Chapter 20
Predicting Molybdenum Deposit Growth

John H. Schuenemeyer, Lawrence J. Drew and James D. Bliss

Abstract In the study of molybdenum deposits and most other minerals deposits, including copper, lead and zinc, there is speculation that most undiscovered ore results from an increase (or "growth") in the estimated size of a known deposit due to factors such as exploitation and advances in mining and exploration technology, rather than in discovering wholly new deposits. The purpose of this study is to construct a nonlinear model to estimate deposit "growth" for known deposits as a function of cutoff grade. The model selected for this data set was a truncated normal cumulative distribution function. Because the cutoff grade is commonly unknown, a model to estimate cutoff grade conditioned upon the deposit grade was constructed using data from 34 deposits with reported data on molybdenum grade, cutoff grade, and tonnage. Finally, an example is presented.

Keywords Porphyry molybdenum · Deposit growth · Cutoff grade
Truncated cumulative distribution model fitting and estimation · Confidence and prediction intervals for nonlinear estimation

20.1 Introduction

Initial estimates of a mineral deposit size based on limited data usually underestimate the ultimate size of a mineral deposit, often by a significant amount. The initial size estimate may be of only marginal interest but the size estimate after some exploration and development can be of significant interest. The steps in this process are the subject of this chapter. "Mineral resources" are defined as concentrations or occurrences of material of economic interest in or on the Earth's crust in such form, quality, and quantity that there are reasonable prospects for eventual economic extraction (Zientek and Hammarstrom 2014), and the term "mineral reserves" is restricted to the economically mineable part of a mineral resource.

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The reported size of known mineral or oil and gas deposit reserves recorded in the mining literature typically increases through time as subsequent development drilling and mining enlarge the deposit's footprint. This phenomenon is referred to as "deposit growth". In a sense, a deposit is never finished "growing" until it is completely mined out. Research on the growth of a deposit's reserves has been a topic of investigation for many years within the United States Geological Survey. Drew (1997) illustrated the growth of oil and gas fields over time in the United States and determined that a large percentage of the ultimate production of a region could come from deposit growth, if the forecast was made early enough in the discovery process. Long (2008) defined reserve growth as the ratio of current reserves plus past production to original reserves. He examined reserve growth in porphyry copper deposits and found that about 20% of porphyry copper mines in the Western Hemisphere had experienced reserve growth of a factor of 10 or better over initial reserves. Reserve growth at these mines added reserves comparable in size to reserves added through discovery of new deposits during the same time period.

Three variables are required to estimate the ultimate size of a deposit: (1) the grade of the deposit, (2) cutoff grade of the deposit, and (3) associated tonnage of ore at successive points in the development of the deposit (Long 2008). The grade of a deposit is defined as the relative quantity of ore mineral within the orebody, typically expressed as a percentage (or g/t). The grade may vary across an orebody, but commonly an average grade may be applied to the orebody as a whole. A cutoff grade is the lowest grade of mineralized material that qualifies as economically mineable and available in a given deposit (Committee for Mineral Reserves International Reporting Standards 2006). Mined material with a grade below the cutoff grade is not processed into metal but is set aside. As deposit development and mining progress, over time the cutoff grade usually declines in an orderly manner. Tonnage is typically reported in metric tons (mt) and includes the mass of total production, reserves and resources of pre-mined material.

The purpose of this study was to construct a nonlinear model to estimate the incremental deposit "growth" for known mineralized areas as a function of cutoff grade, using porphyry molybdenum deposits as an example. Porphyry molybdenum deposits are related to granitic plutons, mostly of Tertiary age, and are formed by hydrothermal fluids associated with the emplacement of granites. They typically occur as large tonnage, low-grade deposits that are commonly mined using open-pit methods.

Two issues must be addressed to predict porphyry molybdenum deposit growth. The first is that, in many instances, the cutoff grade is not available for a given deposit and thus must be estimated. Thus, the first part of this study uses the known molybdenum grade of a deposit to predict probable cutoff grade. The second part of this study in turn uses this predicted cutoff grade to estimate deposit growth as a function of cutoff grade. Two data sets were used in this study. Nearly all porphyry molybdenum deposits used in this study are for unworked deposits; that is, deposits that have been delineated by drilling but are yet unmined. The first data set (Appendix 1) consists of 34 porphyry molybdenum deposits used to model molybdenum cutoff grade in percent (COG) as a function of molybdenum deposit grade, also expressed in percent. The second data set (Appendix 2) is used to model the deposit growth as a function of cutoff grade. The references to Appendices 1 and 2 are Barnes et al. (2009), Baudry (2009), Becker et al. (2009), British Columbia Ministry of Energy and Mines (2012, 2014a, b), Chen and Wang (2011), Ewert et al. (2008), General Moly (2012), Geological Survey of Finland (2011), Geoscience Australia (2012), Kramer (2006), Lowe et al. (2001), Ludington and Plumlee (2009), Mercator Minerals (2011), Mindat.org (1992, 2011), Nanika Resources Inc (2012), Northern Miner (2010), Raw Minerals Group (2011), RX Exploration Inc (2010), Singer et al. (2008), Smith (2009), Taylor et al. (2012), Thompson Creek Metals Company Inc (2011), TTM Resources Inc (2009), US Geological Survey (2011), Wu et al (2011), Yukon Geological Survey (2005). The authors know of no subset of publications that cite the deposits presented in Appendices 1 and 2.

20.2 Cutoff Grade as a Function of Deposit Grade

The first and most straightforward of the two models to analyze is the relationship between molybdenum cutoff grade (Mo COG, %) as a function of molybdenum deposit grade (Mo Grade, %) for the 34 deposits shown in Appendix 1. A scatter plot between these two variables plus a fitted linear regression line, 95% confidence intervals, and 95% prediction intervals are shown in Fig. 20.1.

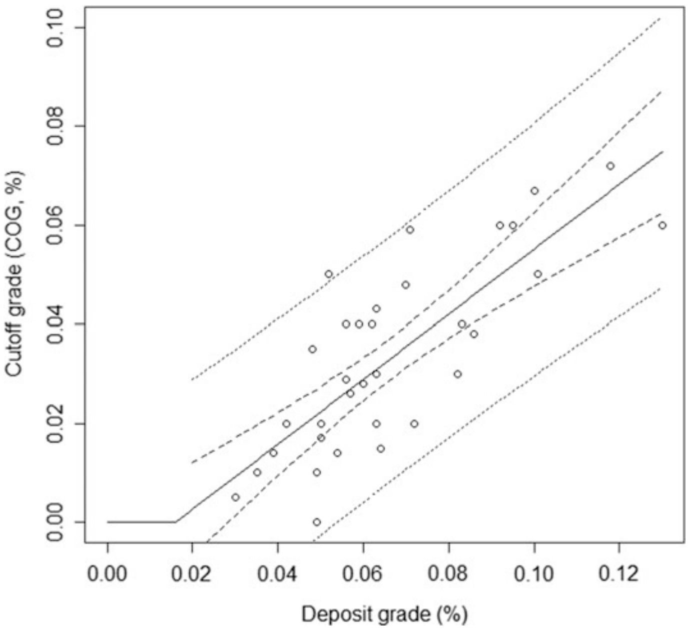

Fig. 20.1 Cutoff grade (COG, %) versus deposit grade (%) plus a fitted linear model and the 95% confidence intervals (dashed lines) and corresponding prediction intervals (dotted lines) for the 34 deposits (Appendix 1)

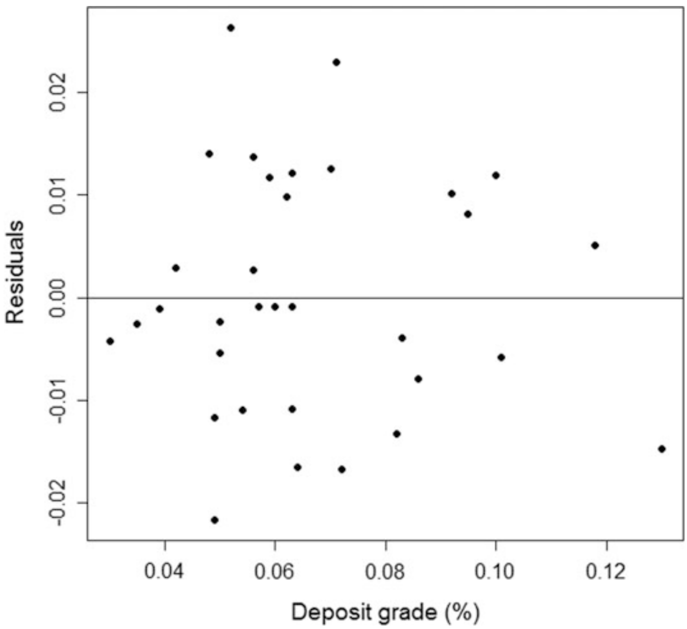

Fig. 20.2 Residuals versus deposit grade for the linear model fit (Fig. 20.1)

The model to fit cutoff grade U as a function of deposit grade D is

$$U = \begin{cases} 0 & 0 \le D < c \\ \beta_0 + \beta_1 D + \varepsilon & D \ge c \end{cases}$$

where ε is the random error, assumed to be normal $N(0, \sigma^2)$. The constant c is determined from the linear regression fit since the COG ≥ 0.

The fitted model is:

$$\hat{U} = \begin{cases} 0 & 0 \le D < c = 0.0159 \\ \beta_0 + \beta_1 D = -0.01042 + 0.6553D & D \ge 0.0159 \end{cases}$$

where $\hat{U}$ is the estimated cutoff grade in percent and D is the deposit grade in percent. The residual standard error is 0.012 on 32 degrees of freedom and the adjusted $R^2 = 0.61$. The model is statistically significant and reasonable for the given data set. The residual plot is shown in Fig. 20.2.

There is no evidence to suggest that the residuals are non-normal. Thus, within the domain of the deposit grade, namely from 0.03 to 0.13, the linear model shown above appears to be appropriate. Predictions outside of this interval will depend on the same linear relationship holding.

20.3 Deposit Growth as a Function of Cutoff Grade

The second model is the fraction of growth as a function of estimated cutoff grade. In this example the growth data (Fig. 20.3) consists of 58 observations from eight deposits (Appendix 2). The inverse S shaped form of the data corresponds to an inverse cumulative distribution function. Therefore, this relationship is modeled as an inverse cumulative distribution function, since the fraction growth is a number between 0 and 1, inclusive. Several models including the gamma, lognormal, normal and their left truncated forms were candidates to fit this data. Of these, the left truncated normal was the best fit by visual inspection and by a nonlinear least squares fit. The form of the left truncated normal probability distribution function is:

$$f_L(x|\Theta) = \frac{f(x|\Theta)}{1 - F(\lambda|\Theta)} \quad x > \lambda$$

where $\Theta' = (\mu, \sigma^2)$ and the left truncation point λ is assumed known. The probability density function for the normal distribution with mean μ and standard deviation σ is:

$$f(x|\mu, \sigma^2) = \frac{e^{-(x-\mu)^2/2}}{\sqrt{2\pi}\sigma}$$

The corresponding left truncated cumulative distribution function, cdf, is:

$$F_L(x|\Theta) = \frac{F(x|\Theta) - F(\lambda|\Theta)}{1 - F(\lambda|\Theta)}, \quad x > \lambda$$

The truncated distributions' models used for model fitting are from the package truncdist (r-project.org) by Novomestky and Nadarajah (2012) based upon work by Nadarajah and Kotz (2006).

As Fig. 20.1 shows, there is uncertainty in the COG when estimated from the deposit grade. However, when estimating the left truncated normal cumulative distribution function (cdf), the estimates are conditioned upon the COG being known. A possible alternative is an errors-in- variables approach (Schennach 2004) where both the fraction growth and cutoff grade are considered to be random variables.

The chosen optimization criterion to estimate the fraction growth (Fig. 20.3) is

$$\min(\sum_{i=1}^{n} (F(x_i|\Theta) - \hat{F}(x_i))^2,$$

where x_i is the ith COG and F is the cumulative distribution function. Θ contains the estimated parameters. If F is a normal distribution the parameters would be $\hat{\mu}$ and $\hat{\sigma}$.

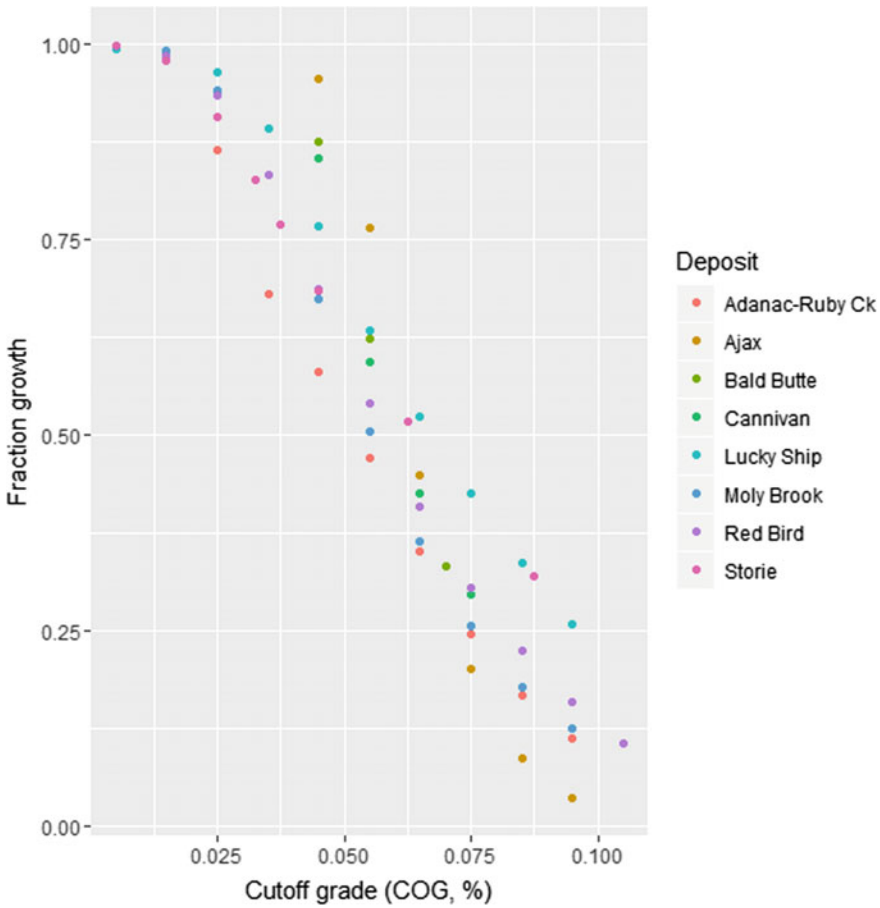

Fig. 20.3 Deposit fraction growth plotted against cutoff grade (COG) in percent for the 8 deposits used in this study

The ith COG is represented by x_i and $\hat{F}(x_i)$. Note that $\hat{F}(x_i) = 1 - \hat{G}(x_i)$ where $\hat{G}(x_i)$ is the fraction growth. The nonlinear least squares package used to estimate the left truncated normal model parameters is nls2 (r-project.org). See Grothendieck (2013). The left truncation point is $\lambda = 0$.

Deposit growth as a function of cutoff grade was modeled for each of the eight deposits (not shown). These results indicate that the data could have been generated from the same population Thus, the observations were pooled and a single model was fit. The reason to fit a cumulative distribution function was twofold. One was that eight deposits were used so the data was not in the form of a stepwise function. The second was that the data were not randomly or systematically spaced across the domain of the empirical distribution. The data, expressed as an empirical distribution function, together with the cumulative left truncated normal distribution fit and confidence intervals, are shown in Fig. 20.4. The results of the least square fit were $\hat{\mu} = 0.0609$ and $\hat{\sigma} = 0.0282$. The residual sum of squares, RSS = 0.3631.

The 95% confidence and prediction intervals for nonlinear estimation are approximate. The confidence interval shown in Fig. 20.4 (dashed lines) is from package propagate, r-project library predictNLS programmed by Spiess (2014) based upon work by Bates and Watts (2007), and others. It uses a second-order Taylor series expansion and Monte Carlo simulation. The second order approximation captures the nonlinearities around $f(x)$. A corresponding algorithm for the prediction interval has not been developed. The prediction interval shown in Fig. 20.4 (dotted lines) is based upon a linear model of the form $H = \alpha_0 + \alpha_1 U + \varepsilon$ where U was the COG. H is a linear estimate of growth. The next step was to estimate the upper and lower prediction intervals for the linear model with $U = 0$, 0.001, 0.002, …, 0.150. These are vectors **LPIu** and **LPIl** respectively. The upper and lower 95% nonlinear confidence interval vectors estimated above are **CIu** and **CIl** respectively. The differences between the linear prediction intervals and the nonlinear confidence intervals are computed as follows. Let **Lud** = **LPIu** − **CIu** and **Lld** = **CIl** − **LPIl**. The estimated upper and lower predictions intervals, **UP** and **LP**, for the nonlinear fit (Fig. 20.4) are **UP** = **CIu** + **Lud** and **LP** = **CIi** − **Lld.** These estimates appear reasonable in the given domain, namely for COG between 0.04 and 0.10.

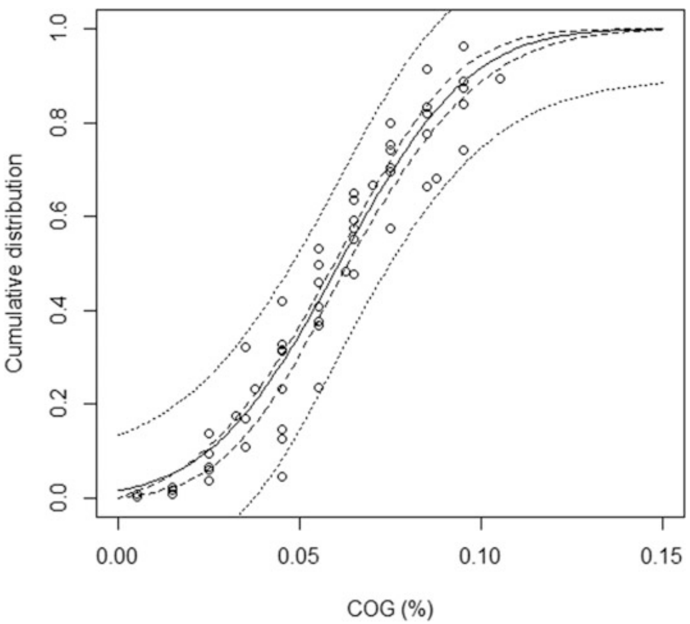

Fig. 20.4 Data fit to a left truncated (at 0) normal distribution is the solid line. The approximate 95% confidence interval is the dashed line. The approximate 95% prediction interval is the dotted line

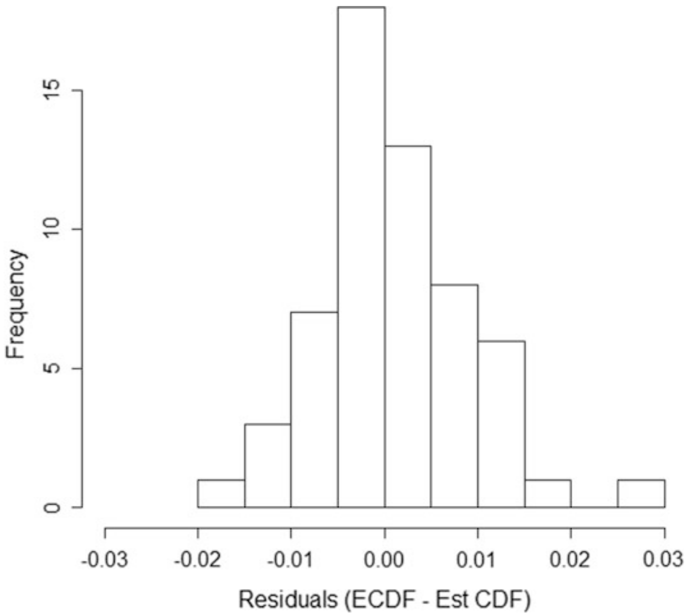

Fig. 20.5 Histogram of residuals for fit to a left truncated normal distribution

A histogram of the residuals, which appear normal, is shown in Fig. 20.5. The truncated normal probability density function corresponding to the cumulative distribution function (Fig. 20.4) and COG data are shown in Fig. 20.6.

Figure 20.7 is like Fig. 20.4 except that the variable plotted on the vertical axis is the fraction growth as opposed to the cumulative distribution. There is no suggestion that the model illustrated in Fig. 20.7 is universal, even for molybdenum deposits. Clearly different deposits may require different models.

20.4 An Example

Suppose the problem is to estimate the fraction growth corresponding to a COG (%) = 0.06 using the model shown in Fig. 20.7. Then, given that the assumed distribution is a truncated normal at zero with estimated model parameters, $\hat{\mu} = 0.0609$ and $\hat{\sigma} = 0.0282$, the results are shown in Table 20.1. The point estimate of fraction growth, namely 0.479, is straightforward to compute. Namely it is:

$$\hat{F}_L(x|\hat{\Theta}) = \frac{F(x|\hat{\Theta}) - F(\lambda|\hat{\Theta})}{1 - \hat{F}(\lambda|\hat{\Theta})}, \quad x > 0, \hat{\Theta}' = (\hat{\mu}, \hat{\sigma}^2)$$

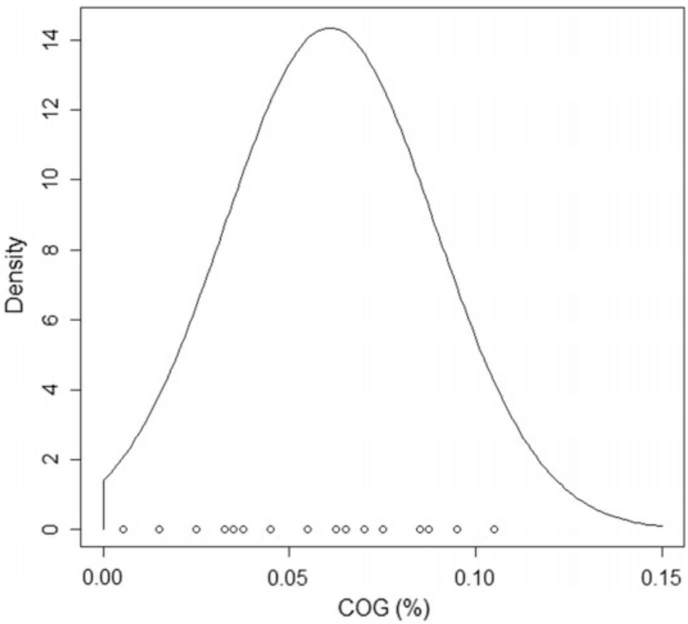

Fig. 20.6 The fitted truncated normal probability density function and COG data (the circles)

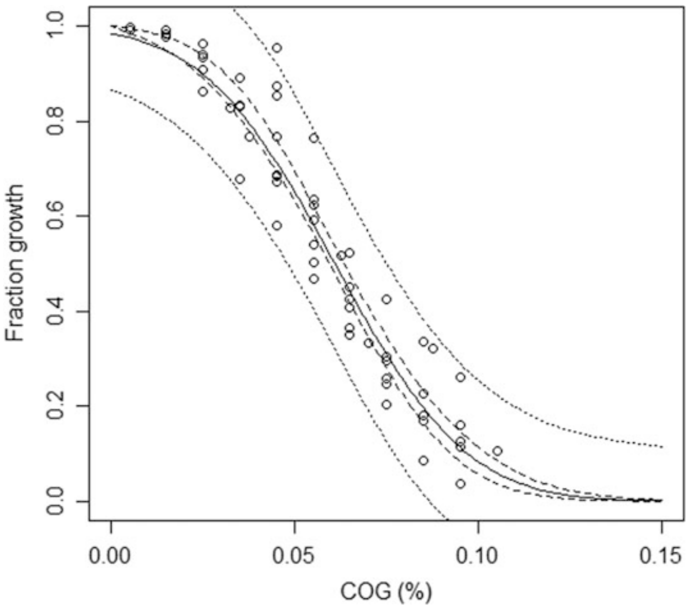

Fig. 20.7 Fraction growth as a function of COG (%) and corresponding fitted values (solid line), 95% confidence interval (dashed line) and 95% prediction interval (dotted line)

Table 20.1 Estimated fraction growth, 95% confidence and prediction intervals for COG (%) = 0.06

		Confidence interval		Prediction interval	
COG (%)	Fraction growth	2.50%	97.50%	2.50%	97.50%
0.06	0.479	0.450	0.507	0.291	0.666

The confidence and prediction intervals are more difficult to compute; however, the R code is available on request from John Schuenemeyer.

20.5 Conclusions

Mineral deposit growth commonly constitutes most unknown resources. The growth considered in this study is due to a progressively lower cutoff grade, which may be unknown. In this study, a statistical model was constructed to model cutoff grade as a function of deposit grade, followed by construction of a model to estimate the fraction growth as a function of cutoff grade. This latter model involves estimation of a truncated normal distribution and second order Taylor series estimates to characterize uncertainty.

Acknowledgements Data used in this chapter represent part of an extensive and ongoing data compilation effort on porphyry molybdenum deposit types. This study evolved over several years through discussions with current and former U.S. Geological Survey employees including Arthur A. Bookstrom, Mark D. Cocker, Robert J. Kamilli, Keith R. Long, Steve Ludington, Barry C. Moring, Greta J. Orris, Ryan D. Taylor, Jay A. Sampson, and Gregory T. Spanski. Eric Seedorf, University of Arizona, Tucson provided his bibliography on porphyry molybdenum deposits, which was of considerable use in this study.

Appendix 1

Porphyry molybdenum data for 34 selected deposits used to model molybdenum cutoff grade as a function of deposit grade.

[Country and state codes: AUQL = Australia, Queensland; CHHN = China; CHNA = China; CNBC = Canada, British Columbia; CNNF, Canada, Newfoundland and Labrador; CNON = Canada, Ontario; CNYT = Canada, Yukon Territory; GRLD = Greenland; MCDA = Macedonia; MNGA = Mongolia; MXCO = Mexico; RUSA = Russia; USAK = USA, Alaska; USID = USA, Idaho; USMT = USA, Montana; USNV = USA, Nevada; USWA = USA, Washington]

Name	ID	Country-State	Mo grade (%)	Deposit size (Mt)	Mo COG (%)
Ada nac-Ruby Creek	101	CNBC	0.042	791	0.020
Adjax-Le Roy	102	CNBC	0.062	552	0.040
Anduramba	103	AUQL	0.054	32	0.014
Bald Butte	106	USMT	0.059	176	0.040
Big Ben	108	USMT	0.092	245	0.060
Buckingham	110	USNV	0.063	1800	0.043
Cannivan Gulch-White Cloud	111	USMT	0.056	327	0.040
Carmi	113	CNBC	0.057	40	0.026
Cave Creek	114	USTX	0.130	28	0.060
Chu	115	CNBC	0.050	673	0.017
Creston	118	MXCO	0.071	215	0.059
Endako	124	CNBC	0.050	1232	0.020
Jiguanshan (Jiganshuan)	130	CHNA	0.095	100	0.060
Joem-Haskin Mountain	131	CNBC	0.101	11	0.050
Kitsault (Updated 11/2015)	132	CNBC	0.070	688	0.048
Lobash	140	RUSA	0.063	365	0.030
Lone Pine	143	CNBC	0.072	179	0.020
Lucky Ship	144	CNBC	0.064	85	0.015
Mac	145	CNBC	0.048	248	0.035
Malmbjerg	148	GRLD	0.118	229	0.072
Moly Brook	151	CNNF	0.049	199	0.010
Mount Hope	152	USNV	0.039	1148	0.014
Mount Tolman	156	USWA	0.056	2200	0.029
Pidgeon-Lateral Lake	163	CNON	0.083	59	0.040
Pine Nut	165	USNV	0.060	181	0.028
Qua rtz Hill	167	USAK	0.082	1310	0.030
Red Bird-Haven Lake	169	CNBC	0.049	201	0.010
Red Mountain	170	CNYT	0.100	187	0.067
Sphinx	178	CNBC	0.035	62	0.010
Storie Molie	180	CNBC	0.049	105	0.000
Sudulica-Mackatica-Kucisnjak-Groznatova Dolina	146	MCDA	0.030	383	0.005
Tangjiaping	183	CHHN	0.063	373	0.020
Thompson Creek	184	USID	0.086	575	0.038
Zuun Mod	195	MNGA	0.052	408	0.050

Appendix 2

Molybdenum data for estimating fraction deposit from cutoff grade; $n = 58$

Deposit name	COG (%)	Fraction growth	Deposit name	COG (%)	Fraction growth
Adanac-Ruby Creek	0.095	0.113	Moly Brook	0.095	0.126
Adanac-Ruby Creek	0.085	0.168	Moly Brook	0.085	0.180
Adanac-Ruby Creek	0.075	0.247	Moly Brook	0.075	0.258
Adanac-Ruby Creek	0.065	0.351	Moly Brook	0.065	0.365
Adanac-Ruby Creek	0.055	0.470	Moly Brook	0.055	0.504
Adanac-Ruby Creek	0.045	0.581	Moly Brook	0.045	0.673
Adanac-Ruby Creek	0.035	0.679	Moly Brook	0.035	0.831
Adanac-Ruby Creek	0.025	0.864	Moly Brook	0.025	0.941
Ajax	0.095	0.037	Moly Brook	0.015	0.991
Ajax	0.085	0.087	Red Bird	0.105	0.107
Ajax	0.075	0.202	Red Bird	0.095	0.160
Ajax	0.065	0.450	Red Bird	0.085	0.226
Ajax	0.055	0.765	Red Bird	0.075	0.305
Ajax	0.045	0.956	Red Bird	0.065	0.409
Bald Butte	0.070	0.333	Red Bird	0.055	0.540
Bald Butte	0.055	0.623	Red Bird	0.045	0.687
Bald Butte	0.045	0.875	Red Bird	0.035	0.833
Cannivan	0.075	0.296	Red Bird	0.025	0.935
Cannivan	0.065	0.426	Red Bird	0.015	0.984
Cannivan	0.055	0.593	Storie	0.088	0.320
Cannivan	0.045	0.854	Storie	0.063	0.518
Lucky Ship	0.095	0.260	Storie	0.045	0.685
Lucky Ship	0.085	0.337	Storie	0.038	0.768
Lucky Ship	0.075	0.426	Storie	0.033	0.827
Lucky Ship	0.065	0.523	Storie	0.025	0.907
Lucky Ship	0.055	0.634	Storie	0.015	0.977
Lucky Ship	0.045	0.767	Storie	0.005	0.998

(continued)

(continued)

Deposit name	COG (%)	Fraction growth	Deposit name	COG (%)	Fraction growth
Lucky Ship	0.035	0.891			
Lucky Ship	0.025	0.963			
Lucky Ship	0.015	0.985			
Lucky Ship	0.005	0.993			

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