

Contents

1	Introduction	1
1.1	Origination of Well Logging	1
1.2	What Is Well Logging?	1
1.3	Development of Well Logging	3
1.3.1	Resistivity Logs	3
1.3.2	Sonic Logs	5
1.3.3	Nuclear Logging	5
1.4	Use of Logs	7
2	Electrical Logging	9
2.1	The Foundation of Electrical Resistivity	9
2.1.1	Resistivity	9
2.1.2	Archie Formula	12
2.1.3	Electrical Properties of Rocks and Brines	13
2.1.4	Borehole Environment	14
2.1.5	Conclusions	15
2.2	Spontaneous Potential Logging	15
2.2.1	The SP Log	18
2.2.2	Electrochemical Component of the SP	19
2.2.3	Spontaneous Potential (SP) Tool	21
2.2.4	R_w from the SP	23
2.2.5	Log Example of the SP	23
2.2.6	Applications of SP	25
2.3	Resistivity Logs	26
2.3.1	Normal Devices	27
2.3.2	Focused Tools	29
2.3.3	Induction Tools	35
2.3.4	Array Induction Tools (AIT)	41
2.3.5	FMI (Full Borehole Microresistivity Image Logging)	43
2.3.6	ARI (Azimuthal Resistivity Imager)	45

2.4	Dipmeter Logging.....	47
2.4.1	Principle	48
2.4.2	Measurement Process.....	48
2.4.3	SHDT	50
2.4.4	Colored Dip Patterns	51
2.4.5	Results Presentation.....	53
2.4.6	Stick Plot.....	54
2.4.7	Azimuth Frequency Plots.....	55
2.5	Summary	56
3	Sonic Logs	59
3.1	The Foundational Principle of Acoustic Logs.....	60
3.1.1	Elastic Properties of Rocks	60
3.1.2	Acoustic Waves.....	61
3.1.3	Sound Wave Propagation, Reflection, and Refraction	62
3.2	Sonic Log.....	64
3.2.1	Principle	64
3.2.2	Borehole-Compensated Sonic (BHC).....	68
3.2.3	Long Spacing Sonic (LSS)	70
3.2.4	Dipole Shear Sonic Imaging (DSI)	73
3.2.5	Interpretation	78
3.2.6	Environmental and Other Effects.....	79
3.3	Acoustic Wave Amplitude Logging	81
3.3.1	Introduction.....	81
3.3.2	Cement Bond Logging (CBL).....	81
3.3.3	Variable Density Log (VDL).....	83
3.3.4	Cement Evaluation Tool (CET).....	89
3.3.5	Segmented Bond Tool (SBT)	90
3.4	Ultrasonic Imager Logs (USI).....	90
3.5	UltraSonic Borehole Imager (UBI)	96
3.5.1	Introduction.....	96
3.5.2	Image Presentations.....	98
3.5.3	Interpretation	99
3.5.4	Applications.....	101
3.6	Circumferential Borehole Imaging Log (CBIL).....	108
3.6.1	Tools	108
3.6.2	Acoustic Imaging Tool Interpretation Generalities....	110
4	Nuclear Logs	115
4.1	Gamma Ray Logs.....	115
4.1.1	Rudimentary of Radioactivity	115
4.1.2	Radioactivity of Rocks	116
4.1.3	Interaction Between Formation and GR.....	117
4.1.4	Gamma Log.....	122

4.1.5	Spectral Gamma Ray Device	123
4.1.6	Measurement of Gamma Radiation	127
4.1.7	Applications of GR	129
4.2	Interaction Between Formation and Neutron	132
4.2.1	Fast Neutron Scattering	132
4.2.2	Thermal Neutron Interaction	134
4.3	Basic Definitions for Neutron Logging	137
4.3.1	Bulk Density (ρ_b)	137
4.3.2	Electron Density (P_e)	137
4.3.3	Photoelectric Absorption Index (P_e)	138
4.3.4	Bulk Photoelectric Absorption Index (U)	138
4.3.5	Hydrogen Index (H_x)	138
4.4	Nuclear Logging	140
4.4.1	Borehole Compensated Density Tools	140
4.4.2	Litho-Density Tool	141
4.4.3	Physical Principle of the Tool	141
4.4.4	Applications	141
4.4.5	Fluid Effects	144
4.4.6	Schlumberger Neutron Tools	145
4.4.7	CNL Log as a Gas Locator	147
4.5	Thermal Neutron Decay Time Logs	151
4.5.1	Introduction	151
4.5.2	Measurement Principle	152
4.5.3	Log-Inject-Log	154
4.5.4	Log Presentation	154
4.6	C/O	155
5	Nuclear Magnetic Resonance	161
5.1	Fundamental of Nuclear Magnetic Resonance (NMR)	161
5.1.1	Longitudinal Relaxation, T_1	163
5.1.2	Transverse Relaxation, T_2 , and Spin Dephasing	164
5.1.3	Spin Echoes	164
5.1.4	Relaxation and Diffusion in Magnetic Gradients	166
5.2	A Brief History of Nuclear Magnetic Resonance Tool	168
5.3	LWD NMR	168
5.4	Applications of Nuclear Magnetic Resonance	170
5.4.1	Porosity and Free Fluid Porosity	173
5.4.2	Pore Size Distribution and Permeability Estimation	176
5.5	Summary	178
6	Production Logging (PL)	181
6.1	Definition Production Logging	181
6.2	Spinner Flowmeter Logging	183

6.3	Fluid-Identification Logs	187
6.3.1	Fluid-Density Logs	188
6.3.2	Gradiomanometer Tool	188
6.3.3	Nuclear Fluid-Density	189
6.3.4	Temperature Tools	190
6.3.5	Capacitance Logs	193
6.3.6	Radioactive Water-Hold up Log	193
6.4	Radioactive-Tracer Logging	193
6.4.1	Introduction	193
6.4.2	Tools and Operations	194
6.4.3	Running a Tracer-Loss Log	195
6.4.4	Tracer-Loss Log Interpretation	196
6.5	Other Production Well Logging	197
6.5.1	Pulsed Neutron Logs for Flow Profiling	197
6.5.2	Repeat Formation Tester	199
7	Logging-While-Drilling (LWD)	211
7.1	What Is MWD/LWD?	211
7.2	Schlumberger Scope LWD Series	213
7.2.1	EcoScope	213
7.2.2	PeriScope	215
7.2.3	StethoScope	216
7.3	LWD Technology of Halliburton	217
7.4	Integrated MWD and LWD Instruments of Baker Hughes	219
7.4.1	AziTrak Deep Azimuthal Resistivity LWD System	219
7.4.2	OnTrak Integrated MWD and LWD System	221
7.5	Resistivity Measurements While Drilling	222
7.5.1	Resistivity at the Bit	222
7.5.2	Azimuthal Measurements	225
7.6	Density Measurements While Drilling	226
7.7	Nuclear Measurements While Drilling	229
7.8	Sonic Measurements While Drilling	232
7.9	Geosteering	233
8	Rock Mechanics	237
8.1	Basic Stress and Strain Analysis	238
8.1.1	Static Stress and Strain Relation	238
8.1.2	Parameters of Rock Elastic Properties	241
8.2	Natural Fracture Classification and Stress Analysis	243
8.2.1	Natural Fractures	244
8.2.2	Geological Classifications of Natural Fractures	244
8.2.3	Fracture Detection	246
8.2.4	Visual Identification of Fractures	253

8.3	Critical Pressure and Stress Relationship in the Borehole	254
8.3.1	Mohr–Coulomb Failure Criterion.	255
8.3.2	Stress Relationship at the Wellbore	257
8.3.3	Estimating Critical Borehole Pressure in Vertical Wells	258
8.3.4	Critical Pore Pressure	259
8.3.5	Porosity as Strength Indicator to Evaluate Sand Production	260
8.3.6	Estimation of Unconfined Compressive Rock Strength from Porosity Data	261
8.4	Rock Drillability	261
8.4.1	Technical Steps: Determination of Lithology.	263
8.4.2	Rock Strength from Sonic Log	265
8.5	Borehole Stability	267
9	The Advanced Well Logging Technology	271
9.1	Eclips-5700.	271
9.1.1	Eclips-5700 Well Logging System	271
9.1.2	Eclips-5700 Imaging Logging Instrument	273
9.2	Excell-2000 Well Logging System	275
9.2.1	System Software	276
9.2.2	System Configuration	277
9.2.3	System Features.	277
9.2.4	Applications.	278
9.3	Sondex Production Logging System	278
9.3.1	Flowmeter	278
9.3.2	Single Gauge Quartz Pressure Tool (QPS)	281
9.3.3	Platinum Resistance Thermometer (PRT)	281
9.3.4	Enhanced Capacitance Water Holdup Tool (CWH)	282
9.3.5	Fluid Density Radioactive (FDR)	282
9.3.6	Multifinger Imaging Tool (MIT 60 Finger)	283
9.4	Cased-Hole Resistivity Measurements (CHFR).	284
10	Integrated Interpretation of Well Logging Data	289
10.1	Reservoir Classification.	290
10.2	Formation Evaluation	296
10.2.1	Identification of Permeable and Non-permeable Zones from Logs	296
10.2.2	Determine and Divide the Formations into Water Bearing and Hydrocarbon	297
10.3	Method to Determine Lithology: $M-N$ PLOT.	298
10.4	U_{maa} MID Plot	299
10.5	Resistivity Versus Porosity Crossplot (Pickett Map).	301

10.6	Porosity Determination in Complex Conditions	302
10.6.1	Neutron-Density Crossplots	303
10.6.2	Sonic-Neutron Crossplots	304
10.6.3	Sonic-Density Crossplot.	304
10.7	Resistivity Ratio Methods to Identify Fluid Type	307
10.8	Permeability Calculation	313
10.8.1	Permeability from POR	314
10.8.2	Permeability from NMR	314
10.8.3	Permeability from the RFT	315
10.9	Structure Analysis.	316
10.9.1	Tensile Stress.	316
10.9.2	Compressive Stress	317
10.9.3	Structural Analysis from Dipmeters.	318
10.10	Multi-well Integrated Interpretation.	319
Appendix A: Vocabulary		325
Appendix B: Nomenclature (名词术语)		343
Appendix C: Conversion Factors and Tables		347
Appendix D: Typical Parameters' Physical Value		349
References		351