

# Understanding Faults

Detecting, Dating, and Modeling

---

*Edited by*

David Tanner

Christian Brandes

...



# Contents

List of contributors	xi
Preface	xiii
<b>1. Introduction</b>	<b>1</b>
<i>David C. Tanner and Christian Brandes</i>	
<b>Definition of a fault surface, fault kinematics and displacement</b>	<b>5</b>
<b>References</b>	<b>9</b>
<b>2. Fault mechanics and earthquakes</b>	<b>11</b>
<i>Christian Brandes and David C. Tanner</i>	
<b>2.1 Introduction</b>	<b>12</b>
<b>2.2 Fractures</b>	<b>13</b>
<b>2.3 From intact rocks to opening-mode fractures to faults</b>	<b>16</b>
2.3.1 Griffith cracks	16
2.3.2 The Coulomb failure criterion and the Mohr circle	18
2.3.3 Hydrofractures	22
2.3.4 Stress state and dynamic fault classification of Anderson	23
2.3.5 Wallace-Bott hypothesis	24
<b>2.4 Fault zone processes and structure</b>	<b>25</b>
2.4.1 The fault zone	25
2.4.2 Principal slip surface	30
2.4.3 Pseudotachylites	31
2.4.4 Strain hardening/strain softening of the fault core	32
2.4.5 Fault surface geometry and roughness	33
2.4.6 The process zone	35
2.4.7 Deformation bands	36
2.4.8 Fault groups and their characterization	41
2.4.9 Fault evolution with depth	44
2.4.10 Fault-related folding	44
<b>2.5 Fault movement and seismicity</b>	<b>46</b>
2.5.1 Fault rupture	47
2.5.2 Fault creep	56
2.5.3 Slow earthquakes	58

2.5.4	The Cosserat theory as a concept to describe fault and deformation band behaviour	58
2.5.5	Large overthrusts and the effect of fluid pressure	60
<b>2.6</b>	<b>Faults in soft-sediments</b>	<b>62</b>
	References	64
<b>3.</b>	<b>Fault detection</b>	<b>81</b>
	<i>David C. Tanner, Hermann Bunn, Jan Igel, Thomas Günther, Gerald Gabriel, Peter Skiba, Thomas Plenefisch, Nicolai Gestermann and Thomas R. Walter</i>	
<b>3.1</b>	<b>Introduction</b>	82
<b>3.2</b>	<b>Active seismics</b>	84
3.2.1	Seismic method	84
3.2.2	Resolution	84
3.2.3	Seismic imaging of faults	85
3.2.4	Imaging of faults – 2-D and 3-D	88
3.2.5	Fracture detection	89
<b>3.3</b>	<b>Ground-penetrating radar (GPR)</b>	91
3.3.1	Principle	92
3.3.2	Imaging of faults	93
3.3.3	Examples	95
<b>3.4</b>	<b>Electrical resistivity tomography (ERT)</b>	97
3.4.1	Background	97
3.4.2	Large-scale fault imaging with structural information	101
<b>3.5</b>	<b>Gravimetry and magnetics</b>	103
3.5.1	Gravity and magnetic anomalies – definition and instruments for measurement	103
3.5.2	Gravity and magnetic anomalies - interpretation	105
<b>3.6</b>	<b>Seismology</b>	111
3.6.1	Detecting and illuminating faults by earthquake hypocentre distribution	112
3.6.2	Describing faults by interpretation of source mechanisms	117
3.6.3	Examples of detecting faults using hypocentre distributions and focal mechanisms	123
<b>3.7</b>	<b>Remote sensing</b>	127
3.7.1	History and background of remote sensing	127
3.7.2	Instruments and data	130
3.7.3	Fault mapping and kinematics	132
3.7.4	Summary and outlook	139
	References	139
<b>4.</b>	<b>Numerical modelling of faults</b>	<b>147</b>
	<i>Andreas Henk</i>	
<b>4.1</b>	<b>Introduction</b>	147
<b>4.2</b>	<b>Numerical methods for hydromechanical fault zone modelling</b>	148
<b>4.3</b>	<b>Material parameters of fault zone rocks required for modelling</b>	151

<b>4.4</b>	<b>An example of numerical modelling</b>	154
4.4.1	Modelling concept and parameters	154
4.4.2	Model geometry and discretization	156
4.4.3	Hydromechanical rock properties	156
4.4.4	Boundary and initial conditions	157
4.4.5	Modelling results	157
<b>4.5</b>	<b>Conclusions</b>	162
	References	163
<b>5.</b>	<b>Faulting in the laboratory</b>	167
	<i>André Niemeijer, Åke Fagereng, Matt Ikari, Stefan Nielsen and Ernst Willingshofer</i>	
<b>5.1</b>	<b>Fault friction in the quasi-static regime</b>	168
5.1.1	Laboratory measurements of friction	168
5.1.2	General observations of steady state friction	171
5.1.3	Rate-and-state friction	173
5.1.4	Observations of variations in velocity dependence of friction at room temperature	176
5.1.5	Strength recovery (healing)	177
5.1.6	Effect of hydrothermal conditions on velocity dependence of friction	178
<b>5.2</b>	<b>Fault friction in the dynamic regime</b>	180
5.2.1	Dynamic weakening mechanisms in gouges and solid rocks	180
5.2.2	Melt lubrication	181
5.2.3	Flash heating and flash weakening	183
5.2.4	Thermal pressurization	185
5.2.5	Thermal decomposition and pressurization	186
5.2.6	Fluid phase changes	186
5.2.7	Powder lubrication	187
5.2.8	Activation of crystal-plastic (viscous) mechanisms	188
5.2.9	Dynamic rupture in laboratory experiments	189
5.2.10	Frontiers	194
<b>5.3</b>	<b>Faults in scaled physical analogue models</b>	194
5.3.1	Introduction	194
5.3.2	Scaling tectonic faulting to the laboratory	195
5.3.3	Rock analogue materials and their bulk properties	196
5.3.4	Quantifying stress and strain in analogue models	197
5.3.5	Fault formation in analogue models	197
5.3.6	Faulting in single and multi-layer systems	201
5.3.7	Frontiers	202
<b>5.4</b>	<b>Microstructures of laboratory faults</b>	202
5.4.1	Introduction of localization features	202
5.4.2	Development of gouge microstructure with strain/displacement	203
5.4.3	Distribution of slip on structural elements	205
5.4.4	Role of Y or B shears in generation of unstable slip	206

5.4.5	Clay-bearing versus non-clay bearing	207
5.4.6	Frontiers	208
	References	209
<b>6.</b>	<b>The growth of faults</b>	<b>221</b>
	<i>Andrew Nicol, John Walsh, Conrad Childs and Tom Manzocchi</i>	
<b>6.1</b>	<b>Introduction</b>	<b>221</b>
<b>6.2</b>	<b>Geometric indicators of fault growth</b>	<b>225</b>
6.2.1	Conceptual 'ideal isolated fault' model	226
6.2.2	Mechanical layering and displacement variations	226
6.2.3	'Isolated' fault lateral displacement profiles	229
6.2.4	Interaction and lateral displacement profiles	230
6.2.5	Relay zones and lateral interactions	231
6.2.6	Damage zones and lateral growth	235
<b>6.3</b>	<b>Direct kinematic indicators of fault growth</b>	<b>235</b>
6.3.1	Displacement through time	237
6.3.2	Fault lateral propagation	239
6.3.3	Fault upward propagation and reactivation	240
<b>6.4</b>	<b>Displacement-length relations and fault growth</b>	<b>241</b>
<b>6.5</b>	<b>End-member fault growth models</b>	<b>243</b>
<b>6.6</b>	<b>Earthquakes and incremental growth</b>	<b>246</b>
<b>6.7</b>	<b>Concluding remarks</b>	<b>247</b>
	References	248
<b>7.</b>	<b>Direct dating of fault movement</b>	<b>257</b>
	<i>Sumiko Tsukamoto, Takahiro Tagami and Horst Zwingmann</i>	
<b>7.1</b>	<b>Dating of authigenic clay minerals in brittle faults</b>	<b>257</b>
7.1.1	Outline of the concept and the analytical method	257
7.1.2	K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ clay dating principles	259
7.1.3	Fault gouge dating constraints	259
7.1.4	Authigenic clay gouge age interpretation	261
7.1.5	Case studies	263
<b>7.2</b>	<b>Dating methods based on thermal reset</b>	<b>266</b>
7.2.1	Outline of the method	266
7.2.2	Fission track dating	267
7.2.3	(U-Th)/He dating	268
7.2.4	Trapped charge dating	269
7.2.5	Case studies	273
	References	278

<b>8. Fault sealing</b>	283
<i>Michael Kettermann, Luca Smeraglia, Christopher K. Morley, Christoph von Hagke and David C. Tanner</i>	
<b>8.1 Introduction</b>	284
<b>8.2 How does a fault seal?</b>	285
<b>8.3 General tools for fault seal analysis</b>	287
8.3.1 2D juxtaposition and Allan maps	288
8.3.2 Juxtaposition diagrams	288
<b>8.4 Fault sealing in siliciclastic rocks</b>	291
8.4.1 Clay smear	292
8.4.2 Deformation bands	293
8.4.3 Fault seal predicting algorithms	294
8.4.4 Fault permeability from fault seal algorithms	298
8.4.5 Clay injection and mechanical clay injection potential (MCIP)	300
8.4.6 Assessing fault reactivation and seal breach risk	301
8.4.7 Analogue and numerical experiments of fault clay smear	303
<b>8.5 Fault sealing in carbonates</b>	311
8.5.1 Introduction	311
8.5.2 Fault processes in low-porosity carbonates	311
8.5.3 Faulting processes in high-porosity carbonates	316
8.5.4 Carbonate faults cutting through heterogeneous stratigraphy	316
8.5.5 Normal, thrust, and strike-slip fault architectures in carbonates	318
8.5.6 Fault permeability, fluid circulation, and seal in carbonate hydrocarbon reservoirs	319
<b>8.6 Evaporites and fault seals</b>	320
<b>8.7 Case studies of fault seal</b>	321
8.7.1 The Molasse Basin in Germany and the Rhenish Massif	321
8.7.2 Inboard area of the Baram Delta Province, NW Borneo	326
8.7.3 Clay smears in aquifers of the Lower Rhine Embayment	336
<b>References</b>	339
 Conclusions	 351
Index	355