

# Contents

<i>Preface</i>	<b>xvii</b>
<i>Acknowledgments</i>	<b>xxii</b>
<i>About the authors</i>	<b>xxiii</b>
<i>Glossary of main symbols</i>	<b>xxiv</b>
<i>Unit conversion factors</i>	<b>xxv</b>
<b>1 Introduction and overview</b>	<b>1</b>
1.1 Geophysics for exploration and drilling . . . . .	1
1.2 Conventional borehole seismic methods . . . . .	3
1.2.1 Vertical Seismic Profile . . . . .	3
1.2.2 Typical acquisition geometries of conventional VSP . . . . .	5
1.2.3 Conventional processing of VSP data . . . . .	6
1.2.4 Other uses of conventional VSP . . . . .	10
1.2.5 Synthetic seismogram . . . . .	12
1.2.6 Integrated interpretation of well seismic data . . . . .	14
1.3 Motivation for seismic while drilling . . . . .	14
1.4 History of the use of the drill-bit signal . . . . .	17
1.5 Overview of the different approaches to SWD . . . . .	20
1.6 Seismic-while-drilling method . . . . .	21
1.7 Main products obtainable while drilling . . . . .	24
1.8 Measurement while drilling and SWD perspectives . . . . .	24
<b>2 Principles of drilling</b>	<b>27</b>
2.1 Introduction . . . . .	27
2.2 Drilling a well . . . . .	27
2.3 Main well components . . . . .	28
2.3.1 Drilling site . . . . .	28
2.3.2 Derrick . . . . .	29
2.3.3 Rig power system . . . . .	32
2.3.4 Drawwork . . . . .	32
2.3.5 Rope lines . . . . .	32
2.3.6 Mobile-hoisting block . . . . .	33

2.3.7	Rotary systems . . . . .	33
2.3.8	Drilling floor or rotary kelly-bush level . . . . .	39
2.3.9	Wellhead and blow out preventers . . . . .	40
2.3.10	Drill string . . . . .	40
2.3.11	The bit . . . . .	45
2.3.12	Casing . . . . .	51
2.3.13	Pumps . . . . .	51
2.3.14	Drilling mud . . . . .	53
2.3.15	Mud circulating line . . . . .	55
2.3.16	Logistics and laboratories . . . . .	55
2.3.17	Drilling parameters and mudlogging . . . . .	57
2.3.18	Measurement while drilling and mud-pulse telemetry . . . . .	58
2.3.19	Logging while drilling . . . . .	59
2.3.20	Wellsite communication systems . . . . .	60
2.4	Drilling offshore . . . . .	61
2.5	Directional and deviated wells . . . . .	62
2.5.1	Directional drilling . . . . .	64
2.5.2	Horizontal and extended-reach drilling . . . . .	67
2.5.3	Multi-lateral wells . . . . .	69
2.5.4	Steering of drilling . . . . .	69
2.5.5	Slim holes and coil tubing . . . . .	69
2.6	Designing a well . . . . .	70
2.6.1	Evaluation of the borehole pressure . . . . .	72
2.6.2	Selection of the casing depths (seats) . . . . .	73
2.6.3	Design of the mud plan and subsurface well control . . . . .	73
2.6.4	Design of the bottom-hole assembly . . . . .	75
2.6.5	BHA rigidity and drill-string stabilization . . . . .	76
2.6.6	Stiffness of the drill collars . . . . .	80
2.6.7	Bit planning . . . . .	85
2.7	Classification of drill-bit types . . . . .	89
2.7.1	Roller-bit classification according to IADC . . . . .	89
2.7.2	Diamond bit classification . . . . .	91
<b>3</b>	<b>General theory: drill-bit seismic waves</b>	<b>93</b>
3.1	Introduction . . . . .	93
3.2	Reciprocity principle . . . . .	94
3.3	Normal while-drilling VSP . . . . .	95
3.3.1	Seismic measurement while drilling SMWD . . . . .	95
3.4	Drill-bit seismic source . . . . .	97
3.4.1	Drill-bit signal characterization . . . . .	97
3.5	Total drilling power . . . . .	98
3.5.1	Energy losses for drill-string torque friction . . . . .	99
3.5.2	Effects of drag friction . . . . .	99
3.5.3	Downhole motor drilling . . . . .	100
3.6	Energy analysis in terms of drilling parameters . . . . .	100

3.6.1	Specific energy – required to drill a unit volume of rock . . . . .	100
3.6.2	“ <i>Perfect-cleaning</i> ” theory of drilling . . . . .	101
3.6.3	Dimensionless drilling parameters . . . . .	102
3.6.4	Rotary-drilling model (dimensionless parameters) . . . . .	102
3.7	Energy balance in rock fracture . . . . .	103
3.7.1	New-surface energy . . . . .	104
3.7.2	“ <i>Elastic-strain</i> ” (heat) energy . . . . .	104
3.7.3	Stress waves produced in loading/unloading . . . . .	105
3.8	Radiation of energy from the bit (far-field effects) . . . . .	107
3.8.1	Radiation from a surface harmonic force . . . . .	109
3.8.2	Radiation from a downhole harmonic force . . . . .	110
3.8.3	Integrated downhole-radiation impedance . . . . .	113
3.8.4	Total $P+SV$ power radiated in the formation . . . . .	114
3.8.5	Radiation from a non-harmonic force. . . . .	115
3.9	Near-field effects . . . . .	115
3.9.1	Phase of the harmonic wave components . . . . .	117
3.9.2	Near-field axial displacement . . . . .	118
3.9.3	Energy flux and near-field effects . . . . .	120
3.9.4	Complex impedance . . . . .	121
3.9.5	Waves from a pressure source at the origin . . . . .	122
3.9.6	Relation between rotary-drilling power and radiated power . . . . .	123
3.10	Balance of the borehole and radiated power . . . . .	124
3.10.1	Measuring the power of axial drill-string waves . . . . .	127
3.11	Drill bit versus conventional seismic sources . . . . .	128
3.12	Roller-cone bit as a periodic vibration source . . . . .	129
3.12.1	Vibrations induced by teeth indentation . . . . .	130
3.12.2	Vibrations induced by lobed patterns . . . . .	132
3.12.3	Pore pressure and roller-cone bit forces . . . . .	135
3.12.4	Effects of teeth wear on roller-cone vibrations . . . . .	139
3.13	Roller-cone bit as a wideband seismic source . . . . .	140
3.13.1	Unevenness of the formation, random breakage process . . . . .	140
3.13.2	Bandwidth amplification by vibration-mode coupling . . . . .	142
3.13.3	Roller-cone bit as a high-frequency source . . . . .	144
3.14	PDC bit as a vibration source . . . . .	144
3.15	Analysis of PDC single-cutter forces . . . . .	144
3.15.1	Direction of single-cutter force . . . . .	146
3.15.2	Influence of wear on PDC performance parameters . . . . .	146
3.15.3	Influence of downhole pressure on cutter forces . . . . .	147
3.16	Dynamic variation of PDC-cutter forces . . . . .	147
3.16.1	Dynamic models of the PDC axial vibrations . . . . .	149
3.17	Summary of large bit-vibration modes . . . . .	150
3.18	Bit vibrations induced by mud pressure modulation . . . . .	150
3.19	Numerical examples of drill-bit vibrations . . . . .	152
3.20	Radiation properties of conventional sources . . . . .	155
3.20.1	Vibroiseis source . . . . .	155

3.20.2	Radiation from marine sources . . . . .	157
3.21	Radiation from drill-bit and conventional sources . . . . .	158
<b>4</b>	<b>General theory: drill-string waves and noise fields</b>	<b>163</b>
4.1	Introduction: drill-string vibration analysis . . . . .	163
4.2	Drill-string waves . . . . .	164
4.2.1	Axial drill-string waves . . . . .	165
4.2.2	Torsional drill-string waves . . . . .	167
4.2.3	Transversal and flexural drill-string waves . . . . .	168
4.2.4	Coupled extensional and flexural drill-string waves . . . . .	170
4.3	Attenuation of extensional waves . . . . .	170
4.3.1	Attenuation of vibrations by shock absorbers . . . . .	171
4.4	Waves in <i>periodic</i> and <i>non-periodic</i> drill strings . . . . .	174
4.4.1	Wave propagation in <i>periodic</i> strings . . . . .	174
4.4.2	Wave propagation in <i>non-periodic</i> strings . . . . .	177
4.4.3	Group velocity in <i>non-periodic</i> string . . . . .	177
4.4.4	Average drill-string properties . . . . .	178
4.4.5	Group velocity at low frequency . . . . .	180
4.5	Drill-bit mud waves . . . . .	181
4.5.1	Acoustic properties of drilling mud . . . . .	182
4.5.2	Velocities of the acoustic mud waves . . . . .	183
4.5.3	Sensitivity analysis for acoustic mud velocity . . . . .	183
4.5.4	Velocities of the guided waves . . . . .	185
4.5.5	Sensitivity analysis for velocity of mud guided waves . . . . .	186
4.6	Coupled pipe-mud-formation guided waves . . . . .	187
4.6.1	Conical head waves in the formation (borehole radiation) . . . . .	189
4.7	Summary of drill string waves . . . . .	190
4.8	Surface/rigsite noise wavefields . . . . .	191
4.9	Drill-string noise and borehole interactions . . . . .	193
4.10	Drill-string transmission line . . . . .	198
4.10.1	Reflection coefficients in the drill string . . . . .	199
4.11	Bit/rock reflection coefficient . . . . .	201
4.11.1	Bit/rock reflection coefficient (plane-wave approximation) . . . . .	202
4.11.2	Complex bit/rock reflection coefficient (near-field approximation) . . . . .	204
4.11.3	Drill-string waves and near-field effects . . . . .	204
4.12	Dual fields in the drill string . . . . .	208
4.12.1	Dual (displacement and strain) reflection coefficients . . . . .	209
4.12.2	Dual fields in the drill-string transmission line . . . . .	212
<b>5</b>	<b>Acquisition of SWD data</b>	<b>213</b>
5.1	Introduction . . . . .	213
5.2	Signal recognition and acquisition layout . . . . .	214
5.3	Pilot sensors and transducers . . . . .	216
5.3.1	Accelerometers . . . . .	217
5.3.2	Piezoelectric accelerometers . . . . .	220

5.3.3	Damped geophones as accelerometers . . . . .	221
5.3.4	Strain gages . . . . .	221
5.3.5	Force and pressure transducers . . . . .	222
5.3.6	Torque transducer . . . . .	224
5.4	Surface pilot sensors (rig pilots) . . . . .	224
5.4.1	Pilot sensors on the top of the drill string . . . . .	225
5.4.2	Surface pilot sensors in the rotating drill string . . . . .	227
5.5	Downhole pilot sensors . . . . .	228
5.6	Use of dual sensors in drill strings . . . . .	231
5.7	Other pilot sensors at the rig . . . . .	233
5.7.1	Connections of rig pilots to the recording system . . . . .	235
5.8	SWD data-acquisition system . . . . .	236
5.8.1	Other SWD commercial systems . . . . .	238
5.9	SWD-data acquisition and drilling control . . . . .	240
5.9.1	Automatic SWD acquisition by using drilling parameters . . . . .	242
5.10	Drilling depth and seismic depth . . . . .	245
5.11	Spatial sampling of SWD signals . . . . .	247
5.12	SWD-source pattern with bit deepening . . . . .	248
5.13	Onshore acquisition . . . . .	250
5.13.1	Seismic line . . . . .	250
5.14	Receiver arrays in SWD . . . . .	255
5.14.1	Analysis of optimum arrays . . . . .	259
5.14.2	Coherent and random noise in SWD geophone arrays . . . . .	262
5.14.3	Experiments with receiver arrays in onshore SWD . . . . .	266
5.15	Acquisition of shear and converted waves . . . . .	268
5.16	Survey preparation procedures . . . . .	270
5.16.1	Refraction statics for seismic while drilling . . . . .	270
5.16.2	Field statics in SWD arrays . . . . .	272
5.17	Survey operations . . . . .	275
5.18	Summary of quality-control procedures . . . . .	276
5.19	Onshore 3D-SWD acquisition . . . . .	281
5.20	Offshore acquisition . . . . .	282
5.20.1	Offshore SWD application (using <i>fixed</i> receivers) . . . . .	284
5.20.2	Extension of offshore SWD (using <i>towed streamers</i> ) . . . . .	288
<b>6</b>	<b>Preprocessing of SWD data</b> . . . . .	<b>291</b>
6.1	Introduction . . . . .	291
6.2	Preprocessing . . . . .	291
6.3	SWD data in the crosscorrelated domain . . . . .	292
6.3.1	Basic crosscorrelation properties . . . . .	292
6.3.2	Energy in crosscorrelation . . . . .	294
6.3.3	Delays in crosscorrelation . . . . .	294
6.3.4	Crosscorrelation and filtering . . . . .	295
6.3.5	Crosscorrelation of signal and noise . . . . .	299
6.4	Stack of while-drilling data . . . . .	301

6.5	Deconvolution of the drill-bit source function . . . . .	303
6.6	Pilot deconvolution . . . . .	306
6.6.1	Crosscorrelation, stack and pilot deconvolution . . . . .	307
6.7	Discussion about pilot deconvolution . . . . .	308
6.8	Beam-steering deconvolution . . . . .	309
6.8.1	Focused pilot . . . . .	309
6.8.2	Optimum beam forming of the drill-bit signature . . . . .	312
6.8.3	Autocorrelation bias . . . . .	313
6.9	Deconvolution in rotation-angle domain . . . . .	314
6.9.1	Analysis of synthetic and real data in rotation-angle domain . . . . .	315
6.10	Modeling of drill-string response . . . . .	315
6.10.1	Propagation matrix for drill-bit signal . . . . .	315
6.10.2	Propagation matrix for rig noise . . . . .	317
6.10.3	Reflection coefficients in two-way travel time (TWT) . . . . .	318
6.11	Fitting with real data . . . . .	319
6.12	Drill-string waves in the correlated and deconvolved data . . . . .	321
6.13	Interpretation of drill-string multiples . . . . .	324
6.13.1	Drill-string multiples in pilot data . . . . .	324
6.13.2	Drill-string multiples in geophone data . . . . .	326
6.14	Rig ghost . . . . .	327
6.15	Processing of dual drill-string wavefields . . . . .	329
6.15.1	Synthetic dual wavefields . . . . .	329
6.15.2	Real examples with axial dual waves . . . . .	330
6.15.3	Deconvolution of pilot dual fields . . . . .	333
6.16	Pilot-delay correction . . . . .	334
6.17	Signal rephasing . . . . .	336
6.18	Example of preprocessing parameters . . . . .	340
<b>7</b>	<b>Processing of signal and noise RVSP fields</b>	<b>345</b>
7.1	Introduction . . . . .	345
7.2	Entropy and repeatability of the drill-bit source . . . . .	345
7.3	Common-level stack of correlations with noise . . . . .	347
7.3.1	Vertical-stack model . . . . .	348
7.3.2	Optimum weights (general case) . . . . .	350
7.3.3	Special cases of level stack . . . . .	351
7.4	Selective stack by drilling parameters . . . . .	352
7.5	Noise cancellation by orthogonal pilot traces . . . . .	354
7.6	Noise separation by independent pilot traces . . . . .	357
7.6.1	Uncorrelated drill-bit signal and RVSP's . . . . .	359
7.6.2	Incorrelation and independence . . . . .	359
7.6.3	Statistical independence of drill-bit data . . . . .	362
7.7	Analysis of torsional pilot waves . . . . .	365
7.8	SWD with downhole-motor drilling . . . . .	366
7.8.1	Downhole pilot signals . . . . .	368
7.8.2	Mud guided-waves pilot signals . . . . .	368

7.8.3	Interpretation of mud-guided waves . . . . .	372
7.9	RVSP processing of SWD-VSP seismograms . . . . .	375
7.9.1	Direct-arrival, First-Break picking (FB) . . . . .	375
7.9.2	Gain recovery . . . . .	376
7.9.3	Wavefield separation . . . . .	376
7.9.4	VSP deconvolution . . . . .	378
7.9.5	Velocity analysis . . . . .	380
7.10	Analysis of impulsive drill-bit signal . . . . .	380
7.11	Correction for geophone group-array filters . . . . .	386
7.12	Other SWD methods based on correlation . . . . .	386
7.12.1	Crosscorrelogram migration . . . . .	386
7.12.2	Formation analysis by pilot seismograms . . . . .	387
<b>8</b>	<b>Applications</b> . . . . .	<b>393</b>
8.1	Introduction . . . . .	393
8.2	SWD products . . . . .	394
8.2.1	Checkshot . . . . .	394
8.2.2	Reflectivity characterization . . . . .	395
8.2.3	Prediction ahead-of-the-bit . . . . .	397
8.2.4	Multioffset VSP . . . . .	398
8.2.5	Geophysical monitoring of the well . . . . .	400
8.3	Drilling and real-time migration . . . . .	400
8.4	Deviated-well monitoring . . . . .	402
8.5	Geological and lithological aspects . . . . .	404
8.5.1	SWD with different lithological conditions . . . . .	404
8.5.2	Estimating acoustic impedance from SWD data . . . . .	408
8.6	Comparison of SWD and wireline VSP results . . . . .	408
8.7	Prediction by SWD in favorable conditions . . . . .	409
8.8	SWD in geologically-complex and poor-seismic-response area . . . . .	411
8.8.1	SWD applications in the Val d'Agri . . . . .	416
8.8.2	Comparison of SWD and seismic velocities . . . . .	417
8.8.3	Prediction of acoustic interfaces ahead of the bit . . . . .	417
8.8.4	Structural reconstruction near the well by multioffset . . . . .	417
8.8.5	Isolation of zones with different pressure gradients . . . . .	422
8.8.6	Prediction by SWD-RVSP tomography . . . . .	422
8.9	Crosshole SWD seismic survey . . . . .	424
8.10	3D-RVSP application . . . . .	436
8.10.1	Modeling of 3D-SWD survey . . . . .	436
8.10.2	3D-RVSP survey organization and layout . . . . .	438
8.10.3	Azimuthal analysis of rig-radiated noise . . . . .	441
8.10.4	While-drilling analysis of 3D data . . . . .	441
8.10.5	Analysis of shear-wave data . . . . .	447
8.10.6	3D-RVSP migration of SWD data . . . . .	448
8.11	While-drilling application of 3D-RVSP imaging . . . . .	453
8.12	New trends for SWD . . . . .	454

8.12.1 SWD in deep water . . . . .	454
8.12.2 SWD in highly-deviated wells . . . . .	462
8.12.3 Geopressure prediction and assessment . . . . .	462
8.12.4 The road ahead: SWD by downhole technology . . . . .	465
8.12.5 Drilling diagnostics and geosteering . . . . .	466
8.13 Geosteering . . . . .	467
<b>Bibliography</b>	<b>469</b>
<b>Name index</b>	<b>493</b>
<b>Name index</b> . . . . .	<b>493</b>
<b>Subject index</b>	<b>501</b>
<b>Subject index</b> . . . . .	<b>501</b>