MICROSTRUCTURAL EVOLUTION
IN CRYSTAL-MELT SYSTEMS

by

Youngdo Park

A Dissertation
Submitted to the University at Albany, State University of New York
in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Philosophy

College of Arts and Sciences
Department of Geological Sciences
1994
ABSTRACT

Microstructural development in a rock analog crystal-melt system is focused on in this study, using an experimental technique in which microstructural changes can be observed in situ and processes can be inferred from the microstructural changes. The aim of the work has been to contribute to the basis for understanding the origin and significance of textural features of rocks that have passed through a melt-present interval in their history.

During isothermal deformation experiments, microstructures indicating crystal plasticity and dynamic recrystallization are observed at fast strain rates. At slow strain rates, a pressure solution-like process, contact melting/redeposition, is active, resulting in optically strain-free crystals. Grain boundary sliding is also active during slow strain rate deformation, with concurrent accommodation process of contact melting/redeposition and assisting process of grain boundary migration.

Textural metamorphism such as dendrite segmentation and coarsening, and grain and phase boundary migration is observed to start in the analog system even at supersolidus conditions. Stimulated by observations of coarsening in the analog system, some physical and numerical experiments were carried out to discover the rates of coarsening in silicate crystal-melt systems. Results from experiment and simulation suggest that the kinetics of forsterite coarsening is fast enough to remove small crystals in a short period of time compared to the time required for complete solidification of a magma. These processes may introduce complications when attempting to infer the rates of processes in rocks such as crystal growth and nucleation, and the order of crystallization.

The validity of this type of analog experiment is checked using scale modelling. It is found that non-steady state structures in the experiment can be identical to that in the
natural system only when the experimental relative rates of processes at an instant are identical to those in the natural system. Given these complications, the experimental results from the analog system may not have any parallels in natural conditions. However, this type of experiment, even if unscaled, can provide some building blocks for the later more thorough models which can better link processes and microstructural changes.
ACKNOWLEDGMENTS

I wish to thank Dr. W.D. Means for making this dissertation possible. The thesis project was conceived by Dr. Means, and he also developed the experimental techniques with his very hard work during the earlier stage of this project. Most of the ideas presented in my thesis are the results of continuous discussions with Dr. Means. I thank him for his patience with my slowness and English when we had discussions. I will be always grateful all these nice considerations given to me by Dr. Means.

I would like to thank the members of the thesis committee, Drs. W.D. Means, J.W. Delano, M.B. Bayly, and E.B. Watson for taking the time to read my thesis, and discussions with them helped to improve the content of my thesis. Dr. Delano provided the lab equipment and material for the coarsening experiments, and he also taught me what hard work is by showing himself working harder than most of graduate students. I thank him for the valuable lesson.

I am also indebted to many people who helped me directly or indirectly to finish the work. I thank Dr. W.S.F. Kidd for his considerations, Dr. G.D. Harper for his continuous encouragement and interest in the thesis work, Dr. Hauser of the chemistry department for the suggestion of the experimental material, Dr. Buckingham for helping to identify the blue phase crystals, and Diana Paton for pleasant humors and helping me whenever I had administrative troubles. I thank Ben Hanson for being such a nice friend especially when I was depressed, and for setting up and doing the coarsening experiments. Jin-Han Ree is appreciated for taking time to help me in many ways and bring me into the very interesting discussions; without him I would not have met my advisor Dr. Means. Discussions with the people who participated in the seminar series of igneous petrology were beneficial. They are Dr. Means, Dr. Harper, Angela Coulton, Charlie Stuart, Mike Edwards, Taohong Li, Bruno Ciscato, and Stefan
Kosanke. Many graduate students are thanked for their friendship, encouragement, and helpful discussions. They are Christoph Arz, Rolf Herrmann, Jin-Han Ree, Yun Pan, Rob Alexander, Ben Hanson, Steve Schimmirich, Steve Tice, Wolfram von Kiparski, John Waechter, Volker Brüchert, Bok-Nam Ree, Angela Coulton, Nancy Griesau, Young-Joon Lee, Andreas Plesch, Susi Vogel, Chris Achong, Mike Edwards, Michael Haschke, Albert Hiller, Bruno Ciscato, Steffi Dannenmann and Stefan Kosanke. There are also many people whose names were not mentioned, although their help was greatly appreciated. They are Dr. Putman, Dr. Delong, Dr. Spear, Brian Taylor, Mark Jessell, Paul Bons, Mary Roden, Mary Lou Hill, Dr. Myer, Dr. Goodwin, Vinny Grassi, Rick and David Valentino, and Barbara Bloomfield.

Lastly, but not leastly, I wish to thank my wife and all the family members for their love and continuous support.
# TABLE OF CONTENTS

**ABSTRACT**  
i

**ACKNOWLEDGMENTS**  
iii

**TABLE OF CONTENTS**  
v

**LIST OF FIGURES**  
x

**LIST OF TABLES**  
 xiii

**CHAPTER 1. INTRODUCTION**  
1-1

**CHAPTER 2. ISOTHERMAL DEFORMATION PROCESSES IN EXPERIMENTAL CRYSTAL-MELT MIXTURES**  
2-1

2.1 INTRODUCTION  
2-1

2.2 EXPERIMENTS  
2-3
  
  2.2.1 Techniques  
  2-3
  
  2.2.2 Materials and Sample Preparation  
  2-5

2.3 CRYSTAL SCALE DEFORMATION PROCESSES  
2-12
  
  2.3.1 Crystal Plastic Deformation and Dynamic Recrystallization  
  2-12
  
  2.3.2 Contact Melting/Redeposition  
  2-20
  
  2.3.3 Sliding on Crystal Boundaries  
  2-26

2.4 FRAMEWORK SCALE DEFORMATION PROCESSES  
2-28
  
  2.4.1 Filter Pressing  
  2-28
  
  2.4.2 Grain Flow  
  2-28
  
  2.4.3 Development of Micro Shear Zone  
  2-31

2.5 DISCUSSION  
2-31
  
  2.5.1 Recognition of Crystal Scale Microstructures Formed by Melt-Present Deformation  
  2-31
  
  2.5.2 Recognition of Framework Scale Microstructures Formed by Melt-Present Deformation  
  2-38
  
  2.5.3 Scaling Problem  
  2-40

2.6 CONCLUSIONS  
2-41
CHAPTER 3. MIXING AND ROTATION OF CRYSTALS AND DEFORMATION-INDUCED CRYSTAL GROWTH DURING GRAIN FLOW 3-1

3.1 INTRODUCTION 3-1
3.2 STARTING MATERIAL AND EXPERIMENTAL CONDITIONS 3-2
3.3 DESCRIPTION OF DEFORMATION 3-8
3.4 DISPLACEMENT PERTURBATION AND MIXING OF CRYSTALS 3-17
3.5 ROTATION OF CRYSTALS AND MODIFICATION OF THE INITIAL SHAPE FABRIC DURING DEFORMATION 3-24
3.6 DEFORMATION-INDUCED CRYSTAL GROWTH 3-33
3.7 CONCLUDING REMARKS 3-43

CHAPTER 4. DEFORMATION OF CRYSTAL-MELT MIXTURES DURING COOLING AND HEATING 4-1

4.1 INTRODUCTION 4-1
4.2 RATES OF DEFORMATION AND TEMPERATURE CHANGE 4-1
4.3 DEFORMATION DURING CRYSTALLIZATION 4-5
   4.3.1 Crystal Growth toward the Stretching Direction during Simple Shearing 4-5
   4.3.2 Crystal Growth and Deformation in a Collapsing Melt Pocket 4-8
   4.3.3 Contact Melting During Crystal Growth 4-8
4.4 DEFORMATION DURING MELTING 4-12
   4.4.1 Local Melt Fraction Increase and Development of a High Strain Rate Zone 4-12
   4.4.2 Melt Extraction During Deformation 4-18
4.5 DISCUSSION 4-22

CHAPTER 5. SCALING PROBLEMS OF EXPERIMENTS ON HIGH TEMPERATURE DEFORMATION PROCESSES 5-1

5.1 INTRODUCTION 5-1
5.2 SCALING: A REVIEW 5-1
5.3 SCALING LAW FOR MICROSTRUCTURAL SIMILARITY 5-2
   5.3.1 Microstructures and Processes 5-2
   5.3.2 Scaling Law 5-3
   5.3.3 Example: Application of Scaling Law 5-4
5.4 DISCUSSION 5-9
5.4.1 Differences between Scaling Law for Microstructural Similarity and Mechanical Scaling Law 5-9
5.4.2 Steady State Structures 5-10
5.4.3 Non-Steady State Structures 5-10
5.4.4 Scaling in the Analog Experiments of this Study 5-12

5.5 CONCLUDING REMARKS 5-14

CHAPTER 6. EVOLUTION OF IGNEOUS TEXTURES BY MELT-PRESENT TEXTURAL METAMORPHISM 6-1
6.1 INTRODUCTION 6-1
6.2 MELT-PRESENT TEXTURAL METAMORPHISM 6-2
   6.2.1 Segmentation of Dendritic Crystals 6-2
   6.2.2 Coarsening during Thermal Cycling 6-10
   6.2.3 Grain Boundary Migration 6-13
   6.2.4 Phase Boundary Migration 6-20
6.3 DISCUSSION 6-26
6.4 SUMMARY 6-31

CHAPTER 7. EFFECT OF SURFACE ENERGY DRIVEN COARSENING (OSTWALD RIPENING) ON CRYSTAL SIZE IN IGNEOUS ROCKS 7-1
7.1 INTRODUCTION 7-1
   7.1.1 Coarsening Theories 7-3
   7.1.2 Observation of Coarsening Process in an Analog System 7-9
7.2 EXPERIMENTAL INVESTIGATION OF FORSTERITE COARSENING IN THE ANORTHITE-ENSTATITE-DIOPSIDE SYSTEM 7-11
   7.2.1 Experimental System 7-11
   7.2.2 Experimental Procedure 7-14
   7.2.3 Results 7-16
   7.2.4 Rate Limiting Process during Coarsening 7-23
7.3 COMPUTER MODELLING OF DIFFUSION LIMITED COARSENING 7-26
   7.3.1 Assumptions 7-27
   7.3.2 Geometry of Crystal Distribution 7-28
   7.3.3 Mass Transfer by Diffusion and Resulting Crystal Growth 7-30
CHAPTER 8. CRYSTAL BOUNDARIES IN IGNEOUS ROCKS: GENETIC CLASSIFICATION AND GEOMETRIC FEATURES

8.1 INTRODUCTION

8.1.1 Definitions: Crystal Boundary, Material Age, Isochron, and Growth Vector

8.2 GENETIC CLASSIFICATION OF CRYSTAL BOUNDARIES

8.2.1 Growth Impingement Boundaries
8.2.2 Displacement Impingement Boundaries
8.2.3 Migrated Boundaries
8.2.4 Dissolution Boundaries

8.3 GEOMETRIC FEATURES OF BOUNDARIES

8.3.1 Growth Impingement Boundaries
8.3.2 Displacement Impingement Boundaries
8.3.3 Migrated Boundaries
8.3.4 Dissolution Boundaries

8.4 DISCUSSION

8.4.1 New Type of Boundary Classification
8.4.2 Cut Effect
8.4.3 Crystal Boundaries as a Tool to Understand Magma Processes: Example - Construction of Paleo-isotherms in Magma

8.5 CONCLUDING REMARKS

REFERENCES

APPENDIX A: COMPUTER PROGRAM FOR SIMULATION OF DIFFUSION-LIMITED QUARTZ GROWTH IN RHYOLITIC MAGMA
APPENDIX B: COMPUTER PROGRAM FOR SIMULATION OF ENRICHMENT OF SLOW DIFFUSING ELEMENTS IN FRONT GROWING QUARTZ CRYSTAL IN RHYOLITIC MAGMA A-13
APPENDIX C: COMPUTER PROGRAM FOR SIMULATION OF COARSENING A-39
APPENDIX D: COMPUTER PROGRAM FOR SIMULATION OF DEVELOPMENT OF GROWTH IMPINGEMENT BOUNDARIES A-98
APPENDIX E: NIH IMAGE MACRO LANGUAGE FOR ON-SCREEN DIGITIZATION A-136
LIST OF FIGURES

2.1 Sample assembly and experimental apparatus 2-4
2.2 Photomicrograph of the sample material 2-7
2.3 Schematic phase diagram of the experimental system 2-9
2.4 Crystal plastic deformation and growth of a recrystallized crystal 2-13
2.5 Segmentation of crystals by propagation of cuspy interfaces 2-16
2.6 Melt-present dynamic recrystallization 2-17
2.7 Contact melting/redeposition 2-21
2.8 Contact melting/redeposition 2-24
2.9 Grain boundary migration assisted grain boundary sliding 2-27
2.10 Grain flow 2-29
2.11 Development of a micro shear zone 2-32
2.12 Recognition of microstructures formed by contact melting 2-36
3.1 Photomicrographs taken during experiment TAC-112 3-3
3.2 Sample assembly and reference frame 3-6
3.3 Photomicrograph with labels of crystals used for constructing displacement maps 3-9
3.4 Particle trajectories during deformation 3-10
3.5 Sketches of white phase crystals during deformation 3-11
3.6 Incremental displacement maps 3-14
3.7 Definition of displacement vector 3-18
3.8 Incremental displacement perturbation maps 3-21
3.9 Mixing of crystals and displacement perturbation 3-25
3.10 Plots of passive line rotation vs. measured rotation 3-28
3.11 Spatial distribution of rotational behavior of crystals 3-29
3.12 Spatial distribution of rotational behavior of crystals 3-30
3.13 Shape fabric orientation vs. passive line orientation 3-32
3.14 Photomicrograph with labels of crystals used for orientation and length measurement 3-34
3.15 Plots of orientation vs. crystal length 3-35
3.16 Growth and dissolution of blue phase crystals during deformation 3-38
3.17 Result from a computer model that calculates orientation dependent crystal growth during simple shearing 3-41
4.1 Effect of cooling rates and strain rates on crystal growth mechanism and deformation mechanism 4-2
4.2 Crystal growth toward stretching direction during cooling 4-6
4.3 Crystal growth and deformation in a collapsing melt pocket during cooling 4-9
4.4 Contact melting and phase boundary migration during cooling 4-10
4.5 Development of a high strain rate zone during partial melting 4-13
4.6 Particle trajectories of Figure 4.5 4-16
4.7 Formation of residual phase aggregates by melt extraction during partial melting 4-19
4.8 Details of neighbor switching in Figure 4.7 4-21
4.9 Melt fraction dependence of deformation mechanism 4-23
4.10 A possible microstructure indicating stretching direction 4-25
5.1 Plots for conditions in which the ratio of dislocation creep rate to diffusion creep rate is identical 5-7
5.2 Arrhenius plot of process rates in the original and in the model 5-11
6.1 Crystallization during cooling 6-3
6.2 Eutectic crystallization 6-5
6.3 Isothermal coarsening of dendrite crystals 6-7
6.4 Coarsening during thermal cycling 6-11
6.5 A simple model for increased rate of coarsening during thermal cycling 6-14
6.6 Grain boundary migration during cooling 6-16
6.7 A model for the observed grain boundary migration in Figure 6.6 6-19
6.8 Isothermal phase boundary migration 6-21
6.9 Isothermal phase boundary migration 6-22
6.10 Isothermal coarsening and phase boundary migration 6-25
6.11 Isothermal coarsening and phase boundary migration 6-27
6.12 Possible zonation patterns in crystals after phase boundary migration 6-30
7.1 Particle size dependent solubility 7-4
7.2 Isothermal coarsening of dendritic arms 7-10
7.3 Dissolution of crystals during cooling 7-12
7.4 Phase diagram of the experimental system 7-13
7.5 Plot of coarsening time vs. melt composition 7-17
7.6 Backscattered electron images from the coarsening experiments 7-18
7.7 Forsterite crystal size distribution 7-21
7.8 Plots of crystal size vs. time$^3$ 7-22
7.9 Geometry of crystal distribution in the computer model 7-29
7.10 Flow chart for the computer model 7-32
7.11 Results of coarsening simulation 7-34
7.12 Comparison of the coarsening rates from the experiment and the model 7-37
7.13 Simulation conditions for coarsening during cooling 7-40
7.14 Partial output of the simulation results 7-41
7.15 Plot of time vs. total number of crystals from the model 7-42
7.16 Backscattered electron image of the isothermally coarsened F2-2 bulk composition sample 7-45
8.1 Isochron and growth vector 8-3
8.2 Classified crystal boundaries 8-6
8.3 Geometric features of growth impingement boundaries 8-10
8.4 Geometric features of displacement impingement boundaries, migrated boundaries, and dissolution boundaries 8-14
8.5 Classification of boundaries based on velocities of material points and boundaries 8-19
8.6 Effect of cutting on the younging direction of a growth impingement boundary 8-20
8.7 Patterns of younging directions at triple junctions 8-23
8.8 Hypothetical illustration of preferred orientation of melt consumption directions 8-26
LIST OF TABLES

2.1 Experimental condition ........................................ 2-6
2.2 Properties of phases present in the experimental system 2-8
3.1 Deformation time and strain rates during experiment TAC-112 3-7
3.2 Average and standard deviation of components of deformation tensors 3-20
4.1 Experimental conditions ..................................... 4-4
5.1 Flow law parameters for dry polycrystalline aggregates of olivine 5-5
7.1 Values of parameters used to calculate proportionality constant and effective diffusivity 7-24
7.2 Values of parameters used in computer simulation ........... 7-39