

# CONTENTS

PREFACE .....	VII
ACKNOWLEDGEMENTS .....	VIII
PERMISSIONS .....	IX
GLOSSARY .....	XVI
Units .....	XVI
Frequently used symbols .....	XVII
Frequently used abbreviations of minerals .....	XVII
Chemical symbols and elements .....	XVIII
CHAPTER 1 — THE PROBLEM: FLUID MOTION, GEOCHEMICAL AND TECTONIC PROCESSES .....	1
1.1 Introduction .....	1
1.2 What is a fluid? .....	2
1.3 Rocks of the surface environment .....	5
1.4 Evidence that rocks change position .....	7
1.5 The dominant processes involved in burial and uplift .....	9
1.5.1 Porosity reduction .....	10
1.5.2 Dehydration of minerals .....	11
1.5.3 Solid—solid reactions .....	12
1.5.4 Recrystallization .....	13
1.6 Processes during uplift .....	14
1.7 Simple evidence for the motion of fluids .....	14
1.8 Mass relations — quantities .....	16
1.9 Fluids dissolve and transport solids .....	17
1.10 Is flow focussed? .....	18
CHAPTER 2 — CHEMISTRY OF NATURAL FLUIDS .....	19
2.1 Introduction — Water .....	19
2.2 Observation on chemistry of natural fluids .....	26
2.2.1 Waters of the continental surface .....	27
2.2.2 Composition of ocean water .....	29
2.2.3 Composition of pore water and deep-drill fluids .....	30

2.2.4 Composition of metamorphic fluids . . . . .	33
2.2.5 Composition of fluid inclusions . . . . .	35
2.2.6 Composition of magmatic fluids . . . . .	42
2.3 Concluding statement . . . . .	45
 CHAPTER 3 — VOLATILE SPECIES IN MINERALS . . . . .	 47
3.1 Water . . . . .	47
3.2 Carbon and carbon dioxide . . . . .	50
3.3 Chlorine . . . . .	50
3.4 Fluorine . . . . .	51
3.5 Sulphur . . . . .	52
3.6 Oxygen . . . . .	52
3.7 Nitrogen and inert gases . . . . .	53
3.8 Concluding statement . . . . .	53
 CHAPTER 4 — SOLUBILITY OF MINERALS AND PHYSICAL CHEMISTRY OF THEIR SOLUTIONS . . . . .	 55
4.1 Introduction . . . . .	55
4.2 Solubilities in simple binary systems . . . . .	56
4.3 Solubilities of naturally abundant gases in H <sub>2</sub> O . . . . .	57
4.4 The H <sub>2</sub> O—CO <sub>2</sub> system . . . . .	59
4.5 Other binary gas systems . . . . .	62
4.6 Multicomponent gas mixtures as natural fluids . . . . .	63
4.7 Solubility of minerals in H <sub>2</sub> O and natural fluids . . . . .	64
4.7.1 The system NaCl—H <sub>2</sub> O . . . . .	64
4.7.2 The system NaCl—H <sub>2</sub> O—CO <sub>2</sub> . . . . .	66
4.8 Solubilities of carbonates in natural fluids . . . . .	68
4.9 Solubilities of other common natural salts — fluorite and sulphates . . . . .	72
4.10 Solubilities of silica minerals . . . . .	73
4.11 Solubilities of aluminous silicates and feldspars . . . . .	76
4.12 Controls on the solubility of rock-forming minerals . . . . .	79
4.13 Ionization in aqueous mineral solutions . . . . .	79
4.14 Solubilities of metal sulphides . . . . .	82
4.15 Solubility in alteration-controlled systems . . . . .	86
4.16 Concluding statement . . . . .	87
 CHAPTER 5 — RATES OF METAMORPHIC REACTIONS . . . . .	 89
5.1 Introduction . . . . .	89
5.2 Rates of reaction . . . . .	90
5.2.1 Theory of reaction rates . . . . .	92
5.3 Rates of mineral dissolution in aqueous fluids . . . . .	95
5.3.1 Rates of solution of SiO <sub>2</sub> . . . . .	96
5.3.2 Rates of calcite dissolution . . . . .	99
5.3.3 Rates of alkali-feldspar dissolution . . . . .	99
5.4 Rates of nucleation and growth . . . . .	103
5.4.1 Problems of mineral nucleation . . . . .	103
5.4.2 Problems of mineral growth . . . . .	104
5.4.3 Nucleation and growth-controlled transformations . . . . .	107
5.5 Rates of diffusion . . . . .	110
5.5.1 Measurement of diffusion coefficients . . . . .	111

5.5.2	Diffusion in aqueous solutions . . . . .	113
5.5.3	Diffusion along grain boundaries and through the intergranular film . . .	114
5.5.4	Diffusion through mineral lattices . . . . .	115
5.6	Rates and mechanisms of metamorphic reactions . . . . .	117
5.6.1	Rates of solid—solid reactions . . . . .	117
5.6.2	Rates of hydration and dehydration reactions . . . . .	119
5.7	Metamorphic fluids and rates of reaction — Conclusions . . . . .	125

<b>CHAPTER 6 — THE RELEASE OF FLUIDS FROM ROCKS DURING METAMORPHISM . . . . .</b>	<b>129</b>
---	------------

6.1	Intoduction: Metamorphic processes . . . . .	129
6.2	Release of chemically-bound water during metamorphism . . . . .	129
6.3	Temperatures of natural mineral reactions . . . . .	132
6.4	Fluid pressures and rock pressures . . . . .	135
6.5	Dehydration at very high pressures . . . . .	138
6.6	Dehydration and metamorphic facies . . . . .	139
6.7	Mineral facies and progressive metamorphism of mafic rocks . . . . .	141
6.8	Fluid release during metamorphism of sediments . . . . .	152
6.8.1	Metamorphism of pelitic rocks and fluid release . . . . .	152
6.8.2	Metamorphism of carbonate rocks and fluid release . . . . .	155
6.9	Concluding statement . . . . .	162

<b>CHAPTER 7 — CONTROLS OF FLUID COMPOSITION: BUFFER SYSTEMS AND MELTING . . . . .</b>	<b>163</b>
--	------------

7.1	Introduction . . . . .	163
7.2	Buffering of $H_2O$ and $CO_2$ during rock-dominated metamorphism . . . . .	163
7.3	The behaviour of oxygen and hydrogen . . . . .	170
7.4	The behaviour of sulphur and sulphate . . . . .	172
7.5	The behaviour of halogens . . . . .	174
7.6	The behaviour of fluids during partial fusion . . . . .	177
7.7	Concluding statement . . . . .	184

<b>CHAPTER 8 — EXPERIMENTAL ROCK DEFORMATION: THE STRENGTH OF ROCKS UNDER GEOLOGICAL CONDITIONS . . . . .</b>	<b>185</b>
---	------------

8.1	Introduction . . . . .	185
8.2	Apparatus . . . . .	185
8.3	Confining pressure . . . . .	188
8.4	Temperature . . . . .	190
8.5	Strain rates . . . . .	192
8.6	Creep tests . . . . .	194
8.7	Residual stresses . . . . .	196
8.8	Pore fluids . . . . .	198
8.8.1	The Law of Effective Stress . . . . .	200
8.8.2	Brittle failure . . . . .	204
8.9	Equations of state . . . . .	214
8.10	Concluding statement . . . . .	224

CHAPTER 9 — THE QUANTIFICATION OF CRUSTAL CONDITIONS ( $P$ , $T$ , $\sigma_1 - \sigma_3$ , $\lambda$ , $\epsilon$ ) FROM GEOLOGICAL EVIDENCE . . . . .	225
9.1 Introduction . . . . .	225
9.2 Vertical pressure, temperature and depth . . . . .	225
9.3 Estimation of depth of burial . . . . .	227
9.4 Pore-fluid pressure . . . . .	232
9.5 Differential stress . . . . .	238
9.6 Strain rates . . . . .	242
9.7 Comparison of field and experimental data . . . . .	251
CHAPTER 10 — PERMEABILITY, HYDRAULIC FRACTURE AND ELASTICITY . . . . .	253
10.1 Introduction . . . . .	253
10.2 Permeability . . . . .	255
10.3 Hydraulic fracture . . . . .	259
10.4 Linear elasticity theory . . . . .	266
CHAPTER 11 — DEWATERING OF THE CRUST . . . . .	275
11.1 Introduction . . . . .	275
11.2 Development of fracture systems in undeformed sediments . . . . .	275
11.3 An impervious barrier . . . . .	285
11.4 Hydrothermal solutions and mineral flats and veins . . . . .	288
11.5 Tectonic pumping . . . . .	299
11.6 General remarks regarding the defluidisation of deep metamorphic rocks . . . . .	308
CHAPTER 12 — DIAPIRS AND DIAPIRISM . . . . .	317
12.1 Introduction . . . . .	317
12.2 Igneous diapirism . . . . .	317
12.3 Salt diapirism . . . . .	326
12.3.1 Mechanics of diapirism . . . . .	331
12.3.2 Flow properties of salt . . . . .	332
12.3.3 Trigger mechanism . . . . .	336
12.4 Concluding statement . . . . .	341
CHAPTER 13 — FLUIDS, TECTONICS AND CHEMICAL TRANSPORT . . . . .	343
13.1 Fluids and tectonics . . . . .	343
13.2 The dewatering process . . . . .	349
13.3 Chemical transport . . . . .	349
13.4 Regions of large-scale transport . . . . .	351
13.4.1 Ore deposition . . . . .	351
13.4.2 The environment of weathering . . . . .	352
13.4.3 The ocean ridge . . . . .	353
13.4.4 Subduction zones . . . . .	358

13.4.5 Subduction magmatism . . . . .	361
13.4.6 Shear zones, faults, thrusts, veins, etc. . . . .	363
13.4.7 Magmatic water . . . . .	363
13.5 Fluids and earth history — Conclusion . . . . .	363
REFERENCES . . . . .	367
INDEX . . . . .	377