Contents

Preface ix
Acknowledgments xii

1 Introduction 1
  1.1 What is glaciovolcanism? 1
  1.2 The importance of glaciovolcanism 4
  1.3 History of glaciovolcanic research 5
  1.4 Styles of glaciovolcanism and classification of the products 9
  1.5 The ‘standard tuya model’ 11
  1.6 Compositional classification used in this book 13

2 Distribution of glaciovolcanism on Earth 15
  2.1 Introduction 15
  2.2 Antarctica 15
  2.3 Iceland 26
  2.4 North America 33
  2.5 Other locations 48
  2.6 Summary 56

3 Observations of historical and recent glaciovolcanic eruptions 57
  3.1 Introduction 57
  3.2 Classification of glaciovolcanic eruptions 59
  3.3 Descriptions of observed glaciovolcanic eruptions 60
  3.4 Important lessons learned and observations needed for future eruptions 89

4 Physical properties of ice important for glaciovolcanic eruptions 91
  4.1 Introduction 91
  4.2 Physical structure of an ice mass 91
  4.3 Thermal regime 93
  4.4 Rheology 94
  4.5 Hydraulics 95

5 Chemical and physical properties important to glaciovolcanic lavas 103
  5.1 Introduction 103
5.2 Compositional range 103
5.3 Lava temperatures 111
5.4 Viscosity (η) 117
5.5 Other thermodynamic properties 120
5.6 Summary 124

6 Physics of glaciovolcanism 125
6.1 Introduction 125
6.2 Magma generation 125
6.3 Magma migration 128
6.4 Heat transfer 129
6.5 Fragmentation processes 135
6.6 Volatile saturation and vesiculation 138
6.7 Constraints on modes of emplacement 138
6.8 Formation of cooling fractures 143
6.9 Summary 144

7 Analytical studies of glaciovolcanic materials 145
7.1 Introduction 145
7.2 Morphometry 145
7.3 Major, minor and trace element geochemistry 146
7.4 Volatile elements 149
7.5 Mineral, glass and palagonite compositions 154
7.6 Stable isotope studies 157
7.7 Geochronometric studies 158
7.8 Quantitative analysis of grain sizes 159
7.9 Summary 160

8 Landform classification and morphometry of glaciovolcanic centres 162
8.1 Introduction 162
8.2 Classification of glaciovolcanic landforms 162
8.3 Glaciovolcanic landforms constructed under cold-based ice 177

9 Lithofacies in glaciovolcanic sequences 180
9.1 Introduction 180
9.2 Terminology 180
9.3 Primary coherent lithofacies 184
9.4 Primary fragmental lithofacies 197
9.5 Coeval deformation features 213

10 Mafic glaciovolcanic sequences 215
10.1 Introduction 215
10.2 Ice-impounded lavas 215
10.3 Pillow mounds and ridges 216
10.4 Tindars and tuyas 220
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5 Pillow sheets: fact or fiction?</td>
<td>238</td>
</tr>
<tr>
<td>10.6 Sheet-like sequences</td>
<td>240</td>
</tr>
<tr>
<td>10.7 Large polygenetic glaciovolcanic centres</td>
<td>247</td>
</tr>
<tr>
<td>11 Intermediate-composition glaciovolcanic sequences</td>
<td>250</td>
</tr>
<tr>
<td>11.1 Introduction</td>
<td>250</td>
</tr>
<tr>
<td>11.2 Ice-impounded lavas</td>
<td>251</td>
</tr>
<tr>
<td>11.3 Domes</td>
<td>255</td>
</tr>
<tr>
<td>11.4 Tuyas</td>
<td>259</td>
</tr>
<tr>
<td>11.5 Other intermediate-composition glaciovolcanic sequences</td>
<td>261</td>
</tr>
<tr>
<td>11.6 Large polygenetic glaciovolcanic centres</td>
<td>264</td>
</tr>
<tr>
<td>12 Felsic glaciovolcanic sequences</td>
<td>268</td>
</tr>
<tr>
<td>12.1 Introduction</td>
<td>268</td>
</tr>
<tr>
<td>12.2 Ice-impounded lavas</td>
<td>268</td>
</tr>
<tr>
<td>12.3 Domes</td>
<td>271</td>
</tr>
<tr>
<td>12.4 Tuyas</td>
<td>275</td>
</tr>
<tr>
<td>12.5 Tindars</td>
<td>284</td>
</tr>
<tr>
<td>12.6 Sheet-like sequences</td>
<td>287</td>
</tr>
<tr>
<td>12.7 Other felsic glaciovolcanic sequences</td>
<td>292</td>
</tr>
<tr>
<td>12.8 Large polygenetic glaciovolcanic centres</td>
<td>296</td>
</tr>
<tr>
<td>13 Glaciovolcanic sequences as palaeoenvironmental proxies</td>
<td>298</td>
</tr>
<tr>
<td>13.1 Introduction</td>
<td>298</td>
</tr>
<tr>
<td>13.2 Ancient ice</td>
<td>298</td>
</tr>
<tr>
<td>13.3 Sedimentary evidence for glacial conditions and basal thermal regime</td>
<td>299</td>
</tr>
<tr>
<td>13.4 Glaciovolcanic evidence for ancient ice</td>
<td>300</td>
</tr>
<tr>
<td>13.5 Calculating ice thicknesses and surface elevation from glaciovolcanic sequences</td>
<td>318</td>
</tr>
<tr>
<td>13.6 Effect of volcanic heat on basal thermal regime of ice</td>
<td>325</td>
</tr>
<tr>
<td>13.7 Strengths and disadvantages of glaciovolcanic palaeoenvironmental investigations</td>
<td>329</td>
</tr>
<tr>
<td>13.8 Examples of palaeoenvironmental investigations using glaciovolcanic sequences</td>
<td>331</td>
</tr>
<tr>
<td>14 Climate triggers for glaciovolcanism</td>
<td>342</td>
</tr>
<tr>
<td>14.1 Introduction</td>
<td>342</td>
</tr>
<tr>
<td>14.2 Historical studies</td>
<td>342</td>
</tr>
<tr>
<td>14.3 How can waxing and waning of glaciers and ice sheets affect volcanism?</td>
<td>344</td>
</tr>
<tr>
<td>14.4 Likelihood of present-day climate change increasing volcanic activity</td>
<td>348</td>
</tr>
<tr>
<td>14.5 Potential glacial–volcanic climate feedback mechanisms</td>
<td>349</td>
</tr>
</tbody>
</table>
Contents

15 Hazards associated with glaciovolcanic eruptions 350
  15.1 Introduction 350
  15.2 Lava flows 351
  15.3 Ash falls 356
  15.4 Pyroclastic density currents 358
  15.5 Meltwater floods and associated mass flows 359
  15.6 Avalanches 360
  15.7 Lightning 362
  15.8 Short-term versus long-term climate impacts 362
  15.9 Summary 363

16 Glaciovolcanism on Mars 364
  16.1 Introduction 364
  16.2 Geological background 364
  16.3 A water inventory for Mars 367
  16.4 The hydrological cycle on Mars and glacial–interglacial cyclicity 374
  16.5 Theoretical aspects of Mars’ glaciovolcanism 375
  16.6 Observations of Mars’ glaciovolcanism 378

17 Outstanding challenges and possibilities 392
  17.1 Introduction 392
  17.2 Towards a better understanding of the physics and chemistry of glaciovolcanism 392
  17.3 Understanding boundary conditions: how does the ice–bedrock interface influence eruptions? 395
  17.4 Differentiating between marine and freshwater glaciovolcanic eruptions 396
  17.5 Ice melting rates and the ‘space problem’ 397
  17.6 Towards better assessment, monitoring and mitigation of glaciovolcanic hazards 397
  17.7 Geochronology 398
  17.8 Improving our understanding of planetary glaciovolcanism: Earth–Mars comparisons 399
  17.9 Towards improved integration of information from ancient glaciovolcanic deposits into planetary climate models: the past as a guide to modelling future Earth climate 399

Glossary: Terminology of Glaciovolcanism 400
References 410
Index 461

Colour plates are to be found between pp. 212 and 213.