AN ECONOMIC EVALUATION OF THE ROSH PINAH POLYMETALLIC DEPOSIT USING THE NET SMELTER RETURN MODEL

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2018

DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

Signed: ....

This.......13.......day of.......MARCH.......year.......2018.......

ABSTRACT

The economic evaluation of polymetallic deposits differs significantly from the economic evaluation of single metal deposits. Polymetallic deposits are mineral deposits that consist of two or more metals of economic interest. Rosh Pinah Zinc Corporation (RPZC) mine is a polymetallic deposit that consists of zinc (Zn), lead (Pb) and silver (Ag). One of the critical aspects of an economic evaluation of a mineral deposit is the determination of cut-off grades.

Mortimer (1950) and Taylor (1972) can be credited for undertaking pioneering work on cut-off grades. Lane (1988) subsequently made significant strides towards addressing the cut-off grade problem by producing an algorithm that generated six potential cut-off grades, three of which are limiting cut-off grades while the other three are balancing cut-off grades. Lane's algorithm took into account the capacities of the mine, mill and market. However, the greatest handicap of Lane's algorithm was that it could not determine cut-off grades in polymetallic deposits. The Net Smelter Return (NSR) model is a useful model in the economic evaluation of polymetallic deposits and provides a means to determine cut-off grades by readily determining the economic value of a polymetallic deposit. The other more widely used method in the economic evaluation of polymetallic deposits is the equivalent grade method, which suffers the handicap of assuming constant price relationships between constituent metals.

The NSR model was constructed in Microsoft Excel™. In addition, a Visual Basic Application (VBA) platform was used to create a user interface. Data was collected from both RPZC mine and the public domain. The model was constructed following the '*Guidelines for Technical Economic Evaluation of Minerals Industry Projects*' for spreadsheet modelling. Sensitivity analysis was used to investigate the relationships that exist between different factors while Monte Carlo simulation was used to account for risk and uncertainty. These analyses revealed that mineralogical factors have a greater impact on the mine netback in comparison to economic factors.

The NSR model was successfully applied in the economic evaluation of the RPZC polymetallic deposit. By applying a cut-off NSR value, it is possible to determine appropriate cut-off grades that are economically viable. Cut-off grades of approximately 10%, 1.5% and 15 g/t for Zn, Pb and Ag, respectively, were determined using the NSR model for a cut-off NSR/t value of US$70. However, the Monte Carlo simulation generated NSR/t values that were as low as US$40.

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NOMENCLATURE

CIF	Cost Insurance and Freight
COGS	Cut-off Grade Strategy
COMEX	Commodities Exchange
DMT	Dry Metric Tonne
EOF	Eastern Ore Field
EPL	Exclusive Prospecting Licence
FOB	Free On Board
JORC	Joint Ore Reserves Committee
JSE	Johannesburg Stock Exchange
LME	London Metal Exchange
LOM	Life-of-Mine
LSE	London Stock Exchange
MVT	Mississippi Valley Type
NPV	Net Present Value
NSR	Net Smelter Return
NO	Northern Orefield
PGM	Platinum Group Metal
PLC	Private Limited Company
RC	Refining Charge
ROM	Run-of-Mine
RPZC	Rosh Pinah Zinc Corporation
SEDEX	Sedimentary Exhalative
SHFE	Shanghai Futures Exchange
SHG	Special High Grade
SO	Southern Orefield
TC	Treatment Charge
USA	United Stated of America
WMT	Wet Metric Tonne
WO	Western Orefield

1 INTRODUCTION

1.1 Chapter overview

This chapter introduces the setting of the research study. It provides an overview of the Rosh Pinah Zinc Corporation (RPZC) mine by providing information on the mine's history and current ownership, geology, Mineral Resources and Mineral Reserves, mining method, and mineral processing used at the mine. An overview of the Namibian base metals industry is also provided, further setting the context of the research study. The chapter also outlines the research questions that this research study aimed to address and provides a justification for the use of the RPZC mine and the Net Smelter Return (NSR) model. Finally, the chapter gives insight into the research study by providing the structure of the report.

1.2 Background on Rosh Pinah Zinc Corporation mine

The background information on RPZC mine is outlined in the following sections. These sections cover information relating to mine ownership, brief history, geology, Mineral Resources and Mineral Reserves, mineral processing and mining method. Information on the Namibian base metal industry is also given.

1.2.1 Mine ownership and history

RPZC mine is a polymetallic (zinc (Zn), lead (Pb) and silver (Ag)) mine located in a town called Rosh Pinah, which is about 800 km south of Windhoek, the capital city of Namibia. Currently, the mine is owned by a London Stock Exchange (LSE) listed global diversified natural resources conglomerate specialising in multiple commodities trading called Glencore Xstrata Private Limited Company (plc). Glencore Xstrata plc has an 80.08% shareholding while the remaining 19.92% belongs to PE Minerals Namibia (Anon., 2012). The geographical location of the town in which the mine is located is shown in Figure 1.1.

The mine has had several other owners during its existence, including Exxaro Resources. Exxaro Resources, a Johannesburg Stock Exchange (JSE) listed diversified coal, mineral sands and base metal miner, sold its stake in RPZC mine to Glencore Xstrata plc in 2012 in a cash deal worth R931 million (Anon., 2012).

Glencore Xstrata plc is one of the world's largest diversified natural resource companies, with a network spanning over 50 countries. The conglomerate's core business revolves around metal commodities, energy products, agriculture, marketing and logistics (Anon., 2016).

Currently, Glencore Xstrata plc is concluding negotiations with Trevali Mining Corporation to sell its 80.08% shareholding in RPZC mine to the latter. The broad ranging negotiations have reached a definitive stage. It is envisaged that Trevali Mining Corporation will acquire a portfolio of Zn assets from Glencore Xstrata plc, including Glencore plc's 90% stake in Perkoa mine in Burkina Faso for an aggregate purchase price of approximately US$400 million (Trevali Mining Corporation, 2017).

RPZC mine commenced operations in 1969 with an initial Life-of-Mine (LOM) estimated at 8 years. However, continued exploration extended the LOM and in 2014, the LOM was estimated at 7 years (Rosh Pinah Zinc Corporation, 2014). Currently, the LOM is estimated at 7.6 years (Trevali Mining Corporation, 2017).

Figure 1.1 Location of Rosh Pinah Zinc Corporation mine
(Source: Adapted from Google, 2017)

1.2.2 Geology

The geology of the RPZC deposit is best explained using the Sedimentary Exhalative (SEDEX) model for deposition of base metals on the sea floor. Figure 1.2 is a diagrammatic representation of the SEDEX model. Bi-modal heating served as the source of heat for the process under a hydrothermal plumbing system. This resulted in the deposition of approximately 40Mt of deposit under continental rifting (Anon., 2014).

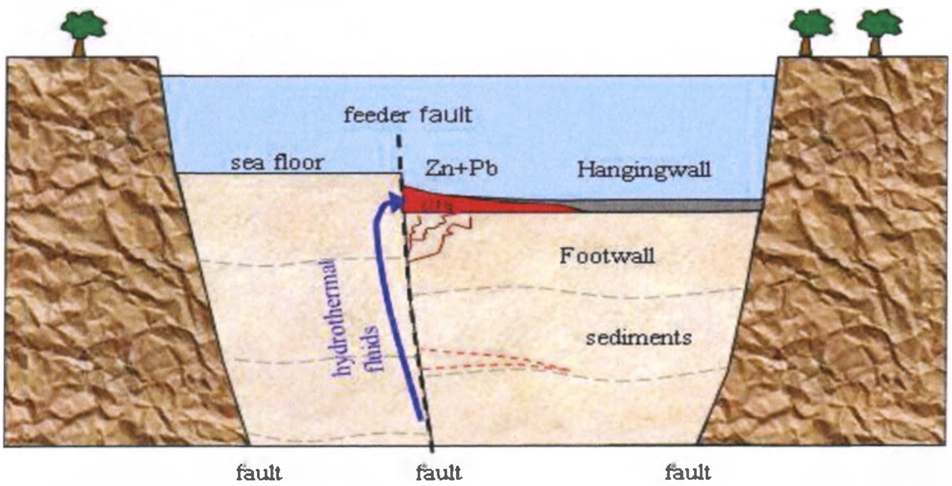


Figure 1.2 Sedimentary Exhalative (SEDEX) model
(Source: Rosh Pinah Zinc Corporation, 2014)

The deposit is of Neoproterozoic age and its genesis is closely related to the Rosh Pinah graben, discovered in 1963. The mineralisation is hosted by carbonate, argillite and arkose host rock, which are highly competent, hence the underground workings rarely utilise artificial supports. The geological setting of the RPZC deposit is shown in Figure 1.3.

The RPZC deposit has a strike length varying from 90 – 300m, due to the separate ore bodies that make up the RPZC deposit. The widths vary from 5 - 60m, with individual orebody heights varying between 40 – 250 m. The orebody is divided into a number of mining sections, namely, Western Ore Field (WOF), Eastern Ore Field (EOF), Southern Orefield (SO) and Northern Orefield (NO).

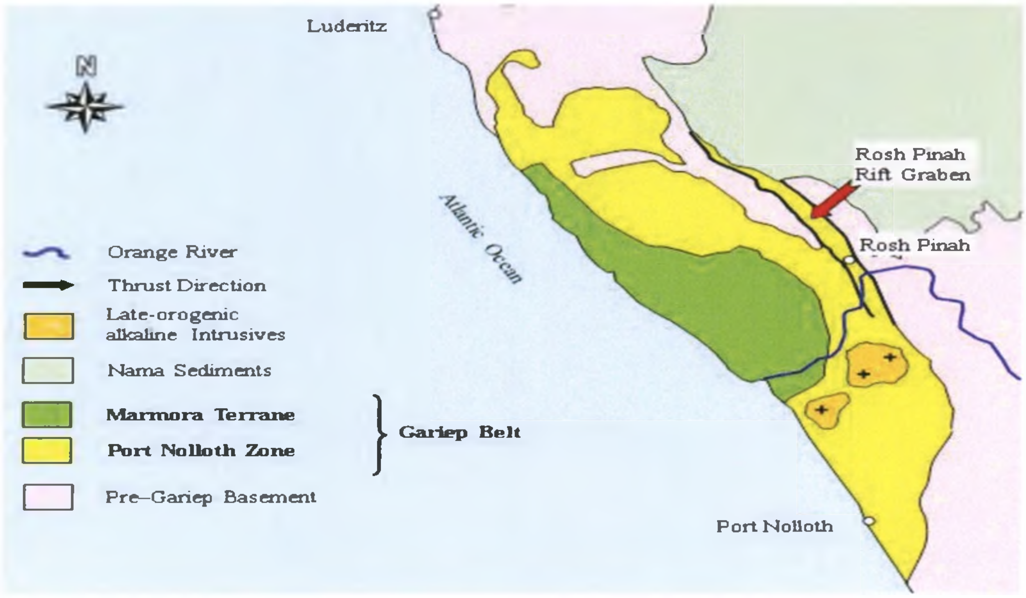


Figure 1.3 Geological setting of the Rosh Pinah deposit
(Source: Rosh Pinah Zinc Corporation, 2014)

1.2.3 Mineral Resources and Mineral Reserves

Following Trevali Mining Corporation's prospective acquisition of RPZC mine, a Mineral Resource and Mineral Reserve statement for the RPZC deposit was compiled. Table 1.1 shows the Mineral Resources and Mineral Reserve quantities, in their respective categories. It also shows the respective contained metal quantities for Zn, Pb and Ag. The Mineral Resource and Mineral Reserve statement is Joint Ore Reserves Committee (JORC) code compliant.

Table 1.1 Current Mineral Resources and Mineral Reserves of RPZC mine
(Source: Adapted from Trevali Mining Corporation, 2017)

	Category	Tonnes	Zn (%)	Pb (%)	Ag (g/t)
Mineral Reserves	Proven	1 611 600	9.9	1.0	17
	Probable	3 469 600	8.3	1.1	22
Mineral Resources	Measured	3 352 400	8.7	1.7	27
	Indicated	6 588 100	7.4	1.4	23
	Inferred	2 929 300	6.0	1.1	26

1.2.4 Mining method

The underground RPZC mining operation is mined using a sub-level open stoping method. It is accessed by adits, three declines and two incline shafts situated at different locations around the Rosh Pinah Mountain. Access to the ore body is provided at various sub-levels between the main haulage levels in order to drill and blast the ore. Stope drilling is carried out from drilling sills on the sub-levels, and the ore is blasted in slices towards an open face and the blasted ore gravitates to the bottom of the stope and is collected through draw points. Figure 1.4 shows a typical sub-level open stoping layout as applied at RPZC mine.

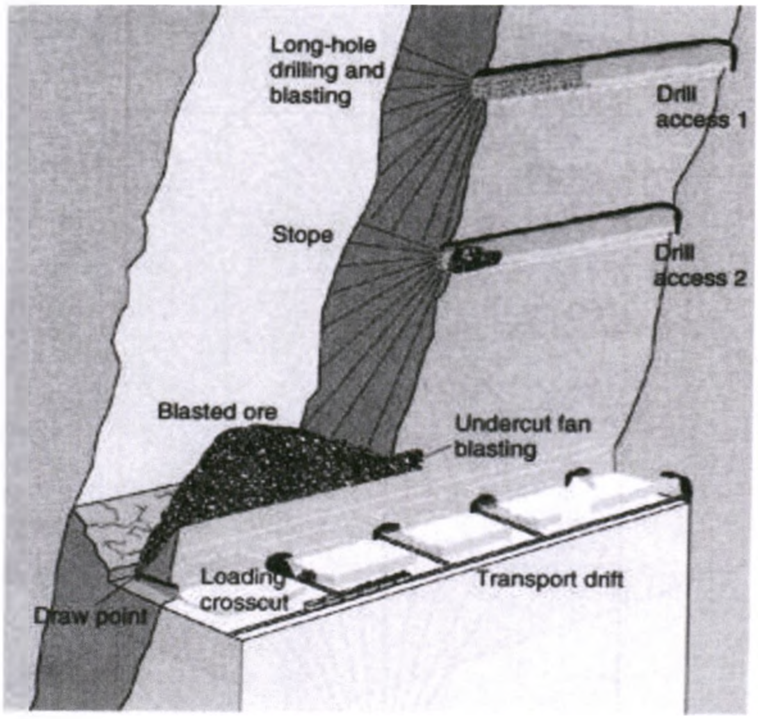


Figure 1.4 A typical sub-level open stoping layout
(Source: QueensMineDesignWiki, 2014)

1.2.5 Mineral processing

The RPZC metallurgical process is planned to operate 24 hrs, 358 days per year producing Zn and Pb sulphide concentrates. In terms of operations the plant is divided into four main circuits as shown in Figure 1.5, namely the crushing, milling, Pb floatation and the Zn floatation circuit. Pb floatation is done prior to Zn floatation owing to the higher relative floatability of Pb. Zn floatation is thus done on the residue of Pb floatation. The products from both processes are separately dried while the residue from Zn floatation is discarded as tailings. The Ag reports to the Zn and Pb concentrates.

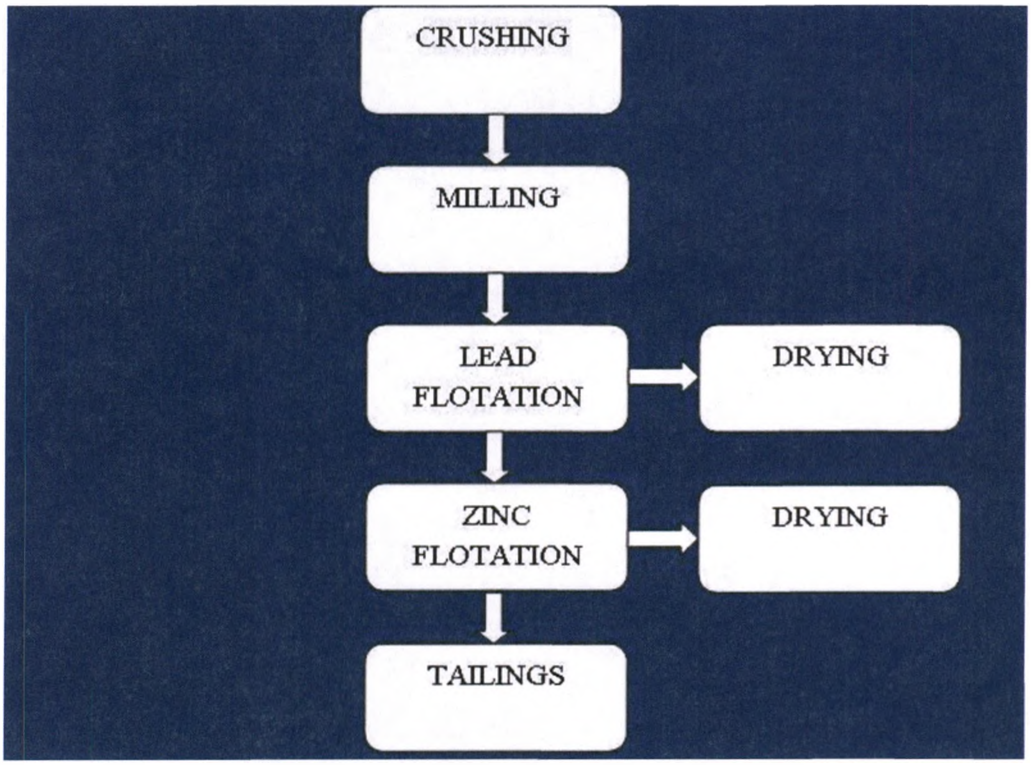


Figure 1.5 Processing flowsheet at Rosh Pinah Zinc mine
(Source: Rosh Pinah Zinc Corporation, 2014)

Primary crushing is carried out underground using a Jaw crusher and secondary and tertiary crushing are then carried out on surface, down to a size of below 9mm, both with the use of a cone crusher. The crushed ore is then ground in a ball mill down to a size of below 100μm (microns). In the floatation circuit the Pb concentrate is floated first using conventional agitation floatation banks in the Pb rougher and scavenger banks. The Pb rougher concentrate is floated through a series of cleaner cells comprising a column cell, a tank cell and a smart cell. During floatation, sodium cyanide is used as a sphalerite/pyrite depressant. Xanthate is added as a galena collector, and senfroth as a frother. Copper sulphate is used as an activator of the depressed sphalerite.

The Pb concentrate (Galena) is dried using a vacuum belt to a moisture content of approximately 15%. The tailings of the Pb circuit are then fed into the Zn circuit, where the Zn is floated off in a battery of conventional agitation cells in the rougher circuit. The Zn rougher concentrate is cleaned through a sole cleaner column and the concentrate is dried to approximately 15% moisture, using the vacuum belt filter.

1.3 The base metal industry in Namibia

There are two players in the base metal industry in Namibia, namely RPZC and Skorpion Zinc (Pty) Ltd. The latter is wholly owned by the LSE listed Vedanta Resources plc through its subsidiary company Vedanta Limited. Skorpion Zinc (Pty) Ltd is the 8th biggest Zn producer in the world, with a refinery on site. Anglo American plc formerly owned Skorpion Zinc (Pty) Ltd through its base metals business unit, Anglo Base Metals.

The rest of the Namibian mining industry is relatively small as compared to the rest of the Southern African region. It largely consists of uranium, gold and diamond mining. To put the comparison into perspective, the South African mining industry contributed R286 billion (equivalent of US$24 billion) to Gross Domestic Product (GDP) in the 2015 to 2016 financial year (Chamber of Mines of South Africa, 2016), while the Namibian mining industry contributed N$29 billion (equivalent of US$2.4 billion) to GDP during the same period (The Chamber of Mines of Namibia, 2016).

For the 2015 to 2016 financial year, the Namibian diamond sector, which is the largest single contributor of corporate tax in Namibia, contributed an estimated N$2 billion (equivalent of US$168 million) in tax remittances in the 2015 to 2016 financial year while the combined mining industry registered a turnover of N$25 billion (equivalent of US$2 billion). The base metals sector contributed an estimated N$150 million (equivalent of US$12.6 million) in corporate tax for the period under review (The Chamber of Mines of Namibia, 2015). All US$ equivalents were calculated at the prevailing US$/ZAR exchange rate of approximately 1:12.

Figure 1.6 shows the 2003 to 2015 production levels for RPZC mine. Latest published results indicate that Zn and Pb concentrate production fell short of the budgeted targets (The Chamber of Mines of Namibia, 2015). These drops have been attributed to recovery losses and below target Zn mill feed grades. RPZC mine produces about 2000 tonnes of Run-of-Mine (ROM) ore per day.

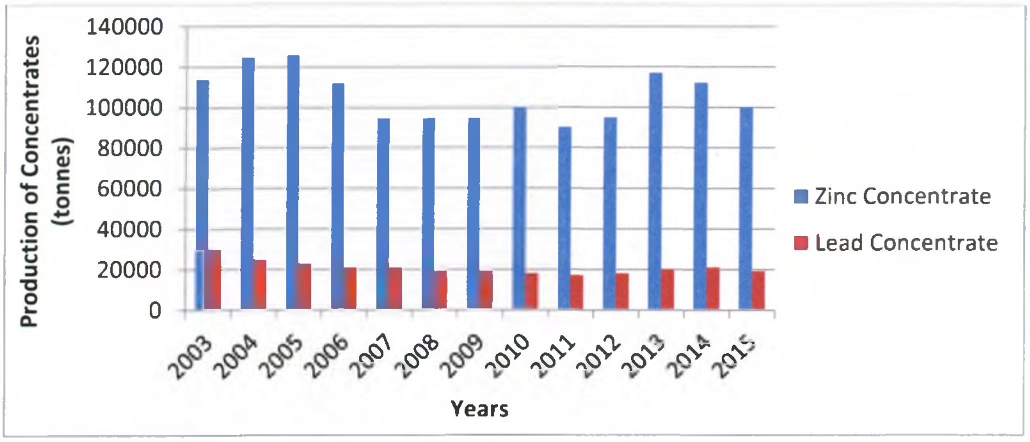


Figure 1.6 Rosh Pinah output - Pb and Zn concentrates
(Source: Adapted from The Chamber of Mines of Namibia, 2015)

Skorpion Zinc (Pty) Ltd.'s production during the period under review also declined against a backdrop of declining ore grades. A planned maintenance shutdown of the refinery further compounded the decline in production output. Figure 1.7 shows Skorpion Zinc (Pty) Ltd.'s output of Special High Grade (SHG) Zn for the period 2003 to 2015.

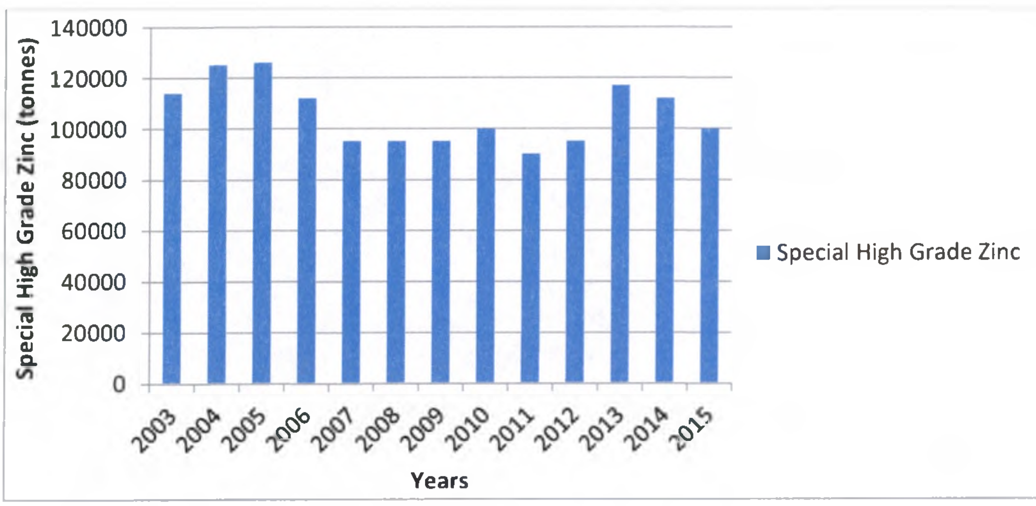


Figure 1.7 Skorpion Zn output of Special High Grade Zn
(Source: Adapted from The Chamber of Mines of Namibia, 2015)

International Base Metals, an unlisted Australian explorer with a subsidiary, Craton Mining and Exploration, has a package of mineral rights in Namibia of approximately 11 600 km² made up of ten Exclusive Prospecting Licences (EPLs) and four EPL applications to explore for copper (Cu) and base metals (Solomon, 2012).

1.4 Justification for the use of the Net Smelter Return model

The economic evaluation of a mine with a polymetallic deposit differs considerably from the evaluation of a single metal deposit. This is due to the level of complexity that a polymetallic deposit presents owing to the occurrence of more than one metal in varying quantities within the orebody. This complexity is further compounded by the fact that the different payable metals within the deposit are sold at fluctuating prices during the LOM. RPZC mine exploits a polymetallic deposit and produces Pb and Zn concentrates for further smelting and refining. The Ag is contained in both the Zn and Pb concentrates and refined as a payable metal.

The NSR model is a model that is used during the exploration, evaluation and exploitation of polymetallic deposits. It is therefore applicable in almost all the important stages during the LOM in which economic value is of importance. In the evaluation phase, it is useful in establishing cut-off grades and production rates in the depletion of mineral deposits (Goldie and Tredger, 1991). However, it is important to draw attention to the fact that the NSR model is not the only model that is useful in the economic evaluation of polymetallic deposits.

The other more widely used model is the equivalent grade model. In this method, the concentrations of different metals are converted to one metal equivalent according to their relative prices. This approach of using one common denominator has got two major handicaps. Firstly, it makes the assumption that treatment costs and metal losses in processing are the same for all the recoverable metals. This, of course, is not true. Secondly, despite the reality of different commodity price fluctuations for each metal, the model tends to maintain the equivalence factors at their initially calculated levels. These shortcomings served as the basis for the disqualification of the equivalent grade method for the purposes of this study, despite its wide application.

Furthermore, it is important to note that the NSR model readily allows for the rapid conversion of ore grades to economic value per tonne. Therefore, it is possible to make a quick comparison of Mineral Reserves to the applicable costs so that viability could readily be determined. Thus, NSR cut-off grades become the cut-off grades. This was particularly important since the determination of cut-off grades was a key objective of this research study. An additional reason for the selection of the NSR model was that it allowed for the effect of commodity price fluctuations to be evaluated quickly, hence making it possible for the performance of quick metal price sensitivity studies. This is particularly important during periods of price volatility such as the one under which this study was conducted.

The above mentioned reasons served as the basis for the selection of the NSR model in carrying out the economic evaluation of the RPZC polymetallic deposit. The RPZC deposit, due to its polymetallic nature, presented a good opportunity for the use of the NSR model in carrying out an economic evaluation of the deposit. The essence of any economic evaluation is to gain an understanding of the underlying investment. A more in-depth outline of the model is provided later in the literature review chapter.

1.5 Research question

The primary research question in this study was to determine whether the NSR model could be successfully applied to the RPZC mine to determine cut-off grades as part of an economic evaluation of the deposit.

In addition to the above primary research question, the secondary research question within this study included a comparative analysis of the merits and demerits of using the NSR model to other evaluation techniques that are used in the economic evaluation of polymetallic deposits, particularly the equivalent grade method.

1.6 Structure of the report

This chapter provides a background to the research study. It further provides a statement on the problem that this research study addressed and a justification of why it was necessary to carry out this research study. Figure 1.8 shows the structure of the report.

Chapter 2 is a literature review of the research study. The chapter addresses in more detail the subject of ore deposit evaluation, particularly from a cut-off grade perspective. It also reviews other cut-off grade techniques that are employed in the determination of cut-off grades in polymetallic deposits. Additional justification for the selection of the NSR model is also made by providing a more detailed outline of the NSR model. The chapter identifies case studies to illustrate specific concepts within the broader subject of economic evaluation and the NSR model in particular.

Chapter 3 outlines the research methodology and approach. It also describes the data sources and how the data was treated in order to generate reliable results for analysis.

Chapter 4 explains the data collection procedure that was adopted for this research study and outlines the various sources of data.

Chapter 5 gives an analysis of the results that are derived in Chapter 4.

Conclusions and recommendations of this research study are presented in Chapter 6.

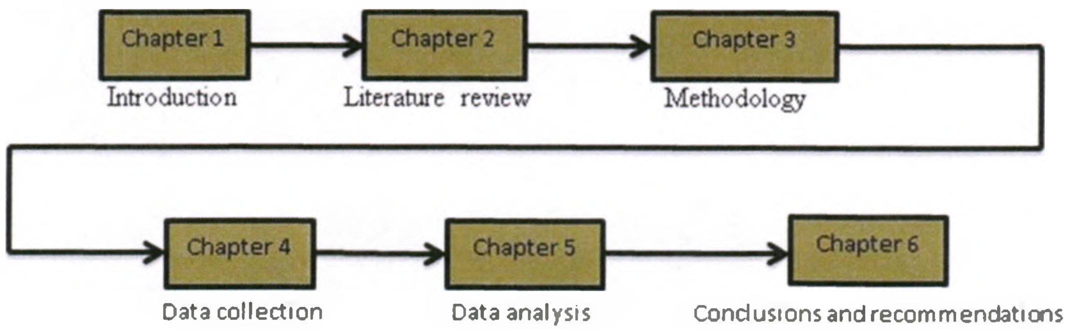


Figure 1.8 Structure of the report

2 LITERATURE REVIEW

2.1 Chapter overview

This chapter focuses on ore deposit evaluation and the various models that are used in ore deposit modelling and how they have been applied in other polymetallic deposits. In addition, it gives a background to the concept of cut-off grade and places emphasis on cut-off grade in polymetallic deposits. Methods used in the determination of cut-off grades in polymetallic deposits are discussed. Their strengths and weaknesses are also examined.

2.2 Ore deposit evaluation

There are two components to an ore deposit model. The first component is the empirical model which is an assemblage of data. This data can be observational data that aids in the characterisation of the deposit. The second component is the conceptual model which is an interpretation of the data through a unifying theory of genesis (Roberts, 1988). A NSR model also follows this form, with an empirical model that is obtainable from operating mines, while the conceptual component provides the economic geologist with a framework for the evaluation of specific projects (Goldie and Tredger, 1991). It must be noted that NSR models are applicable in exploration, evaluation and exploitation of mineral deposits.

The other more widely used model applicable in the evaluation of polymetallic deposits as stated in Section 1.4, is the equivalent grade method. By considering costs and revenues, the profit for an operation producing two metal products can thus be determined by Equation 2.1.

$$P = (s_1 - r_1)Q_{r1} + (s_2 - r_2)Q_{r2} - mQ_m - cQ_c - fT \qquad \textbf{Equation 2. 1}$$

The parameters in the above equation are defined as follows:

P: profit ($);

m: mining cost ($/tonne of material moved);

c: concentrating cost ($/tonne of material concentrated);

r_1: refinery cost ($/unit of product 1);

r_2: refinery cost ($/unit of product 2);

s_1: selling price of product 1;

s_2: selling price of product 2;

T: the length of the production period in years;

f: fixed cost per year;

Q_m: quantity of material to be mined;

Q_c: quantity of ore to be sent to the concentrator;

Q_{r1}: the amount of product 1 actually produced over this production period; and

Q_{r2}: the amount of product 2 actually produced over this production period.

If *d* is the discount rate, the difference v_t between the present values of the remaining reserves at time t = 0 and t = T is given by Equation 2.2.

$$v_t = P - VTd \qquad \text{Equation 2. 2}$$

Where V is the present values at time t = 0. Substituting Equation 2.1 into Equation 2.2 gives Equation 2.3.

$$v_t = (s_1 - r_1)Q_{r1} + (s_2 - r_2)Q_{r2} - mQ_m - cQ_c - (f + Vd)T \qquad \text{Equation 2. 3}$$

The quantities of refined metals Q_{r1} and Q_{r2} are related to the quantities that are sent to the concentrator (Q_c), hence:

$$Q_{r1} = g_1 y_1 Q_c \qquad \text{Equation 2. 4}$$

$$Q_{r2} = g_2 y_2 Q_c \qquad \text{Equation 2. 5}$$

Where g_1 and g_2 represent the average grades of metal 1 and metal 2 sent for concentration, respectively and y_1 and y_2 represent the recoveries of metal 1 and metal 2 from the ore, respectively. Substituting Equation 2.4 and Equation 2.5 into Equation 2.3 results in Equation 2.6.

$$v_t = [(s_1 - r_1)g_1 y_1 + (s_2 - r_2)g_2 y_2 - c]Q_c - mQ_m - (f + Vd)T \qquad \text{Equation 2. 6}$$

Equation 2.6 relates v_t to the average grades of metal 1 and metal 2. Ideally, mine scheduling is carried out in such a manner that reduction in the Net Present Value (NPV) should take place earlier in the LOM rather than later. This is because earlier cash flows are subject to smaller discount factors than the later cash flows. The overall effect is a higher NPV. v_t thus has to be maximized to get the net effect of the highest NPV.

However, as highlighted earlier, v_t is a function of two variables, namely average grade of metal 1 and average grade of metal 2. In order to express the metal grade of metal 2 in terms of metal 1, an equivalent factor is used. Consequently, v_t will be a function of metal 1 and Equation 2.6 can be expressed as Equation 2.7.

$$v_t = [(s_1 - r_1)y_1(g_1 + F_{eq}g_2) - c]Q_c - mQ_m - (f + Vd)T \qquad \textbf{Equation 2. 7}$$

F_{eq} represents the equivalent factor.

In order to calculate the average equivalent grade of ore based upon equivalent factor and average grade of each metal, the Equation 2.8 is used.

$$g_{eq} = g_1 + F_{eq}g_2 \qquad \textbf{Equation 2. 8}$$

Substituting Equation 2.8 into Equation 2.7 yields Equation 2.9.

$$v_t = [(s_1 - r_1)y_1g_{eq} - c]Q_c - mQ_m - (f + Vd)T \qquad \textbf{Equation 2. 9}$$

2.3 Evolution of cut-off grade theory

This section introduces the concept of cut-off grades by providing its background. It further outlines early work and advancements that contributed to the evolution of cut-off grade theory.

2.3.1 Mortimer's theory on cut-off grade

Seminal work on the concept of cut-off grades points in the direction of Mortimer's work describing grade control in South African gold mines in the late 1940s. Though his work is given relatively less recognition, Mortimer established an essential pioneering milestone in the evolution of cut-off grade theory. Mortimer (1950) established the fundamental principles in the definition of ore by establishing the criteria for what can be classified as ore.

The first criterion that Mortimer established was that the average grade of the rock must provide a certain minimum profit per tonne treated. The second criterion was that the lowest grade of rock must pay for itself. An immediate recognition from the criteria is that modern cut-off grade theory is closely aligned to the criteria established by Mortimer. For instance, in defining ore, Mortimer's criteria show a close alignment with every company's goals, namely that some specified profit margin has to be achieved. An even more important realisation that forms the basis of modern cut-off grade theory is that every tonne must pay for itself. Modern cut-off grade theory dictates that a break-even cut-off grade must categorically fulfil the implicit goal that 'rock must pay for itself'.

In order for the grade to generate a minimum profit, the costs that need to be covered would include the following (Hall, 2014):

- Total mining costs;
- Total milling costs;
- Total site administration and services costs;
- Depreciation and amortisation;
- Head office charges;
- Interest on debt; and
- The required profit margin.

Mortimer's definition can be considered a two-dimensional (2D) model in that in addition to taking cognisance of costs and prices, it also accounts for the grade distribution within a deposit. On the other hand, a simple break-even analysis would be considered a one-dimensional (1D) model as it only takes cost factors into account. Most researchers have used break-even cut-off grade criteria to define ore as a material that will just pay off mining and processing costs (Osanloo, 2003). However, the readily recognisable handicap of Mortimer's definition is that it does not provide for the maximisation of any value measurement.

2.3.2 Taylor's cut-off grade theory leading to Lane's algorithm

Taylor (1972) defined cut-off grade as any grade that, for any reason, is used to separate two courses of action. He exemplified the two courses of action as either to mine or to leave, and to mill or to dump. Subsequent to Taylor's work, significant work on cut-off grades was done by Lane (1988). Cut-off grade has always been a key parameter in the evaluation of any mining project. The planning of a mining operation is dependent upon several factors. However, cut-off grade is one of the most significant aspects as it provides a basis for the determination of the quantity of ore and waste in a given period (Asad, 2011). Emphasis on this concept is further reinforced by listing cut-off grade as one of the '*15 Must-Ask Questions for Your Strategic Mine Plan*' (Lambert, 2015). The optimal cut-off grade depends on all the salient technological features of mining, such as capacity of extraction and of milling, the geometry and geology of the orebody, and the optimal grade of concentrate sent to the smelter (Cairns, 2004). Cairns' assertion caters for the majority of the advances that have been made on the concept of cut-off grades.

It must be noted that within the mining industry, the concept of cut-off grade has always been a complex subject and a considerable proportion of mine planning practitioners possess a limited understanding of how cut-off grades should be derived. Lane (1988) noted a key concern that cut-off grades are often arbitrarily assigned and they are never changed. This is despite constantly changing economic and technical factors. Lane (1988) listed some of the reasons that are provided by mine planning practitioners as being the reasons for using a particular cut-off grade at a mine as being (Lane, 1988, p.2):

- "The operation has always worked with 0.3%;
- Head office decided 5% combined metals some years ago; and
- Several cut-offs were examined in the feasibility and 1% seemed best."

The above reasons for selecting and/or maintaining a cut-off grade demonstrate a limited understanding and appreciation of the concept and its importance. Hall (2014) stated that cut-off grade is perhaps the least understood driver of value for a mining operation. He further asserted that cut-off grade is an integral part of optimising the mining strategy and that contrary to common understanding; cut-off grade should be an outcome of the strategic planning and mine optimisation process, not an input into the process. A closely related term is cut-off grade policy. This refers to a planned sequence of cut-off grades for an operation over a period of time (Hall, 2014). The term recognises that cut-off grade values should change over the LOM to account for changing technical and economic factors.

2.3.3 Lane's algorithm

Ken Lane published the foundation work for value-based cut-off grade optimisation. His work was later published in his book '*The Economic Definition of Ore: Cut-off Grades in Theory and Practice*' in 1988 followed by a subsequent publication in 1997.

Lane (1988) asserted that the resource's value is ultimately the value of the cash that was generated from it. By taking into account the concept of the time value of money, Lane's methodology inherently sets out to maximise the NPV of the resource (Hall, 2014). The notion that cut-off grades must maximise the NPV of a resource has remained a guiding principle in the determination of cut-off grades. Lane developed a comprehensive theory for the calculation of cut-off grades.

A crucial aspect of Lane's algorithm in the evolution of cut-off grade theory was the establishment of six potential cut-off grades, three of which are limiting cut-off grades while the other three are balancing cut-off grades. The limiting cut-off grades (g_m ; g_c ; g_r) are derived as break-even cut-off grades by making the assumption that each production stage is independently constraining the overall production rate. g_m is the cut-off grade if mining is independently constraining production rate, g_c is the cut-off grade if concentrating is independently constraining production rate and g_r is the cut-off grade if refining is independently constraining production rate.

The algorithm that Lane developed maximises a project's NPV by taking the time value of money into account under three constraints, namely mine, mill (concentrator) and market (refinery) (Myburgh, *et al.*, 2014). The logic that Lane (1988) put forward was that there are three components to a mining operation whose throughput needed to be related to the cut-off grade. The three throughputs are:

- Mineralised material;
- Ore; and
- Mineral.

Lane (1988) argued that a mining operation can be likened to a retail operation that does not necessarily add to its stock any goods which yield a marginal profit. A retail operation is subject to constraints such as storage space and it is precisely within this limitation that a retail operation would stock the more profitable items. This is analogous to a mining operation whose throughput is subject to certain limitations, namely the mineralised material (mining component), ore (treatment or concentrating component) and mineral (marketing or refining component).

If costs per tonne are considered under conditions of the aforementioned components, then the maximum throughput of each respective component becomes the constraint (hence limiting). Figure 2.1 shows the different cost contributors for each component in underground and surface mining.

	Underground	Surface
Mining	Developing Raising Cross-cutting	Drilling and blasting Loading Hauling
Treating	Stoping Tramming Hoisting Crushing Grinding Separating	Crushing Grinding Separating
Marketing	Smelting Refining Selling	Smelting Refining Selling

Figure 2.1 Mining, treating and marketing components and cost contributors
(Source: Adapted from Lane, 1988)

For example, costs are incurred per tonne of mineralised material made accessible and the maximum rate at which the mineralised body can be opened up would represent the capacity of the mining component. In other words, the maximum rate of mining imposes a limit on the costs incurred under the mining component.

In the same manner, the maximum costs incurred per tonne of ore under the treatment component are subject to the maximum throughput that the treatment plant can handle. However, it is important to realise that the fixed costs regarded as mining, treatment or marketing costs must be differentiated from the fixed costs such as administration and other overheads. The term fixed is however used cautiously in this context as it must be realised that such costs normally vary with time and it would be more appropriate to refer to them as time or period costs. Table 2.1 aids in explaining this concept.

Table 2.1 Notation for mine analysis
(Source: Adapted from Lane, 1988)

Component	Throughput	Variable cost	Variable cost/unit throughput	Capacity (throughput/year)
Mining	Mineralised material	1	m	M
Treating	Ore	x	h	H
Marketing	Mineral	$xy\bar{g}$	k	K

Where:

x: the proportion of mineralised material that is classified as ore, hence (1-x) is waste;

$\bar{g}$: the average grade of the ore;

y: yield of mineral in the treatment process (100 y%);

f: time costs per year;

p: price per unit of mineral;

c: cash flow per unit of mineralised material; and

τ: time taken to work through one unit of mineralised material.

It must be noted that any of these parameters can vary from year to year. Equation 2.10 represents the cash flow derived from one unit of mineralised material.

$$c = (p-k)xy\bar{g} - xh - m - f\tau$$ **Equation 2. 10**

Worth noting is the fact that τ is dependent upon the component which is limiting throughput and none of the derived cut-off grades is in any way related to the grade distribution of the orebody in question. They are solely dependent on costs, prices and capacities regardless of the grade distribution or variation within the orebody. This, in some respects, is counterintuitive. Logic would suggest that a cut-off grade of an orebody would be in one way or the other be related to the grade distribution of the orebody under consideration. This is generally agreeable and forms the basis of Lane's three balancing cut-off grades, namely '*mining and concentrating*' (g_{mc}), '*concentrating and refining*' (g_{rc}) and '*mining and refining*' (g_{mr}). However, before proceeding to the concept of balancing cut-off grades, it is imperative to outline the following significant points regarding limiting cut-off grades.

Firstly, it is important to point out that g_m would theoretically be lower than g_r and g_c. This is due to the fact that if the mine is limiting, the result is that the treatment plant and the market are starved of throughput. Consequently, all the mineable material ends up being classified as ore, hence a low g_m. On the other hand, the treatment cut-off grade is higher than the mining cut-off grade. The difference between these two would thus reflect the premium resulting from earlier cash flows in the event that only the treatment plant is limiting throughput. The effect of a market limitation is that it limits the extent to which cash flow patterns are influenced by the cut-off grade policy. Thus, every limiting component imposes an opportunity cost to the overall project value.

The three balancing cut-off grades occur when two production stages operate at capacity. There are thus three combinations of capacities that may be balanced, namely '*mining and concentrating*', '*concentrating and refining*' and '*mining and refining*'. Lane's methodology provides for the reduction of the six potential cut-off grades to one optimum cut-off grade that the mine can actually use for the short and long terms. Lane's work represents major advances in cut-off grade theory and provides important milestones in the comprehension of the too often counter-intuitive outcomes of cut-off grade optimisation. Minnitt (2004) applied the algorithm to determine cut-off grades for a small Wits-type gold mining operation and described the method as an elegant and simple way of optimising cut-off grades.

Beyond Mortimer's contributions, Lane recognised that the capacity of the mine, mill and the market were important parameters that needed to be factored into the optimisation of cut-off grades. Thus, Lane's algorithm can be considered a three-dimensional (3D) model. This marked a significant stride in the evolution of cut-off grade theory but there are important aspects that Lane's methodology did not address such as the determination of cut-off grades in polymetallic deposits, yet most metallic deposits are often a source of more than one element or metal.

2.3.4 Cut-off grades in polymetallic deposits

One of the key objectives of this research study was to establish optimal cut-off grades for a polymetallic deposit. Optimum cut-off grades are not always easy to define, particularly for polymetallic deposits (Horsely, 2002). The model that Lane derived is quite complex, even for a single operation with constant costs, prices and capacities, let alone a scenario with multiple elements with varying costs, prices and capacities. The reality is that mining operations involve some or all of the following complications (Whittle, 2007):

- Multiple mines;
- Multiple elements;
- Stockpiling of mined material;
- Alternative processing paths;
- Stockpiling of processed material;
- Alternative products;
- Blending; and
- Changing prices, costs, recoveries and capacities over time.

The greatest handicap with Lane's theory was that it could not be applied to polymetallic deposits. The reason for this drawback was that while in single metal deposits six points are possible candidates for the optimum cut-off grade, whilst in multiple metal deposits an infinite number of points are possible candidates for the optimum cut-off grades (Lane, 1988). The objective function of an infinite set of points would therefore, be impossible to construct.

Dagdelen and Kawahata (2007) concurred with this observation and stated that Lane's algorithm cannot be applied directly if one wants to optimise cut-off grade in the face of multiple processing streams, stockpiles or multi-element commodities. Whittle (1995) introduced the concept of pseudo costs, namely delay cost and change cost in an attempt to address some of the drawbacks in Lane's approach. Their approach however could also not tackle the complexity of multiple metal deposits.

To date, significant work and research has been carried out on the subject of cut-off grades in polymetallic deposits. However, what is clear in modern literature is that the use of classical algorithms in trying to establish cut-off grades has generally lost preference to evolutionary, hybridised and heuristic approaches. Every time the problem changes, the algorithm also has to change and that makes classical algorithms less robust as they thrive on making a problem fit within the constraints of an existing framework (Myburgh, *et al.*, 2014). On the other hand, evolutionary algorithms are characterised by a high level of self-adaptiveness and agility that contributes greatly to their ability to successfully solve complex real world problems through easy hybridisation with other optimisation techniques.

Ataei and Osanloo (2004) used a hybrid approach to solve the polymetallic deposit cut-off grade optimisation problem. A genetic algorithm and a grid search technique for a polymetallic deposit can yield a significantly better derivation of the optimal cut-off grade for a polymetallic deposit. Further work carried out to illustrate that another important dimension can be added to the problem of polymetallic deposits was by way of incorporating stockpiles (Asad, 2005).

Asad (2007) factored the impact of metal price fluctuations and cost escalations into polymetallic deposit scenarios. This work on uncertainties was complemented by the use of real options in the evaluation of cut-off grades and mine plans (Dimitrakopoulos, 2007). It can also be illustrated that long-term stockpiles can also be incorporated into the problem (Asad, 2012). A method of determining cut-off grades by considering technical, economic, environmental and social aspects was also established (Rahimi, 2015).

Several methods have been applied in the determination of cut-off grades in polymetallic deposits. These include equivalent grade factor method, critical level method, single grade cut-off approach and dollar value cut-off approach. Hall (2014), explored the concept on the grade descriptors by defining a grade descriptor as any parameter that describes the value of a block and to which one may apply a cut-off to separate material into different categories. The concept is particularly useful in polymetallic mines and generates a single value to quantify the relative value of each block.

2.3.5 The rationale of Net Present Value maximisation

The approach adopted in this research study was to determine cut-off grades that maximise the NPV of the project. It is generally agreed that the objective of establishing a cut-off grade policy is to maximise NPV. The rationale behind opting for a cut-off grade policy that maximises NPV is premised on the concept of the time value of money. A mine would rather have a dollar today than a dollar several years in the future (Whittle Consulting, n.d.). This is because it can invest it in other income producing activities in the meantime.

The second reason is that the further away in time the dollar is, the more things can go wrong resulting in the mine not getting the expected revenues (Whittle, 2007). Therefore, value is central to cut-off grade when addressing value in the mining business. Hence there is a need to migrate from mining engineering to financial engineering in the economic evaluation of deposits (Horsely, 2002).

Figure 2.2 and Figure 2.3 illustrate the risks and rewards of optimum cut-off grades as opposed to the risks and rewards that accrue from sub-optimal cut-off grades from a value perspective (Hall, 2014). Higher prices enable the cut-off grade to be lowered and lower prices force cut-off grades to be raised.

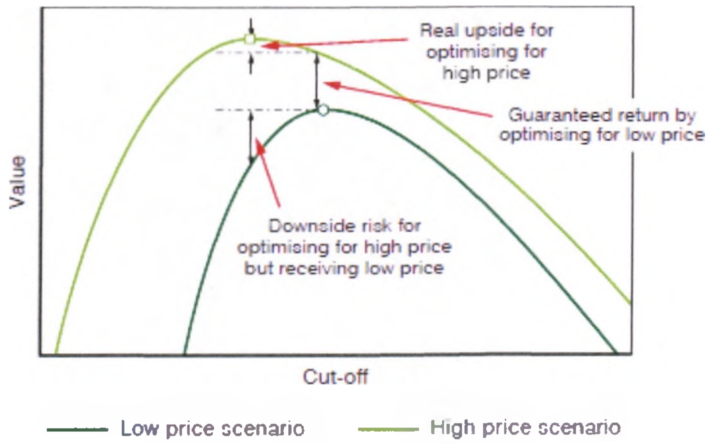


Figure 2.2 Risks and rewards of optimum cut-off grades
(Source: Hall, 2014)

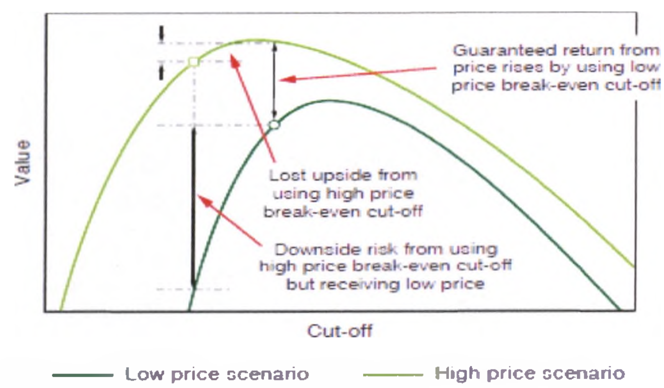


Figure 2.3 Risks and rewards of sub-optimum cut-off grades
(Source: Hall, 2014)

2.4 The Net Smelter Return model

A more rational approach to determine cut-off grade in polymetallic deposits is to evaluate them based on a value per tonne of ore, hence the NSR concept becomes relevant. NSR would represent the total value of metals recovered from each tonne of ore minus the cost of smelting (Annels, 1991). With this method, it would be possible to express the grade of one metal in terms of the value of the other (Zhang, 1998). Other approaches include critical level method, single grade cut-off approach and dollar value cut-off approach (Baird, 1999). All these methods exhibit some weaknesses such as the inability to consider grade distribution of the deposit. Another weakness is that the methods do not take into account the time value of money (Osanloo, 2003). An outline of the inputs that are required in using the NSR model is presented in the next section.

2.5 Net Smelter Return inputs

A number of inputs are required in utilising the NSR model. This section provides an explanation on these parameters as applied to the NSR model. The major inputs are outlined below:

- Recovery in the beneficiation process;
- Concentrate grade;
- Freight costs;
- Treatment charge (TC);
- Treatment losses;
- Refining charge (RC); and
- Metal prices.

Additional parameters are explained within the broader parameters listed above. These include concentration factor and mass recovery.

2.5.1 Recovery in the beneficiation process

The amount of metal that is contained per tonne of ore that is fed to the mill is termed mill head grade. The process in the mill involves crushing the ore feed in order to separate the valuable minerals and concentrating them. The result is concentrate and tailings. The concentrate from the mill consists of a higher metal content than the original ore feed while the tailings contain much lower metal content than the original ore feed.

The proportion of metal that reports in the concentrate to the metal that is contained in the original ore feed is referred to as mill recovery. Wills (2006) stated that concentrate grade and recovery are the most widely accepted measures of assessing metallurgical performance.

2.5.2 Concentrate grade

Figure 2.4 shows the relationship that exists between concentrate grade and NSR at high and low commodity prices. The figure illustrates an almost linear relationship between concentrate grade and NSR before a peak NSR is reached. The peak NSR occurs at the optimum concentrate grade beyond which NSR assumes an almost inverse relationship with concentrate grade. From Figure 2.4, it can be observed that the optimum concentrate grade which gives the highest NSR is lower than the optimum grade giving the highest NSR at lower prices. It is also evident that higher prices give a higher NSR compared to the lower prices.

Wills (2006) further emphasised this relationship by showing how transport and treatment costs vary with the cost per tonne, further reinforcing the notion that the highest NSR is achieved at the optimum concentrate grade. Figure 2.5 illustrates this relationship. Wills (2006) emphasised that while moving away from the optimum grade might result in losses in the order of few pounds or cents per tonne treated, the financial implication is huge if the volumes of tonnes is high, as is typically the case in most mining operations.

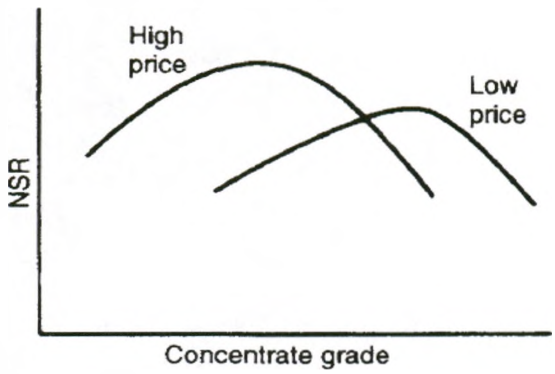


Figure 2.4 Relationship between NSR and concentrate grade at high and low prices
(Source: Wills, 2006)

Treatment and transportation costs diminish as concentrate grade increases. Project valuation however follows a slightly different trend. From Figure 2.5, it can be noted that project valuation is highest at lower concentrate grades. This can be explained in terms of the opportunity cost that results from the processing of low grade ores. Beyond the optimum concentrate grade, project valuation tends to diminish as well.

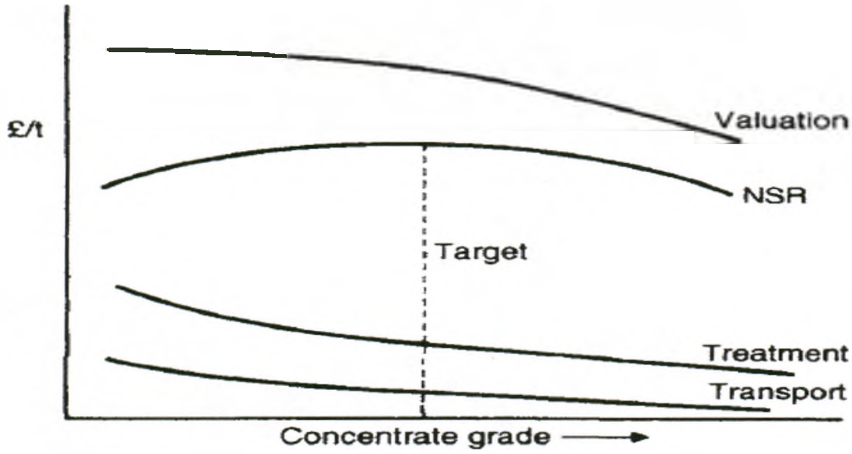


Figure 2.5 Relationship between concentrate grade and cost per tonne
(Source: Wills, 2006)

Concentration factor refers to the tonnage of ore material that is required to generate a tonne of concentrate. This is also referred to as the ratio of concentration. The determinants of this factor are concentrate grade, ore grade and recovery. This factor is essential in the evaluation of a mineral deposit as it enables one to determine the value of the ore (Wellmer, *et al.*, 2007). Equation 2.11 shows how the factors affecting concentration factor are mathematically related.

$$\textbf{Concentration Factor} = \frac{\text{concentrate grade} \times \text{ore grade}}{\text{recovery}} \qquad \textbf{Equation 2.11}$$

2.5.3 Freight costs

Freight costs are an important component in the calculation of NSR. Two key abbreviations need to be explained under this section. These are 'FOB' and 'CIF'. FOB stands for 'free on board' while CIF stands for cost, insurance and freight. FOB means that the producer, in this case the seller of the concentrate, delivers the product 'free on board' the means of transport at the agreed place. This implies that freight charges are borne by the purchaser.

On the other hand, CIF means that costs such as customs, documentation, freight and insurance are borne by the seller. In such a case, the concentrate producer would bear the freight costs to the designated point of delivery.

2.5.4 Treatment charges (TC)

In the case of Zn concentrates, it is important to realise that treatment charges are payable per tonne of concentrate not per tonne of market metal. Table 2.2 shows typical smelter charges as applied by different smelters.

Table 2.2 Typical smelter charges
(Source: 911metallurgist, 2017)

Smelter	Cu Smelter	Pb Smelter	Zn Smelter	Crude Pb-Zn milling ore
Treatment Charge	$12.50 per dry ton	$12.50 per dry ton on Pb content 25% wet assay plus 10c per ton for each unit under 25%	$51.50 per dry ton based on 12c market price. Add $1.25 per net ton for each 1c or fraction above 12c	$4.00+ per dry ton

2.5.5 Treatment losses

The penalty charge is specific to particular elements that result in additional process activities being necessary to remove them from the final metal product, or that need to be disposed of in an environmentally friendly manner. It is common practice to assign a penalty for a specific deleterious element. Normally, minimum thresholds are set and a penalty charge is set for deleterious content above the threshold. These deleterious elements can in many instances be antimony, arsenic, bismuth, tin or sulphur.

A careful analysis of these elements needs to be done through intensive laboratory work as they can be costly for the concentrate venture and in many cases, they have resulted in significant losses for the investors by greatly affecting the NSR. By definition, a penalty is a charge that is imposed by the smelter if the concentrate contains unduly high concentrations of contaminants.

The penalty on the aforementioned metals is principally due to the difficulty they add to the smelting process. In certain instances, they result in by-products that are very difficult and expensive to treat. For example, if arsenic is present in the furnace charge, it tends to be highly volatilised. Consequently, on condensation, it contaminates the dust chamber by-products. This is an expensive problem to address and therefore the presence of arsenic attracts a penalty for the concentrator.

It can be noted that deleterious metals are also dependent on the price of the said deleterious metal. During periods of low cadmium prices, cadmium in a Zn concentrate can attract a penalty. However, during periods of high cadmium (Cd) prices, the same smelter might end up having to pay a credit for the same cadmium in the same Zn concentrate. Penalty charges are thus an important factor in evaluating the economic potential of a deposit.

On the other hand, certain levels of deleterious materials might render the concentrate product unsaleable. A consequence with less impact might necessitate additional on-site facilities to further treat a concentrate before a smelter accepts it. The economics surrounding such cases demand careful monitoring as the miner migrates from one ore zone to another.

Dayton (1982) outlined a case to illustrate the above mentioned point. The case involved Equity Silver and Samatosum operations in British Columbia at which 78% of the antimony (Sb) and 21% of the arsenic (As) in one part of the ore body reported to the Cu-Ag-Au concentrate. These levels of antimony and arsenic rendered the concentrate unsaleable. Equity Silver and Samatosum mooted the idea of a leach plant which, with varying degrees of success, reduced the antimony and arsenic to acceptably low levels. They still attracted penalties after they were accepted by one smelter. On migration to another section of the ore body within the same operation, it was realised that it was more economical to ship concentrates to the same smelter without making use of the leach plant. It was no longer economical to continue operating the leach plant (Dayton, 1982).

The smelting destination is also of primary concern, particularly when it comes to penalties and premiums. If a concentrator sends a Pb-Cu concentrate to a Pb smelter, it will receive about 30 cents a dollar less for the Cu, while if this same Pb-Cu concentrate is shipped to a typical Cu plant, the concentrator will be paid for only half the Pb and will eventually earn about 40 cents a dollar less for the Pb (Goldie and Tredger, 1991). Goldie and Tredger (1991) illustrated this point by giving several examples to illustrate this concept. However, if the Pb and Cu minerals were to be separated into two products by selective floatation and each shipped to the respective smelter, the concentrator would receive the maximum return. This typical scenario indicates the complexities within the concentrator business and how fundamental it is for the concentrator to understand their product and where best they should sell it in order to derive the maximum return.

2.5.6 Metal prices

The gross value per tonne is a function of the metal prices. Metal prices fluctuate based mainly on the supply and demand dynamics in the concentrate market. Additional factors have an impact on the metal prices. There is significant literature on the pricing of base metal commodities and it is imperative to gain a fundamental understanding on the pricing of base metal commodities for the purposes of this research study.

An understanding of the dynamics that shape the pricing of base metal and/or mineral commodities in general is important in understanding the mining business. Typical price trends for metal commodities are shown in Figure 2.6 and Figure 2.7 for Zn and Pb spot prices, respectively, for the period January 2012 to January 2017.

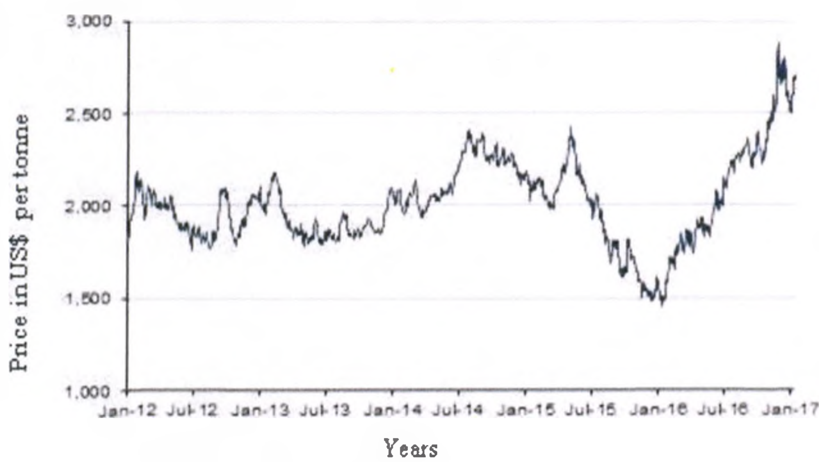


Figure 2.6 Five year Zn prices
(Source: FocusEconomics, 2017)

A spot price is the current price in the market place at which a given asset such as a security, commodity or currency can be bought or sold for immediate delivery. In contrast to spot price, a security, commodity or currency's futures price is its expected value at a specified future time and place (Korniotis, 2009).

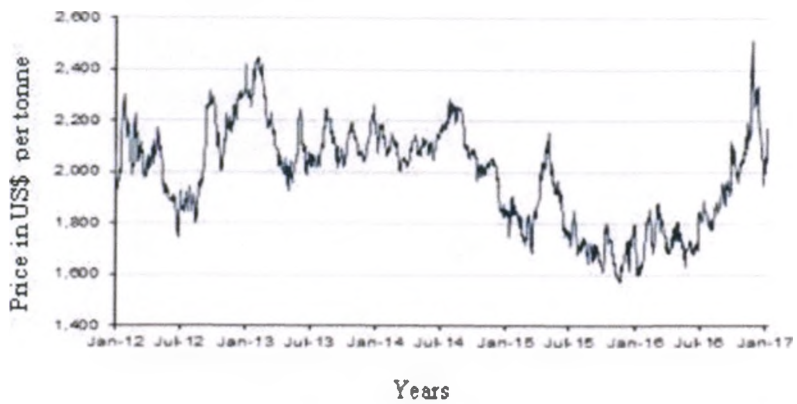


Figure 2.7 Five year Pb prices
(Source: FocusEconomics, 2017)

Base metals are traded mainly on the London Metal Exchange (LME). The six base metals that are traded are aluminium (Al), Cu, tin (Sn), Pb, nickel (Ni) and Zn. Other metal markets are the Commodities Exchange (COMEX) in the United States of America (USA) and the Shanghai Futures Exchange (SHFE) in China. The LME is the largest market of the three metal exchanges.

All the three metal exchanges are predominantly futures markets. While it is clear that the subject of futures trading plays a key role in the pricing of commodity prices, it is beyond the scope of this research study. It is worth mentioning though that the minerals industry leverages the future markets for price hedging purposes, thus making them less prone to commodity price risks and sudden price swings. They do however pay a premium for hedging against these risks.

The main difference between base metals and precious metals is that base metals are largely for industrial applications and consumption. On the other hand, precious metals are purchased for investment purposes. Base metal prices can range from about US$ 25 000, 00 per tonne for Ni and Sn, down to about US$10 000, 00 per tonne for Cu and can be as low as US$2 500, 00 per tonne for Al, Pb and Zn.

Metal prices are cyclical (Tilton, 2015). Economic cycles can be traced back to at least the biblical times when Joseph interpreted the dreams of Pharaoh to mean seven years of plenty followed by seven years of famine (Peters, 1996). Gaining an understanding into the metal price cycles is of significant interest to the mining industry in general as metal prices are the centre of the mining business. It helps in aiding decisions on either to add or reduce capacity, to place operations on care and maintenance, to invest in new mines or withhold investment. Other decisions that may be taken include hedging production by locking in the prevailing price (Cowen, *et al.*, 2012).

Additional theories include the inventory theory which suggests that metal commodity prices are also dependent on the volume of stock in inventory. Studies have been undertaken to establish the relationship between price, volatility and quantity held up in inventory, for both the spot and future markets (Papp, *et al.*, 2008). Figure 2.8 and Figure 2.9 show the relationship between stocks in inventory and prices for Zn and Pb, respectively, as compiled by the International Lead and Zinc Study Group (ILZSG) for the period 2011 to 2016.

The ILZSG is a United Nations (UN) organisation that provides regular information on the supply and demand position of Pb and Zn and its probable development. The organisation also makes special studies on the world situation in Pb and Zn. The study group is one of the longest established International Commodity Organisations (ICO) and as such has been the role model for other bodies such as the International Nickel Study Group (INSG) and the International Copper Study Group (ICSG) (International Lead and Zinc Study Group, 2017).

It can be concluded that when stocks in inventory are high, commodity prices are lower. On the other hand, if stocks deplete, a rising trend for commodity prices is experienced. For the period October 2012 to October 2013, an increase in global Zn stocks was experienced. A drop in prices was experienced for this period. However, October 2014 to October 2015 shows a drop in Zn stock accompanied by a rise in prices during the same period.

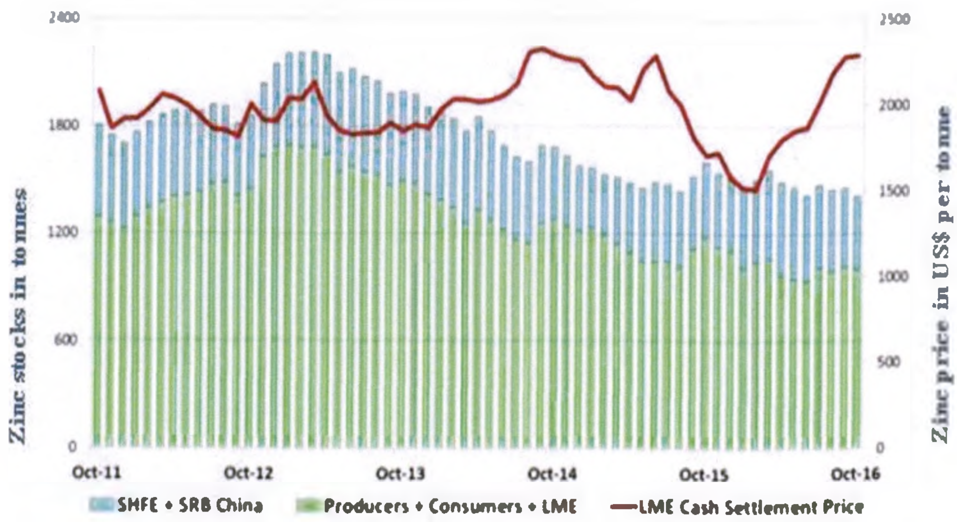


Figure 2.8 Zn stocks in relation to Zn prices
(Source: ILZSG, 2016)

Pb followed a similar trend for the same period as shown in Figure 2.9. Pb prices generally experienced a sustained increase during periods of low global stocks. Both figures show cash settlement prices that prevailed at the LME for the period under review. The largest gains are expected in Zn and Pb due to mine supply constraints because of permanent and discretionary closures. Important gains are also expected for Cu, Ni and Sn (FocusEconomics, 2017).

From the foregoing, it becomes clear that metal prices are a key component of the NSR model and their understanding is thus central to this study. In fact, considerable intelligence is invested into this subject, particularly the marketing of base metal concentrates and their pricing. It must be noted that the intelligence is a significant investment on the part of the concentrator and would normally come at a cost.

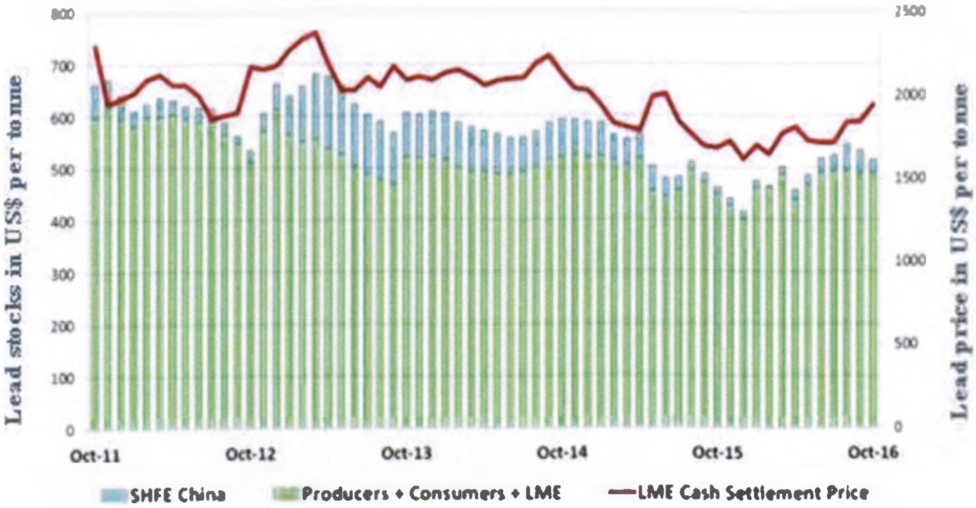


Figure 2.9 Pb stocks in relation to Pb prices
(Source: ILZSG, 2016)

Another factor that determines the prices of base metal prices is China's economic outlook. Figure 2.10 shows China's increasing consumption of metals from across the world for the period 2002 to 2014.

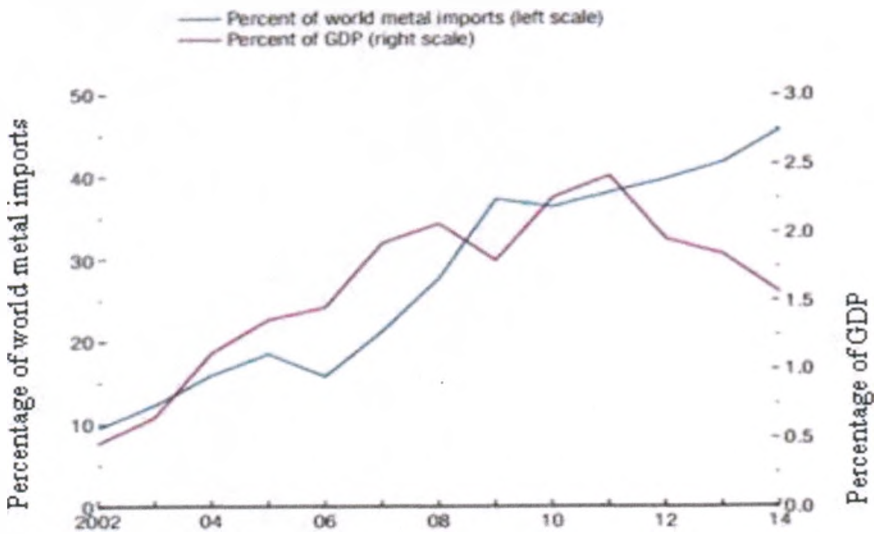


Figure 2.10 China's world metal imports
(Source: International Monetary Fund, 2015)

China is currently one of the fastest growing economies and its consumption of mineral commodities, both base metals and precious metals, is high and is crucial in shaping overall global demand. Therefore, an understanding of China's economic trajectory is important.

2.6 Mine netback

The gross value of a tonne of ore is the value of the economic metals contained in the ore. It is the monetary value of a tonne of ore, assuming that the refinery pays for all of the payable or accountable metals. This is seldom the case as the refinery hardly pays for all the metal contained. This disparity gives rises to a very important parameter in the concentrate business called netback. Goldie and Tredger (1991) defined netback as the ratio of NSR to the gross value per tonne of ore. This mathematical relationship is shown in Equation 2.12. This is a very significant parameter as it gives an indication of the actual returns that a mine gets per tonne of ore.

$$\textbf{Mine netback} = \frac{\textbf{NSR}}{\textbf{gross value per tonne of ore}} \qquad \textbf{Equation 2.12}$$

In simple terms, a high netback indicates that the mine is getting paid for a greater proportion of the payable metal content. A low netback on the other hand is an indication that the mine is in fact getting paid for a smaller proportion of the payable metal content per tonne of ore. Therefore, netback is an indication of *how much of the actual contained metal that the mine is getting paid for*. The pertinent question that therefore needs to be addressed is what gives rise to these disparities within the concentrate business. This subject will be discussed later on.

Mine netback is more dependent on mineralogical factors than it is on economic factors. In other words, mine netback varies greatly for different ore types, resulting in differences ranging from 20% to as high as 40%. However, for the same ore type, mine netback can be as low as 4% within a complete price cycle, thus rendering economic factors such as price and exchange rate fairly insignificant on mine netback.

A correlation can also be established between mine netback, which is an important parameter derived from NSR, and metal prices. It can be established that during cyclical peaks in metal prices, netbacks are higher than during troughs (Goldie and Tredger, 1991). This is a fairly simple interpretation to make as mines would obviously get paid more for what is contained in the concentrates during price peaks. However, a higher NSR does not necessarily translate into a higher mine netback. It can be established that a mine can have the same NSR with different netbacks. These scenarios will be examined in greater detail in the next chapters.

2.7 Smelter contracts

The terms agreed between the concentrator and smelters are of paramount importance in the economics of mining and milling operations (Wills, 2006). These terms are expressed in what is referred to as a smelter contract and concentrates are sold under contract to custom smelters at prices based on quotations on metal markets such as the London Metal Exchange (LME) and the Commodities Exchange (COMEX). A smelter contract exists between the miner and the smelting and refining facility. These contracts are fairly complex in nature and the objective is generally to ensure that the miner earns higher margins in periods of commodity boom while the smelter should generally earn stable returns over the life of the capital asset (Cowen, *et al.*, 2012). Table 2.3 is an example of a simplified smelter contract for tin (Sn).

Table 2.3 Simplified smelter contract
(Adapted from: Wills, 2006)

Material	Sn concentrate, assaying no less than 15% Sn, to be free from deleterious impurities not stated, and to contain sufficient moisture as to evolve no dust when unloaded at our works.
Quantity	Total production of concentrates.
Valuation	Sn, less 1 unit per dry tonne of concentrate, at the lowest of the official LME prices.
Pricing	On the 7^{th} market day after completion of arrival of each sampling lot into our works.
Treatment Charge	US$385 per dry tonne of concentrates.
Moisture	24% of moisture per tonne.
Penalties	As 40 cents per unit per tonne.
Lot Charge	US$175 per lot sampled of less than 17 tonnes.
Delivery	Free to our works in regular quantities, loose on a tipping lorry, or in any other manner acceptable to both parties.

It is generally agreeable that it is within the miner's capacity to control the quality of the concentrate delivered to the smelter. On the other hand, the smelter has got more leverage and control of cost and efficiency of recovery. The interest of every concentrate producer is to get the highest commercial return by developing a detailed understanding of its own processes. Possibilities on potential alterations that present an opportunity to produce concentrates for which there is a market need to be explored.

The mining business is inherently risky, characterised by uncertainties in resource definition and commodity price risk. On the other hand, smelters have greater leverage on the concentrates that they take and more importantly, cost structures. As a result, a smelter contract must address these issues in clear terms and must seek to address appropriate allocation of benefits derived from operational efficiency, costs and price volatility. They thus take into cognisance a complex array of quality and economic factors.

Nyrstar (2009) outlined typical pricing terms for Zn and Pb concentrates. Zn smelters typically pay for 85% of the Zn contained in Zn concentrates (typically at 54% Zn content) valued at LME price averaged over the Quotation Period (QP) if it exceeds certain threshold levels and the penalties depend on the contained deleterious materials (Nyrstar, 2009). Additionally, they pay for Ag content in concentrate if it exceeds a certain threshold. For Pb concentrates, smelters typically pay for 95% of the contained Pb in the concentrate (typically at 60% Pb content) valued at LME price averaged over the QP. A Pb smelter will pay for Ag, Au, Cu and Zn content in concentrates if it exceeds certain thresholds.

Another concept embedded in smelter contracts to ensure the aforementioned factors is price participation. Other literature refers to basically the same concept as profit sharing. As mentioned earlier on, both the miner and the smelter have business interests to protect. The miner aims at sustainably depleting the deposit while the smelter seeks steady returns over the life of the capital asset. The nature of smelter contracts is such that they disallow one party from neither excessively benefitting nor losing during periods of metal price peaks and troughs, respectively. They allow for a shared decline in profits in periods of depressed commodity prices while allowing for shared gains in periods of price peaks.

Reynard (1991) referred to a trigger price within a price participation agreement. This can also be referred to as the base price. If the metal price goes above a certain trigger price a price participation agreement dictates that the base TC also escalates by the same percentage as the price increase. An escalator is the percentage increase to the base TC for each US$ LME price increase above the base price (or trigger price). This will ensure that the smelter also derives benefit from a commodity price increase. A de-escalator on the other hand, is a percentage decrease to base TC for each US$ LME price decrease below the base price (Nyrstar, 2009). In the same manner, this will ensure that the miner does not bear the economic burden of a depressed commodity price alone but, rather shares it with the smelter by effectively paying lower smelting fees. Table 2.4 is an example of more specific contract clauses specifying how price increases can relate to TC. The impact of price participation agreements on the NSRs for different metal commodities is beyond the scope of this study.

Table 2.4 Escalators and de-escalators
(Source: 911metallurgist, 2017)

Clause	Escalator/De-escalator
1	TC increases by $0.90 for every $1 increase between $2500 - $3000 of index price.
2	TC further increase by $0.08 for every $1 increase between $3000 - $3500 of index price.
3	TC decrease by $0.04 for every $1 decrease between $2500 - $2000 of index price.
4	TC further decreases by $0.06 for every $1 decrease between $2000 - $1500 of index price.

A similar logic also follows for concentrate grade. A concentrate with a high grade must translate into a benefit for the miner, hence a lower unit smelting fee and unit freight charges for a high grade concentrate.

In conclusion, it can be noted that the terms of a smelter contract are usually valid for a year and applicable to an Annual Delivered Quantity (ADQ). However, not all concentrate may be delivered during the contract period and in such cases, it is permissible to carry over the terms into the following year with prior period terms.

2.8 Chapter summary

The two most widely used models in the determination of cut-off grades in polymetallic deposits are the equivalent grade method and the NSR model. However the net smelter return model is preferred because it allows for the rapid conversion of metal grades to monetary value per tonne of ore. Cut-off grade theory has evolved through many stages with seminal work having been done by Mortimer (1950), followed by Taylor (1972) and Lane (1988).

Lane made significant contributions to cut-off grade theory but the algorithm he developed could not address cut-off grades in polymetallic deposits. The NSR model provides a means through which cut-off grades in polymetallic deposits can be determined. It consists of a number of inputs. The next chapter outlines the methodology that was adopted in order to use the NSR model to determine cut-off grades for the RPZC polymetallic deposit.

3 RESEARCH METHODOLOGY

3.1 Chapter overview

This chapter outlines the research approach and methodology adopted to meet the research objectives and address the research questions of this study. An explanation and justification of the sequential steps that were taken to meet the aforementioned objectives is made. The chapter also outlines the necessary tools that made it possible for the research to draw conclusions and recommendations.

3.2 Approach

A quantitative research approach using data which were mostly acquired from RPZC mine was adopted. Other complementary data, particularly economic data like exchange rates and commodity prices were used and they were sourced from the public domain. These sources included the *Canadian Mining Journal*, *Costmine* and *Kitco*. In cases where the use of assumptions and benchmarks was made, the basis of such assumptions and benchmarks was stated.

3.3 Methodology

The methodology outlined below was developed. It consists of the various sequential steps that were followed in order to meet the objectives of this research study.

3.3.1 Data collection and validation

The relevant data that serve as inputs to the model were collected at the initial stage of the project. Prior to their use, the data was taken through a validation process. Sample data can be biased and it is therefore necessary to establish the relationship between the sample value and true population values.

3.3.2 Data correlation

The validated data acquired were then correlated using in-built statistical tools in Microsoft Excel™ to establish any significant correlations between factors that would have an impact on the simulation process. As mentioned in the preceding chapter, NSR is a function of many parameters. The process made it possible to establish whether or not there were complex interactions between the factors and also determine their significance. These factors include ore grades, recoveries, commodity prices, freight charges, TC and RC.

3.3.3 Tools

The model was constructed using Microsoft Excel™. Sensitivity analysis was also used to test for correlation and relationship between and amongst factors. In order to account for risk and uncertainty, sensitivity analysis and Monte Carlo simulation were utilised. The model was constructed in close adherence to the Australian Institute of Mining and Metallurgy's (AusIMM) '*Guidelines for Technical Economic Evaluation of Minerals Industry Projects'*. The following section provides a more detailed account of how the model was constructed.

3.3.4 Model construction

The model was constructed in modular form. It consists of the following modules:

- Introduction;
- ROM;
- Pb concentrate characteristics;
- Zn concentrate characteristics;
- Treatment and freight charges;
- Payable metals;
- Commodity prices;
- Revenues;
- NSR; and
- Summary.

Figure 3.1 shows a schematic illustration of the model architecture showing the major worksheets. It also illustrates the logical flow of calculations as they converge towards the NSR per tonne of ore.

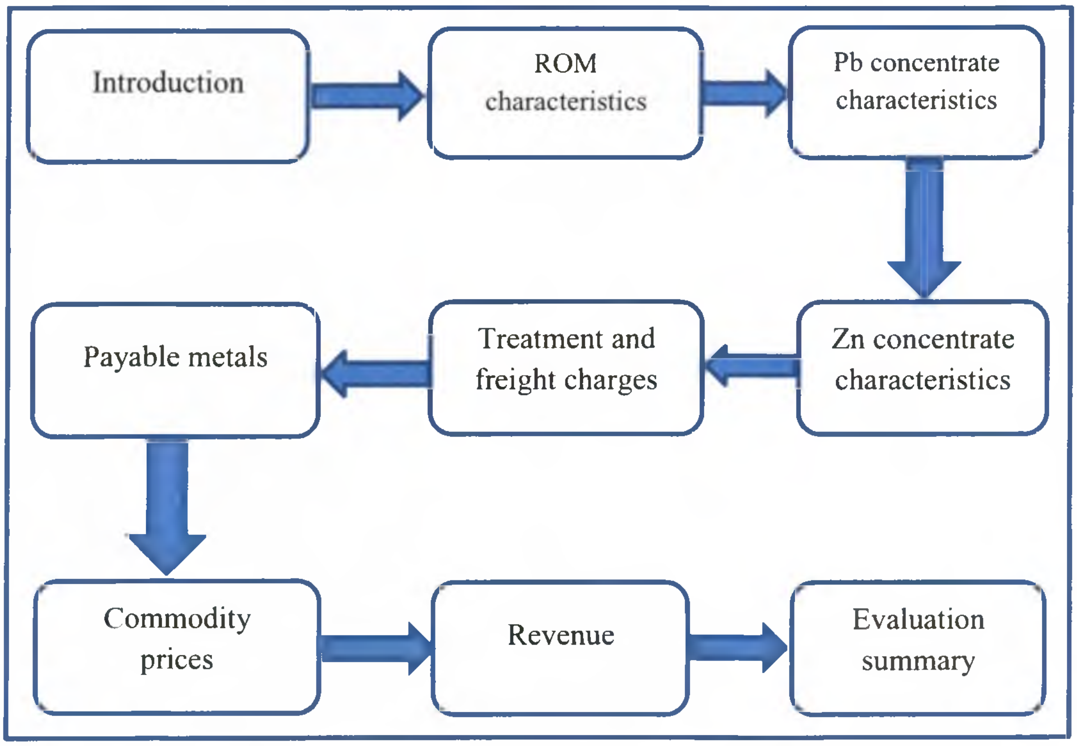


Figure 3.1 Schematic illustration of NSR model

The introduction worksheet provides a general background to the model. It also outlines the purpose of the model and provides warnings that the user must take into consideration when using the model. The ROM worksheet contains the ROM characteristics in the form of Zn, Pb and Ag ore grades. It also captures recovery of both Zn and Pb to the Pb concentrate and the recoveries of both metals to the Zn concentrate as well. This would logically, converge towards the amount of payable metals, which when combined with commodity prices, results in total revenue generated. An evaluation summary provides an overview of the key inputs and results of the model.

The Zn and Pb concentrate characteristics worksheets capture the Zn, Pb and Ag components per tonne of ore. In addition, they also capture the smelter, refining and freight charges per tonne of ore. The treatment and freight charges worksheet consequently sums up the treatment, refining and freight charges per tonne of ore for both concentrate streams.

The modules are constructed in a simple and easy-to-follow way as prescribed by the '*Guidelines for Technical Economic Evaluation of Minerals Industry Projects*' guidelines for spreadsheet modelling. Figure 3.2 shows the introductory sheet in the model outlining the purpose of the model and other relevant information.

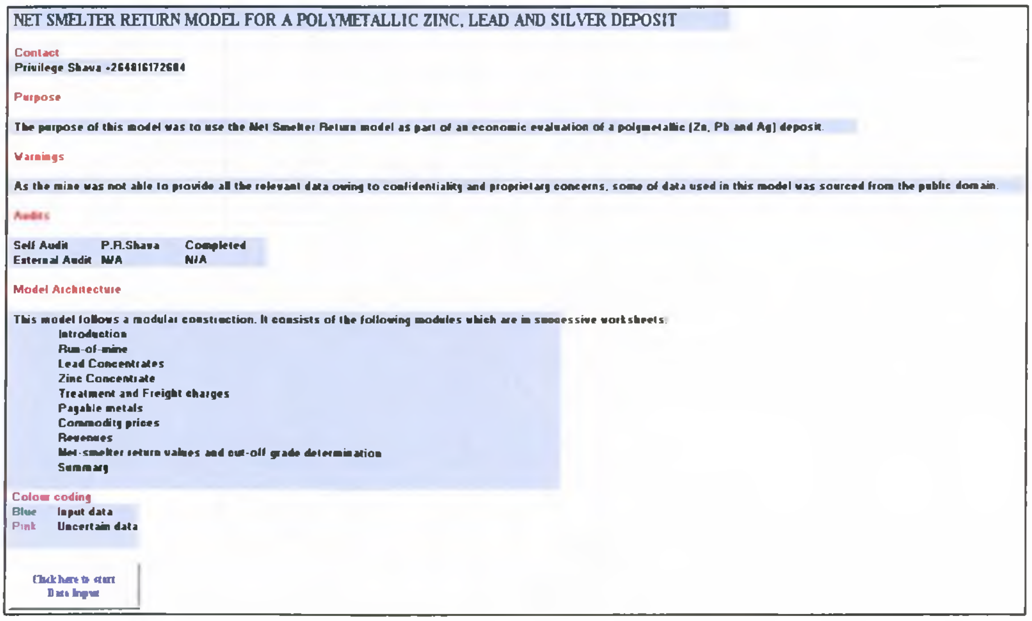
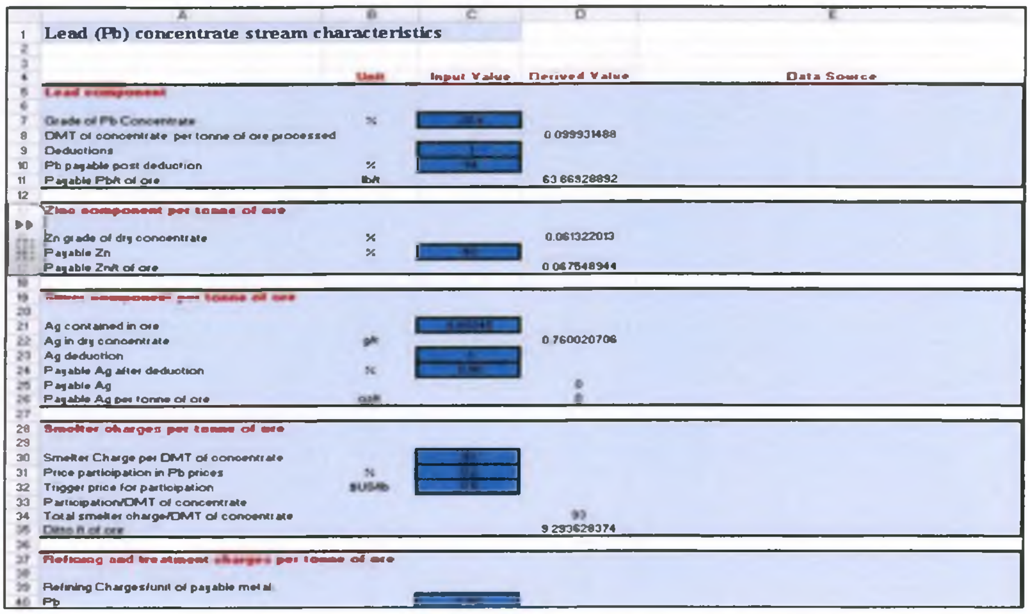


Figure 3.2 Introduction sheet in the NSR model

Figure 3.3 shows an example of a model module. It is separated into distinct sections, for example, the Pb component is separated from the Zn component. This is meant to ensure clarity in the model. A complete view of the model architecture can be gleaned from the model.



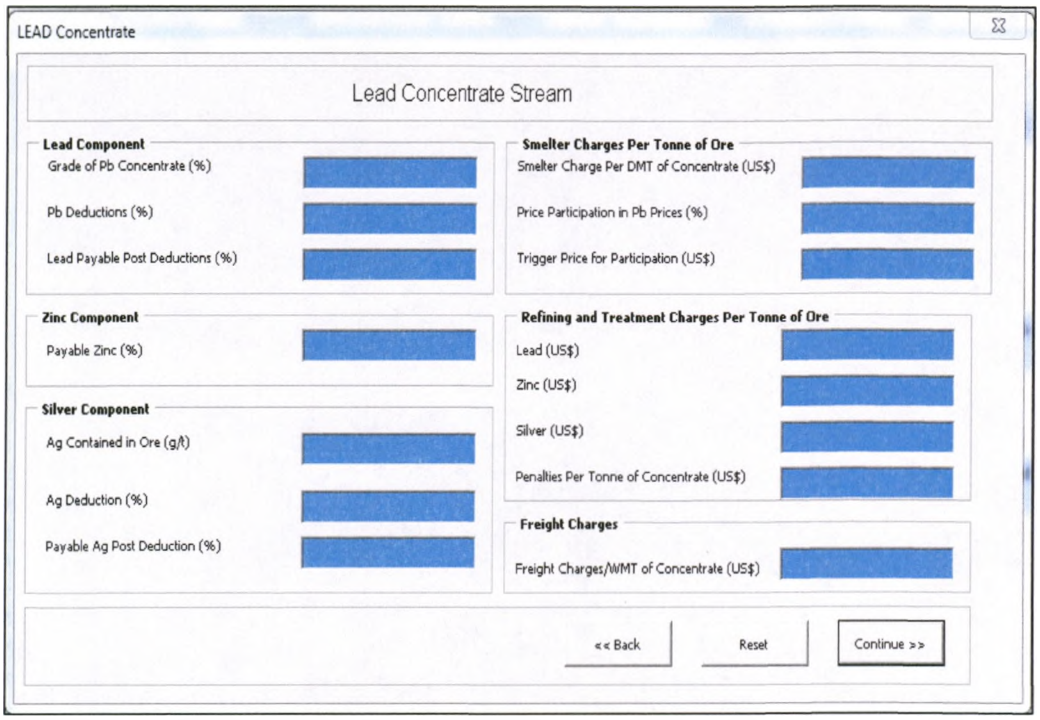
Note: DMT – Dry Metric Tonne

Figure 3.3 Example of module in spreadsheet model

The model also followed the other tenets of model construction, which include (Australian Institute of Mining and Metallurgy, 2012, p.8):

- “Tailored to purpose;
- Transparent;
- Disciplined, rigorous and consistent;
- Recording all sources of data; and
- Rapid to audit”.

In order to make the model more amenable for use, a user interface was developed using the Visual Basic Application (VBA) platform. Figure 3.4 shows an example of the input interface with which the user interacts in order to enter the required values.



Note: WMT – Wet Metric Tonne

Figure 3.4 Example of data input form for the NSR model

This interface allows for the user to input data without necessarily having to interact with the model itself and it defaults to the summary sheet which gives a consolidated summary of the computations. However, the model is readily accessible to the user if there is need to examine or revise the architecture of the model.

3.3.5 Results analysis and rationalisation

A comprehensive analysis of the results generated by the model was conducted. Of primary importance was the understanding of how the NSR model aids in determining cut-off grades for a polymetallic deposit as well as determining the impact of various parameters on the NSR/t. The structure of the economic evaluation that was adopted followed the outline below:

- Analysis of tonnages and grades;
- Processing recoveries and concentrate characteristics;
- Derivation of costs (treatment, refining and freight costs);

- Derivation of commodity prices;
- Calculation of net returns per tonne of ore; and
- Final economic evaluation, mine netbacks and establish interaction between various factors.

3.4 Chapter summary

Various models can be used in the economic evaluation of polymetallic deposits. Microsoft Excel™ is a readily available tool and the model that was selected in the evaluation of the RPZC polymetallic deposit was constructed in Microsoft Excel™. To ensure that a robust model of the highest quality was derived from the data, due diligence was employed in acquiring reliable input data. A statistical analysis of the data was performed to generate results from which useful outcomes and conclusions were drawn. The next chapter is a collection of the data that were used in testing the NSR model to carry out an economic evaluation of the RPZC polymetallic deposit and derive appropriate cut-off grades for Pb, Zn and Ag for the deposit.

4 DATA COLLECTION

4.1 Chapter overview

This chapter provides an outline of the data that was collected in order to meet the objectives of this study. Some of the data was acquired from the mine while some was sourced from the public domain.

4.2 Data collected

This section provides the data that was collected during the research study. It also outlines the sources of the data.

4.2.1 Ore grades and tonnages

Data pertaining to the tonnages, Zn, Pb, Cu and Ag content was acquired from the mine. Zn, Pb and Cu content was given in percentage per tonne while Ag content was presented in ppm (parts-per-million). Cu was however not of significance in this research study since it is not in sufficient concentrations to be a payable metal. Data pertaining to production levels was also collected. This was in addition to the lithological data which divided the lithological types into three categories, namely PRR, SLT and SRS. The full meanings of these abbreviations were however not provided. Table 4.1 shows a typical data set that was made available for this research study. Complete data are provided in Appendix 8.1 to Appendix 8.4.

Table 4.1 Typical metal contents for Rosh Pinah mine

Level	Type	Block	Tonnes	Zn (%)	Pb (%)	Cu (%)	Ag (%)
90	PRR	A	87165	10.11	2.11	0.09	36.37
90	PRR	D	6641	10.02	2.21	0.03	47.46
90	SLT	A	4209	7.00	2.25	0.10	64.43
60	SRS	C	567	12.48	1.29	0.20	14.50
30	SRS	D	1036	4.36	1.34	0.03	7.11
0	SRS	C	745	9.69	0.92	0.22	4.09
-60	SLT	B	1740	9.45	0.12	0.27	11.50
-90	SRS	D	919	7.58	0.72	0.08	5.89
-90	SRS	E	1014	6.68	1.52	0.35	27.33

4.2.2 Recovery in the beneficiation process

Typical recoveries in the beneficiation process were sourced from the public domain. This mainly included figures from the *Canadian Mining Journal*. These figures consider a range of operations that produce Pb and Zn concentrates, and their respective concentrate grades and recoveries to concentrates.

4.2.3 Treatment charges and refining charges

Typical treatment charges were sourced from the public domain, particularly *CostMine*. *CostMine* specialises in gathering information that helps in determining mining costs under their Mining Cost Service. This data provided a suitable basis for smelter terms as it is based on a wide ranging survey of smelters in the USA, Canada and Asia as shown by the example in Figure 4.1. Additional information was sourced from other businesses in the Zn and Pb smelting business, particularly Nyrstar.

Model Smelter Schedule – Lead Concentrates

Payments

Lead: Pay for 95% of the lead content at market value, with minimum deductions of 1.5 to 3.0 units per dry tonne.

Gold: Deduct 0.03 to 0.07 troy ounce per dry tonne and pay 95% of the remaining gold at market value.

Silver: Deduct 0.5 to 2.0 troy ounce per dry tonne and pay for 95% of the remaining silver at markett value.

Copper: Some smelters will pay for as much as 40% of contained copper while at some other smelters copper is considered deleterious.

Deductions

Treatment Charge: Terms for clean, very loe silver material for 2012 settled at $200.00 to $210.00 per tonne (flat), of $200.00 per tonne at a basis $2100.00 per tonne with variety of up and down escalators and a silver Refining Charge (RC) of $0.40 to $0.60 per ounce. Terms for clean, very low silver material for 2013 are estimated at about $200.00 at a basis $2000.00 per tonne with variety of up and down escalators and a silver RC of $1.50 per ounce. In 2012, Treatment Charges (TC) for high silver content (100 ounces per tonne) concentrates settled at about $300.00 per tonne, basis $2100.00 with an up escalator of 4% and a down escalator of 1%, and a silver RC of $1.50 per ounce. Generally, high silver long-term contracts from $210.00 to $300.00 per tonne, with silver refining charges at $0.60 to $1.50 per ounce.

Complex Concentrates: Smelters are charging an additional $50.00 to $100.00 per tonne for low grade, high silver, complex or bulk concentrates.

Refining Charges: $6.00 - $ 10.00 per ounce of payable gold and $0.60 - $1.50 per ounce of payable silver.

Penalties

Deleterious Element Penalties: Lead concentrates containing excessive amounts of the following elements may be penalised or rejected: Arsenic, Antimony, Bismuth, Nickel, Copper, Alumina. Tellurium and Mercury. Iron in excess of 10% is also considered deleterious.

Moisture: High moisture content may also be penalised due to material handling difficulties.

Figure 4.1 Example of data source used available in the public domain

4.2.4 Metal prices

Metal prices were sourced from information in the public domain. LME prices of the three payable metals that were considered were sourced from reliable websites such as *Infomine* and *Kitco* that specialise in mineral commodity pricing. Table 4.2 shows the price summaries for Pb, Zn and Ag in 2016. The complete price trends from 1989 to 2016 for Zn, Pb and Ag are provided in Appendix 8.18, Appendix 8.19 and Appendix 8.20, respectively.

Table 4.2 Zn, Pb and Ag metal prices

Metal	Current price (USD)	1 year high (USD)	1 year low (USD)
Zn (lb)	1.26	1.35	0.96
Pb (lb)	1.03	1.12	0.81
Ag (oz)	15.63	20.67	15.37

4.2.5 Marketing costs, insurance costs and transportation losses

This data was sourced from the public domain. Literature suggests that these costs are in the range of 2% to 4% of total revenues. It was reasonable to use a value of 3% in this research study.

4.3 Data input quality

All the necessary measures were taken to ensure that the data used in this research study were either sourced from the mine or from reliable sources in open literature. Hence the data used in the economic evaluation can be regarded to be reliable. The evaluation would have been much more reliable if all the information was specific to the mine. However, data that is not necessarily from the mine is benchmarked data and would give a close approximation of the actual values from the mine, which might not be the scenario.

4.4 Chapter summary

The data that was used as inputs for this research study was collected from the mine while some of the data was collected from the public domain. The mine could not provide some of the data for proprietary reasons. Data collected from the mine consisted of data on ore grades, tonnages and lithology. Cost data and commodity prices were drawn from the public domain. Caution was taken to ensure that input data was of the highest possible quality through benchmarking and the use of industry averages in order to draw reliable conclusions from the NSR model.

5 DATA ANALYSIS

5.1 Chapter overview

This chapter provides an analysis of the data that was acquired during this research study. Furthermore, it provides an analysis of the results that were generated from the NSR model. It also provides an insight into the comparison of the NSR model and the metal equivalent method.

5.2 Metal content analysis

In order to enable a more rigorous analysis of the occurrence of metals in a polymetallic deposit, several methods can be used. This section provides a statistical insight into the occurrence of the respective metals in the RPZC polymetallic deposit. Two techniques were used, namely an analysis of the metal ratios and regression analysis.

5.2.1 Metal ratios

It is often useful to determine the ratio in which metals occur in a polymetallic deposit. This ratio makes it possible to illustrate zoning in polymetallic deposits, particularly when resort is made to the use of isoline maps. In cases where the ratios of occurrence show a narrow spread, the ratios can be used in their raw form. However, in cases where the ratios of occurrence result in a wide spread, resort is made to standardisation. The spread refers to the range of values that are derived from the metal ratios. Table 5.1 shows the Zn/Pb and corresponding Pb/Zn ratios from data randomly selected from the RPZC polymetallic deposit.

Table 5.1 Zn/Pb and Pb/Zn ratios

Random data set	Zn (%)	Pb (%)	Zn/Pb	Pb/Zn
1	10.11	2.11	4.79	0.21
2	12.20	0.53	23.09	0.04
3	5.97	0.06	96.08	0.01
4	12.56	0.26	53.23	0.02

The results show a high variability in the Zn/Pb ratios, ranging from approximately 5 to 96 for the selected pairs of metal content. The Pb/Zn ratios are direct inverses of the Zn/Pb ratios. In the former, a standardisation factor is used. This factor is expressed as:

$$\frac{Zn}{Zn+Pb} \qquad \textbf{Equation 5.1}$$

Mathematically, this factor can only vary between 0 and 1. In the case where Zn = 0, the ratio is 0. If Pb=0, then the ratio is 1.

5.2.2 Regression analysis

It is often useful to examine how the major elements in a polymetallic deposit correlate with each other and how they correlate with the minor elements. Regression analysis is a statistical tool that makes it possible to establish the degree of correlation between various elements in a polymetallic deposit. If perfect positive correlation exists, all data pairs would fall perfectly in the line of regression and the correlation coefficient r, would be equal to 1.

On the other hand, if no correlation exists at all, then it would imply that there is no relationship whatsoever in the occurrence of one metal relative to the other. In that case, the correlation coefficient r, would be equal to 0. Frequently, these relationships are non-linear and it is only rational to attempt regression analysis when some level of correlation is assumed.

Two cases can be distinguished, namely positive correlation and negative correlation. Positive correlation would imply that as one metal increases, the other metal increases as well. A good example is the occurrence of Ag and Pb in polymetallic volcanogenic deposits. Ag is often positively correlated with Pb. This assertion will be statistically tested in this section.

Negative correlation, on the other hand, implies that as one metal increases, the content of the other metal decreases. Often, the occurrence of Pb and Zn in a polymetallic deposit shows negative correlation. A perfect negative correlation, denoted by a correlation coefficient of -1, thus implies that there is absolute tendency of one variable to be decreasing while the other is increasing. Correlation coefficient values approaching +1 and -1, for instance +0.97 and -0.97 indicate, respectively, strong positive and negative correlation between variables. Again, this assumption will be tested in this section using regression analysis. Regression analysis is used in this section to establish the level of correlation between the two major elements, namely Pb and Zn, as well as their correlation with the minor elements, namely Cu and Ag.

An analysis of the correlation that exists between the various metals in the RPZC polymetallic deposit was carried out based on the data that was provided. Table 5.2 shows the consolidated results of the analyses. The results show a weak correlation between the two major metals, namely Zn and Pb. A relatively stronger correlation exists between Pb and Ag. The strongest correlation exists between Zn and Cu. Data pertaining to Cu content was also provided due to the fact that Cu recovery is of prospective interest to the mine.

Table 5.2 Correlation of metal combinations

Metal Combination	Correlation coefficient
Zn-Pb	0.09
Zn-Cu	0.32
Pb-Ag	0.26

However, carrying out a regression analysis is not sufficient for statistical purposes. It is important to establish whether the regression is significant at a specified confidence level. In order to achieve this, the F-test was carried for all the regression analysis done so that the significance of the results could be useful and relevant in the subsequent analysis. Table 5.3 shows the regression summary generated using Microsoft Excel™ statistical tools for the Pb and Ag combination.

Table 5.3 Regression summary for Pb and Ag

Multiple R	0.51							
R Square	0.26							
Adjusted R Square	0.25							
Standard Error	10.92							
Observations	108.00							
ANOVA								
	df	SS	MS	F				
Regression	1.00	4396.00	4396.00	37.00				
Residual	106.00	12633.00	119.00					
Total	107.00	17030.00						
	Coefficients	Standard Error	t stat	P value	Lower 95%	Upper 95%	Lower 90%	Upper 90%
Intercept	7.31	1.74	4.21	0.00	3.87	10.76	4.43	10.19
Pb%	8.44	1.39	6.07	0.00	5.69	11.19	6.14	10.75

Where

R: correlation

R square: coefficient of determination

ANOVA: analysis of variance

df: degrees of freedom

SS: sum of squares

MS: mean square

F: F-test

The adjusted R square is more reliable as it takes into account sample size. It indicates the proportion of variability in the dependent variable that can be explained by the independent variable. Hence in this case, about 26% of the variability in Ag occurrence can be explained in terms of Pb occurrence. The P-value of 0 indicates that this regression analysis is in fact significant at the 95% confidence level, otherwise it would have been necessary to increase the sample size in order to make the analysis significant. The corresponding scatter plot for this analysis is shown in Appendix 8.5.

A similar analysis was done to test the correlation between the two major elements, namely Zn and Pb. The analysis revealed that there is no correlation in the occurrence of the two major metals. Additional analysis was done to test for correlation between Zn and Cu, since Cu is of prospective interest to the mine and

Cu values were also part of the data that was provided. The resultant regression summary is shown in Table 5.4.

Table 5.5 shows the regression summary for the Zn and Pb combination. Both cases revealed that the regression analyses were significant at the 95% confidence level, with Zn and Pb showing negative correlation while the Zn and Cu combination showed positive correlation with an R-square value of approximately 32%.

Table 5.4 Regression summary for Zn and Cu

Multiple R	0.57							
R Square	0.32							
Adjusted R Square	0.32							
Standard Error	0.15							
Observations	108.00							
ANOVA								
	df	SS	MS	F				
Regression	1.00	1.18	1.18	50.52				
Residual	106.00	2.45	0.02					
Total	107.00	3.66						
	Coefficients	Standard Error	t stat	P value	Lower 95%	Upper 95%	Lower 90%	Upper 90%
Intercept	-0.12	0.05	-2.42	0.02	-0.21	-0.02	-0.20	-0.04
Zn%	0.04	0.01	7.11	0.00	0.03	0.05	0.03	0.05

Table 5.5 Regression summary for Zn and Pb

Multiple R	0.30							
R Square	0.09							
Adjusted R Square	0.08							
Standard Error	0.73							
Observations	108.00							
ANOVA								
	df	SS	MS	F				
Regression	1.00	5.40	5.40	10.10				
Residual	106.00	53.30	0.50					
Total	107.00	61.70						
	Coefficients	Standard Error	t stat	P value	Lower 95%	Upper 95%	Lower 90%	Upper 90%
Intercept	1.69	0.23	7.37	0.00	1.23	2.14	1.31	2.07
Zn%	-0.08	0.02	-3.18	0.00	-0.13	-0.03	-0.12	-0.04

It is important to note that this regression analysis was done for the entire deposit; without paying attention to any form of categorisation and hence might not suffice for a more detailed analysis of the polymetallic deposit in question. A more insightful analysis was conducted based on lithological types to examine if correlation between payable metals could be linked to lithology.

An analysis of the results generated showed that different lithologies exhibit different correlations between metals. The overall trend followed that of the entire deposit but there are significant differences between correlations of different metal combinations. Table 5.6 summarises the results. Summarily, lithology type SRS showed relatively stronger correlation between Zn and Pb and also showed the strongest correlation between Zn and Cu. The PRR-type lithology showed stronger correlation between Pb and Ag.

Table 5.6 Correlation of metal combinations based on lithology

Metal Combination	Lithological type		
	PRR	SLT	SRS
Zn-Pb	0.09	0.06	0.14
Zn-Cu	0.27	0.30	0.55
Pb-Ag	0.41	0.33	0.21

More detail leading to these conclusions is shown in Appendix 8.9 to Appendix 8.17. The appendices show the various scatter plots generated with their respective regression equations and R-square values. All the regression analyses carried out showed that the analysis were significant at the 95% confidence level.

5.2.3 Level analysis

Data collected was sorted in order to determine if metal grades were associated with production levels. The production levels are depth levels. Weighted average grades for each metal in each level were computed. From the subsequent data analysis, it was realised that significant differences in metal grades exist amongst the different production levels. For instance, level -12 shows a Zn grade of 11.81% while level 30 shows a Zn grade of just 8%. Pb and Ag also show differences amongst the levels, with level -12 showing a Pb weighted average grade of as low as 0.33% while level 60 has a Pb weighted average grade of 1.29%. Ag on the other hand showed a relatively high value of 34.63 ppm in level 90 while level -30 has a value of 10.39 ppm. Table 5.7 shows the results of this analysis.

Table 5.7 Metal grades per level

Level	Weighted average grades			Tonnage
	Zn (%)	Pb (%)	Ag (ppm)	
-90	11.34	0.42	13.02	804030
-60	10.69	0.62	12.72	665150
-30	8.76	0.70	10.39	72702
-15	9.24	1.09	15.29	226298
-12	11.81	0.33	11.24	468299
0	7.91	1.29	14.16	276206
30	8.01	1.19	12.66	601985
60	10.56	1.52	21.55	339864
90	9.93	2.05	34.63	121597

The other objective of this analysis was to enable the determination of net values per level. By using the weighted average grades into the model, it is possible to generate the total ore values for each level since tonnages per level can be determined.

5.3 Mine netback

As mentioned in the preceding chapters, mine netback is an important measure of the NSR model. It is the ratio of the NSR per tonne of ore and the gross value of a tonne of ore. Hence, it is an indication of how much of the *in-situ* contained metal the mine gets paid for.

From the model, it can be concluded that mine netback is more responsive to changes in mineralogical factors than to economic factors. Mineralogical factors include ore grades, recoveries and concentrate grades. The presence or absence of deleterious materials would also be categorised as a mineralogical factor. On the other hand, mine netback is not so responsive to economic factors such as exchange rate and commodity price.

Further analysis on mine netback was also carried out to determine mine netback per level and mine netback per lithology. It is however more useful in this context to determine mine netback per level since levels present a more practical way of mining, rather than lithology, unless selective mining is practiced. For the purposes of getting a deeper insight into the polymetallic deposit, both analyses were carried out and yielded the results in Table 5.8 and Table 5.9. Both analyses were carried out deterministically using a static model.

Table 5.8 NSR/t and netback per level

Level	NSR/t (USD)	Netback (%)
-90	121.95	37.57
-60	118.42	38.07
-30	99.75	38.48
-15	112.93	40.13
-12	124.02	41.13
0	102.42	41.13
30	101.01	40.48
60	135.00	41.33
90	145.25	45.00

Table 5.9 NSR/t and netback per lithology

Lithology	NSR/t (USD)	Netback (%)	Zn revenue contribution (%)
PRR	124.94	42.89	85.78
SLT	124.82	45.13	82.02
SRS	123.02	44.40	83.50

It can be concluded that according to these analyses, level 90 is significantly different from level -30 in terms of NSR/t. On the other hand, from a lithological point of view, PRR-type lithology offers a relatively higher NSR/t compared to the other two lithological types. Table 5.9 also shows that Zn is the biggest contributor to revenue.

5.4 Risk and uncertainty

It is important to consider risk and uncertainty when carrying out an economic evaluation. In order to account for risk and uncertainty, sensitivity analysis and Monte Carlo simulation were used in order to analyse the extent to which metal grades, recoveries and commodity prices influence the outcome of the economic evaluation.

5.4.1 Sensitivity analysis

Sensitivity analysis was used in a deterministic approach, using a static model. The analysis was done to determine the sensitivity of various model outputs such as percentage contribution of the three payable metals to various input parameters. The results showed that percentage contribution is not influenced by metals prices significantly.

This was expected because the three payable metals in question generally follow the same price trends. There was however considerable changes in the mine netback value between the two extreme price data sets used. A difference of up to 9% was realised. Mineralogical factors had a more significant impact on mine netback as discussed earlier.

In terms of the metal grades' impact on the NRS/t values, the sensitivity analysis done showed that NSR/t values were more responsive to Zn content increases than for Pb and Ag. For instance, a 1% increase in Zn grade resulted in a US$4/t increase in the NSR/t value, while a 1g increase in the Ag content resulted in a US$1 increase in the NSR/t value.

5.4.2 Monte Carlo simulation

Monte Carlo simulation is a technique used to estimate the value of unknown quantities using inferential statistics. In order to carry out the Monte Carlo simulation, minimum and maximum values of metal grades, metal recoveries to their respective concentrates, metal prices and exchange rates were determined. This provided a basis for the values between which random values would be generated in the simulation.

Minimum prices for 2016 were used to accommodate the worst case scenario. The rationale behind using the 52-week low for the prices was that Trevali Mining Corporation actually used metal price assumptions that are higher than the current market prices in the evaluation of the deposit. Hence the 52-week low provided a reasonably pessimistic basis for the purposes of the simulation, as they were much lower than the peak 'forward looking' prices used by the company. Table 5.10

shows the minimum and maximum values that were used in the simulation for each parameter.

Table 5.10 Minimum and maximum values for Monte Carlo simulation

Parameter	Unit	Minimum value	Maximum value
Zn grade	%	6.00	27.93
Zn recovery to Zn concentrate	%	60.00	75.00
Pb grade	%	0.06	1.70
Pb recovery to Pb concentrate	%	70.00	85.00
Ag grade	%	5.80	27.33
Zn price	USD/lb	0.96	1.30
Pb price	USD/lb	0.81	1.12
Ag price	USD/oz	15.37	20.67
Exchange rate	USD/NAD	10.00	15.00

A total of 5000 simulations were done. It is important to note that when carrying out a Monte Carlo simulation, the bigger the number of simulations, the more likely the outcome converges with a more probable outcome. A Microsoft Excel™ spreadsheet containing the simulation and the results generated is part of this report. Summarily, the Monte Carlo simulation provided an insight into the level of risk by providing probabilistic analysis of the model. Table 5.11 shows the percentile results generated at the 25, 50 and 75 percentiles. The interpretation of these percentile results is that, for instance, at the 25^{th} percentile, there is 25% likelihood that any value in the simulation will be lower or equal to a NSR per tonne of ore of USD 103.36. The same interpretation follows for the other percentile results. Hence, by altering the percentile values, it is possible to determine the expected NSR per tonne of ore with varying probabilities. Thus, it becomes possible to determine the level of risk associated with the derived values.

Table 5.11 Percentile results of Monte Carlo simulation

Percentile	NSR/t
25	103.46
50	141.80
75	182.16

It was also worthwhile, by reverting back to the static model, to determine the metal grades associated with these percentile values. For the 25 percentile value of US$103.46/t of ore, values of 17%, 1.5% and 13 g/t for Zn, Pb and Ag, respectively, were determined. For the 50 percentile value of US$141.80/t of ore, values of 25%, 1.5% and 15 g/t for Zn, Pb and Ag, respectively, were determined. It must be noted that while the percentile values were generated using a dynamic model that randomised input variables between minimum and maximum possible values, the associated metal grades were determined using a static model that kept all the other variables at a minimum, hence the high metal content values. The same approach was used to determine cut-off grades for the three payable metals.

5.5 Chapter summary

This chapter provides an analysis of the data that was analysed during the course of the research study. Tonnages and grades data was analysed. Two approaches were used to gain an insight into tonnages and grades data, namely metal ratios and regression analysis. Tonnages were computed for each level for the purposes of generating net returns per level. On the other hand, metal grades were analysed using regression analysis for different lithologies to establish if different lithologies exhibit different metal grades correlation.

The results showed that relatively higher correlation existed between Zn and Cu combination in the SRS-type lithology while the PRR-type showed higher correlation than the other lithologies for the Pb and Ag combination. Furthermore, price data was analysed and used as input into the NSR model. The 52-week low and 52-week high prices were used.

Sensitivity analysis was used deterministically and Monte Carlo simulation were carried out to cater for risk and uncertainty in the factors contributing to NSR. The factors that were randomised are metal grades, recoveries, metal prices and exchange rate. Finally, it is important to realise that the most important unit of measurement in the economic evaluation of polymetallic deposits is not the grams per tonne, ounces per tonne or parts per million; it is the net dollar per tonne. The availability of relatively cheap computational capacity makes it possible to readily determine cut-off grades for a polymetallic deposit through the use of the NSR model.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Chapter overview

This chapter outlines the conclusions and recommendations of this research study. The conclusions are based on the analysis that was carried out in the previous chapter while the recommendations are based on experiences gained in the course of the research study. It also provides the major limitations to the research study.

6.2 Research limitations

The biggest limitation of this research study was access to real data for some of the inputs. Economic data for corporates is generally regarded as sensitive. As mentioned in the introductory chapter, the mine under study is currently undergoing purchase agreements and this made access to some data difficult, in spite of the researcher proposing to commit to a non-disclosure agreement. As a result, part of the data used in this economic evaluation was either drawn from the public domain or benchmarked with industry averages.

6.3 Findings

The NSR model is a useful method for carrying out an economic evaluation of a polymetallic deposit. A lot of work has been done on the cut-off grade problem and the resultant methodologies have failed to address the complexity that results from polymetallic deposits. However, this research study provides a basis to conclude that the NSR model is indeed a useful, yet simple, model as far as the economic evaluation of polymetallic deposits is concerned.

6.3.1 Revenue

The biggest contributor to revenue for the deposit under consideration is Zn. This was expected because Zn is the primary metal of interest for the mine; hence the model generated higher Zn contributions for the various analyses that were carried out.

6.3.2 Cut-off grade

It is evident that the NSR model is a simple way of determining cut-off grades in a polymetallic deposit by making use of the most important unit of measurement for a mining operation, the dollar. The cut-off grade is thus not a fixed value for a particular individual metal, for instance 3% Zn, but is in fact subject to the combined value of the different metal constituents. What is therefore important is that the cut-off NSR meets the criterion for a cut-off grade, namely that the tonne must pay for itself and a specified minimum profit per tonne treated must be realised. The NSR model makes it possible, through the consideration of a host of mineralogical and economic factors, the determination of cut-off grades that would generate a specified minimum monetary value.

6.3.3 Comparison of NSR model and equivalent factor method

The use of metal equivalents necessarily implies the use of constant price relationship between metals. This is obviously not true. On the other hand, the use of the NSR model entails a number of factors to be addressed. This makes it a more realistic way of evaluating a polymetallic deposit.

6.4 Recommendations

This section outlines the issues that form areas for possible future research. This research study identified a few areas that might be of interest to other researchers or alternatively serve as a basis for more advanced study. Areas that are particular to this research and areas that concern the broad concept of NSR modelling are identified.

6.4.1 Evaluation of mine netbacks

Scope for further work on comparative analysis mine netbacks also exists as an extension of this research study. It is worthwhile to conduct a study on how mine netbacks vary in different parts of the world for different types of deposits containing the same payable metals. For instance, a study comparing Mississippi Valley Type (MVT), SEDEX and volcanic-hosted Zn-Pb-Ag deposits can be done and analyses conducted in this research study done on a comparative basis to establish differences is metal content correlations, metal ratios and other parameters like netback.

Such analyses would help to determine which types of deposits are more attractive to mining companies. Additionally, this would help in identifying key value drivers in the mining industry and the international benchmarking of mining operations. This will also enhance the ability of companies to make key strategic decisions, particularly when it comes to project ranking. A mining company would opt to invest where the company gets paid for a higher proportion of the in-situ metal content or invest in a deposit type that poses less metallurgical challenges; given that all the other factors are equal.

6.4.2 Application of NSR model in other forms of polymetallic deposits

During the course of this research study, it was recognised that there is generally limited literature on the subject of NSR model, particularly in other forms of polymetallic deposits like Platinum Group Metals (PGMs). There is broad scope for research in this area and it is recommended to undertake more work on the economic evaluation of PGMs using the NSR model. As mentioned earlier on, the NSR model is applicable in exploration, evaluation and exploitation of polymetallic deposits. Hence, with vast untapped PGM resources in South Africa and Zimbabwe, there is scope for the application of the NSR model in PGM deposits.

6.5 Chapter summary

Data collected from the mine and from the public domain was used in the analysis. The biggest limitation to this research study was access to data owing to corporate privacy issues. The NSR model provides a simple way of carrying out an economic evaluation of a polymetallic deposit. Several factors impact on NSR. These include ore grades, recoveries in the beneficiation process, commodity prices and other associated costs. Mine netback is impacted upon by mineralogical factors as compared to economic factors. Potential exists for studies regarding mine netbacks for comparable deposits and application of the NSR model in PGMs.

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8 APPENDICES

8.1 Grades and tonnages data for level 90, level 60 and level 30

Level	Type	Block	Tonnes	Zn (%)	Pb (%)	Cu (%)	Ag (ppm)
90	PRR	A	87165	10.11	2.11	0.09	36.37
90	PRR	B	16718	10.37	1.50	0.10	13.69
90	SLT	A	4209	7.00	2.25	0.10	64.43
90	SLT	D	1119	7.93	1.78	0.02	38.95
90	SLT	C	2340	7.66	3.94	0.04	24.54
90	SLT	B	1800	8.29	0.97	0.09	12.80
90	SRS	A	813	8.56	2.40	0.15	110.09
90	SRS	B	792	11.17	0.84	0.12	16.20
60	PRR	A	77787	9.32	1.87	0.04	25.97
60	PRR	C	91755	12.37	1.20	0.09	20.78
60	PRR	B	61051	8.70	1.89	0.06	21.99
60	PRR	D	46427	12.20	0.53	0.10	11.94
60	SLT	C	6960	11.61	1.54	0.09	25.33
60	SLT	D	2932	9.30	1.28	0.09	15.02
60	SLT	B	9159	8.40	2.37	0.05	27.61
60	SRS	C	567	12.48	1.29	0.20	14.50
60	SRS	D	656	12.33	1.01	0.09	10.87
60	SRS	B	504	6.67	0.16	0.03	5.82
30	PRR	B	169243	9.53	1.07	0.08	11.68
30	PRR	C	141592	7.44	1.00	0.06	11.28
30	PRR	D	112045	6.01	1.63	0.05	11.23
30	PRR	A	75493	8.82	0.91	0.19	20.14
30	PRR	E	4793	7.87	0.09	0.07	21.82
30	PRR	P	56949	8.18	1.66	0.06	11.44
30	SLT	C	10916	7.40	1.33	0.07	16.28
30	SLT	A	7095	6.40	0.50	0.13	10.03
30	SLT	D	9696	5.71	1.97	0.05	9.21
30	SLT	B	9170	10.66	0.80	0.10	10.78
30	SLT	E	1348	5.91	0.09	0.06	22.08
30	SRS	C	807	7.92	0.94	0.04	14.33
30	SRS	D	1036	4.36	1.84	0.03	7.11
30	SRS	B	794	6.93	0.85	0.06	16.43
30	SRS	E	1008	5.97	0.06	0.05	14.52

8.2 Grades and tonnages data for level 0, level -15 and level -30

Level	Type	Block	Tonnes	Zn (%)	Pb (%)	Cu (%)	Ag (ppm)
0	PRR	B	22449	6.17	1.24	0.11	23.40
0	PRR	C	128307	8.11	1.42	0.17	12.40
0	PRR	A	24481	10.03	0.64	0.18	16.48
0	PRR	D	45099	7.96	1.42	0.17	13.19
0	PRR	E	14999	7.43	1.45	0.07	11.70
0	PRR	P	17894	7.60	0.88	0.13	18.66
0	SLT	A	2299	6.52	0.73	0.14	12.53
0	SLT	E	2717	6.78	1.44	0.07	14.47
0	SLT	B	3510	5.62	1.02	0.12	19.13
0	SLT	D	5910	6.01	1.96	0.11	14.51
0	SLT	C	4628	7.14	0.58	0.17	4.47
0	SRS	A	648	8.43	0.28	0.17	11.40
0	SRS	E	749	6.63	1.62	0.10	11.60
0	SRS	B	746	9.76	0.73	0.22	8.97
0	SRS	D	1025	7.10	2.27	0.17	19.61
0	SRS	C	745	9.69	0.92	0.22	4.09
-15	PRR	A	144526	9.22	0.60	0.38	12.27
-15	PRR	E	31056	10.48	1.59	0.14	16.95
-15	PRR	D	30775	7.61	2.85	0.21	25.87
-15	SLT	A	10682	10.04	0.90	0.43	15.99
-15	SLT	E	4872	12.56	0.24	0.14	15.76
-15	SLT	D	3745	6.94	2.92	0.23	29.65
-15	SRS	A	642	8.51	0.35	0.55	8.68
-30	PRR	B	18395	8.93	0.16	0.16	6.29
-30	PRR	C	28752	7.51	1.25	0.09	10.85
-30	PRR	A	20295	10.71	0.49	0.58	14.03
-30	SLT	C	918	6.95	0.22	0.10	9.10
-30	SLT	A	490	9.49	0.31	0.90	11.99
-30	SLT	B	1821	6.46	0.21	0.12	4.75
-30	SRS	C	1103	6.92	0.83	0.10	11.65
-30	SRS	B	928	9.14	0.20	0.20	7.75

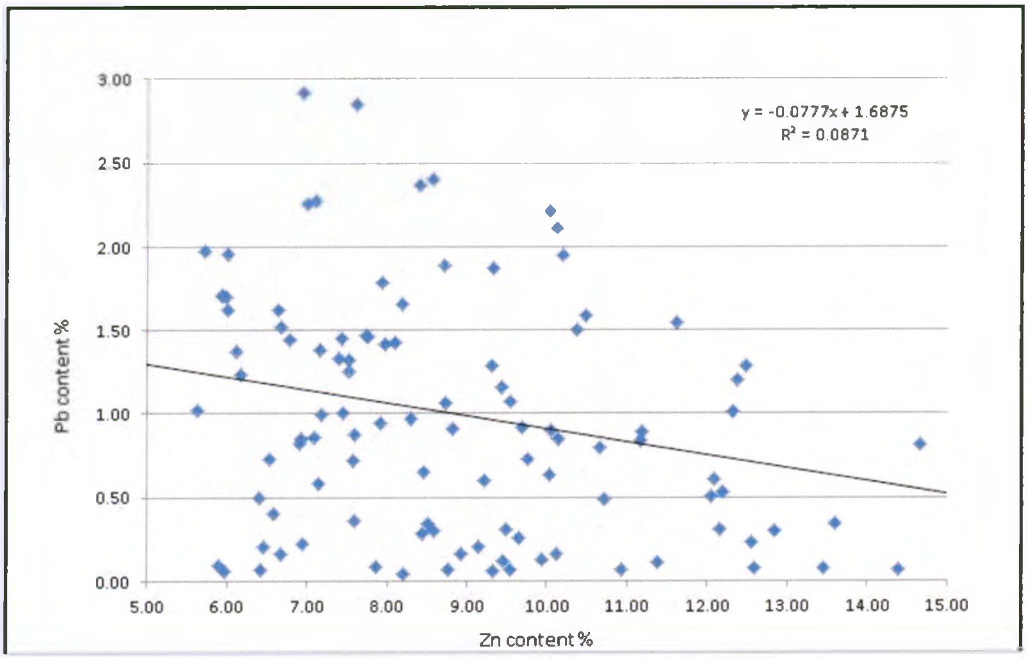
8.3 Grades and tonnages data for level -60 and level -90

Level	Type	Block	Tonnes	Zn (%)	Pb (%)	Cu (%)	Ag (ppm)
-60	PRR	E	94435	8.72	1.07	0.23	15.75
-60	PRR	C	284589	12.05	0.50	0.54	13.52
-60	PRR	F	73518	7.51	1.32	0.09	10.94
-60	PRR	B	18397	11.37	0.11	0.43	11.53
-60	PRR	A	90204	12.59	0.07	0.28	11.33
-60	PRR	D	64123	8.45	0.65	0.15	9.27
-60	SLT	C	12812	12.85	0.30	0.83	14.34
-60	SLT	E	5598	7.75	1.46	0.18	13.19
-60	SLT	A	5801	13.45	0.08	0.27	11.70
-60	SLT	D	5535	6.58	0.40	0.17	6.77
-60	SLT	B	1740	9.45	0.12	0.27	11.50
-60	SLT	F	2732	7.17	1.39	0.08	13.12
-60	SRS	A	957	14.40	0.07	0.31	14.13
-60	SRS	E	1027	9.43	1.16	0.33	16.17
-60	SRS	C	774	12.09	0.61	0.28	16.65
-60	SRS	D	716	6.12	1.37	0.11	9.75
-60	SRS	B	1264	9.94	0.13	0.35	12.46
-60	SRS	F	928	7.73	1.47	0.08	10.44
-90	PRR	C	151581	9.65	0.26	0.28	8.59
-90	PRR	A	56214	9.33	0.06	0.25	6.89
-90	PRR	B	422215	13.60	0.34	0.62	13.50
-90	PRR	D	28874	7.09	0.86	0.15	7.10
-90	PRR	E	105320	7.18	1.00	0.35	22.14
-90	SLT	C	9710	8.58	0.30	0.22	7.80
-90	SLT	A	4821	8.77	0.07	0.24	6.97
-90	SLT	B	13843	14.66	0.82	0.78	19.37
-90	SLT	D	1959	7.59	0.36	0.12	5.80
-90	SLT	E	4655	6.00	1.70	0.28	19.84
-90	SRS	C	866	10.11	0.16	0.25	8.84
-90	SRS	A	1176	10.94	0.07	0.27	7.36
-90	SRS	B	863	27.93	0.26	0.91	13.60
-90	SRS	D	919	7.58	0.72	0.08	5.89
-90	SRS	E	1014	6.68	1.52	0.35	27.33

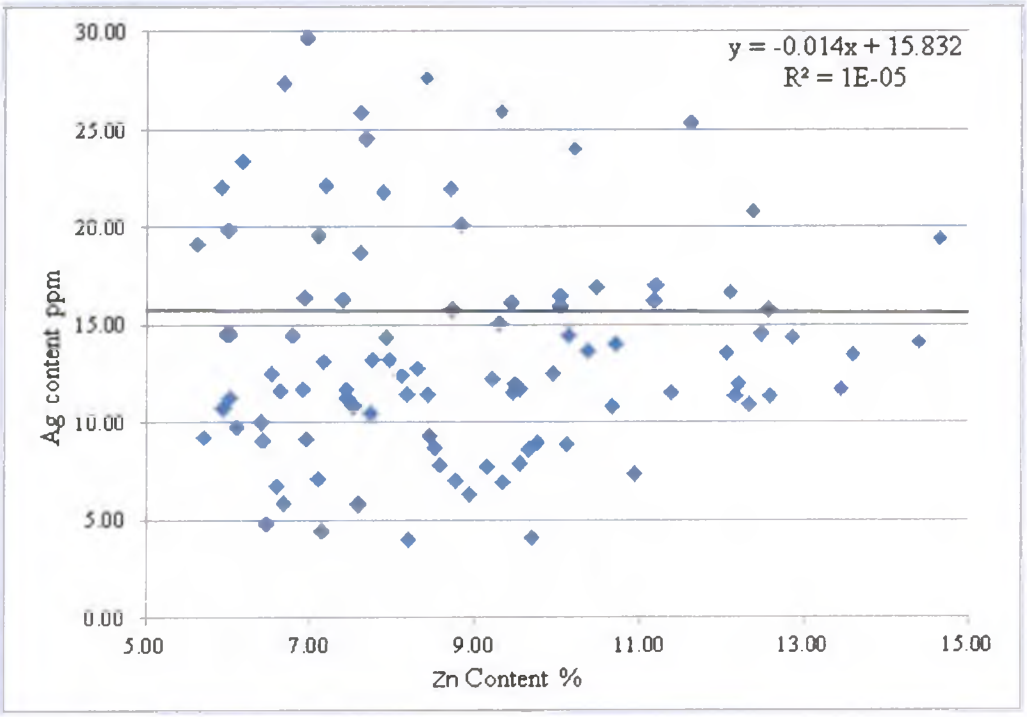
8.4 Grades and tonnages data for level -12

Level	Type	Block	Tonnes	Zn (%)	Pb (%)	Cu (%)	Ag (ppm)
-12	PRR	C	17973	9.54	0.07	0.39	7.86
-12	PRR	P	416827	12.15	0.31	0.50	11.36
-12	PRR	A	10236	8.20	0.05	0.09	3.98
-12	SLT	C	2300	6.43	0.07	0.36	9.08
-12	SLT	P	14409	11.18	0.90	0.59	17.04
-12	SLT	A	5126	4.56	1.38	0.20	12.72
-12	SRS	P	714	5.93	1.71	0.27	10.73
-12	SRS	A	714	5.93	1.71	0.27	10.73

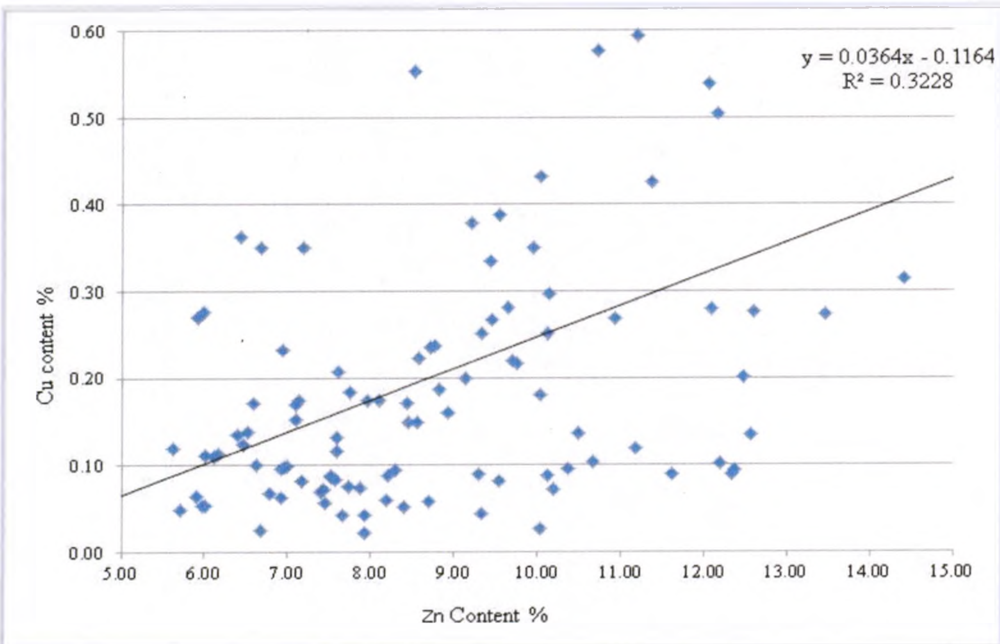
8.5 Scatter plot for Zn and Pb



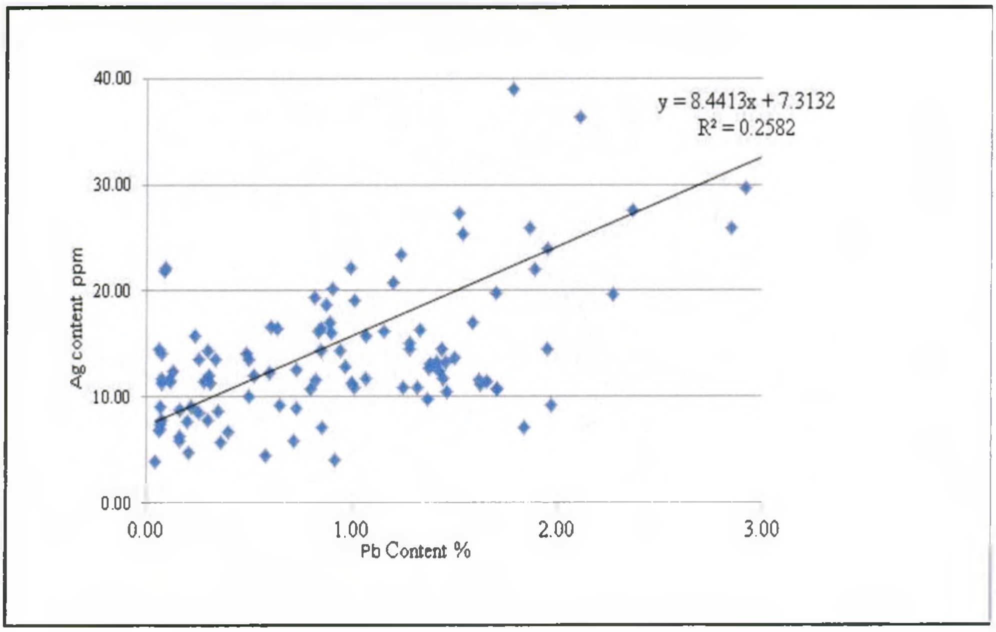
8.6 Scatter plot for Zn and Ag



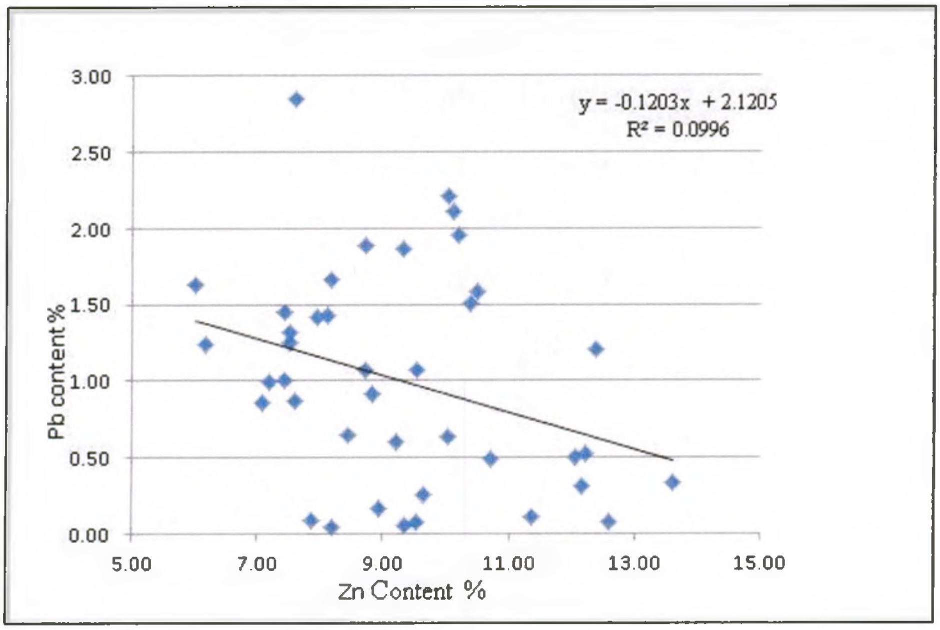
8.7 Scatter plot for Zn and Cu



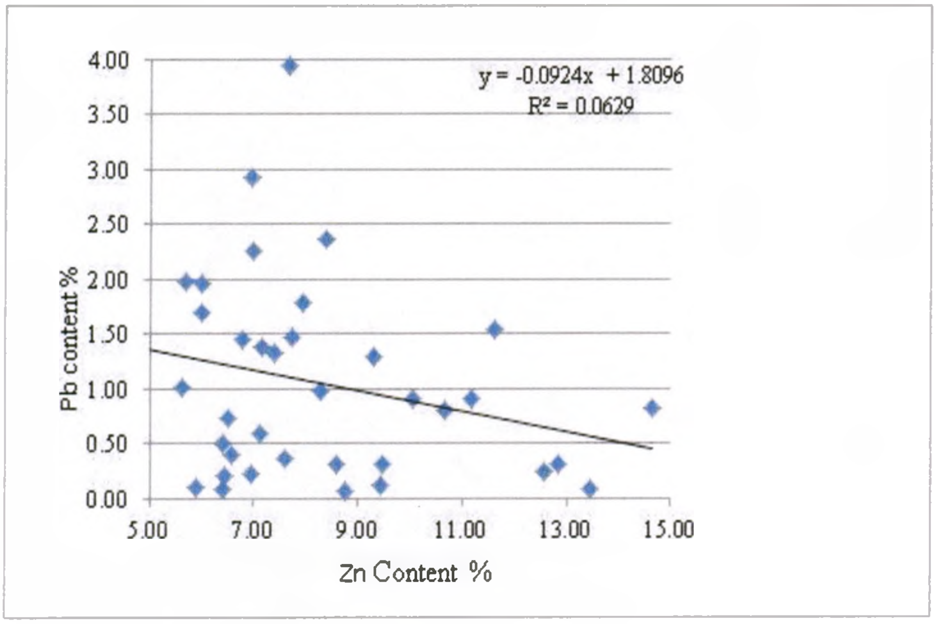
8.8 Scatter plot for Pb and Ag



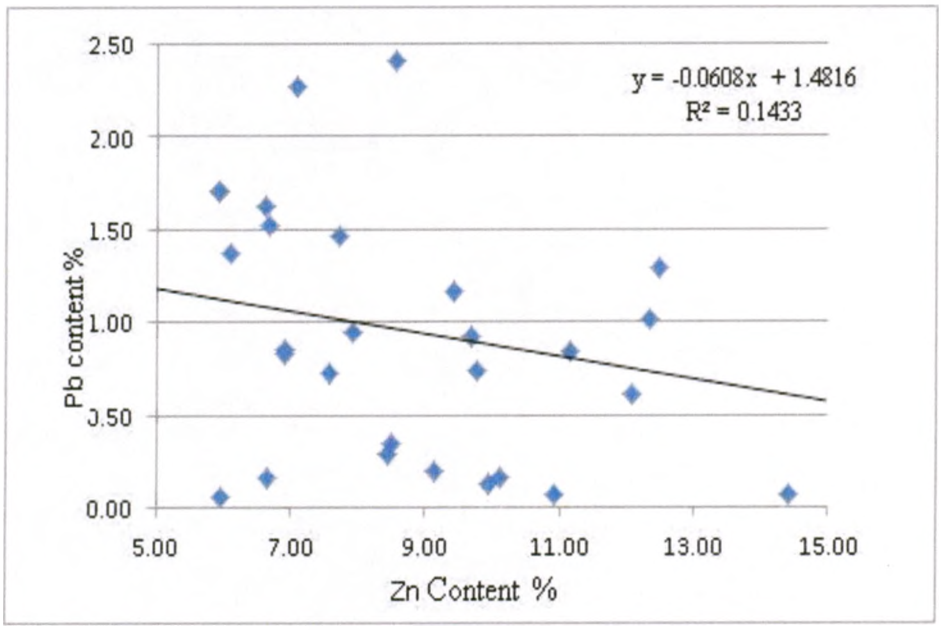
8.9 Scatter plot for Zn and Pb in PRR-type lithology



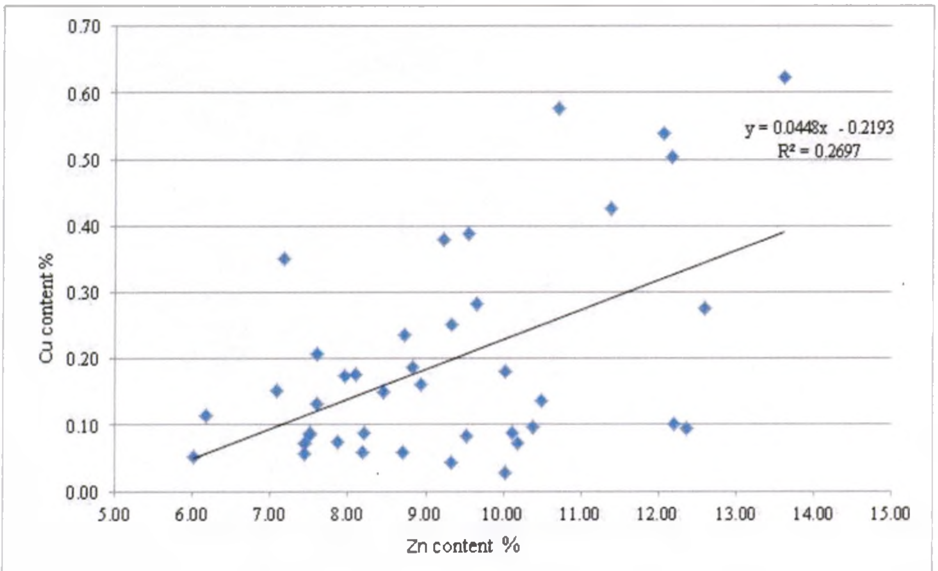
8.10 Scatter plot for Zn and Pb in SLT-type lithology



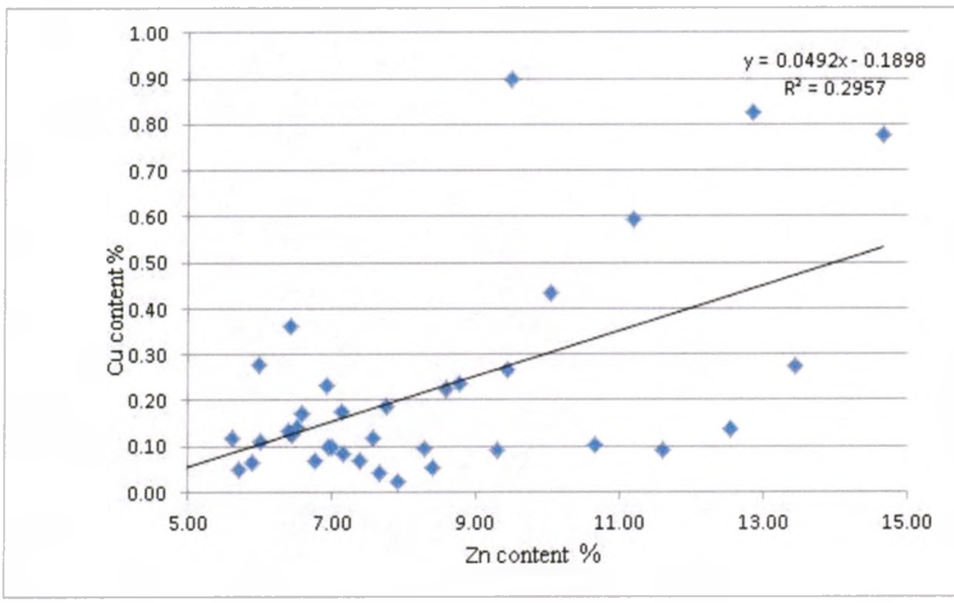
8.11 Scatter plot for Zn and Pb in SRS-type lithology



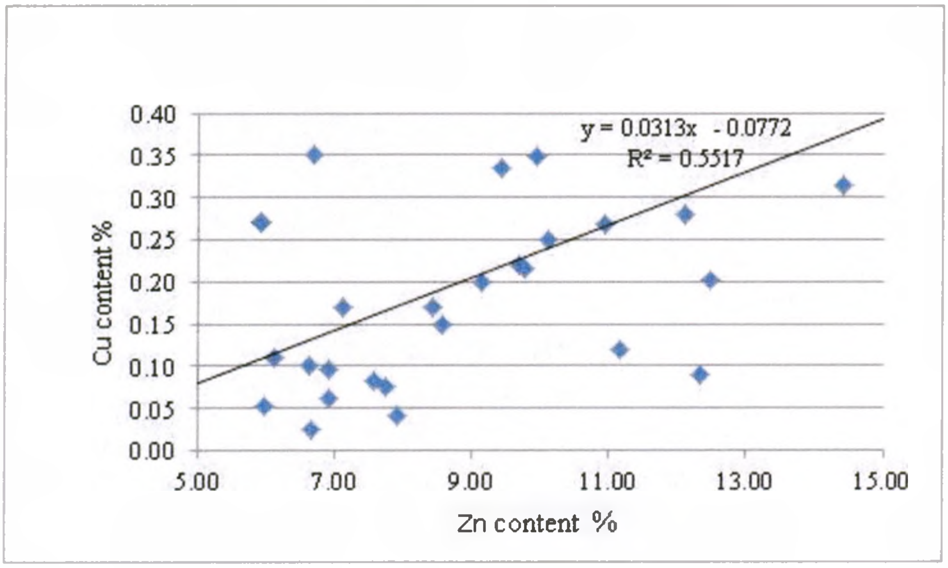
8.12 Scatter plot for Zn and Cu in PRR-type lithology



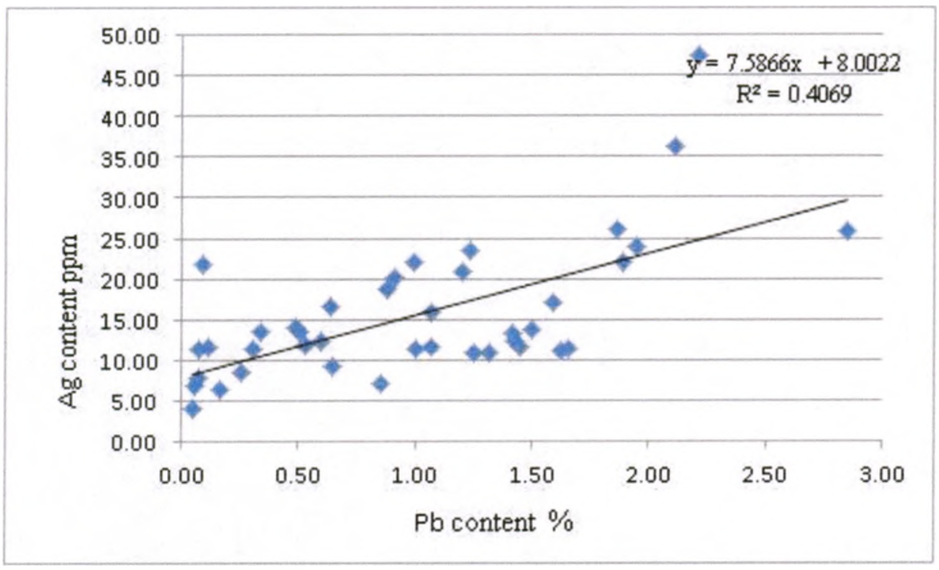
8.13 Scatter plot for Zn and Cu in SLT-type lithology



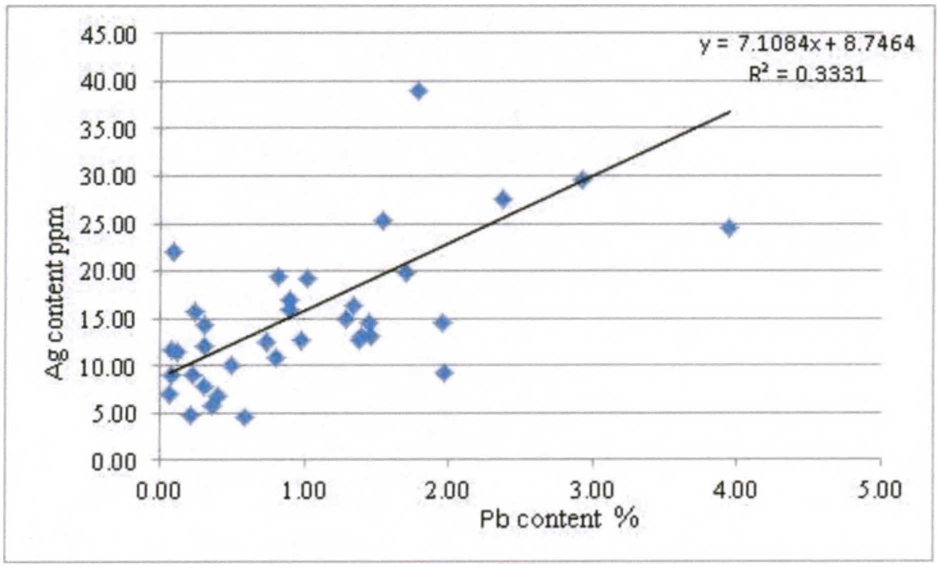
8.14 Scatter plot for Zn and Cu in SRS-type lithology



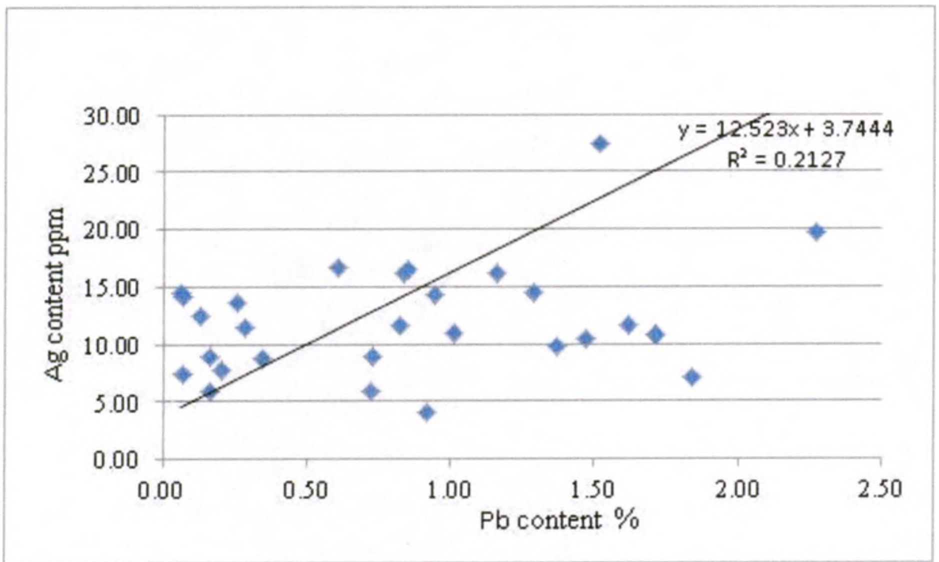
8.15 Scatter plot for Pb and Ag in PRR-type lithology



8.16 Scatter plot for Pb and Ag in SLT-type lithology



8.17 Scatter plot for Pb and Ag in SRS-type lithology



8.18 Zn historical prices

8.19 Pb historical prices

8.20 Ag historical prices