4 Definition of Estimation Domains

Abstract

Estimation of grades proceeds within domains defined on the basis of geological and statistical considerations. The definition and modeling of these domains is an important step in mineral resource estimation. This Chapter presents practical aspects of the development of estimation domains, the limitations faced when defining these domains, details of the modeling of estimation domains, and the most commonly used methods to assign estimation domains to a resource block model.

4.1 Estimation Domains

Estimation domains are the geological equivalent to geostatistical stationary zones and are defined as a volume of rock with mineralization controls that result in approximately homogeneous distributions of mineralization. The spatial distributions of grade exhibit consistent statistical properties. This does not mean that the grades are constant within the domains; however, the geological and statistical properties of the grades facilitate its prediction.

The concept of statistically homogeneous populations is termed stationarity. Stationarity is a two-fold decision. First, there is a choice of the data to pool together for common analysis. Second, there is a choice of how statistics such as the mean vary by location within the domain. Stationarity is a property of the random function model (Isaaks and Srivastava 1989) and is not an intrinsic characteristic of the variable. It is a decision made by the resource estimator and is necessary to make inferences. Stationarity was formally defined by Matheron (1962–1963) in the context of geostatistics and is also discussed in Chap. 6.

Exploratory data analysis (EDA) may indicate the existence of several populations with significantly different summary statistics. The understanding of the statistical characteristics of the data, coupled with geologic knowledge, leads to subdividing the deposit into domains for estimation. This is considered more reasonable than taking the entire deposit at one time. Domain definition depends on the availability of enough data to reliably infer statistical parameters within each domain. Moreover, the domains must have some spatial predictability and not be overly mixed with other domains.

A good definition of estimation domains is very important. The consequences of defining inadequate estimation domains are rarely evaluated. It is common to confuse the concepts of geologic and estimation domains. Geologic domains are commonly described by a single geologic variable. Estimation domains are defined by a set of mineralization controls and may contain more than one geological domain.

In multi-element deposits it is common to assume that the estimation domains defined for the main element/mineral of interest applies to all secondary elements that may be present. In practice, different grades are controlled by different geologic variables, and thus they may be predicted using different estimation domains.

For example, porphyry deposits with copper and gold mineralization may exhibit an inverse spatial relationship, that is, gold may not leach through weathering as copper does. Gold may form a cap on the upper part of the deposit. In such cases, copper and gold should be modeled using different estimation domains. In epithermal deposits, gold and silver mineralization may exhibit little correlation since they are deposited differently. Estimating gold and silver using the same estimation domains would lead to suboptimal results.

Estimation domains must make spatial and geologic sense (Coombes 2008). The combination of geologic variables used to define the domains must have spatial and geologic characteristics that are recognizable in drilling and/or production data. The estimation domain must be sufficiently

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represented in the database and in the deposit. These conditions provide constraints on what can realistically be modeled in practice.

4.2 Defining the Estimation Domains

A thorough stepwise approach is suggested here. It is based on a combination of geological and statistical analyses. This approach is more detailed and time-consuming, but it provides better support for estimation. The concept is based on decomposing the problem by describing and modeling the relationships between each geologic variable. The combination of variables results in a matrix that ranks the most critical grade controls as identified by the data. These should be explained in terms of plausible natural processes, to ensure that the controls derived from the data are consistent with known geology.

Development of the grade domains begins and ends with geologic knowledge. The first step is to define the geologic variables that are used as the building blocks for the estimation domains definition. Typical variables mapped from drill hole data include lithology, alteration, mineralogy, weathering (oxide/sulfide, for example), and structures or structural domains. Not all these variables are always mapped; some may not be relevant for a particular deposit type.

The second step is to decide the specific geologic variables that are the most important. This is based on geologic considerations, overall abundance within the deposit, and drill hole information.

Third, estimation domains based on all reasonable combinations of the geologic attributes are defined. Consider, for example, 3 geologic attributes each with 4 variables, and thus a total of 64 theoretically possible estimation domains. For example, porphyry, andesites, breccias, and dacites could be the 4 variables of lithology in a porphyry copper-type deposit. Data abundance will filter out a number of these. Consideration of practical aspects will further reduce the number of theoretical domains, such as existing or planned mineral processing facilities. In copper, gold, and many other precious and base metal deposits, for example, it is not advisable to mix oxide and sulfide mineralization, since they are frequently treated at separate processing plants, or, if one of the two metallurgical types is small in volume or low grade, it may be simply stockpiled. Another criterion often used is proximity: certain units may be at the periphery of the deposit, and therefore should not be mixed with units at the central portion of the deposit.

The fourth step involves a statistical description of the initial domains. The main purpose is to remove or group domains according to geologic considerations. Variables that have little representation in the database should be removed, regardless of whether they represent a strong mineralization control or not. A rule of thumb threshold is 1 % of the total number of intervals in the database, although this is dependent on the total size of database.

Next, statistical comparisons between the initial domains accepted will often lead to grouping. Statistical tools such as histograms, probability plots, box plots, scatterplots, quantile-quantile (Q-Q) plots, proportional effect plots, and variograms are used. They allow comparisons of grade distributions within each of the domains proposed. Analysis of the statistics requires a degree of subjectivity, since an acceptable degree of similarity needs to be defined. Once two variables are shown to provide a similar degree of mineralization control, and assuming it makes geologic sense, they are grouped, and the statistical analysis repeated.

This iterative process can be labor-intensive, and is usually repeated until a group of geologic variables and elements have been defined that clearly separates different types of mineralization. Some of the variables will be grouped even though there are clear differences in the spatial characteristics of the mineralization. This is often done because of practical limitations, including data quantity, metallurgical considerations, and other economic and technical factors.

Alternative Statistical Techniques Other multivariate statistical techniques could be used to describe the relationships between geology and grade. For example, some practitioners have proposed the use of Classification and Regression Tree analysis (CART, Breiman et al. 1984) to determine and categorize relationships between geology and grade distributions. Techniques such as Principal Component Analysis and Cluster Analysis have also been proposed. A common problem, however, is that these techniques are often used to classify the relationships based on statistical parameters without geological consideration.

The proportional effect may also be used to define domains. The proportional effect appears in the presence of positively skewed distributions. It indicates that, as the average of the variable increases, so does its variability. These plots, when comparing means and standard deviations of groups of data defined according to geologic variables, may show clusters of data. The assumption is that data within each cluster belong to a quasi-stationary population, thus defining estimation domains. These data clusters should be correlated to specific geologic controls.

The iterative process using simple statistics described is recommended. An important by-product is that the more labor-intensive process leads to a more thorough understanding of the geology. It ensures that the estimation domains are a group of quasi-stationary domains that make spatial and geologic sense, as opposed to only statistical groupings.

4.3 Case Study: Estimation Domains Definition for the Escondida Mine

The process of defining estimation domains is best illustrated with an example. The following has been taken from a definition of Total Copper (TCu) estimation domains at BHP Billiton's Escondida copper deposit. It is reproduced here courtesy of BHP Billiton, Base Metals Division.

Not all the aspects of a given geologic variable are valid or useful at the time of defining estimation domains. The first step in the process is to define those aspects that will be considered. This initial selection of important geologic attributes should be decided by the geologists who know the deposit well. An understanding of how geologic variables may impact resource estimation is also required.

The definition of estimation domains at Escondida was greatly assisted by the operating mine. The open pit afforded the opportunity for confirmation by direct observation of the assumed relationships described by the drill hole data. At Escondida, the geologic variables considered were mineralization type, alteration, lithology, and structural domains.

In the case of mineralization types, all high enrichment mineralization (HE1, HE2, and HE3) would be modeled as below Top of Sulfides (TDS) and above Top of Chalcopyrite (TDCpy). It was shown through statistical and additional chemical analyses that the Covelite-Pyrite (Cv + Py) unit has the statistical and spatial characteristics of low enrichment mineralization. Also the Chalcocite-Chalcopyrite-Pyrite (Cc + Cpy + Py) unit has characteristics of high enrichment mineralization, particularly for higher benches where the proportion of Cc in this unit is more significant. This is to be expected, since these mineral assemblages are transitions from higher to lower enrichment mineralization.

Following similar reasoning for all alteration, lithology and structure categories, the original codes in the database were translated into a simplified version, and are shown in Table 4.1. The most important characteristics of the resulting mineralization codes are the following:

- All mineralization with some cuprite described was grouped into a single code (Cuprite, Cuprite + Ox, Cuprite + Mx, and Cuprite + Cc + Py into Cuprite). This is because Cu cannot be recovered from cuprite using the existing processing facilities, and is detrimental to the overall Cu recovery in a flotation plant.
- High Enrichment is defined as of Cc + Py and Cc + Cv + Py.
- Low Enrichment groups the units Cc + Cpy + Py, Cc + Cv + Cpy + Py, Cv + Cpy + Py, and Cv + Py.
- All primary mineralization is lumped into one category (Py, Cpy + Py, and Bn + Cpy + Py), because, at the time of the study, the bulk of the processed ore will come from enriched mineralization units.
- All other elements used are the original codes: Leach (code 0), green Oxides (code 1), Partial Leach (code 4), and Mixed (code 5).

A similar process of developing new variables for lithology and alteration was completed. The grouping of initial mapped elements resulted in three alteration codes, QSA, SCC, and K-B (white, green and potassic-biotite alteration, respectively), and three lithologies: porphyry, andesite, and rhyolite.

With respect to lithology, the following characteristics are noted:

- Tuffs were grouped with Rhyolite, (PC).
- The following codes were ignored due to lack of spatial representation: Dacites, Gravels, Tectonic Breccias, Undifferentiated Porphyry (9), Diorites, and Pebble Dykes.
- Hydrothermal Breccias and Igneous Breccias were grouped with the main Escondida Porphyry unit.

With respect to alteration, the following groupings were made:

- A new code QSA was formed grouping all Quartz, Sericite, and Clays (Sericite, Clays, Silicified, and Advanced Argillic). This also known as white alteration.
- Similarly, a new SCC code was formed by grouping Propilitic, Sericite-Chlorite-Clays, K-S Transition in Porphyry, Silicified in Andesites, and Silicified in Porphyry. This is sometimes referred to as "green alteration" because of the presence of chlorite. Propilitic alteration is very different from the other components of this SCC grouping described. However, it is deemed pertinent here because there are very few intervals coded as propilitic alteration. Normally, in other porphyry deposits, propilitic alteration is observed as a halo on the outskirts of the deposit, and would be advisable to model it separately.
- A third alteration K-B was formed by grouping Potassic (K) and Biotite alterations (B).
- The fresh, unaltered rock is volumetrically unimportant and was ignored.

With the simplification of the original codes, completed by Escondida geologists, the basic elements of the geological model have been defined, and combinations of these elements define the initial set of estimation domains.

Five structural domains were identified based on observations in the pit and drill hole data. At Escondida, like most mineral deposits, structures control the spatial distribution of TCu grades in different areas of the deposit. Figure 4.1 shows the domains and the current pit projection as modeled by structural geologists. Domain 5 (to the West of the deposit-bounding Ferrocarril fault, in brown) was not considered, since there is no evidence of mineralization. The basic building blocks for defining the estimation domains were defined with the remaining four structural domains.

4.3.1 Exploratory Data Analysis of the Initial Database

The database consisted of 2,140 drill holes with 215,681 assays, lithology, mineralization, and alteration records. Histo-

Table 4.1 Original and simplified geologic codes, Escondida database

LITHOLOGY	GROUPING	Alpha CODES	Numeric Codes
K-Porphyry	OK	PF	1
Quartz-Porphyry	Grouped with Tuffs	PC	2
Undifferentiated Porphyry	Ignore	PU	-99
Andesite	OK	AN	3
Igneous Breccias	Grouped with PF	BI	4 (1)
Hydrothermal Breccias	Grouped with other PF	BH	7 (1)
Tectonic Breccias	Ignore	BT	-99
Gravel and Pebble Dykes	Ignore	GR/PD	-99
Late Dacite	Ignore	DT	-99
Diorite	Ignore	DR	-99
Tuff	Grouped with PC	TB	2
MINERALIZATION TYPES	**GROUPING**	**Alpha Codes**	**Numeric Codes**
Leach	OK	LX	0
Green Cu Oxides	OK	OX	1
Cuprite	Grouped with other Cuprite	CP	2
Cuprite + Ox Cu	Grouped with other Cuprite	CPOX	2
Cuprite + Mixto	Grouped with other Cuprite	CPMX	2
Cuprite + Cc + Py	Grouped with other Cuprite	CPCCPY	2
Partial Leach	OK	PL	4
Mixed Oxide and Sulfides	OK	MX	5
Chalcocite/Pyrite	Grouped with HE2	HE1	6
Chalcocite/Covelite/ Pyrite	Grouped with HE1	HE2	6
Covelite/Pyrite	Grouped with LE	HE3	7
Chalcocite/Chalcopyrite/ Pyrite	Grouped with LE	LE1	7
Chalcocite/Covelite/ Chalcopyrite/Pyrite	Grouped with LE	LE2	7
Covelite/Chalcopyrite/ Pyrite	Grouped with LE	LE3	7
Pyrite	Grouped with other Primary	PR1	8
Chalcopyrite/Pyrite	Grouped with other Primary	PR2	8
Bornite/Chalcopyrite/ Pyrite	Grouped with other Primary	PR3	8
ALTERATION	**GROUPING**	**Alpha Codes**	**Numeric Codes**
Fresh rock	Ignore	F	-99
Propilitic	Grouped with SCC	P	2
Clorite-Sericite-Clay	OK	SCC	2
Quartz-Sericite	OK	S	1
Potassic	OK	K	3
Biotitic	Grouped with K	B	3
Advanced Argilic	Grouped with S	AA	1
Clay	Grouped with S	AS	1
Silicified	Grouped with S	Q	1
K-S Transition in Porphyry	Grouped with SCC	QSC	2
SCC Silicified in Andesite	Grouped with SCC	SCC-An	2
QSC Silicified in Porphyry	Grouped with SCC	SCC-Pf	2

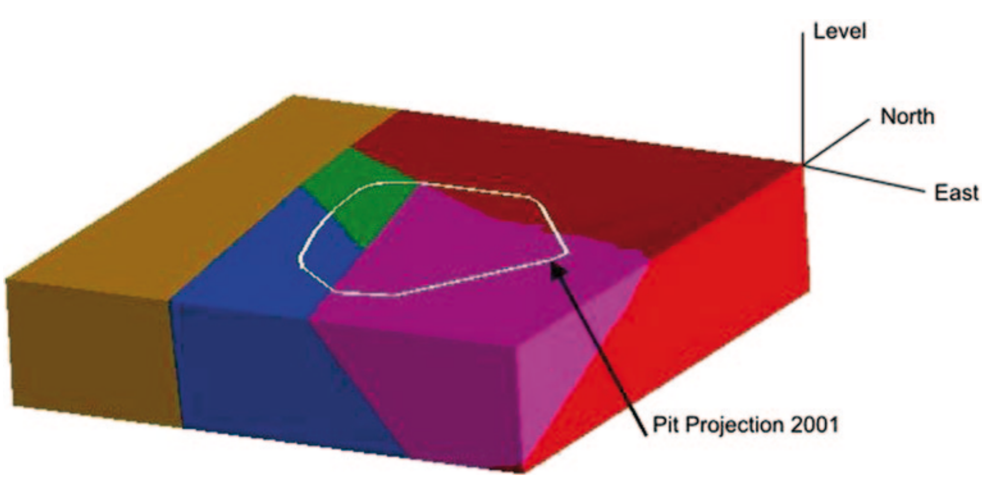


Fig. 4.1 Diagram showing the four structural domains. Domain 5 (in brown, west of the Ferrocarril fault) is non-mineralized, and outside the area of interest. For scale, the projection of the 2001 pit to the surface has an approximate dimension of 3 × 3 km, and no vertical exaggeration

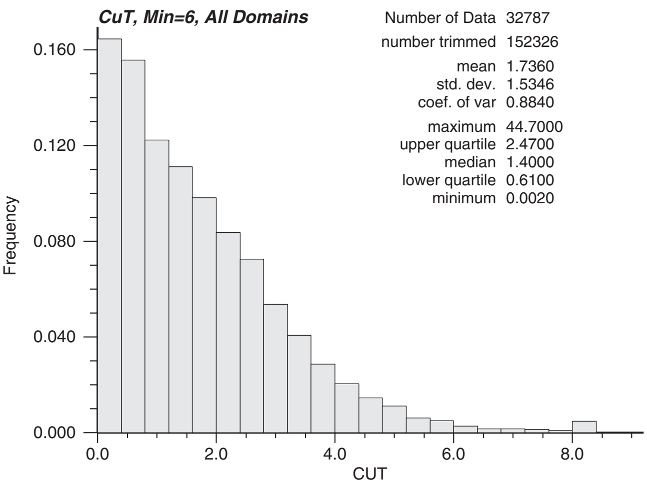


Fig. 4.2 Histogram and basic statistics of TCu (%), Cc+Py unit

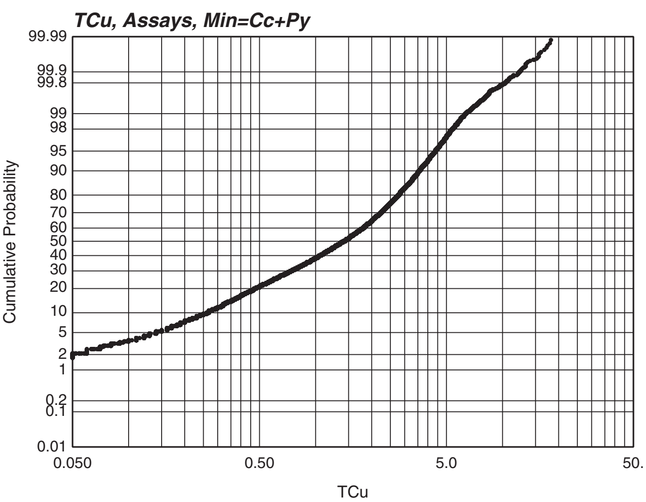


Fig. 4.3 Probability plot of TCu (%), Cc+Py unit

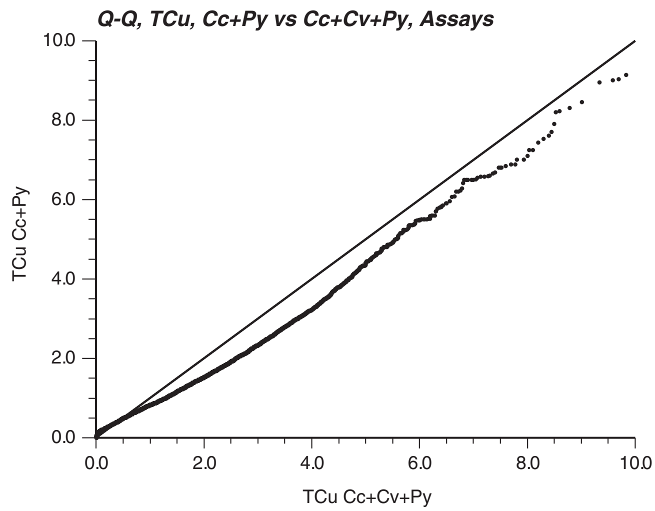


Fig. 4.4 Quantile-Quantile plot of TCu (%), Cc+Py vs. Cc+Cv+Py mineralization

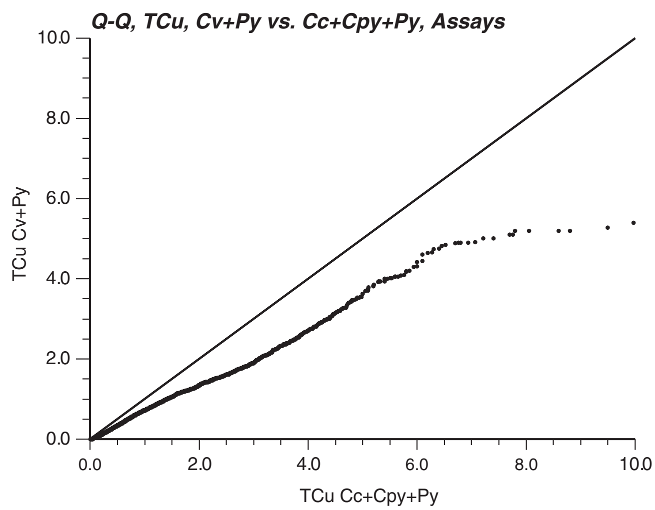


Fig. 4.5 Quantile-Quantile plot of TCu (%), Cc+Cpy+Py and Cv+Py mineralization

grams were used to provide a global description of the variable, along with summary statistics. Figure 4.2 shows the histogram and summary statistics for TCu, all assays logged as chalcocite plus pyrite (Cc+Py, HE1 in Table 4.1). The histogram shows a positively-skewed distribution with an average grade of 1.74% TCu and a coefficient of variation of 0.88, which is considered low for assay data.

The cumulative frequency plot is often used to describe important characteristics of the distribution, such as looking for breaks along an expected continuous line. Figure 4.3 shows the probability plot corresponding to the data in Fig. 4.2 (TCu, Cc+Py). Note how the curve has inflection points, one at approximately 2% TCu, and the other at about 6% TCu, suggesting a mixture of populations in the domain.

Two distributions can be compared using quantile-quantile (Q-Q) plots. Figure 4.4 shows a Q-Q plot comparing Cc+Py and Cc+Cv+Py mineralization, while Fig. 4.5 shows the comparison for Cc+Cpy+Py and Cv+Py. These and other similar figures illustrate the similarity of the grade distributions based on mineralization types alone.

4.3.2 Initial Definition of Estimation Domains

The definition of preliminary estimation domains was done by analyzing all geologically feasible combinations of the four variables: mineralization, lithology, alteration, and structural domains.

Table 4.2 Initial estimation domains

Estimatoin Domain	*Mineralization*	*Lithology*	*Alteration*	*Structural Domain*	*Comments*
0	Leach	ALL	ALL	ALL	Mostly barren.
1	Oxides	ALL	ALL	ALL	Defined by Interpreted Oxide Envelope
2	Cuprite	ALL	ALL	ALL	Cannot be processed, mined as waste regardless of grade
3	Partial Leach	ALL	ALL	ALL	Small bodies, difficult to model
4	Mixed	ALL	ALL	ALL	Small bodies, difficult to model
5	ALL	Rhyolites	ALL	ALL	Eastern edge of the deposit, low grade, little development in the near future.
6	Cc+Py; Cc+Cv+Py	ALL	QSA	1+4	High Enrichment
7	Cc+Py; Cc+Cv+Py	ALL	SCC	1+4	High Enrichment
8	Cc+Py; Cc+Cv+Py	ALL	QSA	3	High Enrichment
9	Cc+Py; Cc+Cv+Py	ALL	SCC	3	High Enrichment
10	Cc+Cpy+Py; Cv+Py Cc+Cv+Cpy+Py; Cv+Cpy+Py	ALL	QSA	1+4	Low Enrichment
11	Cc+Cpy+Py; Cv+Py Cc+Cv+Cpy+Py; Cv+Cpy+Py	ALL	SCC	1+4	Low Enrichment
12	Cc+Cpy+Py; Cv+Py Cc+Cv+Cpy+Py; Cv+Cpy+Py)	ALL	QSA	3	Low Enrichment
13	Cc+Cpy+Py; Cv+Py Cc+Cv+Cpy+Py; Cv+Cpy+Py	ALL	SCC	3	Low Enrichment
14	Cpy+Py; Py; Bn+Cpy+Py	Porphyries + Breccias	K+B	1+4+2	Primary
15	Cpy+Py; Py; Bn+Cpy+Py	Andesites	K+B	1+4+2	Primary
16	Cpy+Py; Py; Bn+Cpy+Py	Porphyries + Breccias	K+B	3	Primary
17	Cpy+Py; Py; Bn+Cpy+Py	Andesites	K+B	3	Primary
18	Cc+Py; Cc+Cv+Py	ALL	ALL	2	High Enrichment
19	Cc+Cpy+Py; Cv+Py Cc+Cv+Cpy+Py; Cv+Cpy+Py	ALL	ALL	2	Low Enrichment

Table 4.2 shows the 20 initial estimation domains defined. The initial six estimation domains are defined based on mineralization alone, and is due to two factors: as these are all non-sulfide units (with the exception of Partial Leach), their economic importance is minor if compared to the supergene sulfide mineralization. Also, the spatial distribution of these mineralization units, with the exception of the leached cap, is complex and difficult to model. Typical sizes of oxide and mixed bodies are at best approximately equal to the better drilling spacing available (50–70 m of lateral extension). Subdividing these small domains even further is likely to result in poor grade estimates.

It was found that within the supergene enrichment zone the lithological control is redundant with alteration. Lithology is an important control for mineralization types, but in the supergene areas alteration overprints and obliterates the Lithologic control.

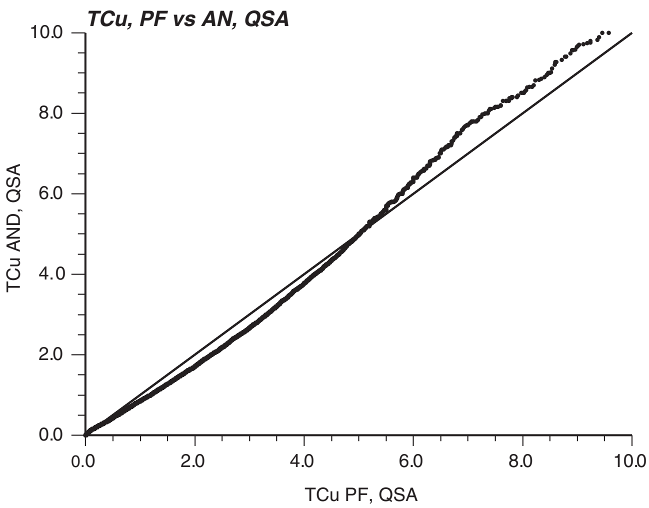


Fig. 4.6 Q-Q plot of TCu (%), Porphyry vs. Andesite, QSA alteration

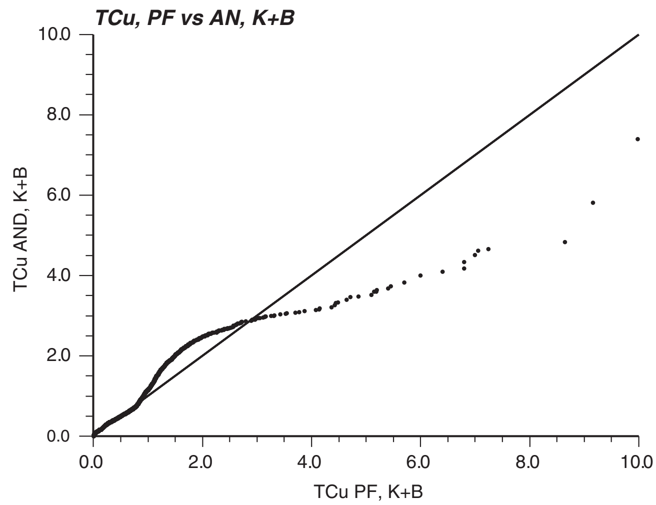


Fig. 4.8 Q-Q plot of TCu (%), Porphyry vs. Andesite, Potassic+Biotite alteration

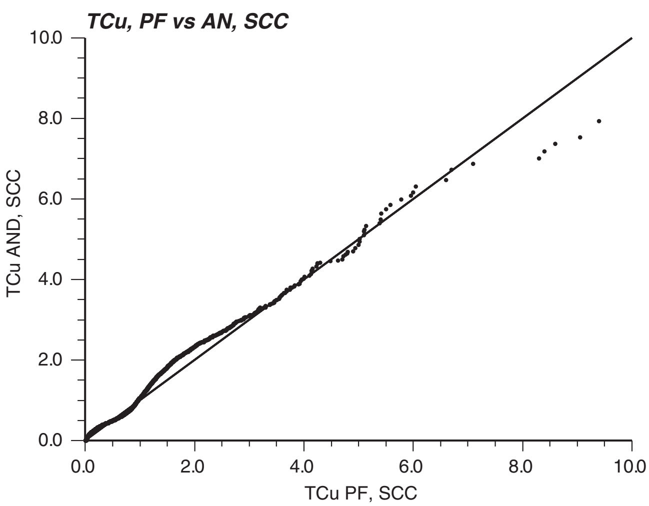


Fig. 4.7 Q-Q plot of TCu (%), Porphyry vs. Andesite, SCC alteration

Figures 4.6 and 4.7 show the Q-Q plots of all Escondida Porphyry vs. andesite lithologies, conditioned to the two main alterations, QSA and SCC, respectively. Note how the plots are close to the 45° line, which implies similar statistical distributions. Therefore, TCu grades do not change much in andesite or Escondida porphyries, as long as the alteration remains the same. Lesser grades can be expected if the alteration is SCC, regardless of whether lithology is andesite or Porphyry. Approximately 18 % of the total assay intervals are andesite with QSA alteration, while there are approximately 4 % of Escondida porphyry assays with SCC alteration.

This is not the case for primary mineralization where there are significant differences in the statistical characteristics of TCu grades when comparing andesites with the Escondida porphyry. Figure 4.8 shows the Q-Q plot of both lithologies for alteration K+B; note how the distributions are quite different. The number of assays available in primary mineralization with potassic and biotite alterations is relatively small since drilling targets the supergene enriched mineralization. This is why they were grouped. Primary mineralization is not as important economically as the upper part of the deposit, so it appears reasonable, mostly for pragmatic reasons, to group the primary mineralization units.

Structural domains 1 and 4 present a clear difference in terms of TCu grades, compared to structural domains 2 and 3. Domain 3, in particular, is the most different. This is evident both from descriptive statistics and TCu correlogram models for the different domains.

Figures 4.9, 4.10, 4.11, and 4.12 show the Q-Q plots of HE versus LE mineralization (Cc+Py vs. Cc+Cpy+Py) for Domains 1 through 4, respectively.

Figure 4.9 (structural domain 1) shows that the global Cc+Py distribution has significantly more grade for the 1–4 % TCu range. The quantile values for higher grades tend to be similar, which implies that both distributions have a significant high grade tail.

Figure 4.10 (structural domain 2) shows that the low enrichment material (Cc+Cpy+Py) has a higher-grade distribution. This is an indication that there is less chalcopyrite in structural Domain 2, probably due to a deepening of the enrichment process in a down-thrown structural block. Therefore, it would be reasonable to combine HE and LE into a single group. Structural domain 2 is the smallest in volume of the four domains considered.

The grade distributions in structural Domain 3 (Fig. 4.11) behave as expected, with the HE distribution consistently showing higher grade, while the grade distributions for structural domain 4 (Fig. 4.12) are very similar, again prob-

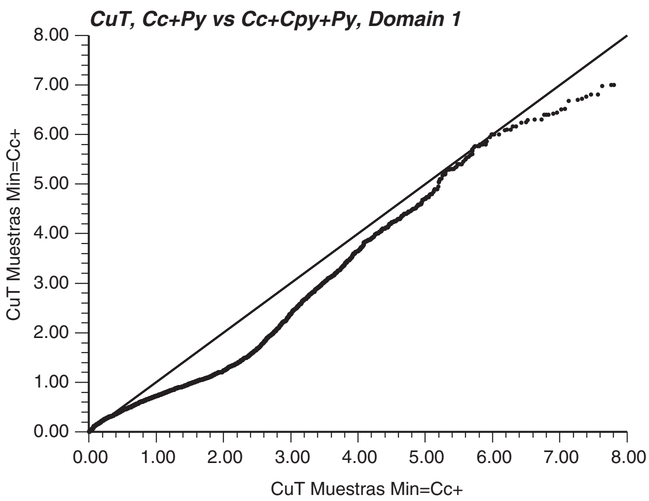


Fig. 4.9 Q-Q plot of TCu (%), Cc+Py vs. Cc+Cpy+Py, Structural Domain 1

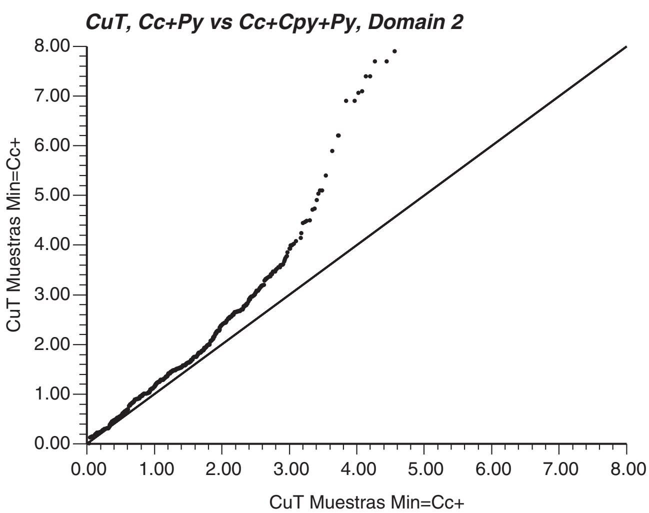


Fig. 4.10 Q-Q plot of TCu (%), Cc+Py vs. Cc+Cpy+Py, Structural Domain 2

ably due to the relative abundance of chalcocite vs. chalcopyrite in the LE unit. The analysis of the relative movements of each structural block explains this observation, since the enrichment process also reached deeper levels for structural Domain 4.

In conclusion, the TCu grade distribution shows different statistical characteristics in each structural domain. The structural control on mineralization explains the relationship between high enrichment and low enrichment mineralization for different parts of the deposit.

In developing Table 4.2 it was assumed that supergene enrichment mineralization (HE and LE) do not show potassic or biotite alteration. This is based on a geologic assumption. Assay intervals logged as HE or LE with K-B alteration were dismissed as incorrectly logged intervals.

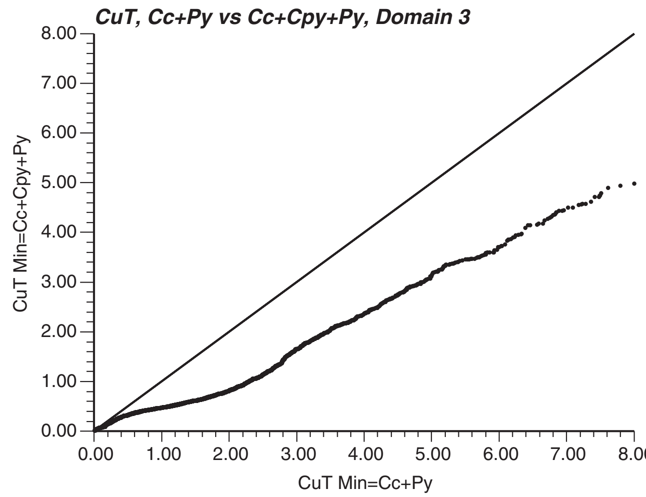


Fig. 4.11 Q-Q plot of TCu (%), Cc+Py vs. Cc+Cpy+Py, Structural Domain 3

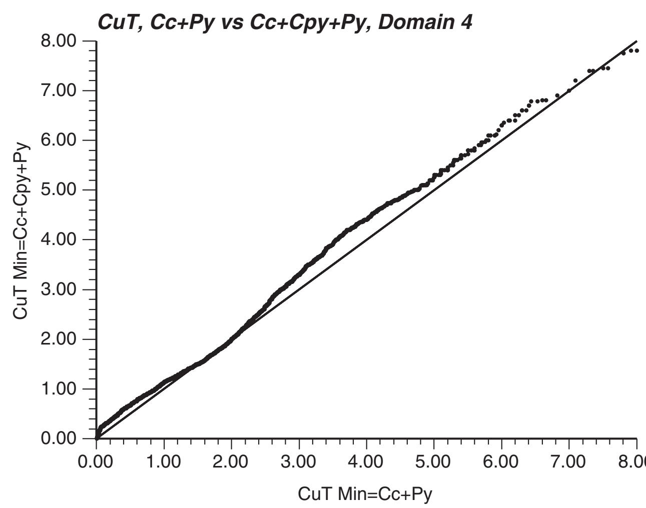


Fig. 4.12 Q-Q plot of TCu (%), Cc+Py vs. Cc+Cpy+Py, Structural Domain 4

4.3.3 Tcu Grade Correlogram Models by Structural Domains

Another perspective of the differences between domains can be gained by analyzing the spatial continuity of the TCu grade distribution, considering again HE mineralization (Cc+Py) as an example. Correlograms (Chap. 6) were run and modeled for all main geologic variables and for each structural domain.

There are practical aspects that need to be considered when analyzing correlogram models within the scope of estimation domain definition. Correlograms and other spatial continuity models are affected by the amount of data available. At Escondida, this implies that the models for structural domain 2, primary mineralization, and some of the low enrichment mineralization units are less reliable compared to the more populated units.

The correlogram models developed showed the following:

- The prevalent anisotropy directions are NE and NW as expected, but not in the horizontal plane. The main axes of continuity are dipping 20–50° towards the center of the deposit, depending on the mineralization unit and domain. This is not a simple, layered deposit that it is sometimes envisioned when dealing with porphyry type deposits.
- Structural Domain 3 consistently presents a much higher nugget effect than the other domains. The grade distribution is more erratic and discontinuous. More dilution can be expected at the time of mining, relative to other domains, which indeed has been the operation's experience.
- Correlograms from structural Domains 2 and 4 show evidence of a deeper enrichment process, consistent with field observations. A NW trending zone of deeper enrichment results in better mineralization as observed in the pit. Correlograms from structural Domain 1 tend to plunge towards the W-SW, while correlograms from Domains 3 and 4 tend to plunge towards the S-SE.
- Structural Domains 1 and 4 show a stronger NE anisotropy, with less emphasis on the NW or SW dipping structures. Structural Domain 2 shows also significant (long-range) NE anisotropy overprinting the expected NW short range anisotropy. The longer-range N-NE anisotropies observed correspond to the general orientation of the two main intrusive bodies that are thought to be the mineralization source.

4.3.4 Final Estimation Domains

Several simplifications were made to the original proposed estimation domains since additional constraints need to be considered to obtain the final estimation domains. First, both enrichment mineralization units in structural Domain 2 (18 and 19) were joined into a single estimation domain, partly because of the similarity of the grade distribution, and partly because of lack of data. Estimation Domains 7 and 11 were merged into a single domain (HE and LE, with SCC alteration, for Domains 1+4), again because of statistical similarity and lack of data. All primary mineralization was combined into a single domain because of lack of data; low TCu grades, and also because production of Cu from primary mineralization will not happen until much later in the mine life.

The final estimation domains are shown in Table 4.3. Descriptive statistics, clustering analysis, contact analysis, and variography are used to confirm the statistical characteristics of TCu within each domain. The results of the domain definition study can be summarized as follows:

1. Fourteen estimation domains (GUs) were defined for TCu. These include the GUs defined for the upper portion of the deposit.
2. Two unexpected features at the time were the use of structural domains and the lesser role that lithology plays as mineralization control in the supergene enrichment zone.
3. The correlogram models obtained for the different datasets and conditioned to different geologic attributes and the GUs show a pattern of anisotropies consistent with geologic knowledge and observations in the pit.
4. There are important details in terms of correlogram models that result from the addition of the structural domains. The most important one is that in Domain 3 the relative nugget effect is significantly higher than for the other domains. This is a result of a local mixture of phyllic (QSA) and SCC alterations, with a corresponding increase in grade variability.
5. The anisotropies detected confirm that the shorter-range, higher-grade mineralization trends mostly NW, but with significant N-NE long-range anisotropies. Also, for units to the south and west of the deposit, the dips and plunges of the ellipsoids of continuity generally will dip to the SW and plunge towards the NE; for units to the north and North East of the deposit, the dip may still be SW, but the plunge is more commonly to the SE.

4.4 Boundaries and Trends

The geological interpretations and modeling of estimation domains produce boundaries that often carry significant uncertainty. The treatment and definition of boundaries have implications on resource estimation such as dilution, lost ore or a mixture of geological populations. The treatment of boundaries at the time of grade estimation is of practical importance. The terms *hard* and *soft* boundaries are used to describe whether the change in grade distribution across the contact is abrupt or not, respectively. Conventional grade estimation usually treats the boundaries between geological units as hard boundaries, whereby no mixing occurs across the boundary. Soft boundaries allow grades from neighboring domains to be used. Sometimes, soft and hard boundaries can be predicted or expected from geological knowledge, but should always be confirmed with statistical contact analysis (Ortiz and Emery 2006; Larrondo and Deutsch 2005).

Contact analysis helps determine whether the grade estimation for any given unit should incorporate characteristics of a neighboring unit. It is a practical tool to describe grade trends and behavior near contacts and define the data to be used in the estimation of each unit.

The behavior of grades across contacts can be analyzed by finding pairs of data in the two estimation domains of interest at pre-defined distances. There are different methods

Table 4.3 Estimation domains for total copper, Escondida 2001 resource model

Estimation Domain	Mineralization	Lithology	Alteration	Structural Domain
0	LIX (0)	ALL	ALL	ALL
1	OXIDE (1)	ALL	ALL	ALL
2	CUPRITE	ALL	ALL	ALL
3	PARTIAL LEACH	ALL	ALL	ALL
4	MIX	ALL	ALL	ALL
5	ALL	PC+TB (Rhyolite+Tuffs)	ALL	ALL
6	6+9 (Cc+Py; Cc+Cv+Py)	ALL	QSA (1)	1+4
7	6+9+7+10+13+14 (Cc+Py; Cc+Cv+Py; Cc+Cpy+Py; Cv+Py; Cc+Cv+Cpy+Py; Cv+Cpy+Py)	ALL	SCC (2)	1+4
8	6+9 (Cc+Py; Cc+Cv+Py)	ALL	QSA (1)	3
9	6+9 (Cc+Py; Cc+Cv+Py)	ALL	SCC (2)	3
10	7+10+13+14 (Cc+Cpy+Py; Cv+Py Cc+Cv+Cpy+Py; Cv+Cpy+Py)	ALL	QSA (1)	1+4
11	7+10+13+14 (Cc+Cpy+Py; Cv+Py Cc+Cv+Cpy+Py; Cv+Cpy+Py)	ALL	QSA (1)	3
12	7+10+13+14 (Cc+Cpy+Py; Cv+Py Cc+Cv+Cpy+Py; Cv+Cpy+Py)	ALL	SCC (2)	3
13	8+10+12 (Cpy+Py; Py; Bn+Cpy+Py)	ALL	K+B (3)	ALL
14	6+9+7+10+13+14 (Cc+Py; Cc+Cv+Py; Cc+Cpy+Py; Cv+Py;Cc+Cv+Cpy+Py; Cv+Cpy+Py)	ALL	ALL	2

to define the pairs, but a true three-dimensional method is preferred to avoid directional biases. In this method, pairs within pre-specified distances are found through a three-dimensional search of nearby assay intervals belonging to a different unit.

Figure 4.13 shows the grade averages at either side of the contact between the Cc + Py and the Cc + Cpy + Py units from the Escondida case study. Each point in the figure corresponds to the TCu average grouped at 2 m distance classes from the contact. Despite the high variability in the averages, the grade transition is smooth, from higher grades in the Cc + Py unit to lower grades in the Cc + Cpy + Py unit, and as would be expected from units that are defined as transitional mineralogical assemblages. A trend could be modeled as a function of distance from the contact.

Another example (Fig. 4.14) shows that the profile of average TCu grades at the contact between the final estimation Domains 6 and 7 at Escondida (see Table 4.3) is hard. In this case, the TCu grades change significantly crossing from one unit to the other in a very short distance. Therefore, it is not advisable to use composites from estimation Domain 7 to estimate TCu grade in estimation Domain 6.

Considering stationary domains in the presence of soft boundaries is often inappropriate. In general, soft boundaries as the one shown in Fig. 4.13 are characterized by a non-stationary behavior near the contact. The mean, variance or covariance are not constant within a zone of influence of one rock type into the other and their values depend on the location relative to the boundary, as illustrated by Fig. 4.15.

The correct reproduction of soft boundaries in resource models improves dilution and mineral resource estimates. The areas close to contacts are usually areas of higher uncertainty, as shown by the abundance of red colors in Fig. 4.16.

In the presence of complex contacts and multiple boundaries, it may be appropriate to model the non-stationary features present in the local neighborhood. The non-stationary features of the mean, variance, and covariance can be parametrized into a local model of coregionalization (Larrondo and Deutsch 2005). Estimation of the grades can be performed using a form of non-stationary cokriging (Chap. 8).

Trends within estimation domains are also common. In certain circumstances, trends need to be explicitly modeled or taken into account, particularly when simulating grade distributions (Chap. 10). In other instances, such as grade es-

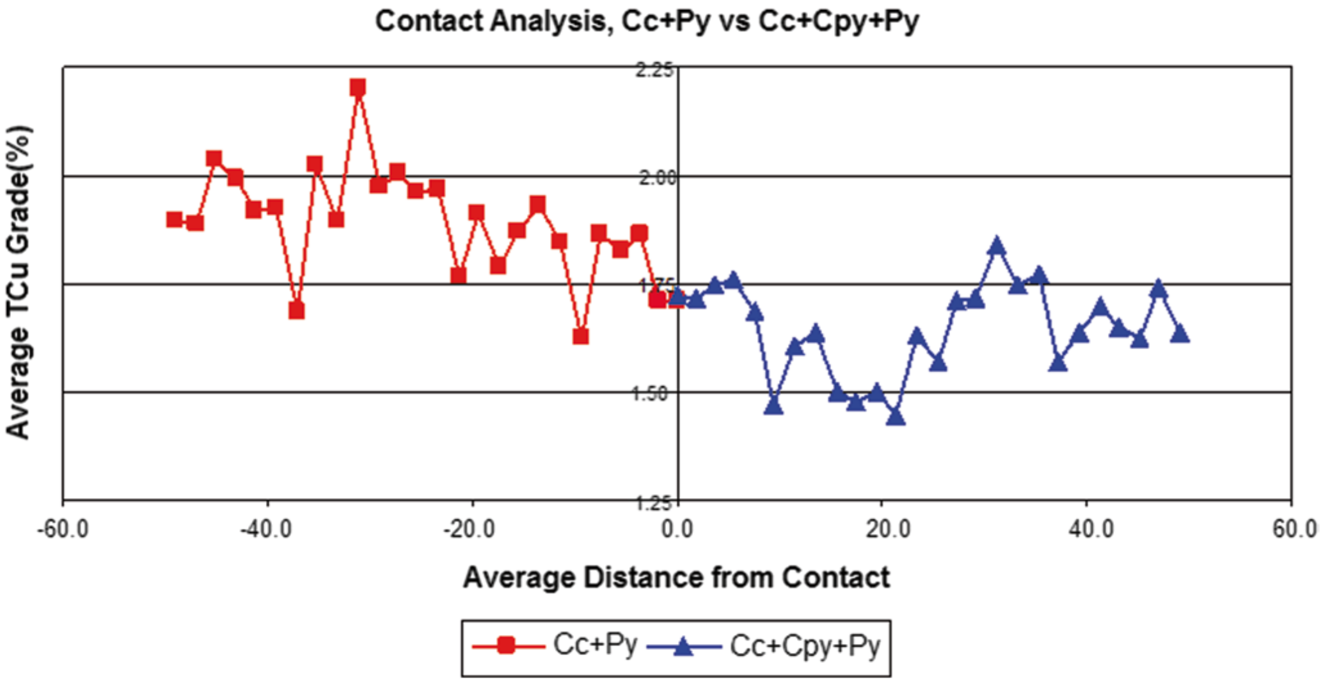


Fig. 4.13 TCu grade transition at the contact between mineralization units Cc+Py and Cc+Cpy+Py, 2 m assays

Fig. 4.14 Contact Analysis, Estimation Domains 6 vs. 7 (see Table 4.3)

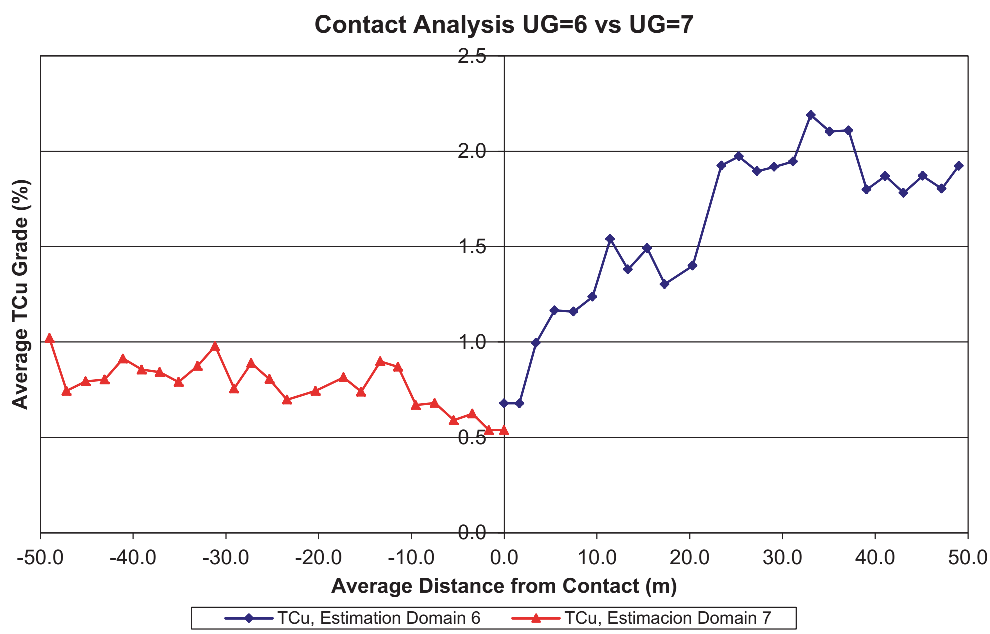
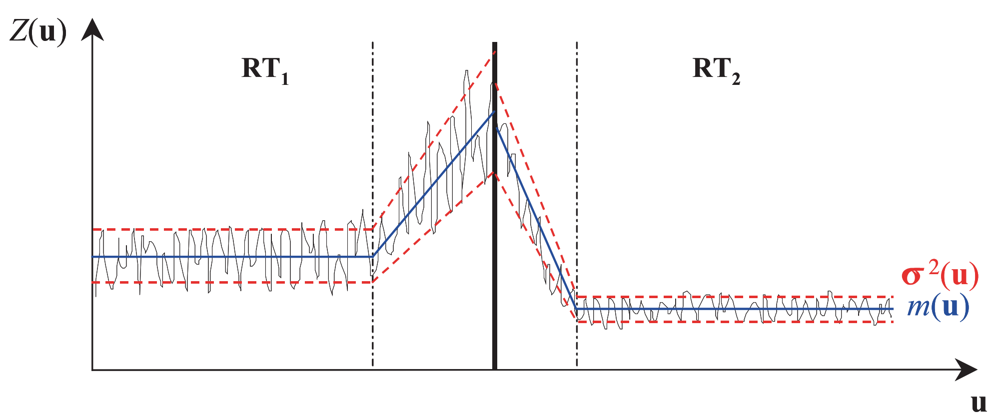


Fig. 4.15 Schematic illustration of trends near boundaries



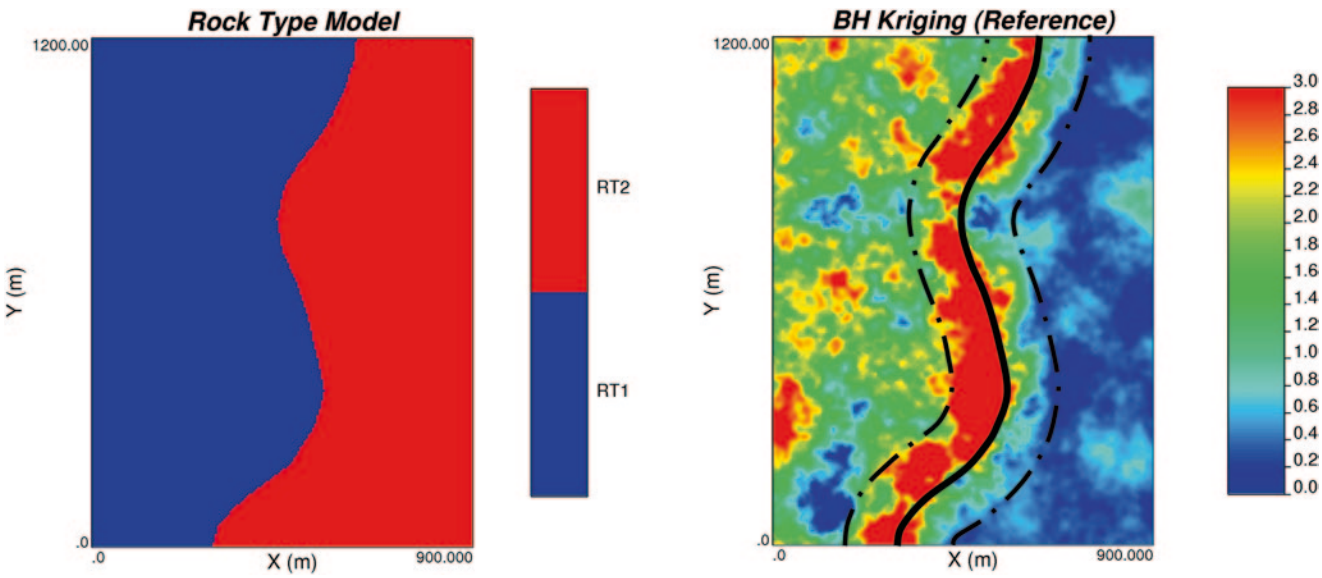


Fig. 4.16 An example of higher uncertainty (and higher grade) near contacts

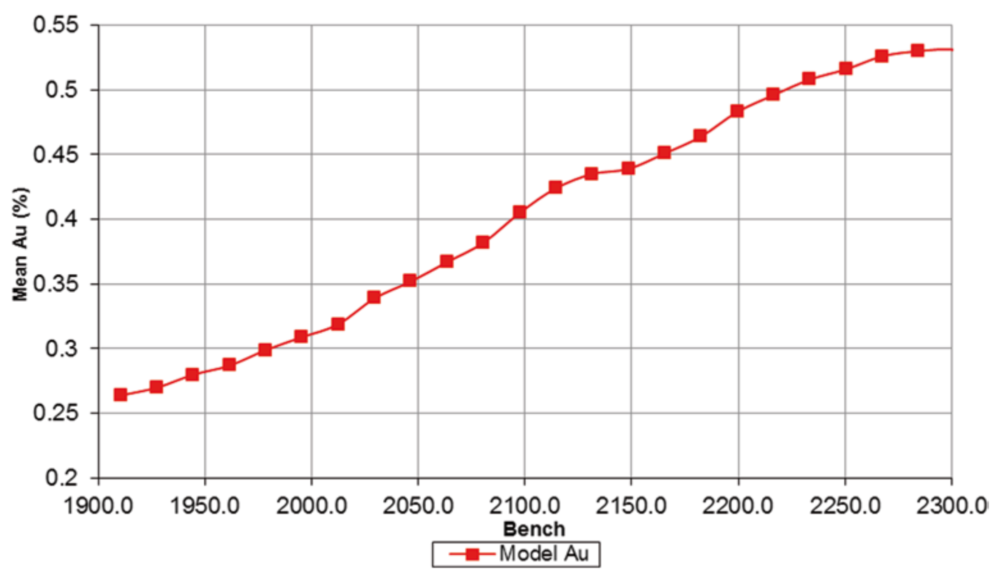


Fig. 4.17 Example of Au grade trend based on bench composites

timation using ordinary kriging and limited search neighborhoods, trends are accounted for by the implicit re-estimation of the mean within the search neighborhood (see Chap. 8 and Journel and Rossi 1989).

Some trends can be inferred from geological knowledge. For example, the distribution of nitrate, borate, and iodine in evaporitic-type deposits is predictable. More commonly, trends are detected and modeled directly from the data. Trends can be described using plots of grade versus distance along a relevant coordinate direction. Figure 4.17 shows the gold grade trend in the vertical direction in a low-grade porphyry Au deposit. The data show that the Au grade declines for lower elevations at an approximate rate of about 0.1 g/t per 100 m. This trend may persist even after defining the final estimation domains. If not taken into account, the trend may result in overestimation of the Au resource for the lower benches.

If trends must be accounted for explicitly, then the following approach is commonly applied in presence of a trend:

- Develop a deterministic trend model and remove it from the data;
- Model the residual component; and
- Add the deterministic trend to obtain the final model.

There are some common deterministic methods for building a trend model. They include hand or computerized contouring, and fitting simple polynomial models. In practice, we might consider 1-D vertical trends and 2-D areal trends that are then merged into a 3-D trend model. There is no unique way to merge 1-D and 2-D trends into a 3-D trend model, but a simple approach is to merge these trends by assuming conditional independence of vertical and areal trends:

$$m(x,y,z) = \frac{m_z(z) \cdot m_{x,y}(x,y)}{m_{global}}$$

Where $m_z(z)$ = mean from vertical trend, $m_{x,y}(x,y)$ = mean from areal trend, m_{global} = global mean from histogram, and $m(x,y,z)$ = mean at location (x,y,z). This equation effectively rescales the vertical trend curve by the areal trend. Other probability combination schemes such as permanence of ratios could be used in situations where assuming conditional independence leads to extreme mean values too close to zero or too high.

4.5 Uncertainties Related to Estimation Domain Definition

The definition of estimation domains is an important prerequisite in the application of most geostatistical tools used in resource modeling. The domains determine the mineralized volume available, and thus is a major factor in the estimated tonnage above economic cutoffs.

The definition of estimation domains is subjective and limited by data and practical considerations. There are many sources of uncertainty contributing to the uncertainty in the definitions of contacts and volumes.

Some of the more typical sources of uncertainty include geologic data: errors, omissions, or imprecise mapping and logging are common. For example, in highly altered rock, the precise description of lithology types can be difficult, more so if diamond drilling is not used. Porphyries of different kinds are difficult to differentiate and different lithologies may not be easy to distinguish. Human perceptions and errors are important since many geologic attributes are subject to visual estimations and interpretations in the field. For example, the alteration intensity or the percentage of sulfides may have to be estimated by the geologist.

Limited data also may be a significant source of uncertainty. It is common that two domains with clearly different mineralization controls have to be combined into one domain because one of them does not have enough drill hole information. This results in a mixture of populations that cannot be resolved until more data are collected. The domain with more data will influence the statistics, the variogram models, and the kriging plans applied to estimate the grades of the combined units.

There is also the uncertainty carried over from the geologic interpretation and modeling which is more significant in sparsely drilled areas. The geologic model can be another important source of uncertainty that, when combined into estimation domains, can result in serious flaws in the resource model.

All these sources of uncertainty combine with the fact that mineralization will be naturally varying from one location to another. This natural variability within the estimation domains exists at different scales and should be considered at the time of estimation.

4.6 Summary of Minimum, Good and Best Practices

At a minimum, the methodology used to define estimation domains should consider the most evident mineralization controls, and include the basic tools needed to demonstrate the relationships between geologic attributes and grade. The main mineralization controls can often be described through mapped geology and a working hypothesis of the genesis of the deposit. Basic exploratory data analyses characterize mineralization controls.

Good practice considers all available geologic information and the relationship between grades and each geologic variable. This process involves a first phase, in which the individual mapped geology, such as mineralization, lithology, alteration, or others, is grouped in part by applying geologic knowledge and common sense, in part applying numeric and statistical constraints.

A new set of descriptive statistics is then developed in a second phase of the study, from which an initial set of estimation domains may be proposed. An iterative process that includes further statistical analysis supported by geologic knowledge results in the final definition of the estimation domains.

The definition of estimation domains is an imperfect process, characterized by compromises between the estimation domains that should be defined (according to geology and statistical analysis) and the amount of data available to define them. Sometimes, limitations in the coding of the original database may also affect the definition of the estimation domains.

Best practice is to define the estimation domains and accompany it by an assessment of its uncertainty and the limitations and assumptions used to define it. The definition should include limitations related to data quality and quantity, geologic information used, and the type of statistical analysis used to assess whether the domains contacts are hard or soft. The better tool to assess geologic uncertainty is simulation.

4.7 Exercises

The objective of this exercise is to construct trend models for a 2-D example and a larger 3-D example. Some specific (geo)statistical software may be required. The functionality may be available in different public domain or commercial software. Please acquire the required software before beginning the exercise. The data files are available for download from the author's website—a search engine will reveal the location.

4.7.1 Part One: Basic Statistics

Consider the 2-D data in `red.dat`. A small exploratory data analysis is required for the five different variables in this dataset: thickness, gold grade, silver grade, copper grade and zinc grade.

Question 1: Tabulate the key statistics for each variable: number of data, minimum, maximum, mean and variance. Plot histograms of the different variables and comment on the results.

Question 2: Plot probability plots of the variables on arithmetic or logarithmic scaling as appropriate. Comment on outliers, inflection points or any other interesting features.

Question 3: Plot scatterplots between all pairs of variables and create a matrix of correlation coefficients to summarize how the variables relate to one another.

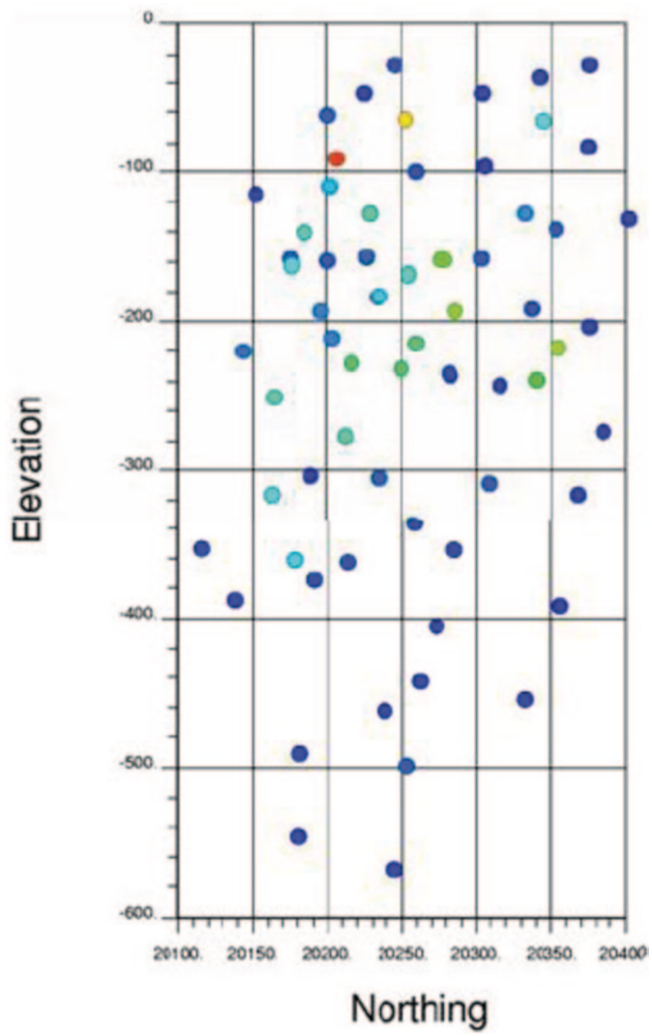
Question 4: Repeat the previous question with normal scores of all the variables.

4.7.2 Part Two: 2-D Trend Modeling

Consider the 2-D data in `red.dat`. There is a significant trend with lower thickness at depth (below about −250 m) to the North and South.

Question 1: Create a contour map that represents the trend. Take care that the contours do not too closely match short scale variations. The general rule is to match large scale variations at a scale of greater than 2–3 times the drillhole spacing.

Kriging or inverse distance (or some other gridding algorithm) can be used as well; however, hand contouring is robust and gives an improved understanding of the data. Post the thickness data with the thicknesses posted on the map. Hand contour the map. Choose your own contour intervals; however, you could take 0.5, 1.0, 2.0, 5.0, or 10.0 if you are unsure.



Question 2: There are a number of programs to get the contour lines in a "point-data" format for gridding algorithms. Create a gridded model of your contour map. Ensure that the map is smooth with no artifacts from your chosen gridding algorithm.

Question 3: Calculate residuals as *res* = *thickness-thicknesstrend*. Plot a histogram of the residuals. Plot a cross plot of the residuals versus the *thicknesstrend* values. Comment on any features that would make it awkward to simulate the thickness residuals independently of the thickness trend.

4.7.3 Part Three: 3-D Trend Modeling

Consider the 3-D data in `largedata.dat` for 3-D trend modeling. Build a trend model for the copper grade.

Question 1: Build a smooth vertical average of the grades by averaging the grades in vertical slices. The 1-D averaging program can be used for this purpose. Consider a number of sensitivity runs with different slice thicknesses and other parameters. Plot the results. Comment on the presence of a vertical trend and the importance of considering it in the simulation model. Present the final result that you choose.

Question 2: Calculate the vertical average of the drillhole data, make a map of the vertical averages, and comment on the need for modeling the areal trend.

Generate a smooth areal trend using kriging, inverse distance, or the contouring approach used in Part One.

Question 3: Construct a 3-D trend model by combining the 1-D vertical trend and the 2-D areal trend. Comment on the practical implications of the conditional independence assumption implicit to the combination approach commonly used. Also comment on the alternatives to construct a 3-D trend.

Question 4: Calculate residuals as *res* = *grade* − *grade trend*. Plot a histogram of the residuals. Plot a cross plot of the residuals versus the *grade trend* values. Comment on any features that would make it awkward to simulate the grade residuals independently of the grade trend.

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