

## Contents

**Preface** XV

**List of Contributors** XIX

<b>1</b>	<b>Reservoir Definition</b>	<b>1</b>
	<i>Patrick Ledru and Laurent Guillou Frottier</i>	
1.1	Expressions of Earth's Heat Sources	1
1.1.1	Introduction to Earth's Heat and Geothermics	1
1.1.2	Cooling of the Core, Radiogenic Heat Production, and Mantle Cooling	2
1.1.3	Mantle Convection and Heat Loss beneath the Lithosphere	4
1.1.3.1	Mantle Heat Flow Variations	4
1.1.3.2	Subcontinental Thermal Boundary Condition	5
1.1.4	Fourier' Law and Crustal Geotherms	6
1.1.5	Two-dimensional Effects of Crustal Heterogeneities on Temperature Profiles	8
1.1.5.1	Steady-state Heat Refraction	8
1.1.5.2	Transient Effects	10
1.1.5.3	Role of Anisotropy of Thermal Conductivity	10
1.1.6	Fluid Circulation and Associated Thermal Anomalies	12
1.1.7	Summary	13
1.2	Heat Flow and Deep Temperatures in Europe	13
1.2.1	Far-field Conditions	14
1.2.2	Thermal Conductivity, Temperature Gradient, and Heat Flow Density in Europe	17
1.2.3	Calculating Extrapolated Temperature at Depth	18
1.2.4	Summary	20
1.3	Conceptual Models of Geothermal Reservoirs	21
1.3.1	The Geology of Potential Heat Sources	22
1.3.2	Porosity, Permeability, and Fluid Flow in Relation to the Stress Field	27
1.3.3	Summary	30
	References	32

<b>2</b>	<b>Exploration Methods</b>	<b>37</b>
	<i>David Bruhn, Adele Manzella, François Vuataz, James Faulds, Inga Moeck, and Kemal Erbas</i>	
2.1	Introduction	37
2.2	Geological Characterization	39
2.3	Relevance of the Stress Field for EGS	44
2.4	Geophysics	52
2.4.1	Electrical Methods (DC, EM, MT)	53
2.4.1.1	Direct Current (DC) Methods	54
2.4.1.2	Electromagnetic Methods	55
2.4.1.3	The Magnetotelluric Method	55
2.4.1.4	Active Electromagnetic Methods	63
2.4.2	Seismic Methods	66
2.4.2.1	Active Seismic Sources	67
2.4.2.2	Seismic Anisotropy and Fractures	71
2.4.2.3	Passive Seismic Methods	73
2.4.3	Potential Methods	76
2.4.3.1	Gravity	76
2.4.3.2	Geomagnetics and Airborne Magnetic	78
2.4.4	Data Integration	80
2.4.4.1	Joint Inversion Procedures	81
2.5	Geochemistry	81
2.5.1	Introduction	81
2.5.2	Fluids and Minerals as Indicators of Deep Circulation and Reservoirs	83
2.5.3	Mud and Fluid Logging while Drilling	85
2.5.4	Hydrothermal Reactions	86
2.5.4.1	Boiling and Mixing	88
2.5.5	Chemical Characteristics of Fluids	91
2.5.5.1	Sodium–Chloride Waters	92
2.5.5.2	Acid–Sulfate Waters	92
2.5.5.3	Sodium–Bicarbonate Waters	93
2.5.5.4	Acid Chloride–Sulfate Waters	93
2.5.6	Isotopic Characteristics of Fluids	94
2.5.7	Estimation of Reservoir Temperature	97
2.5.7.1	Geothermometric Methods for Geothermal Waters	98
2.5.7.2	Silica Geothermometer	98
2.5.7.3	Ionic Solutes Geothermometers	99
2.5.7.4	Gas (Steam) Geothermometers	100
2.5.7.5	Isotope Geothermometers	100
2.5.8	Forecast of Corrosion and Scaling Processes	100
	References	103
	Further Reading	111

<b>3</b>	<b>Drilling into Geothermal Reservoirs</b>	<b>113</b>
	<i>Axel Sperber, Inga Moeck, and Wulf Brandt</i>	
3.1	Introduction	113
3.1.1	Geothermal Environments and General Tasks	114
3.2	Drilling Equipment and Techniques	115
3.2.1	Rigs and Their Basic Concepts	115
3.2.1.1	Hoisting System	115
3.2.1.2	Top Drive or Rotary Table	115
3.2.1.3	Mud Pumps	116
3.2.1.4	Solids Control Equipment	118
3.2.1.5	Blowout Preventer (BOP)	118
3.2.2	Drillstring	118
3.2.2.1	Bottomhole Assembly	118
3.2.2.2	Drillpipe	121
3.2.3	Directional Drilling	122
3.2.3.1	Downhole Motor (DHM)	122
3.2.3.2	Rotary Steerable Systems (RSS)	122
3.2.3.3	Downhole Measuring System (MWD) with Signal Transmission Unit (Pulser)	123
3.2.3.4	Surface Receiver to Receive and Decode the Pulser Signals	123
3.2.3.5	Special Computer Program to Evaluate Where the Bottom of the Hole Is at Survey Depth	123
3.2.4	Coring	125
3.3	Drilling Mud	125
3.3.1	Mud Types	126
3.3.1.1	Water-based Mud	126
3.3.1.2	Oil-based Mud	126
3.3.1.3	Foams	126
3.3.1.4	Air	126
3.3.2	The Importance of Mud Technology in Certain Geological Environments	127
3.3.2.1	Drilling through Plastic/Creeping Formations (Salt, Clay)	127
3.3.2.2	Formation Pressure and Formation Damage (Hydrostatic Head, ECD)	127
3.4	Casing and Cementation	128
3.4.1	Casing and Liner Concepts	129
3.4.2	Casing Materials	129
3.4.3	Pipe Centralization	131
3.4.4	Cementation	132
3.4.5	Cement Slurries, ECD	133
3.4.6	Influence of Temperature on Casing and Cement	136
3.5	Planning a Well	136
3.5.1	Geological Forecast	136
3.5.1.1	Target Definition	137
3.5.1.2	Pore Pressures/Fracture Pressure/Temperature	137

3.5.1.3	Critical Formations/Fault Zones	138
3.5.1.4	Hydrocarbon Bearing Formations	138
3.5.1.5	Permeabilities	138
3.5.2	Well Design	139
3.5.2.1	Trajectory	139
3.5.2.2	Casing Setting Depths	139
3.5.2.3	Casing Sizes	139
3.5.2.4	Casing String Design	140
3.6	Drilling a Well	142
3.6.1	Contract Types and Influence on Project Organization	142
3.6.1.1	Turnkey Contract	142
3.6.1.2	Meter-contract	143
3.6.1.3	Time-based Contract	143
3.6.1.4	Incentive Contract	143
3.6.2	Site Preparation and Infrastructure	144
3.6.2.1	General	144
3.6.2.2	Excavating and Trenching	144
3.6.2.3	Environmental Impact (Noise, Pollution Prevention)	144
3.6.3	Drilling Operations	144
3.6.4	Problems and Trouble Shooting	145
3.7	Well Completion Techniques	148
3.7.1	Casing (Please Refer Also to “Casing String Design”)	148
3.7.1.1	Allowance of Vertical Movement of Casing	148
3.7.1.2	Pretensioning	148
3.7.1.3	Liner in Pay Zone (Slotted/Predrilled) or Barefoot Completion	150
3.7.2	Wellheads, Valves and so on	150
3.7.3	Well Completion without Pumps with Naturally Flowing Wells	151
3.7.4	Well Completion with Pumps	152
3.8	Risks	152
3.8.1	Evaluating Risks	153
3.8.1.1	Poor or Wrong Geological Profile Forecast	153
3.8.1.2	Poor Well Design	153
3.8.2	Technical Risks	154
3.8.2.1	Failure of Surface Equipment	154
3.8.2.2	Failure of Subsurface Equipment	154
3.8.3	Geological–Technical Risks	155
3.8.4	Geological Risks	157
3.8.5	Geotectonical Risks	159
3.9	Case Study Groß Schönebeck Well	159
3.10	Economics (Drilling Concepts)	162
3.10.1	Influence of Well Design on Costs	164
3.10.1.1	Casing Scheme	164
3.10.1.2	Vertical Wells versus Deviated Wells	165
3.11	Recent Developments, Perspectives in R&D	165
3.11.1	Technical Trends	165

3.11.1.1	Topdrive	166
3.11.1.2	Rotary Steerable Systems (RSS)	166
3.11.1.3	Multilateral Wells	169
3.11.2	Other R&D-Themes of high Interest	169
	References	170
<b>4</b>	<b>Enhancing Geothermal Reservoirs</b>	<b>173</b>
	<i>Thomas Schulte, Günter Zimmermann, Francois Vuataz, Sandrine Portier, Torsten Tischner, Ralf Junker, Reiner Jatho, and Ernst Huenges</i>	
4.1	Introduction	173
4.1.1	Hydraulic Stimulation	174
4.1.2	Thermal Stimulation	174
4.1.3	Chemical Stimulation	174
4.2	Initial Situation at the Specific Location	174
4.2.1	Typical Geological Settings	174
4.2.2	Appropriate Stimulation Method According to Geological System and Objective	175
4.3	Stimulation and Well path Design	176
4.4	Investigations Ahead of Stimulation	178
4.5	Definition and Description of Methods (Theoretical)	180
4.5.1	Hydraulic Stimulation	180
4.5.1.1	General	180
4.5.1.2	Waterfrac Treatments	181
4.5.1.3	Gel-Proppant Treatments	182
4.5.1.4	Hybrid Frac Treatments	183
4.5.2	Thermal Stimulation	183
4.5.3	Chemical Stimulation	184
4.6	Application (Practical)	187
4.6.1	Hydraulic Stimulation	187
4.6.1.1	Induced Seismicity	189
4.6.2	Thermal Stimulation	193
4.6.3	Chemical Stimulation	194
4.7	Verification of Treatment Success	197
4.7.1	General	197
4.7.1.1	Wireline Based Evaluation	197
4.7.1.2	Hydraulic Well Tests	197
4.7.1.3	Tracer Testing	198
4.7.1.4	Monitoring Techniques	200
4.7.2	Evaluation of Chemical Stimulations	201
4.8	Outcome	202
4.8.1	Hydraulic Stimulation	202
4.8.1.1	Hydraulic Stimulation – Soultz	202
4.8.1.2	Hydraulic Stimulation Groß Schönebeck	203
4.8.2	Thermal Stimulation	204
4.8.3	Chemical Stimulation	204

4.9	Sustainability of Treatment	206
4.9.1	Hydraulic Stimulation	206
4.9.1.1	Proppant Selection	206
4.9.1.2	Coated Proppants	209
4.9.2	Thermal Stimulation	209
4.9.3	Chemical Stimulation	210
4.10	Case Studies	210
4.10.1	Groß Schönebeck	210
4.10.1.1	Introduction	210
4.10.1.2	Hydraulic Fracturing Treatments in GrSk3/90	211
4.10.1.3	Hydraulic Fracturing in Sandstones (Gel-Proppant Stimulation)	211
4.10.1.4	Hydraulic fracturing in Volcanics (Waterfrac Stimulation)	212
4.10.1.5	Hydraulic Fracturing Treatments in GrSk4/05	213
4.10.1.6	Hydraulic Fracturing Treatment in Volcanics (Waterfrac Stimulation)	214
4.10.1.7	Hydraulic Fracturing in Sandstones (Gel-Proppant Stimulation)	215
4.10.1.8	Conclusions	216
4.10.2	Soultz	217
4.10.2.1	Hydraulic Stimulation	217
4.10.2.2	Chemical Stimulation	223
4.10.3	Horstberg	226
4.10.3.1	Introduction	226
4.10.3.2	Fracturing Experiments	228
4.10.3.3	Summary and Conclusion	232
	References	233
	Further Reading	240
<b>5</b>	<b>Geothermal Reservoir Simulation</b>	<b>245</b>
	<i>Olaf Kolditz, Mando Guido Blöcher, Christoph Clauser, Hans-Jörg G. Diersch, Thomas Kohl, Michael Kühn, Christopher I. McDermott, Wenqing Wang, Norihiro Watanabe, Günter Zimmermann, and Dominique Bruel</i>	
5.1	Introduction	245
5.1.1	Geothermal Modeling	246
5.1.2	Uncertainty Analysis	247
5.2	Theory	248
5.2.1	Conceptual Approaches	248
5.2.2	THM Mechanics	248
5.2.2.1	Heat Transport	249
5.2.2.2	Liquid Flow in Deformable Porous Media	250
5.2.2.3	Thermoporoelastic Deformation	250
5.3	Reservoir Characterization	250
5.3.1	Reservoir Properties	251
5.3.1.1	Reservoir Permeability	251
5.3.1.2	Poroperm Relationships	251

5.3.2	Fluid Properties	254
5.3.2.1	Density and Viscosity	254
5.3.2.2	Heat Capacity and Thermal Conductivity	255
5.3.3	Supercritical Fluids	257
5.3.4	Uncertainty Assessment	258
5.4	Site Studies	260
5.5	Groß Schönebeck	260
5.5.1	Introduction	260
5.5.2	Model Description	261
5.5.2.1	Geology	261
5.5.2.2	Structure	262
5.5.2.3	Thermal Conditions	263
5.5.2.4	Hydraulic Conditions	263
5.5.3	Modeling Approach	264
5.5.4	Results	265
5.5.5	Conclusions	268
5.6	Bad Urach	268
5.6.1	The Influence of Parameter Uncertainty on Reservoir Evolution	268
5.6.1.1	Conceptual Model	268
5.6.1.2	Simulation Results	270
5.6.1.3	Stimulated Reservoir Model	270
5.6.1.4	Monte Carlo Analysis	271
5.6.1.5	Conclusions	275
5.6.2	The Influence of Coupled Processes on Differential Reservoir Cooling	275
5.6.2.1	Conceptual Model	275
5.6.2.2	Development of Preferential Flow Paths due to Positive Feedback Loops in Coupled Processes and Potential Reservoir Damage	276
5.6.3	The Importance of Thermal Stress in the Rock Mass	278
5.7	Rosemanowes (United Kingdom)	279
5.8	Soultz-sous-Forets (France)	280
5.9	KTB (Germany)	284
5.9.1	Introduction	284
5.9.2	Geomechanical Facies and Modeling the HM Behavior of the KTB Pump Test	285
5.10	Stralsund (Germany)	287
5.10.1	Site Description	290
5.10.2	Model Setup	290
5.10.3	Long-Term Development of Reservoir Properties	291
	References	293
<b>6</b>	<b>Energetic Use of EGS Reservoirs</b>	<b>303</b>
	<i>Ali Saadat, Stephanie Frick, Stefan Kranz, and Simona Regensburg</i>	
6.1	Utilization Options	303
6.1.1	Energetic Considerations	303

6.1.2	Heat Provision	306
6.1.3	Chill Provision	308
6.1.4	Power Provision	312
6.2	EGS Plant Design	316
6.2.1	Geothermal Fluid Loop	316
6.2.1.1	Fluid Properties	317
6.2.1.2	Operational Reliability Aspects	323
6.2.1.3	Fluid Production Technology	329
6.2.2	Heat Exchanger	332
6.2.2.1	Heat Exchanger Analysis – General Considerations	333
6.2.2.2	Selection of Heat Exchangers	335
6.2.2.3	Specific Issues Related to Geothermal Energy	337
6.2.3	Direct Heat Use	338
6.2.4	Binary Power Conversion	341
6.2.4.1	General Cycle Design	342
6.2.4.2	Working Fluid	347
6.2.4.3	Recooling Systems	352
6.2.5	Combined Energy Provision	359
6.2.5.1	Cogeneration	359
6.2.5.2	Serial Connection	360
6.2.5.3	Parallel Connection	361
6.3	Case Studies	362
6.3.1	Power Provision	363
6.3.1.1	Objective	363
6.3.1.2	Design Approach	363
6.3.1.3	Gross Power versus Net Power Maximization	364
6.3.2	Power and Heat Provision	366
6.3.2.1	Objective	366
6.3.2.2	Design Approach	367
6.3.2.3	Serial versus Parallel Connection	367
	References	368
<b>7</b>	<b>Economic Performance and Environmental Assessment</b>	<b>373</b>
	<i>Stephanie Frick, Jan Diederik Van Wees, Martin Kaltschmitt, and Gerd Schröder</i>	
7.1	Introduction	373
7.2	Economic Aspects for Implementing EGS Projects	375
7.2.1	Levelized Cost of Energy (LCOE)	375
7.2.1.1	Methodological Approach	376
7.2.1.2	Cost Analysis	377
7.2.1.3	Case Studies	383
7.2.2	Decision and Risk Analysis	393
7.2.2.1	Methodology	394
7.2.2.2	Case Study	397
7.3	Impacts on the Environment	405

7.3.1	Life Cycle Assessment	406
7.3.1.1	Methodological Approach	406
7.3.1.2	Case Studies	408
7.3.2	Impacts on the Local Environment	412
7.3.2.1	Local Impacts	412
7.3.2.2	Environmental Impact Assessment	417
	References	419
<b>8</b>	<b>Deployment of Enhanced Geothermal Systems Plants and CO<sub>2</sub> Mitigation</b>	<b>423</b>
	<i>Ernst Huenges</i>	
8.1	Introduction	423
8.2	CO <sub>2</sub> Emission by Electricity Generation from Different Energy Sources	423
8.3	Costs of Mitigation of CO <sub>2</sub> Emissions	424
8.4	Potential Deployment	426
8.5	Controlling Factors of Geothermal Deployment	426
8.5.1	Technological Factors	426
8.5.2	Economic and Political Factors	427
	References	428
	<b>Color Plates</b>	<b>429</b>
	<b>Index</b>	<b>445</b>

