

Contents

Preface	V
List of contributors	VII
Chapter 1. THE SEISMIC VELOCITY STRUCTURE OF THE DEEP CONTINENTAL CRUST	
W.S. Holbrook, W.D. Mooney and N.I. Christensen	
1. Introduction	1
2. Wide-angle seismic data	2
2.1. Acquisition	2
2.2. Interpretation	5
2.3. Other methods	7
3. Middle- and lower-crustal velocities	7
4. Seismic velocities: constraints on composition	12
4.1. Summary of laboratory measurements	12
4.2. Results	13
5. Fluids and anisotropy	26
6. Discussion	28
6.1. Average continental crustal structure	28
6.2. Bulk lower-crustal composition	29
6.3. Constraints from seismic reflection profiling	31
6.4. Implications for crustal evolution	32
6.5. Directions for future research	33
7. Conclusions	34
Acknowledgments	34
References	34
Chapter 2. MULTI-GENETIC ORIGIN OF CRUSTAL REFLECTIVITY: A REVIEW OF SEISMIC REFLECTION PROFILING OF THE CONTINENTAL LOWER CRUST AND MOHO	
W.D. Mooney and R. Meissner	
1. Introduction	45
2. The seismic reflection method	45
2.1. Early deep crustal seismic reflection profiles	46
2.2. The last 15 years of deep crustal reflection studies	46
2.3. Resolution and uncertainties	46
3. Observations of the continental lower crust and Moho	48
3.1. Terminology and overview of important contributions	49
3.2. Precambrian crust	50
3.3. Ancient orogens	51
3.4. Young (post-Mesozoic) orogens	56
3.5. Recently extended crust	58
3.6. The Moho	59
4. Multi-genetic origin of lower crustal reflections	62
4.1. Origin of reflectivity: concepts with direct borehole or outcrop evidence	62
4.2. Origin of reflectivity: concepts without direct borehole or outcrop evidence	64
5. Reflectivity and viscosity in the lower crust	66
5.1. Geometry of lower crustal reflections	66
5.2. Stress-strain evidence for major displacements in the lower crust	66
5.3. Rheological control of seismic reflectors	67

5.4. Seismically transparent lower crust and mixed reflectivity patterns.....	68
6. Conclusions	68
Acknowledgments	71
References.....	71
 Chapter 3. ELECTRICAL PROPERTIES OF THE LOWER CONTINENTAL CRUST	
A.G. Jones	
1. Introduction	81
1.1. The parameter being sensed: electrical conductivity (σ)	82
2. Review of methods	83
2.1. Magnetotelluric method	84
2.2. Geomagnetic Depth Sounding (GDS) and Horizontal Spatial Gradient (HSG).....	88
2.2. Controlled-source EM methods	88
2.4. Problems and limitations of the MT method.....	89
2.4.1. Static distortions.....	90
2.4.2. Strike determination	92
2.4.3. Model resolution and uniqueness.....	93
3. Summary of results	96
3.1. Shields	97
3.1.1. Baltic shield.....	97
3.1.2. Canadian shield	99
3.1.3. Siberian shield.....	100
3.1.4. Shields: Conclusions	100
3.2. Rifts	100
3.2.1. East African Rift	101
3.2.2. Rio Grande Rift	101
3.2.3. Rhinegraben	102
3.2.4. Baikal rift	104
3.2.5. Midcontinent Rift	105
3.2.6. Rifts: Conclusions	105
3.3. Modern and ancient continental margins.....	105
3.3.1. West coast of North America	106
3.3.2. East coast of North America	107
3.3.3. Iapetus suture	107
3.3.4. Trans-Hudson Orogen	109
3.3.5. Ladoga–Bothnian Bay–Skellefteå zone	111
3.3.6. Continental margins: Conclusions	112
3.4. “Generic” results	113
3.5. Kapuskasing structure	114
3.6. Valhalla complex	115
3.7. Results: Conclusions	116
4. Causes of enhanced electrical conductivity in the continental lower crust	117
4.1. Saline fluids	118
4.1.1. Existence and types of fluids	120
4.1.2. Retention/replacement of fluids	121
4.1.3. Large-scale fluid circulation.....	122
4.1.4. Fluid conductivity	122
4.1.5. Petrological arguments against free fluids	123
4.2. Grain-boundary films	124
4.2.1. Wetting angle paradox and carbon mobility	125
4.2.2. Untestable hypothesis?	125
4.2.3. Black shales	125
4.3. Sulphides/metalllic ores/graphite	126
4.4. Partial melt.....	126
4.5. Anisotropy?	127

4.6. Pore geometry considerations	128
4.7. Causes: Conclusions	129
5. Conclusions	130
Acknowledgments	131
References	131

Chapter 4. MAGNETIC PROPERTIES OF THE LOWER CONTINENTAL CRUST

P.N. Shive, R.J. Blakely, B.R. Frost and D.M. Fountain

1. Introduction	145
2. Long-wavelength magnetic anomalies	145
2.1. Big sources versus deep sources	147
2.2. Satellite magnetic surveys	148
2.3. Aeromagnetic surveys	151
3. Magnetic properties of lower crustal rocks	153
3.1. Types of samples studies	154
3.2. Magnetic susceptibility (induced magnetization) of lower crustal rocks — laboratory data	155
3.3. Magnetic mineralogy of lower crustal rocks — laboratory observations	157
3.4. Effect of coolint on magnetite composition	159
3.5. Effect of metamorphism on magnetite stability	160
3.5.1. Buffer type equilibria	161
3.5.2. Oxygen-conserved oxide-silicate equilibria	161
3.6. Magnetite stability in crustal rocks	162
3.6.1. Granitic rocks	162
3.6.2. Mafic igneous and meta-igneous rocks	163
3.6.3. Ultramafic rocks	164
3.6.4. Metasedimentary rocks	165
3.7. Remanent magnetization in lower crustal rocks	165
4. Nature of magnetic bodies in the lower crust	167
4.1. Sources of magnetization in the lower crust	167
4.2. Depth of magnetic layers	169
5. Concluding remarks	170
References	170

Chapter 5. THERMAL STATE OF THE CONTINENTAL CRUST

D.S. Chapman and K.P. Furlong

1. Introduction	179
2. Geotherm models	180
3. Thermophysical parameters	181
4. Framework geotherms	183
5. Processes and conditions that affect or modify the thermal state of the continental lower crust	185
5.1. Burial by sedimentation	185
5.2. Exhumation	188
5.3. Burial by thrusting	189
5.4. Extensional unroofing	191
5.5. Magmatic underplating	193
6. Crustal heterogeneities	196
7. Conclusion	196
References	198

Chapter 6. RHEOLOGY OF THE LOWER CRUST

E.H. Rutter and K.H. Brodie

1. Introduction	201
2. Deformation mechanisms	202

3. Data from experimental rock mechanics	203
3.1. Limitations of experimental data	203
3.2. Quartz	206
3.3. Olivine	211
3.4. Feldspars	212
3.5. Amphiboles	213
3.6. Pyroxenes	213
3.7. Other minerals and polymimetic rocks	217
4. Localization of strain into shear zones	218
4.1. Cataclastic deformation	220
4.2. Fabric (geometric) softening	220
4.3. Reaction softening	220
4.4. Potential effects of grain-size reduction	220
4.5. Shear heating	226
5. The size of recrystallized grains	226
6. Structures and microstructures of naturally deformed rocks	227
6.1. Crustal rheology during prograde metamorphism	231
6.1.1. Effects of metamorphic reactions on deformability	231
6.1.2. Role of partial melting	235
6.2. Crustal rheology of high-grade rocks after peak metamorphism	237
6.2.1. Isochemical high-temperature deformation	237
6.2.2. Reactivation accompanied by metamorphic retrogression	242
7. Flexure of the continental lithosphere	251
8. Discussion	251
8.1. The state of stress and rheological stratification	251
8.2. Deep seismic soundings	254
8.3. Modelling tectonic processes	255
9. Conclusions	256
Acknowledgments	257
References	257

Chapter 7. XENOLITHS — SAMPLES OF THE LOWER CONTINENTAL CRUST

R.L. Rudnick

1. Introduction	269
2. The samples	272
2.1. Definitions	272
2.2. Occurrence	273
3. Effects of transport	278
4. Mineralogy	280
5. <i>P-T</i> estimates	281
6. Physical properties	284
6.1. Resistivity measurements	285
6.2. Seismic velocities	286
6.3. Heat production	289
7. Chemical composition	289
8. Isotopic studies	292
8.1. Sr and Nd	292
8.2. Pb	295
8.3. Age determinations	296
9. Case studies	298
9.1. The Chudleigh province, north Queensland — A Paleozoic fold belt	298
9.2. The McBride province, north Queensland — A Proterozoic inlier	300
9.3. The Eifel, western Germany — A Cenozoic rift	301
10. A lower crustal composition from xenoliths	303
11. Representativeness of xenoliths as lower crust	303

12. Conclusions	305
Acknowledgments	308
References	308

Chapter 8. EXPOSED CRUSTAL CROSS SECTIONS AS WINDOWS ON THE LOWER CRUST

J.A. Percival, D.M. Fountain and M.H. Salisbury

1. Introduction	317
2. Compressional uplifts	319
2.1. Kapuskasing uplift, Ontario, Canada	319
2.2. Ivrea Zone, Southern Alps, Italy	324
2.3. Calabrian massif, southern Italy	328
2.4. Kohistan arc, Pakistan	330
2.5. Central Australia	332
2.6. Kasila Group, west Africa	334
2.7. Summary — compressional uplifts	334
3. Wide, oblique transitions	335
3.1. Dharwar craton, southern India	335
3.2. Pikwitonei granulite domain, Manitoba, Canada	337
3.3. Western gneiss terrane, Yilgarn block, Australia	339
3.4. Summary — wide, oblique transitions	339
4. Impactogenic uplifts	340
4.1. Vredefort dome, South Africa	340
4.2. Levack gneiss complex, Superior Province, Ontario	340
4.3. Summary — impactogenic uplifts	342
5. Transpressional uplifts	342
5.1. Fiordland, South Island, New Zealand	342
5.2. Tehachapi complex, Sierra Nevada, California	344
5.3. Summary — transpressional uplifts	345
6. Characteristics of lower crust in cross sections	346
7. Implications for the nature of the lower crust	347
Acknowledgments	350
References	350

Chapter 9. MAGMAS AS TRACERS OF LOWER CRUSTAL COMPOSITION: AN ISOTOPIC APPROACH

G.L. Farmer

1. Introduction	363
2. General techniques	363
3. Case example — Western U.S.	368
3.1. Peraluminous granites	369
3.2. Metaluminous granites	375
4. Other examples	383
5. Conclusions	384
Acknowledgments	386
References	386

Chapter 10. FLUIDS IN THE DEEP CRUST — PETROLOGICAL AND ISOTOPIC EVIDENCE

S.M. Wickham

1. Introduction	391
2. Equilibrium thermodynamic calculations	392
2.1. Overview	392
2.2. Fluid fugacity calculations	393
3. Fluid inclusions	398

4. Stable isotope constraints on deep crustal fluids	402
4.1. Overview	402
4.2. Deep crustal CO ₂ fluxes	404
4.3. Oxygen isotope studies of granulites	406
5. Melting and fluid transport	409
5.1. Overview	409
5.2. Experimental studies	410
5.3. Fluid and melt transport properties	411
5.4. Implications for melt and fluid motion	413
5.5. CO ₂ -rich melting and an alternative model of granulite petrogenesis	414
6. Conclusions	416
Acknowledgments	417
References	417

Chapter 11. MAGMA GENESIS AND CRUSTAL PROCESSING

R.W. Kay, S. Mahlburg Kay and R.J. Arculus

1. Introduction	423
2. Magmas in the crust: processes and models	423
2.1. Magma migration by crustal fusion: thermal consequences	424
2.2. Crustal melting	424
2.3. The buoyancy of magmas in the crust	428
2.4. Segregation of crustal melts and fluids	428
2.5. Magma mixing	430
3. Magmatic underplating	430
3.1. Underplating at rifted continental margins: seismic evidence	430
3.2. Underplating of non-rift crust: evidence of silicic volcanism	431
3.3. Underplating in continental interiors: thermal evolution evidence	431
3.4. Underplating at convergent margins: thermal and compositional arguments	432
3.6. Xenolithic evidence	432
4. Anatexis and granitoid melt generation	432
4.1. Himalayan leucogranites: crustal melting in a collision zone	433
4.2. Crustal melting at the Taupo (New Zealand) and Trois Seigneurs (Pyrenees) rift zones	434
4.3. Crustal melting under dry conditions: alkaline, anorogenic, anhydrous (A-type) granitoids	434
5. Continental growth, recycling, and the lower crust	435
5.1. Andesitic crust from the mantle	436
5.2. Lower crustal delamination	437
5.2.1. Tectonic setting for lower crustal delamination	437
5.2.2. Lower crustal delamination: nature of evidence to test the model	439
5.2.2. Lower crustal delamination: signature recognized in mantle-derived magmas?	440
6. Concluding remarks	440
References	441

Chapter 12. TEMPORAL EVOLUTION OF REGIONAL GRANULITE TERRANES: IMPLICATIONS

FOR THE FORMATION OF LOWERMOST CONTINENTAL CRUST

K. Mezger

1. Introduction	447
2. Characteristics of regional granulite terranes	448
2.1. General characteristics	448
2.2. Pressure–temperature conditions	449
2.3. Fluids in granulite terranes	450
2.4. Heat sources and tectonic setting	451
3. Evolution of regional granulite terranes: examples	452
3.1. Napier Complex (Enderby Land, Antarctica)	453
3.1.1. Geologic setting	453

3.1.2. Geologic history	454
3.1.3. Possible tectonic setting	455
3.2. Pikwitonei granulite domain (Superior Province)	456
3.2.1. Geologic setting	456
3.2.2. Geologic history	457
3.2.3. Possible tectonic setting	461
3.3. Adirondack terrane (Grenville Province)	462
3.3.1. Geologic setting	462
3.3.2. Geologic history	462
3.3.3. Possible tectonic setting	465
4. Granulites and the lower crust	467
5. Discussion	468
Acknowledgments	472
References	472
Subject index	479