View from just east of the summit of Sgorr Dhouill, looking north. In the foreground are prominent cliffs of resistant porphyritic granite, occupying the centre of the Ballachulish Igneous Complex. Below the cliffs are the forested slopes of Gleann a' Chaolais, underlain by diorite of the igneous complex. Across Loch Leven, spanned by the Ballachulish Bridge, lie North Ballachulish and the hills of Nether Lorn, underlain by Dalradian metasediments. The small tidal island forming a promontory on the west side of the small anchorage east of North Ballachulish contains incipiently cordierite-spotted phyllites of the Leven Schist, and marks the outer margin of the thermal aureole in this area.
Preface

With the new global tectonics approach in the Earth Sciences, the quantitative aspects of the dynamics of rock-forming processes came into focus: geologists are no longer satisfied knowing the pressure-temperature conditions of the formation of a metamorphic rock or of the emplacement of a magmatic body, but instead would like to learn the time history of these rocks as well, i.e., derive the temperature-pressure-time path and relate it to a tectonic process. To achieve this goal, a knowledge of both pressure-temperature-dependent equilibria and the time scales at which these equilibria may be attained are essential. However, the latter kinetic information is much more difficult to retrieve than that on equilibria: whereas equilibria are controlled by state variables, and proper laboratory experiments may be directly applied to equilibrium natural assemblages, kinetics also depends on factors other than state variables, such as grain size, dislocation density, and especially time (rate of heating, duration of annealing, rate of cooling). Extrapolation of kinetic data obtained at high temperatures on laboratory time scales to more realistic lower temperatures and geological time scales are dangerous because, for example, of possible changes from an intrinsically controlled defect regime to an extrinsic one as temperature is lowered, or from an interface-controlled to a diffusion-controlled reaction mechanism.

Progress in our understanding of the kinetics of rock-forming processes can, therefore, only be expected by a careful comparison of laboratory and field data. With the time history of the evolution of a natural rock being in general poorly known and the factors controlling the kinetics difficult to reconstruct, it is essential to use as many data and techniques as possible, but at the same time keep the number of complicating factors low.

In this book, such a multilateral approach is attempted for one contact aureole, that of the Ballachulish Igneous Complex in the Scottish Highlands. It has been selected because of the large variety of different rock types contained and the relatively simple cylindrical geometry. Also, because of its size, the time scale of contact metamorphism in this aureole (in contrast to that of regional metamorphism) is closer to that of laboratory studies than in regional metamorphism, and a chance might exist for a linkage of results. It is probably not an exaggeration to say that
this is the most comprehensive study of a single igneous complex-contact aureole system yet published.

The work on the Ballachulish igneous body and its aureole presented here started independently in two places: at the Grant Institute of Geology of Edinburgh University, and in a priority program run by the Deutsche Forschungsgemeinschaft, entitled "Kinetics of rock- and mineral-forming processes" in which a number of groups in geophysics, petrology, mineralogy and geochemistry from different German universities participated. It was only by a combination of activities that the complex problem could be tackled.

The editors and authors would like to express their gratitude for support to the Deutsche Forschungsgemeinschaft, Bonn. The following colleagues provided in depth reviews of the manuscripts, helpful discussions or supplementary data: J.R. Ashworth (Birmingham, UK), M.H.P. Bott (Durham, UK), T. Chacko (Edmonton, Alberta, Canada), G. Droop (Manchester, UK), J. Farver (Providence, R.I., USA), C. France-Lanord (Nancy, France), E. Ghent (Calgary, Alberta, Canada), M. Gottschalk (Tübingen, FRG), C.M. Graham (Edinburgh, UK), J. Hoefs (Göttingen, FRG), H. Jaffe (Amherst, Mass., USA), W. Johannes (Hannover, FRG), P. Metz (Tübingen, FRG), W.F. Müller (Darmstadt, FRG), W.S. Pitcher (Liverpool, UK), A. Putnis (Cambridge, UK), P. Ribbe (Blacksburg, Va., USA), J. Rice (Eugene, Or., USA), D.C. Rubie (Bayreuth, FRG), D. Rumble III (Washington, D.C., USA), L. Rybach (Zürich, Switzerland), S. Sheppard (Nancy, France), W.E. Stephens (St. Andrews, Scotland), A.B. Thompson (Zürich, Switzerland), V. Tromms dorff (Zürich, Switzerland), R. Uhrenbacher (Kiel, FRG), J.W. Valley (Edinburgh, UK), G. Werding (Bochum, FRG), W. Wünch (München, FRG), R.A. Yund (Providence, R.I., USA). Technical assistance was provided by T. Baller (Bochum, FRG), P. Dalgetty (Edinburgh, UK), T. Fockenberg (Bochum, FRG), B. Kennedy, E. Löbl (Bayreuth, FRG). To all these persons and institutions our sincere thanks are due.

August 1991

The Editors
Contents

Part I Introduction

1 The Setting of the Ballachulish Intrusive Igneous Complex
   in the Scottish Highlands
   B. Harte and G. Voll ........................................... 3

2 Regional Geology of the Ballachulish Area
   D.R.M. Pattison and G. Voll .................................. 19

Part II The Intrusive Complex

3 Structure, Petrography and Emplacement of Plutonic Rocks
   G. Troll and S. Weiss ......................................... 39

4 Thermal Conditions and Crystallization Sequence,
   as Deduced from Whole-Rock and Mineral Chemistry
   S. Weiss and G. Troll ......................................... 67

5 Nucleation and Growth of Pyroxene in the Hypersthenic Diorites
   S. Weiss ......................................................... 97

6 Microstructures and Thermal Behaviour of Igneous Pyroxenes
   H. Feuer, L. Schröpfer and H. Fuess .......................... 105

7 The Shape of the Intrusion Based on Geophysical Data
   W. Rabbel and R. Meissner ................................... 121

Part III The Contact Aureole and Its Rocks

8 Petrography and Mineral Chemistry of Pelites
   D.R.M. Pattison and B. Harte ................................ 135
9 Field Relations and Petrography of Partially Melted Pelitic and Semi-Pelitic Rocks
   B. Harte, D.R.M. Pattison and C.M. Linklater .............. 181

10 Decarbonation Reactions in Siliceous Dolomites and Impure Limestones
   L. Masch and S. Heuss-Añbichler ................................ 211

11 Microtextures and Reaction Mechanisms of Carbonate Rocks: A Comparison Between the Thermoaureoles of Ballachulish and Monzoni (N. Italy)
   S. Heuss-Añbichler and L. Masch ................................. 229

12 Quartz Grain Coarsening by Collective Crystallization in Contact Quartzites
   G. Buntebarth and G. Voll ....................................... 251

13 Disordering, Re-Ordering and Unmixing in Alkali Feldspars from Contact-Metamorphosed Quartzites
   H. Kroll, C. Krause and G. Voll ................................. 267

14 A Search for Variations in the Structural States of Cordierite in Contact-Metamorphosed Pelites
   W.V. Maresch, P. Blümel and W. Schreyer ...................... 297

15 Detrital Quartz and K-Feldspar in Quartzites as Indicators of Oxygen Isotope Exchange Kinetics
   S. Hoernes and G. Voll ........................................... 315

Part IV Interactions Between the Intrusion and the Contact Aureole

16 P-T-a(H_2O) Conditions in the Thermal Aureole
   D.R.M. Pattison ...................................................... 327

17 Stable Isotope Geochemistry on the Intrusive Complex and Its Metamorphic Aureole
   S. Hoernes, S. MacLeod-Kinsel, R.S. Harmon, D.R.M. Pattison and D.F. Strong .............. 351

18 Thermal Models of Cooling
   G. Buntebarth ....................................................... 379
Contents

IX

Part V Concluding Discussion

19 Evidence of Fluid Phase Behaviour and Controls in the Intrusive Complex and Its Aureole
   B. Harte, D.R.M. Pattison, S. Heuss-Apfbichler, S. Hoernes,
   L. Masch and S. Weiss ....................................... 405

20 Intracrystalline Processes
   H. Kroll ...................................................... 423

21 Summary and Outlook
   G. Voll ....................................................... 443

References ....................................................... 451

Subject Index ................................................... 475