

Editors:

S. Bhattacharji, Brooklyn

H. J. Neugebauer, Bonn

J. Reitner, Göttingen

K. Stüwe, Graz

Founding Editors:

G. M. Friedman, Brooklyn and Troy

A. Seilacher, Tübingen and Yale

Paul D. D. Bons · Daniel Koehn ·
Mark W. Jessell (Eds.)

Microdynamics Simulation

With 185 Figures

 Springer

Paul D. D. Bons
Eberhard Karls Universität
Institut für Geowissenschaften
Fachbereich Mineralogie und
Geodynamik
10 Sigwartstrasse
Tübingen 72076
Germany
paul.bons@uni-tuebingen.de

Mark W. Jessell
IRD LMTG UMR 5563
14 avenue Edouard Belin
Toulouse, France 31400
mjessell@lmtg.obs-mip.fr

Daniel Koehn
Universität Mainz
FB Geowissenschaften
Geographisches Institut
21 Johann-Joachim-Becher-Weg
Mainz 55099
Germany
koehn@uni-mainz.de

“For all Lecture Notes in Earth Sciences published till now please see final pages of the book”

ISBN: 978-3-540-25522-2

e-ISBN: 978-3-540-44793-1

Lecture Notes in Earth Sciences ISSN: 0930-0317

Library of Congress Control Number: 2007937514

© 2008 Springer-Verlag Berlin Heidelberg

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: WMXDesign GmbH

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Preface

Paul Bons, Mark Jessell and Daniel Koehn

From the first observations of microstructures, geologists have tried to model and simulate their formation. Modelling and simulation are closely related terms, often used as synonyms. However, there is a difference. According to the Apple-Macintosh electronic dictionary, a *model* is “a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions”. The same dictionary defines *simulation* as the “imitation of the appearance or character of [something]”. As a special case it also lists “product of a computer model”. A *model* is therefore a theoretical abstraction, whereas the *simulation* is the actual application of the model to a specific case. For example, a rigid ellipsoid in a deforming homogeneous viscous matrix (Fig. 1b) can be a *model* for a porphyroblast or porphyroclast in a deforming rock (Fig. 1a) (Ghosh and Ramberg 1976). Applying and running the model for a specific case would be a *simulation* (Fig. 1c) (e.g. Bons et al. 1997, see also Ch. 4.7). We used the term *simulation* in the title of this book, because we are mainly concerned with the numerical implementation of models as a means to exploring their validity, not so much with the models themselves, which are amply dealt with in such works as Passchier and Trouw (2005).

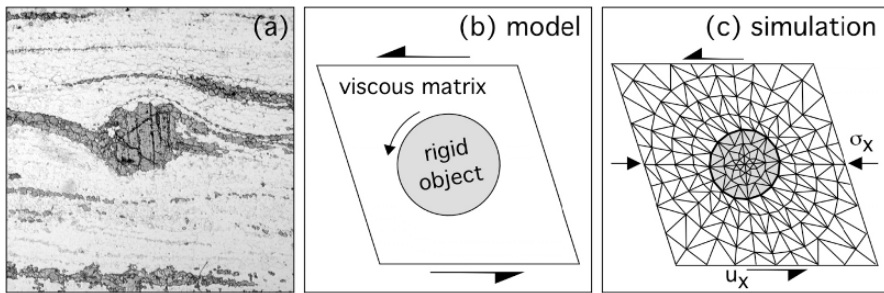


Fig. 1. (a) δ -shaped hornblende porphyroclast in a sinistral shear zone from Hidden Valley, South Australia. Width of view about 5 mm. (b) The model for the development of porphyroclast structures, such as the δ -clast, is that the porphyroclast rotates as a rigid object in a deforming ductile matrix. (c) To study the behaviour of porphyroclasts, the model can be implemented into, for example, a finite element program to run simulations

The purpose of this book is to provide an overview of the possibilities of using numerical techniques to study microstructures in rocks. Although wide-ranging, we cannot cover every technique that was ever applied to a microstructural problem. However we hope at least to demonstrate what is currently possible, and inspire users to investigate the field further if their particular interest is not currently met. In addition most of the numerical experiments we present may be repeated using the accompanying CD-ROM, so that the book can be used as a companion to an undergraduate or graduate level course on microstructures.

Chapter 1 gives a brief overview of the historical development of numerical simulation techniques as applied to grain scale phenomena in rocks, and discusses the principal constraints on applying numerical simulations to microstructural issues


There is no single way to simulate microstructural evolution. Some processes are best simulated using one method (e.g. Finite Elements), while other processes require other simulation methods, and many processes can in fact be adequately simulated by a whole range of techniques. Chapter 2 therefore gives an overview of the main numerical methods that are or can be used. This chapter is intended for those readers with no previous knowledge of numerical simulation methods, or only a subset of them.

A range of microstructural processes is presented in Chap. 3, which is process oriented. The theory of how each process may potentially affect a microstructure is briefly described followed by an overview of the way in which the process has been simulated numerically.

Based on Chap. 3, Chap. 4 gives some examples of the application of numerical simulation to particular problems. This chapter emphasises the need to combine different concurrent processes to simulate what happens in nature. Many highly sophisticated programs have been written to simulate single processes. However, these processes rarely operate in isolation in nature, and one therefore needs to be able to also simulate the interaction between different processes.

Many programs have been developed to simulate microdynamic processes. However, few of these are publicly available as these programs are usually developed for specific research purposes and remain with the

authors. There is currently only one general package, called *Elle*¹ that bundles a variety of simulation software for microdynamic modelling in earth sciences.

Elle is open source software that is developed by an informal consortium of earth scientists, many of whom have contributed to this book. The main advantage of *Elle* is that it is actually a growing collection of codes for individual processes, which allows the user to combine multiple processes in a single simulation. Where possible, *Elle* software is used for the examples presented in this book. “ EXPERIMENT” at the end of a figure legend indicates that the figure can be replicated by running one of the example scripts on the CD-ROM (Appendix B). Thus, with the attached CD-ROM, the reader can run the examples exactly as they are shown in the book. As a next step, the reader can start to modify input parameters or data files to learn both how the simulation works and how particular processes act on a microstructure. The Appendices provide all the information needed to run *Elle*.

The open source *Elle* software is constantly being developed by researchers from all over the world. The software on the CD-ROM represents the state of the code at the time of printing of this book. The latest version of *Elle* can be found on <http://www.microstructure.info/elle>. This web site also provides answers to frequently asked questions, fixes to the inevitable bugs and other information material.

¹ The *Elle* project started in the Department of Earth and Planetary Sciences of Monash University (Melbourne, Australia) during a series of weekly coffee-with-cakes meetings in the early nineties. The (over) ambitious idea was to develop a “super model” that would be able to model everything (metamorphism, deformation, the lot!). The “super model” was quickly baptised “Elle” after a then famous Australian super model by the name of “Elle”. We are indebted to Marlina Elburg to have come up with such a superb, easy to remember, but otherwise meaningless name for the project and software.

Contents

Contributing authors	XVII
Acknowledgements	XXI
1 Introduction.....	1
<i>Paul D. Bons, Mark W. Jessell and Daniel Koehn</i>	
1.1 Historical background	4
1.1.1 Simulation of lattice-preferred orientations.....	5
1.1.2 Simulation of crystal growth in veins	8
1.1.3 Simulation of rigid objects.....	8
1.2 Why numerical simulation of microstructures?	9
1.3 Time and length scaling, resolution	11
1.4 Numerical opportunities and challenges	12
2 Numerical methods	15
<i>Paul D. Bons, Daniel Koehn and Mark W. Jessell</i>	
2.1 Introduction.....	15
2.1.1 Data Structure	15
2.1.2 Variables and parameters	18
2.1.3 Equations	18
2.1.4 Boundary conditions	19
2.2 Lattice data structures: Monte Carlo, Ising, Potts, etc.	20
2.2.1 Introduction to Monte Carlo Principle	20
2.2.2 The Ising model.....	21
2.2.3 Potts models.....	25
2.2.4 Cellular Automata	27
2.2.5 Lattice-Gas and Lattice-Boltzmann method.....	28
2.3 Boundary models.....	33
2.4 Finite Difference method	37
2.4.1 Principles	37
2.4.2 Explicit Finite Difference method.....	39
2.4.3 Implicit Finite Difference method.....	45
2.4.4 The Crank-Nicholson scheme	47
2.4.5 Final remarks on the Finite Difference method.....	47
2.5 Finite Element method	50
2.6 Phase Field modelling	54
2.7 Molecular and Dislocation Dynamics.....	57
2.7.1 Molecular Dynamics	57
2.7.2 Modelling of dislocations	59
2.8 Lattice-Spring models	64
2.8.1 Normal Force model	65
2.8.2 Normal and Angular Force models	66
2.8.3 Elastic Beam models	68

2.8.4 Discrete Element models with contact forces	69
2.8.5 Fracturing or failure	71
3 Microprocess Simulations.....	75
<i>Daniel Koehn, Mark W. Jessell and Paul D. Bons</i>	
3.1 Introduction to <i>Elle</i>	77
<i>Lynn Evans, Mark W. Jessell, Paul D. Bons and Daniel Koehn</i>	
3.1.1 The <i>Elle</i> Project	77
3.1.2 The <i>Elle</i> Data Structure.....	78
3.1.3 Base Libraries	83
3.1.4 Precompiled Binaries	84
3.1.5 The <i>Elle</i> Data File	84
3.1.6 Experiment Scripts	84
3.1.7 Microprocess Simulation	85
3.2 Garnet - biotite cation exchange.....	87
<i>Youngdo Park, Lynn Evans, Dal Park and Jin-Han Ree</i>	
3.2.1 Phenomenological observation.....	87
3.2.2 Natural example	87
3.2.3 Inferred processes.....	89
3.2.4 Driving forces, controls and governing equations	89
3.2.5 Possible and actual simulation techniques.....	90
3.2.6 Implementation in <i>Elle</i>	92
3.2.7 Example <i>Elle</i> Run: garnet-biotite cation exchange.....	94
3.3 Subgrain growth Potts model	97
<i>Sandra Piazzolo and Mark W. Jessell</i>	
3.3.1 Phenomenological observations	97
3.3.2 Natural examples and experiments	97
3.3.3 Inferred processes.....	99
3.3.4 Driving forces, controls and governing equations	99
3.3.5 Possible and actual simulation techniques.....	100
3.3.6 Implementation in <i>Elle</i>	100
3.3.7 Example <i>Elle</i> Runs.....	101
3.4 Nucleation and subgrain formation.....	105
<i>Sandra Piazzolo and Mark W. Jessell</i>	
3.4.1 Phenomenological observations	105
3.4.2 Natural examples.....	106
3.4.3 Inferred processes.....	108
3.4.4 Driving forces, controls and governing equations	109
3.4.5 Possible and actual simulation techniques.....	110
3.4.6 Implementation in <i>Elle</i>	111
3.4.7 Example <i>Elle</i> Run.....	112

3.5 Grain boundary migration.....	115
<i>Paul D. Bons, Mark W. Jessell and Jens Becker</i>	
3.5.1 Phenomenological observations	115
3.5.2 Natural examples.....	115
3.5.3 Inferred processes.....	116
3.5.4 Driving forces, controls and governing equations	117
3.5.5 Possible and actual simulation techniques.....	117
3.5.6 Implementation in <i>Elle</i>	118
3.5.7 Example <i>Elle</i> Run: Grain growth.....	123
3.5.8 Alternative implementations in <i>Elle</i>	125
3.6 Vein microstructures	127
<i>Paul D. Bons and Daniel Koehn</i>	
3.6.1 Phenomenological Observations	127
3.6.2 Modeling of vein microstructures	128
3.7 Melt processes during grain growth.....	133
<i>Jens Becker and Paul D. Bons</i>	
3.7.1 Phenomenological observations	133
3.7.2 Natural examples.....	133
3.7.3 Analogue modeling	134
3.7.4 Driving forces.....	134
3.7.5 Possible and actual techniques	135
3.7.6 Implementation in <i>Elle</i>	135
3.7.7 Example in <i>Elle</i>	136
3.8 <i>Basil</i> : stress and deformation in a viscous material	139
<i>Greg Houseman, Terence Barr and Lynn Evans</i>	
3.8.1 Introduction	139
3.8.2 Formulation and assumptions.....	141
3.8.3 Numerical method.....	143
3.8.4 Porphyroblast example solution	147
3.8.5 Implementation in <i>Elle</i> : Growth and deformation of a porphyroblast	149
3.8.6 Conclusions	153
3.9 A hybrid FEM/Taylor Bishop Hill method	155
<i>Mark W. Jessell</i>	
3.9.1 Introduction	155
3.9.2 Models of Lattice Rotation during Deformation.....	156
3.9.3 Implementation in <i>Elle</i>	158
3.9.4 Example <i>Elle</i> Run.....	159

3.10 Diffusion creep.....	161
<i>John Wheeler and Judy Ford</i>	
3.10.1 Phenomenological observation.....	161
3.10.2 Natural examples.....	162
3.10.3 Inferred processes.....	162
3.10.4 Driving forces, controls and governing equations	162
3.10.5 Possible simulation techniques.....	166
3.10.6 Implementation in <i>DiffForm</i>	167
3.10.7 Simple example and description of input parameters	167
3.11 Fracturing.....	171
<i>Daniel Koehn</i>	
3.11.1 Phenomenological observations	171
3.11.2 Natural examples.....	173
3.11.3 Inferred processes.....	173
3.11.4 Driving forces, controls and governing equations	173
3.11.5 Possible and actual simulation techniques.....	175
3.11.6 Implementation in <i>Elle</i>	176
3.11.7 Example <i>Elle</i> Runs.....	178
3.12 Fluid solid reactions	183
<i>Daniel Koehn</i>	
3.12.1 Phenomenological observations	183
3.12.2 Natural examples.....	184
3.12.3 Inferred processes.....	185
3.12.4 Driving forces, controls and governing equations	185
3.12.5 Possible and actual simulation techniques.....	187
3.12.6 Implementation in <i>Elle</i>	187
3.12.7 Example <i>Elle</i> Runs.....	189
3.13 Solid-solid phase transitions and heat conduction	195
<i>Till Sachau and Daniel Koehn</i>	
3.13.1 Phenomenological observations	195
3.13.2 Natural examples.....	196
3.13.3 Driving forces, equations describing the system.....	197
3.13.4 Possible simulation techniques.....	199
3.13.5 Implementation in <i>Elle</i>	199
3.13.6 Examples.....	204
4 Case studies and coupling of processes	207
<i>Mark W. Jessell, Daniel Koehn and Paul D. Bons</i>	
4.1 Grain shapes and sizes during static grain coarsening in salt.....	209
<i>Mark W. Jessell, Janos L. Urai and Oliver Schenk</i>	
4.1.1 Anisotropic grain growth.....	209
4.1.2 Implementation in <i>Elle</i>	210

4.1.3 Discussion	213
4.1.4 Conclusions	214
4.2 Dynamic recrystallisation and crystalline plasticity	215
<i>Sandra Piazzolo</i>	
4.2.1 Introduction	215
4.2.2 Theoretical background and implementation in <i>Elle</i>	215
4.2.3 Experimental Runs	220
4.2.4 Results	220
4.2.5 Discussion	223
4.2.6 Discussion of technique	223
4.2.7 Conclusions	224
4.3 Localisation of deformation.....	225
<i>Mark W. Jessell, Esteban Siebert, Paul D. Bons, Lynn Evans and Sandra Piazzolo</i>	
4.3.1 Introduction	225
4.3.2 Implementation in <i>Elle</i>	225
4.3.3 Experimental Results	227
4.3.4 Conclusions	230
4.4 Reactions and fracturing	231
<i>Daniel Koehn</i>	
4.4.1 Overview of phenomenon.....	231
4.4.2 Implementation in <i>Elle</i>	232
4.4.3 Experimental runs	232
4.5 Combined phase transition and heat diffusion	237
<i>Till Sachau and Daniel Koehn</i>	
4.5.1 Introduction	237
4.5.2 Implementation.....	238
4.5.3 Example runs	238
4.6 Visco-elastic and brittle deformation.....	241
<i>Daniel Koehn and Till Sachau</i>	
4.6.1 Overview of phenomenon.....	241
4.6.2 Implementation in <i>Elle</i>	242
4.6.3 Experimental runs	244
4.7 Strain localisation and rigid-object kinematics	247
<i>Scott E. Johnson</i>	
4.7.1 Introduction	247
4.7.2 Numerical experiments	249
4.7.3 Results	251
4.7.4 Discussion	252

4.8 Transient strain-rate partitioning during porphyroblast growth.....	255
<i>Wesley G. Groome and Scott E. Johnson</i>	
4.8.1 Overview.....	255
4.8.2 Theoretical background and natural example.....	255
4.8.3 Implementation in <i>Elle</i>	257
4.8.4 Experiments and discussion.....	259
4.8.5 Conclusions	264
References.....	267
Appendices.....	291
Appendix A Installing <i>Elle</i>	293
<i>Mark W. Jessell</i>	
A.1 Windows	293
A.1.1. Installing <i>Basil</i> and <i>Sybil</i>	294
A.2 Linux	294
A.2.1. Installing <i>Basil</i> and <i>Sybil</i>	295
Appendix B Example experiments.....	297
<i>Mark W. Jessell</i>	
The <i>Experiment Launcher</i>	297
Experiment 1 - Diffusion	299
Experiment 2 - Fluid flow in a porous medium.....	301
Experiment 3 - Crystal growth from melt.....	302
Experiment 4 - Fracturing in granular aggregates.....	304
Experiment 5 - Cation exchange reactions	307
Experiment 6 - Subgrain growth	309
Experiment 7 - Grain growth	311
Experiment 8 - Evolution of a partial melt	313
Experiment 9 - Rigid porphyroblast growing in a deforming matrix	314
Experiment 10 - Lattice rotations	317
Experiment 11 - Boudinage	321
Experiment 12 - Dissolution grooves.....	323
Experiment 13 - Stylolites	325
Experiment 14 - Strain-rate partitioning during porphyroblasts growth.....	327
Experiment 15 - Anisotropic grain growth	330
Experiment 16 - Dynamic recrystallisation	332
Experiment 17 - Deformation localisation.....	335
Experiment 18 - Expanding inclusions	338
Experiment 19 - Mud cracks.....	340
Experiment 20 - Visco-elastic deformation and fractures	342
Experiment 21 - Strain localization and rigid object kinematics.....	345

Appendix C The <i>Elle</i> graphical user interface.....	349
<i>Jens Becker</i>	
C.1 Introduction.....	349
C.2 The status bar	350
C.3 The menu-bar	350
C.3.1 The File Menu.....	350
C.3.2 The Run Menu	351
C.3.3 The Graphics Menu	351
C.3.4 The Data Menu	351
C.3.5 The Help Menu	351
C.4 The Run Options dialog	351
C.5 The Preferences Window	353
C.5.1 Flynn Preferences	353
C.5.2 Boundaries Preferences	354
C.5.3 Bnode Preferences	354
C.5.4 Unode Preferences	355
C.5.5 The colour map	356
C.6 The zooming window	357
C.7 The data-windows.....	358
 Appendix D Different ways to run an <i>Elle</i> experiment	 361
<i>Mark W. Jessell</i>	
D.1 Via the <i>Experiment Launcher</i>	361
D.2 Direct launching of experiments	362
D.3 Developer mode (Windows and Linux).....	362
 Appendix E How to create multiple-process experiments.....	 365
<i>Lynn Evans</i>	
E.1 Shelle scripts/batch scripts	365
E.2 Shelle: An <i>Elle</i> Shell Script Generator (v1.24).....	366
E.2.1 How to use the Shelle Script Generator	366
E.2.2 Notes on the Shelle Script	369
E.2.3 Debugging Shell Scripts.....	370
 Appendix F <i>Sybil</i> - The <i>Basil</i> post-processor	 371
<i>Lynn Evans, Terence Barr and Greg Houseman</i>	
F.1 Introduction	371
F.2 Menu Options.....	372
F.2.1 File	372
F.2.2 Record.....	372
F.2.3 XYPlot	373
F.2.4 Profile.....	373
F.2.5 Arrow	374
F.2.6 Contour	375
F.2.7 Locate.....	375
F.2.8 Options.....	376

Appendix G How to use <i>Elle_Latte</i>	379
<i>Till Sachau and Daniel Koehn</i>	
G.1 Introduction.....	379
G.2 The experiment interface for Windows and Linux users.....	380
G.2.1 Introduction.....	380
G.2.2 Installation notes.....	380
G.2.3 The main-window	381
G.2.4 The ‘Files’ tab.....	381
G.2.5 The New file and the Edit file window	382
G.2.6 The Statistics window	384
G.2.7 Remaining tabs	385
G.3 The command line interface for Windows and Linux developers	386
Appendix H Miscellaneous processes and utilities	389
<i>Mark Jessell</i>	
H.1 Introduction.....	389
H.2 <i>elle_gbdiff</i>	389
H.3 <i>elle_diff</i>	389
H.4 <i>elle_met</i>	389
H.5 <i>elle_recovery</i>	390
H.6 <i>elle_viscosity</i>	390
H.7 <i>elle_expand</i> & <i>elle_pblast</i>	390
H.8 <i>elle_manuel</i>	390
H.9 <i>reposition</i>	390
H.10 <i>tidy</i>	391
H.11 <i>elle2poly</i> , <i>basil2elle</i> , <i>elle2oof</i> , <i>goof2elle</i>	391
H.12 <i>ppm2elle</i>	391
H.13 <i>ebsd2elle</i> , <i>elle2ebsd</i>	392
H.14 <i>plotaxes</i>	392
Appendix I How to Create an <i>Elle</i> file.....	393
<i>Mark W. Jessell</i>	
Appendix J The <i>Elle</i> file format	395
<i>Mark W. Jessell</i>	
J.1 Example <i>Elle</i> file	395
J.2 <i>Elle</i> file blocks	397
Index.....	401

Contributing authors

Editors

- Bons, Paul D. Mineralogie und Geodynamik, Institut für Geo-wissenschaften, Eberhard Karls Universität Tübingen. Sigwartstraße 10, 72076 Tübingen, Germany
E-mail: paul.bons@uni-tuebingen.de
- Jessell, Mark W. IRD LMTG UMR 5563, 14 avenue Edouard Belin 31400 Toulouse, France
E-mail: mjessell@lmtg.obs-mip.fr
- Koehn, Daniel Tectonophysik, Institut für Geowissenschaften, Johannes-Gutenberg Universität Mainz, Becherweg 21, 55099 Mainz, Germany
Email: Koehn@mail.uni-mainz.de

Contributing authors

- Barr, Terence AFEX International, 952 Echo Lane, Suite 300, Houston, TX 77024, USA
Email: tdbarr@afexintl.com
- Becker, Jens K. Mineralogie und Geodynamik, Institut für Geowissenschaften, Eberhard Karls Universität Tübingen. Sigwartstr. 10, 72076 Tübingen, Germany
E-mail: becker@jkbecker.de
- Evans, Lynn School of Earth Sciences, University of Melbourne, VIC3010, Australia
E-mail: laevans@unimelb.edu.au
- Ford, Judy Dept of Earth and Ocean Sciences, Jane Herdman Building, University of Liverpool, Liverpool L69 3GP, UK

- Groome, Wesley G. Department of Earth Sciences, Bryand Global Sciences Center, University of Maine, Orono, ME, 04469, USA
E-mail: wesley.groome@umit.maine.edu
- Houseman, Gregory A. School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
Email: greg@earth.leeds.ac.uk
- Johnson, Scott E. Department of Earth Sciences, Bryand Global Sciences Center, University of Maine, Orono, ME, 04469, USA
E-mail: johnsons@maine.edu
- Park, Youngdo Department of Earth and Environmental Sciences, Korea University, Anam-dong, Seongbuk-gu, Seoul 136-701, South Korea
E-mail: youngdo.park@gmail.com
- Park, Dal Department of Earth and Environmental Sciences, Korea University, Anam-dong, Seongbuk-gu, Seoul 136-701, South Korea
- Piazolo, Sandra Department of Geology and Geochemistry, Stockholm University, Svante Arrhenius väg 8C, 106 91 Stockholm, Sweden
Email: sandra.piazolo@geo.su.se
- Ree, Jin-Han Department of Earth and Environmental Sciences, Korea University, Anam-dong, Seongbuk-gu, Seoul 136-701, South Korea
E-mail: reejh@korea.ac.kr
- Sachau, Till Tectonophysics. Institut für Geowissenschaften, University of Mainz, Becherweg 21, 55099 Mainz, Germany
Email: Sachau@mail.uni-mainz.de
- Schenk, O. Geologie-Endogene Dynamik, Fachgruppe Geowissenschaften, Lochnerstraße 4-20, D-52056 Aachen, Germany

- Siebert, Esteban Department of Geology, Faculty of Physical
and Mathematical Sciences, Plaza Ercilla
#803, Santiago, Chili
- Urai, Janos L. Geologie-Endogene Dynamik, Fachgruppe
Geowissenschaften, Lochnerstrasse 4-20, D-
52056 Aachen, Germany
Email: j.urai@ged.rwth-aachen.de
- Wheeler, John Dept of Earth and Ocean Sciences, Jane
Herdman Building, University of Liverpool,
Liverpool L69 3GP, UK
Email: johnwh@liverpool.ac.uk

Acknowledgements

We thank the various funding agencies that have (willingly or reluctantly) funded the work on microdynamic modelling on which this book is based. In particular we would like to mention the Australian Research Council (ARC), the Deutsche Forschungsgemeinschaft (DFG), the USA National Science Foundation (NSF), and the European Union, through its Marie Curie Fellowship scheme.

The development of the code has been the work of the editors and most of the authors in this book, but in particular of Lynn Evans and Jens Becker, without whose technical expertise, and patience, we would not be where we are today.

Over the past 10 years we have held training courses and developer workshops on the numerical simulations of microstructures in Aachen, Hürtgenwald and Mainz (Germany), Leeds (UK), Estremoz (Portugal), Miglos and Toulouse (France), Pisa (Italy), Särghaua (Estonia), Orono, Maine (USA), and Cadaqués (Spain) where the participants of these workshops acted as willing guinea pigs for various versions of the code, and have stimulated its further development.

P. England, K. Stüwe, P. Molnar and other colleagues and students have provided assistance and motivation in the development of the *Basil* software package.

We would also like to thank the proof readers and software testers of this book, Lenka Baratoux, Marlina Elburg, Enrique Gómez-Rivas, Anne Peschler, and Kristjan Urtson, who have considerably reduced the number of internal inconsistencies, mistakes and bugs.

Finally we would like to acknowledge the use of several Open Source and Public Domain codes within the *Elle* platform:

wxWidgets	http://www.wxwidgets.org
Lesstif	http://www.lesstif.org
gnu scientific library	http://www.gnu.org/software/gsl
triangle	http://www.cs.cmu.edu/~quake/triangle.html
Generic Polygon Clipper	http://www.cs.man.ac.uk/~toby/alan/software/gpc.html
Graphics Gems	http://www.acm.org/tog/GraphicsGems/