
Contents

1	Introduction	1
1.1	Objectives and Approach	1
1.2	Scope of Resource Modeling	2
1.3	Critical Aspects	2
1.3.1	Data Assembly and Data Quality	2
1.3.2	Geologic Model and Definition of Estimation Domains	3
1.3.3	Quantifying Spatial Variability	4
1.3.4	Geologic and Mining Dilution	4
1.3.5	Recoverable Resources: Estimation	5
1.3.6	Recoverable Resources: Simulation	5
1.3.7	Validation and Reconciliation	6
1.3.8	Resource Classification	6
1.3.9	Optimal Drill Hole Spacing	7
1.3.10	Medium- and Short-term Models	7
1.3.11	Grade Control	8
1.4	Historical Perspective	8
	References	8
2	Statistical Tools and Concepts	11
2.1	Basic Concepts	11
2.2	Probability Distributions	12
2.2.1	Univariate Distributions	12
2.2.2	Parametric and Non-parametric Distributions	14
2.2.3	Quantiles	15
2.2.4	Expected Values	16
2.2.5	Extreme Values—Outliers	16
2.2.6	Multiple Variable Distributions	16
2.3	Spatial Data Analysis	18
2.3.1	Declustering	19
2.3.2	Declustering with Multiple Variables	20
2.3.3	Moving Windows and Proportional Effect	20
2.3.4	Trend Modeling	21
2.4	Gaussian Distribution and Data Transformations	22
2.5	Data Integration and Inference	23
2.6	Exercises	25
2.6.1	Part One: Calculus and Algebra	25
2.6.2	Part Two: Gaussian Distribution	25
2.6.3	Part Three: Uniform Distribution	25

2.6.4	Part Four: Small Declustering.....	26
2.6.5	Part Five: Large Declustering	26
	References.....	26
3	Geological Controls and Block Modeling	29
3.1	Geological and Mineralization Controls.....	29
3.2	Geologic Interpretation and Modeling.....	32
3.2.1	Distance Functions and Tonnage Uncertainty	35
3.2.2	Geostatistical Geologic Modeling.....	38
3.3	Visualization.....	38
3.3.1	Scale.....	39
3.3.2	Data	41
3.4	Block Model Setup and Geometry.....	41
3.4.1	Coordinate Systems	41
3.4.2	Stratigraphic Coordinates.....	42
3.4.3	Block Models	43
3.4.4	Block Size	44
3.4.5	Block Model Geometry	45
3.4.6	Block Model Volume and Variables.....	46
3.5	Summary of Minimum, Good and Best Practices.....	46
3.6	Exercises	48
3.6.1	Part One: Vein Type Modeling.....	48
3.6.2	Part Two: Coordinate Systems	49
	References.....	50
4	Definition of Estimation Domains	51
4.1	Estimation Domains	51
4.2	Defining the Estimation Domains	52
4.3	Case Study: Estimation Domains Definition for the Escondida Mine.....	53
4.3.1	Exploratory Data Analysis of the Initial Database.....	53
4.3.2	Initial Definition of Estimation Domains	55
4.3.3	Tcu Grade Correlogram Models by Structural Domains.....	58
4.3.4	Final Estimation Domains	59
4.4	Boundaries and Trends.....	59
4.5	Uncertainties Related to Estimation Domain Definition	63
4.6	Summary of Minimum, Good and Best Practices.....	63
4.7	Exercises	64
4.7.1	Part One: Basic Statistics.....	64
4.7.2	Part Two: 2-D Trend Modeling.....	64
4.7.3	Part Three: 3-D Trend Modeling.....	65
	References.....	65
5	Data Collection and Handling.....	67
5.1	Data	67
5.1.1	Location of Drill Holes, Trenches, and Pits.....	67
5.1.2	Sampling Methods and Drilling Equipment Used.....	68
5.1.3	Relative Quality of Each Drill Hole or Sample Type.....	69
5.1.4	Sampling Conditions	69
5.1.5	Core and Weight Sample Recoveries	69
5.1.6	Sample Collection and Preparation Procedures.....	70
5.1.7	Geologic Mapping and Logging Procedures.....	70
5.1.8	Sample Preparation and Assaying Procedures.....	70
5.1.9	Sampling Database Construction	72

5.2	Basics of Sampling Theory	72
5.2.1	Definitions and Basic Concepts.....	72
5.2.2	Error Basics and Their Effects on Sample Results	73
5.2.3	Heterogeneity and the Fundamental Error.....	73
5.3	Liberation Size Method	74
5.3.1	Fundamental Sample Error, FE	74
5.3.2	The Nomograph	74
5.3.3	Nomograph Construction	75
5.3.4	Sampling Fundamental Error	76
5.3.5	Segregation or Distribution Heterogeneity	76
5.3.6	Delimitation and Extraction Errors.....	76
5.3.7	Preparation Error.....	76
5.4	Sampling Quality Assurance and Quality Control	77
5.4.1	General Principles.....	77
5.4.2	Elements of a QA/QC Program.....	78
5.4.3	Insertion Procedures and Handling of Check Material.....	79
5.4.4	Evaluation Procedures and Acceptance Criteria	80
5.4.5	Statistical and Graphical Control Tools	80
5.5	Variables and Data Types.....	82
5.5.1	Raw and Transformed Variables	82
5.5.2	Soft Data	83
5.5.3	Compositional Data	83
5.5.4	Service Variables	87
5.6	Compositing and Outliers.....	89
5.6.1	Drill Hole Composites	89
5.6.2	Composite Lengths and Methods.....	89
5.6.3	Outliers.....	90
5.7	Density Determinations.....	91
5.8	Geometallurgical Data.....	93
5.9	Summary of Minimum, Good and Best Practices	93
5.10	Exercises.....	94
5.10.1	Part One: Prerequisites for the Sampling Nomograph.....	94
5.10.2	Part Two: Nomograph Construction and Fundamental Error.....	95
	References.....	95
6	Spatial Variability	97
6.1	Concepts.....	97
6.2	Experimental Variograms and Exploratory Analysis	99
6.2.1	Other Continuity Estimators	102
6.2.2	Inference and Interpretation of Variograms	103
6.3	Modeling 3-D Variograms	104
6.3.1	Commonly Used Variogram Models.....	105
6.3.2	Basic Variogram Modeling Guidelines.....	106
6.3.3	Goodness of Variogram Fit and Cross Validation.....	109
6.4	Multivariate Case.....	111
6.5	Summary of Minimum, Good and Best Practice	112
6.6	Exercises	113
6.6.1	Part One: Hand Calculations	114
6.6.2	Part Two: Small Set of Data.....	114
6.6.3	Part Three: Large Set of Data	114
6.6.4	Part Four: Cross Variograms.....	115
6.6.5	Part Five: Indicator Variograms for Continuous Data	115
	References.....	115

7 Mining Dilution	117
7.1 Recoverable Versus In-Situ Resources	117
7.2 Types of Dilution and Ore Loss	119
7.3 Volume-Variance Correction	122
7.3.1 Affine Correction	124
7.3.2 Indirect Log-normal Correction	124
7.3.3 Other Permanence of Distribution Models	125
7.3.4 Discrete Gaussian Method	125
7.3.5 Non-Traditional Volume-Variance Correction Methods	126
7.3.6 Restricting the Kriging Plan	126
7.3.7 Probabilistic Estimation Methods	127
7.3.8 Common Applications of Volume-Variance Correction Methods	127
7.4 Information Effect	128
7.5 Summary of Minimum, Good and Best Practices	130
7.6 Exercises	131
7.6.1 Part One: Assemble Variograms and Review Theory	131
7.6.2 Part Two: Average Variogram Calculation	131
7.6.3 Part Three: Change of Shape Models	132
References	132
8 Recoverable Resources: Estimation	133
8.1 Goals and Purpose of Estimation	133
8.1.1 Conditional Bias	133
8.1.2 Volume Support of Estimation	135
8.1.3 Global and Local Estimation	135
8.1.4 Weighted Linear Estimation	136
8.1.5 Traditional Estimation Methods	136
8.1.6 Classic Polygonal Method	136
8.1.7 Nearest-Neighbor Method	136
8.1.8 Inverse Distance Weighting	137
8.2 Kriging Estimators	138
8.2.1 Simple Kriging	138
8.2.2 Ordinary Kriging	139
8.2.3 Kriging with a Trend	140
8.2.4 Local Varying Mean	142
8.2.5 Random Trend Model	142
8.2.6 Kriging the Trend and Filtering	142
8.2.7 Kriging with an External Drift	142
8.3 Cokriging	143
8.3.1 Simple Cokriging	143
8.3.2 Ordinary Cokriging	144
8.3.3 Collocated Cokriging	145
8.3.4 Collocated Cokriging Using Bayesian Updating	145
8.3.5 Compositional Data Interpolation	145
8.3.6 Grade-Thickness Interpolation	146
8.4 Block Kriging	147
8.5 Kriging Plans	147
8.6 Summary of Minimum, Good and Best Practices	148
8.7 Exercises	148
8.7.1 Part One: Kriging Theory	148
8.7.2 Part Two: Kriging by Hand Question	149
8.7.3 Part Three: Conditional Bias	149
8.7.4 Part Four: Kriging a Grid	149
References	149

9 Recoverable Resources: Probabilistic Estimation	151
9.1 Conditional Distributions	151
9.2 Gaussian-Based Kriging Methods	152
9.2.1 Multi-Gaussian Kriging.....	152
9.2.2 Uniform Conditioning	152
9.2.3 Disjunctive Kriging	155
9.2.4 Checking the Multivariate Gaussian Assumption	155
9.3 Lognormal Kriging.....	156
9.4 Indicator Kriging	156
9.4.1 Data Integration.....	157
9.4.2 Simple and Ordinary IK with Prior Means	157
9.4.3 Median Indicator Kriging.....	158
9.4.4 Using Inequality Data.....	159
9.4.5 Using Soft Data.....	159
9.4.6 Exactitude Property of IK	159
9.4.7 Change of Support with IK	159
9.5 The Practice of Indicator Kriging.....	160
9.6 Indicator Cokriging	162
9.7 Probability Kriging.....	163
9.8 Summary of Minimum, Good and Best Practices	163
9.9 Exercises	164
9.9.1 Part One: Indicator Kriging	164
9.9.2 Part Two: MG Kriging for Uncertainty.....	164
References.....	165
 10 Recoverable Resources: Simulation	 167
10.1 Simulation versus Estimation	167
10.2 Continuous Variables: Gaussian-Based Simulation.....	168
10.2.1 Sequential Gaussian Simulation	169
10.2.2 Turning Bands.....	171
10.2.3 LU Decomposition	172
10.2.4 Direct Sequential Simulation.....	173
10.2.5 Direct Block Simulation	174
10.2.6 Probability Field Simulation.....	174
10.3 Continuous Variables: Indicator-Based Simulation	176
10.4 Simulated Annealing.....	176
10.5 Simulating Categorical Variables.....	179
10.5.1 SIS For Discrete Variables.....	179
10.5.2 Truncated Gaussian.....	180
10.5.3 Truncated PluriGaussian.....	180
10.6 Co-Simulation: Using Secondary Information and Joint Conditional Simulations	182
10.6.1 Indicator-Based Approach.....	182
10.6.2 Markov-Bayes Model.....	183
10.6.3 Soft Data Calibration	183
10.6.4 Gaussian Cosimulation	184
10.6.5 Stepwise Conditional Transform	184
10.6.6 Super-Secondary Variables.....	186
10.6.7 Simulation Using Compositional Kriging	187
10.7 Post Processing Simulated Realizations.....	187
10.8 Summary of Minimum, Good and Best Practices	188
10.9 Exercises	189
10.9.1 Part One: Sequential Indicator Simulation	189
10.9.2 Part Two: Sequential Gaussian Simulation	190

10.9.3 Part Three: Simulation with 3D Data.....	191
10.9.4 Part Four: Special Topics in Simulation.....	191
References.....	191
11 Resource Model Validations and Reconciliations.....	193
11.1 The Need for Checking and Validating the Resource Model.....	193
11.2 Resource Model Integrity.....	193
11.2.1 Field Procedures.....	194
11.2.2 Data Handling and Processing.....	194
11.3 Resampling.....	195
11.3.1 Cross-Validation.....	195
11.4 Resource Model Validation.....	196
11.4.1 Geological Model Validation.....	197
11.4.2 Statistical Validation.....	197
11.4.3 Graphical Validation.....	198
11.5 Comparisons with Prior and Alternate Models.....	201
11.6 Reconciliations.....	202
11.6.1 Reconciling against Past Production.....	202
11.6.2 Suggested Reconciliation Procedures.....	203
11.7 Summary of Minimum, Good and Best Practices.....	206
11.8 Exercises.....	207
11.8.1 Part One: Cross Validation.....	207
11.8.2 Part Two: Checking Simulation.....	207
References.....	207
12 Uncertainty and Risk.....	209
12.1 Models of Uncertainty.....	209
12.2 Assessment of Risk.....	210
12.3 Resource Classification and Reporting Standards.....	213
12.3.1 Resource Classification based on Drill Hole Distances.....	217
12.3.2 Resource Classification Based on Kriging Variances.....	217
12.3.3 Resource Classification Based on Multiple-Pass Kriging Plans.....	218
12.3.4 Resource Classification Based on Uncertainty Models.....	218
12.3.5 Smoothing and Manual Interpretation of Resource Classes.....	219
12.4 Summary of Minimum, Good and Best Practices.....	219
12.5 Exercises.....	220
12.5.1 Part One: Sampling Uncertainty.....	220
12.5.2 Part Two: Loss Functions.....	221
References.....	221
13 Short-term Models.....	223
13.1 Limitations of Long-term Models for Short-term Planning.....	223
13.2 Medium- and Short-term Modeling.....	224
13.2.1 Example: Quarterly Reserve Model, Escondida Mine.....	224
13.2.2 Updating the Geologic Model.....	225
13.3 Selection of Ore and Waste.....	226
13.3.1 Conventional Grade Control Methods.....	230
13.3.2 Kriging-based Methods.....	230
13.3.3 Example Grade Control.....	231
13.4 Selection of Ore and Waste: Simulation-based Methods.....	234
13.4.1 Maximum Revenue Grade Control Method.....	235
13.4.2 Multivariate Cases.....	236
13.5 Practical and Operational Aspects of Grade Control.....	236

13.6 Summary of Minimum, Good and Best Practices	237
13.7 Exercises.....	238
References.....	239
14 Case Studies	241
14.1 The 2003 Cerro Colorado Resource Model	241
14.1.1 Geologic Setting	241
14.1.2 Lithology.....	241
14.1.3 Alteration	243
14.1.4 Mineralization Types.....	243
14.1.5 Structural Geology	244
14.1.6 Database.....	244
14.1.7 Estimation Domain Definition	245
14.1.8 Database Checking and Validation.....	246
14.1.9 Comparison of Drill Hole Types.....	247
14.1.10 Laboratory Quality Assurance–Quality Control (QA-QC).....	248
14.1.11 Topography.....	248
14.1.12 Density	248
14.1.13 Geologic Interpretation and Modeling.....	249
14.1.14 Volumetric and Other Checks	249
14.1.15 Exploratory Data Analysis	250
14.1.16 Comparison Between Composites and Blast Hole Data	252
14.1.17 Contact Analysis.....	252
14.1.18 Correlogram Models.....	253
14.1.19 Change of Support to Estimate Internal Dilution	253
14.1.20 Predicted Grade-Tonnage Curves for TCu, Cerro Colorado	254
14.1.21 The Cerro Colorado 2003 Resource Block Model.....	256
14.1.22 The Grade Model	256
14.1.23 Resource Classification	258
14.1.24 Estimation of Geometallurgical Units	259
14.1.25 Estimation of OXSI/OXSA and of SNSI/SNSA.....	259
14.1.26 Estimation of Point Load	262
14.1.27 Resource Model Calibration	263
14.1.28 Statistical Validation of the Resource Model	263
14.1.29 Visual Validation of the Resource Model	265
14.2 Multiple Indicator Kriging, São Francisco Gold Deposit	265
14.2.1 Database and Geology	265
14.2.2 Geologic Modeling	266
14.2.3 Class Definition for Multiple Indicator Kriging.....	266
14.2.4 Indicator Variograms	267
14.2.5 Volume-Variance Correction	270
14.2.6 Block Model Definition and Multiple Indicator Kriging	270
14.2.7 MIK Kriging Plans and Resource Categorization	271
14.2.8 MIK Resource Model: Grade-Tonnage Curves	271
14.3 Modeling Escondida Norte’s Oxide Units with Indicators	272
14.4 Multivariate Geostatistical Simulation at Red Dog Mine.....	276
14.4.1 Geology and Database	277
14.4.2 Multivariate Simulation Approach	278
14.4.3 Profit Comparison	280
14.4.4 Profit Function.....	281
14.4.5 Reference Data	282
14.4.6 Model Construction	284
14.4.7 Results	285

14.5 Uncertainty Models and Resource Classification:	
The Michilla Mine Case Study	285
14.5.1 The Lince-Estefanía Mine	287
14.5.2 Developing the Model of Uncertainty	288
14.5.3 Indicator Variograms for TCu and by Geologic Unit	289
14.5.4 Conditional Simulation Model	289
14.5.5 Probability Intervals by Area	290
14.5.6 Results	295
14.6 Grade Control at the San Cristóbal Mine	296
14.6.1 Geologic Setting	297
14.6.2 Maximum Revenue (MR) Grade Control Method	297
14.6.3 Implementation of the MR Method	299
14.6.4 Results	300
14.7 Geometallurgical Modeling at Olympic DAM, South Australia	301
14.7.1 Part I: Hierarchical Multivariate Regression for Mineral Recovery and Performance Prediction	301
14.7.2 Methodology	302
14.7.3 Analysis	305
14.7.4 Part II: Multivariate Compositional Simulation of Non-additive Geometallurgical Variables	310
14.7.5 Modeling 23 Head Grade Variables	310
14.7.6 Details of the Sequential Gaussian Simulation	311
14.7.7 Modeling Nine Grain Size Variables	314
14.7.8 Modeling 100 Association Matrix Variables	316
14.7.9 Special Considerations for the Association Data	316
14.7.10 Histogram/Variogram Reproduction	316
14.8 Conclusions	318
References	320
15 Conclusions	321
15.1 Building a Mineral Resource Model	321
15.2 Assumptions and Limitations of the Models Used	323
15.3 Documentation and Audit Trail Required	323
15.4 Future Trends	324
References	325
Index	327

Mineral Resource Estimation

Rossi, M.; Deutsch, C.V.

2014, XIV, 332 p. 271 illus., 148 illus. in color. With
online files/update., Hardcover

ISBN: 978-1-4020-5716-8