes derived from melting of the surrounding ice. Building on the Canadian-based work of Mathews (1947), Jones (1970) developed a model comprising an initial phase of subaqueous effusion producing basal pillow lavas and associated hyaloclastite created by quench fragmentation within an englacial lake (Section 1.5). He suggested that, as the volcanic pile approached the surface of the lake, the eruption style became explosive prior to transitioning to subaerial lava effusion. Critically, Jones (1969b) suggested that the mappable transition between the subaerial lavas and the subaqueous deposits, a boundary also observed but not named by Mathews (1947), served to demarcate the water level in the ancient englacial lake. Jones (1969b, 1970) called the surface a 'passage zone' (cf. Jones and Nelson, 1970; Skilling, 2002; Smellie, 2006). Passage zones are now one of the signature tools that allow glaciovolcanic deposits to be used as palaeoenvironmental proxies (e.g. Smellie, 2000, 2006; Edwards et al., 2009b, 2011; Skilling, 2009; Russell et al., 2013; Smellie et al., 2013a).

1.3.2 Canada

Independently of the early Icelandic studies, F.A. Kerr and W.H. Mathews published landmark studies describing the stratigraphy and morphology of a series of steep-sided and flat-topped volcanoes in the Iskut and in the Tuya–Kawdy regions of northwestern British Columbia (Kerr, 1948; Watson and Mathews, 1944; Mathews, 1947).

Kerr's observations from fieldwork in the 1920s along the Iskut River (published postumulously in 1948) are the earliest known descriptions and interpretations of volcano–ice interactions in Canada. Kerr gave a general description of the intermediate composition lavas that form much of Hoodoo Mountain volcano, along the central reach of the lower Iskut River in northwestern British Columbia. He recognised that the over-thickened sections of lava flows along the flanks of the volcano were evidence of confinement by surrounding glacial ice at a time when present-day glaciers in the area (Hoodoo and Twin glaciers) must have been much more extensive. Kerr's observations, while not widely distributed by publication in an international journal, presaged the more detailed and widely distributed work by Mathews in the following decades in northern and southern British Columbia.

In the Tuya–Kawdy area, Watson and Mathews (1944) documented numerous, small, apparently young, volcanoes hosting a variety of distinctive features including flat tops formed from subhorizontal lava flows, circular plan-views, and the predominance within the lower stratigraphy of prominently outward dipping fragmental units. Mathews (1947) suggested that the lavas capping the summits of these mountains did not correlate with each other nor could erosion explain their morphology. Instead, he suggested that they represented individual volcanoes. Mathews (1947) also recognised that these volcanic edifices shared common stratigraphical 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. He proposed the term tuya for these flat-topped, steep-sided volcanoes after a local aboriginal term used to name several local geographical features. He also interpreted the morphology and attendant volcanic lithofacies of these tuyas as indicative of volcanic eruptions from beneath late Pleistocene glacial ice sheets. Mathews (1947) also noted similar-aged, cone-shaped volcanoes lacking flat tops and comprising only pillow lava, 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. Later workers in British Columbia have referred to these edifices as subglacial mounds or conical tuyas (Hickson et al., 1995; Hickson, 2000; Russell et al., 2014; Table 1.1).

1.3.3 Antarctica

Because of its remoteness and its status as the last continent to be discovered, with a history of human exploration only dating back to 1819 (Campbell, 2000), progress on glaciovolcanism was later in Antarctica than elsewhere. Surprisingly, the earliest references to glaciovolcanic outcrops were published almost simultaneously from localities extending right across the continent (Hamilton, 1972 (northern Victoria Land); LeMasurier, 1972a, b (Marie Byrd Land); Bell, 1973 (Antarctic Peninsula)),. Thereafter, apart from numerous studies in Marie Byrd Land by LeMasurier (e.g. LeMasurier and Rex, 1982; LeMasurier, 1990) and a study of isolated outcrops in the Transantarctic Mountains (Stump et al., 1980), there is a significant gap until the late 1980s, when numerous papers mainly on Antarctic Peninsula glaciovolcanic outcrops were published (Wörner and Viereck, 1987; Smellie et al., 1988, 1993; Skilling, 1994; Smellie and Skilling, 1994; Smellie and Hole, 1997; Smellie, 1999) together with a major volume summarising the basic outcrop characteristics of all Cenozoic volcanism in Antarctica, irrespective of its eruptive environment (LeMasurier and Thomson, 1990).

1.3.4 Subsequent work (2000-on)

Publications on glaciovolcanic outcrops and glaciovolcanism have generally increased exponentially since 2000, the year of the first conference on volcano–ice interactions, and the subsequent 15 years can be viewed as a period of increasingly vigorous interest in the topic. Four main studies have reviewed and discussed the classification and nomenclature of glaciovolcanic edifices and their deposits (Hickson, 2000; Smellie, 2007, 2009, 2013; Jakobsson and Guðmundsson, 2008; Russell et al., 2014). Hickson (2000) presented a brief overview of terms and provided a list of examples mainly from western Canada based on morphological diversity (Table 1.1). Jakobsson and Guðmundsson (2008) gave a succinct review of glaciovolcanic terms and the Icelandic literature. In particular they advocated a specific geometrical criterion (>2:1 length to width ratio) to distinguish tindars from tuyas based on a survey of measurements from Iceland. Using a greatly expanded dataset, Smellie (2007, 2009, 2013) proposed a hierarchical classification scheme for subglacial landforms based on morphology and magma composition using 98 examples from Iceland, Antarctica, Canada and Russia. His classification scheme recognised seven 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-fed deltas developed within polar (cold-based) ice sheet regimes would likely be smaller than those emplaced in temperate (warm-based) ice, that tuyas would be taller if erupted through polar ice, and that lavas may flow over the surface of the surrounding ice rather than always melting a passage and will either be advected away or collapse as rubble after ice sheet decay (see Chapter 8). Finally, Smellie (2007, 2009, 2013) observed that mafic tuyas are *defined* by the presence of lava-fed deltas as they give the landform its flat top. By contrast, Russell et al. (2014) suggested a significant modification to traditional classification schemes, and showed how broad-scale ice characteristics (e.g. the ability to trap water in an englacial lake) could exert fundamental controls on edifice morphologies and lithofacies. All of these studies provided important morphological summaries using the long-established classification for glaciovolcanic landforms that evolved progressively over many decades. However, apart from Smellie (2000, 2001, 2007, 2009, 2013), Edwards and Russell (2002), and Russell et al. (2014), few workers have attempted to relate glaciovolcanoes and their deposits to the fundamental physical controls (principally ice thickness, glacier structure, basal regime and hydraulics) imposed upon the volcanic systems by the volumetrically much larger enclosing glacial systems (see Chapter 4).

1.4 Styles of glaciovolcanism and classification of the products

1.4.1 Types of glaciovolcanic eruptions

In addition to endogenous factors (e.g. magma composition, volatile content, rheology), exogenous (i.e. environmental) factors such as the presence or absence of external water or different ice thicknesses can have a major impact on eruptive styles and are very important in glaciovolcanic eruptions. The first attempt to correlate different glaciovolcanic sequence types with exogenous factors, i.e. ‘thick ice’ versus ‘thin ice’, was by Smellie et al. (1993; also Smellie and Skilling, 1994; Smellie, 2000) using Mio-Pliocene monogenetic edifices in the Antarctic Peninsula. It was shown that the different ice thicknesses led to very different sequences of lithofacies and eruptive and depositional processes. Subsequently

Edwards and Russell (2002) showed that deposits at a polygenetic edifice could preserve evidence for eruption under different ice thicknesses (see also Smellie et al., 2008; Skilling, 2009). By contrast, Edwards et al. (2015a) created a classification comprising three generic types of glaciovolcanic eruptions based on a broader range of environmental conditions: those that originate beneath ice (e.g. Gjálp 1996 is type for 'thick' ice, Eyjafjallajökull 2010 is type for 'thin' ice; cf. Smellie and Skilling, 1994); eruptions that deposit material on top of ice (e.g. Redoubt 2009); and eruptions where lava erupts subaerially but is then transported into contact with snow and ice (e.g. Fimmvörðuháls (Eyjafjallajökull) 2010; Tolbachik 2013; see Section 3.3). The examples highlighted by Edwards et al. (2015a) are from observations of modern events and they were selected to encompass eruptions that demonstrate all of the main processes that occur in glaciovolcanism.

1.4.2 Classification of glaciovolcanic products

The existing classification of glaciovolcanic products includes several discrete landform or sequence types for monogenetic eruptions, each with distinctive morphological and lithofacies characteristics that reflect the eruptive conditions (especially ice thickness and thermal regime), magma composition, viscosity, etc. (Smellie, 2007, 2009, 2013; Russell et al., 2014). They comprise tuyas, glaciovolcanic tuff cones, tindars, sheet-like sequences, pillow mounds, and domes (see Glossary for an explanation of these terms); although subglacially erupted polygenetic volcanoes also exist, only rarely do they create distinctive landforms (Chapter 8). Distinctive mafic and felsic variants are also recognised. However, a new and significantly different classification has been proposed by Russell et al. (2014). In it, many of the glaciovolcanic landforms are recast as different types of tuya, and it does not apply to isolated deposits distal to eruptive vents such as sheet-like sequences. The most substantial change in the proposed new classification is the redefinition of what a tuya is. Originally defined by Mathews (1947) as a subglacially erupted edifice uniquely distinguished by its flat top (basaltic in the original but since expanded to incorporate intermediate-composition and felsic examples), it is the most distinctive glaciovolcanic landform. By contrast, in the Russell et al. classification flat-topped edifices are just one variety (called flat-topped tuyas) in a continuum of tuyas that includes at least nine different types. They include conical (cf. tuff cone, subglacial mounds), linear (cf. tindar, which is used as a synonym for linear by Russell et al., 2014) and complex (which applies to edifices that show more than one distinctive morphological characteristic attributable to glaciovolcanism, e.g. Kima'Kho tuya (Canada), which has both a large cone and a flat-topped plateau). Larger polygenetic volcanoes such as Hoodoo Mountain (Canada; Edwards and Russell, 2002) and Mt Haddington (Antarctica; Smellie et al., 2008) are also regarded by Russell et al. (2014) as complex tuyas. It is too early to say whether the system proposed by Russell et al. (2014) will gain widespread acceptance. Accordingly, and without prejudice to the new Russell et al. (2014) classification, this book follows the currently well-established existing classification of glaciovolcanic landforms described by Smellie (2007, 2009, 2013).