**GEOLOGY, MINERALOGY, AND GEOCHEMISTRY OF THE
VAZANTE NORTHERN EXTENSION ZINC SILICATE DEPOSIT,
MINAS GERAIS, BRAZIL**

by

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Abstract

The Vazante Northern Extension is a continuation of the structurally controlled, hypogene nonsulfide zinc deposit from the Vazante Mine, Minas Gerais, Brazil. The deposit is hosted in Neoproterozoic carbonates of the Serra do Poço Verde Formation located in the Brasília Fold Belt along the western margin of the São Francisco Craton. The Northern Extension deposit is hosted within a shear zone that strikes 200 to 225 and dips 30°-70° NW and is associated with substantial folding that occurred in the same deformation (D₂) event and later transcurrent faulting. The shear zone is composed of a tectonic-hydrothermal breccia that can be subdivided into four types: Type 1 Breccia— distally located from the willemite (Zn₂SiO₄) ore, weakly brecciated dolostone with some Fe-carbonate alteration; Type 2 Breccia—Strong Fe-carbonate alteration, intense brecciation; Type 3 Breccia—hematite replacement breccia, usually proximal to the Type 4 Breccia; Type 4 Breccia—willemite ore breccia, containing three generations of hypogene willemite (Zn₂SiO₄) as well as hematite (Fe₂O₃), and franklinite (ZnFe₂O₄). In the southern part of the deposit, late sulfide-rich veinlets are observed cutting the hypogene zinc silicate mineralization, and contain galena, sphalerite, native silver, covellite, and stromeyerite (Cu_{1-x}Ag_{1-x}S). Geochemical studies conducted on the tectonic-hydrothermal breccia showed a strong regional signature enriched in Ag, Cd, Pb, and Zn. The presence of willemite as opposed to sphalerite and the ubiquity of hematite suggest that the zinc silicate mineralization has formed from the mixing between a low sulfur, acid, oxidizing metalliferous basinal brine similar to the fluids found in MVT deposits with a cooler, more oxidizing, meteoric fluid.

Co-Authorship

Chapter 3 of this thesis was prepared as a separate manuscript for a journal publication as a co-authored paper. This chapter is co-authored with Dr. Gema R. Olivo who contributed to field work; structural, mineralogical, and geochemical interpretations; and acted in as a supervisor and editor throughout the entirety of this thesis; Gustavo D. Oliveira, who contributed extensively to the organization and interpretation of field work, core logging, and sampling; and Dr. Marcel A. Dardenne*, who contributed to background research, field interpretations, and stratigraphic studies.

*Deceased

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List of Mineral Formulas

Mineral Name	Formula
Anglesite	PbSO_4
Barite	BaSO_4
Chalcocite	Cu_2S
Covellite	CuS
Galena	PbS
Franklinite	ZnFe_2O_4
Hematite	Fe_2O_3
Hemimorphite	$\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot 2\text{H}_2\text{O}$
Hydrozincite	$\text{Zn}_5(\text{OH})_6(\text{CO}_3)_2$
Phosphohedyphane	$\text{Ca}_2\text{Pb}_3(\text{PO}_4)_3\text{Cl}$
Sauconite	$\text{NaO} \cdot 3(\text{Zn,Mg})_3(\text{Si,Al})_4 \cdot \text{OH}_2\text{nH}_2\text{O}$
Smithsonite	ZnCO_3
Sphalerite	ZnS
Stromeyerite	$\text{Cu}_{1-x}\text{Ag}_{1-x}\text{S}$
Willemite	Zn_2SiO_4
Zincite	ZnO

Chapter 1

Introduction

1.1 Zinc

Zinc is the fourth most widely produced metal in the world after iron, aluminum, and copper (USGS, 2011). Although its main use is for the galvanization of steel, it is also a major component in brass and zinc-based alloys. The top zinc producing countries in the world are: China, Peru, Australia, the United States, and Canada (USGS, 2011). Most of the world's zinc is currently produced from sedimentary exhalative (SEDEX), volcanogenic massive sulfide (VMS), and Mississippi Valley-type (MVT) sulfide deposits. Zinc oxide deposits account for approximately 12 % of the world's production (Fig. 1.1; Hunt, 2006; Goodfellow and Lydon, 2007) and approximately 4.4 % of the world's zinc resource (Penney et al, 2004).

Zinc oxide deposits, more commonly referred to as nonsulfide zinc deposits, were originally mined in Ancient Rome and Medieval Europe. Ancient Romans and Medieval Europeans used these deposits as a source of zinc to make brass, using “calamine” which is composed of zinc oxide and carbonate ore. In the 19th century, the development of the Wälz kiln in Europe allowed for greater processing of the calamine ore (Boni and Large, 2003). In the early 20th century, nonsulfide zinc orebodies were no longer viewed as economically significant due to the development of the differential flotation process and advancements in the smelting of sulfides. With the recent advent of hydrometallurgical acid-leaching, solvent-extraction, and electrowinning technologies, nonsulfide zinc ore deposits have regained some commercial interest as major sources of high-grade (15-20%) zinc (Large, 2001; Hitzman et al., 2003).

Currently, the zinc sulfide deposits, (i.e. SEDEX, VMS, and MVT) provide lead, silver, and copper ($\pm$ gold) as co-products or by-products. Nonsulfide zinc deposits typically lack these

additional metals; however, with the high ore grades in zinc nonsulfide deposits, the lack of additional metals found in sulfide deposits can be offset by cheaper processing and environmental costs typically associated with sulfide ores (Hitzman et al., 2003). The characteristics and genesis of the sulfide zinc deposits has been extensively investigated (e.g., Goodfellow et al., 1986; Guilbert and Park, 1986; Goodfellow et al., 1993; Leach and Sangster, 1993; Hitzman and Beaty, 1996; Nelson et al., 2002; Goodfellow and Lydon, 2007; and Paradis et al., 2007) and are summarized below. However, little is known about the characteristics and genesis of large nonsulfide zinc deposits. The Vazante deposit, which includes the Vazante Mine and Northern Extension, is an example of large nonsulfide zinc deposit and is the focus of this study.

Fig. 1.1 World zinc production per deposit type (from Hunt (2006)).

1.1.1 Sulfide Zinc Deposits

1.1.1.1 SEDEX Deposits

Sedimentary exhalative (SEDEX) deposits are mineral deposit types that consist of interbedded sulfide minerals with sedimentary rocks, both of which were deposited on the sea floor in association with a hydrothermal conduit. SEDEX deposits can be quite substantial in tonnage and account for a substantial amount of the world's lead and zinc reserves (32%- Fig. 1.2, Goodfellow and Lydon, 2007).

SEDEX deposit ages are bimodally distributed to the Middle Proterozoic and Paleozoic. They are hosted in the intracratonic rift basins (Goodfellow and Lydon, 2007), reactivated rift margins (Goodfellow et al., 1986; Goodfellow and Lydon, 2007), and back-arc rifts with large structures acting as fluid conduits for metal precipitation (Nelson et al., 2002; Goodfellow and Lydon, 2007). The rock types that host SEDEX deposits consist of marine basin sedimentary rocks such as chert and shale (Goodfellow and Lydon, 2007).

Fig. 1.2 Comparison of Vazante Zn grade and tonnage versus world SEDEX deposits (modified from Goodfellow and Lydon, 2007).

Mineralization within SEDEX deposits consists of lead, zinc, and silver

sulfides. Copper and gold may also be of economic value in some SEDEX deposits. Alteration minerals are zoned with respect to distance from the hydrothermal source conduit. The alteration assemblages usually contain quartz, muscovite, chlorite, ankerite, siderite, tourmaline, and abundant Fe-sulfide minerals, such as pyrite and pyrrhotite (Goodfellow and Lydon, 2007).

SEDEX deposits form when hot (~300 °C) sulfur-poor, oxidized basinal fluids circulate in a sedimentary rift basin, leaching metals until they find a fluid conduit, such as a fault or vent, in which to move upwards. There, the basinal fluids react with cooler, reduced, sulfur-bearing seawater, precipitating out lead-zinc sulfides (Goodfellow et al., 1993; Goodfellow and Lydon, 2007).

1.1.1.2 MVT Deposits

Mississippi Valley-type (MVT) deposits are a specific type of carbonate-hosted lead-zinc deposits that typically have little to no magmatic input (Guilbert and Park, 1986). Individual

deposits are small (Fig. 1.3); however, deposits tend to occur in clusters, creating large mining

Fig. 1.3 Vazante grade and tonnage compared to world MVT deposits (modified from Paradis et al., 2007).

districts, some of which are comparable in grade and tonnage to SEDEX deposits (Leach and Sangster, 1993).

MVT deposits are hosted in dolostones that have replaced limestones through dolomitization. The mineralization age of these deposits ranges from the Proterozoic to the

Jurassic, with the largest number of deposits being Cambrian in age. MVT deposits occur in carbonate platforms found in orogenic forelands, extensional basins, and intra-cratonic basins (Leach and Sangster, 1993).

Mineralization occurs as filling open space fractures in breccias, massive replacement, and disseminated crystals. Zinc, lead, and iron sulfide minerals are common; however, fluorite and barite may also be of economic significance. Alteration typically occurs as hydrothermal dolomite in dissolution and collapse breccias (Leach and Sangster, 1993; Paradis et al., 2007).

MVT deposits form when deep basinal brines migrate into carbonate sequences along basin margins. Presently, there are three possible models for metal precipitation. The first model involves mixing between a metal-rich brine and an H_2S -bearing fluid in the open spaces of the carbonate rocks, precipitating out base metal sulfide minerals. The second model proposes that the brine transports both metals and a sulfate, which interacts with organic matter in the carbonate rocks to reduce the sulfates to sulfides, causing precipitation of the metals. The last model comprises a fluid containing both reduced sulfur and metals being carried in the basinal fluid. Precipitation is induced by cooling, dilution, or the loss of volatile compounds (Anderson, 1975; Guilbert and Park, 1986; Paradis et al., 2007).

1.1.1.3 Irish-type Deposits

Irish-type deposits differ from SEDEX and MVT deposits in that they involve SEDEX style formation and mineralization but have carbonate host rock settings, much like an MVT deposit (Goodfellow and Lydon, 2007). Irish-type deposits are lead-zinc-silver deposits that are typified by the Navan, Lisheen, Galmoy, and Tynagh mineral deposits in Ireland (Hitzman and Beaty, 1996). Although Irish-type deposits vary in age, most of them are Carboniferous. They form in marine carbonate sequences proximal to normal faults that act as a conduit for metalliferous fluids (Hitzman and Beaty, 1996).

Mineralization in Irish-type deposits is stratabound or podiform in morphology and consists of lead, zinc, and silver-bearing minerals. Minerals containing barium and arsenic may also be present. Alteration minerals are usually hydrothermal dolomite, ferroan dolomite, and calcite (Hitzman and Beaty, 1996).

Irish-type deposits form as a result of metalliferous brines being focused upwards along structure and directly replacing carbonate rocks with sulfide mineralization, creating massive deposits that contain high amounts of copper, silver, and iron in addition to lead and zinc (Hitzman and Beaty, 1996).

1.1.2 Nonsulfide Zinc Deposits

According to Hitzman et al. (2003), there are two subtypes of nonsulfide zinc deposits: supergene deposits and hypogene deposits. Supergene deposits are formed by the oxidation of both zinc oxide and zinc sulfide deposits. They are typically hosted in carbonate rocks and the major zinc minerals are smithsonite (ZnCO_3), hemimorphite ($\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot 2\text{H}_2\text{O}$), hydrozincite ($\text{Zn}_5(\text{OH})_6(\text{CO}_3)_2$), and sauconite ($\text{NaO} \cdot 3(\text{Zn,Mg})_3(\text{Si,Al})_4 \cdot (\text{OH})_2 n\text{H}_2\text{O}$) (Hitzman et al., 2003).

Supergene zinc deposits can be further divided into three categories: direct replacement, wall-rock replacement, and residual karst-fill. These deposits are thought to have been created by

the oxidation of MVT deposits. Direct replacement deposits form when zinc sulfide minerals, such as sphalerite, are oxidized and replaced by smithsonite and hemimorphite. Other secondary lead, copper, and iron oxides may also occur associated with zinc minerals. Wall-rock replacement deposits form near the original sulfide body as a result of groundwater leaching zinc from the sulfide body and precipitating it into the surrounding carbonate host rocks. Residual karst-fill deposits are the result of zinc minerals accumulating in karst depressions and caves that were formed due to a weathering environment (Hitzman et al., 2003).

Hypogene nonsulfide zinc deposits, from now on referred to as hypogene zinc silicate deposits, are not derived from a pre-existing sulfide body. Hypogene zinc minerals include willemite (Zn_2SiO_4), franklinite (ZnFe_2O_4), and zincite (ZnO) and may include the supergene zinc minerals smithsonite, hemimorphite, hydrozincite, and sauconite as well. Hypogene zinc silicate deposits are further divided into two categories based on their controls: structurally controlled and stratiform (Hitzman et al., 2003), though the “stratiform” category should be more aptly dubbed “metamorphic” hypogene nonsulfide zinc, as the type locality for these nonsulfide zinc deposits is the metamorphosed Franklin deposit. There are four major hypogene zinc silicate deposits: the Beltana-Aroona trend, Australia; the Franklin and Sterling deposit, New Jersey, U.S.A; the Kabwe-Lusaka district, Zambia; and the Vazante trend, Brazil (Table 1.1).

Deposits	Location	Size (Mt)	Grade (% Zn)	Host rocks	Host rock Age	Related Structures	Ore minerals	Alteration	T _H (°C)	Salinity (eq. wt %NaCl)	Trace Elements
Beltana ¹	Australia	0.86	37.9	limestone, dolostone	Cambrian	Beltana Fault, district scale folds, breccia	Willemite, coronadite, hedyphane, mimetite, smithsonite	Ferroan dolomite, hematite, quartz	50-170 (wl)	4 – 14	As, Be, Cd, Cu, Fe, Ge, Mn, Pb, Sb, V
Franklin ²	U.S.A.	24	19.6	marble	Neoproterozoic	Zero Fault, district scale folds	franklinite, willemite, zincite, tephroite,	rhodonite, magnetite, calcsilicates	650-700	n/a	As, B, Co, Cu, Fe, Mn, Ni, Pb, V, W
Kabwe ^{3*}	Zambia	13 ⁸	20-25 ⁸	dolostone	Neoproterozoic	Mine Club fault zone, district scale folds, minor breccia	sphalerite, willemite, galena	Quartz, hematite, smithsonite, cerussite	98-178 (sp)	11.5	Ag, Be ⁸ , Cd, Cu, Ga, Ge, In, V, Pb
Vazante Trend	Brazil	18 ⁴	19 ⁴	dolostone	Neoproterozoic	Vazante Shear Zone, district scale folds, breccia ⁴	willemite, sphalerite, franklinite, sphalerite ^{4,5}	Quartz, ferroan and zincian dolomite, hematite ⁴	65-180 ⁶ (wl)	3 – 15 ⁶	Ag, As, Be, Cd, Co, Cu, Ge ⁷ , Fe, Hg, In, Mo, Pb, S, Sb, Se, V ⁴

Table 1.1 Summary of the characteristics on zinc silicate deposits. Temperatures are taken from fluid inclusions within the cited mineral, except for Franklin where the temperatures were estimated based on the equilibrium assemblage of Fe₃O₄ – Mn₃O₄ – ZnFe₂O₄. *Willemite comes, in part, from oxidized sphalerite.

¹ (Groves et al., 2003); ² (Fron del and Baum, 1974); ³ (Kamona and Friedrich, 2007); ⁴ (This study); ⁵ (Monteiro et al., 1999); ⁶ (Dardenne and Freitas-Silva, 1999); ⁷ (Monteiro et al., 2007); ⁸ (Boni et al., 2011).

Hypogene zinc silicate deposits tend to occur in sedimentary basins, Neoproterozoic to Cambrian in age that have been metamorphosed to some degree, usually at least to the sub-greenschist facies (except Franklin, NJ, which is metamorphosed to amphibolites-granulite facies).

Hypogene deposits are found in carbonate rocks associated with major structures, such as district scale faults and folds (in the Beltana, Vazante, and Kabwe districts). Brecciation is commonly associated with mineralization; this is exemplified by the Vazante trend. The breccias at Beltana are associated with karst (Groves et al., 2003); whereas the breccias at Vazante and Kabwe are a result of tectonism and hydrothermal fluid flow (Dardenne, 2000; Kamona and Friedrich, 2007; this study).

All of the deposits are dominated by mineralogical associations containing the zinc silicate, willemite, as well as zinc oxides, such as zincite, franklinite, and the zinc carbonate smithsonite. Ferroan dolomite, hematite, and quartz are all common alteration minerals found in these types of deposits, with Franklin, NJ as the exception due to its high metamorphic grade. Additionally, all of the deposits show a moderate fluid inclusion homogenization temperature (T_H) of 50 – 180 °C, which is interpreted as the minimum temperature of formation (Groves et al., 2003). Higher temperatures up to 300 °C have been determined through $\delta^{18}\text{O}$ isotope analysis in Vazante (Monteiro et al., 1999; 2006; 2007; Appold and Monteiro, 2009) and Kabwe (Kamona and Friedrich, 2007). The extraordinarily high temperatures found in Franklin are a reflection of the amphibolite-granulite facies metamorphism.

The genetic model for hypogene nonsulfide deposits involves the migration of acidic, oxidizing brines (50 – 180 °C) with the metals transported as Cl^- complexes through structural conduits where they interact with cooler, meteoric fluids. Through cooling, and an increase in pH, the willemite precipitates preferentially over sphalerite (Brugger et al., 2003; Groves et al., 2003; Monteiro et al., 2006; Appold and Monteiro, 2009).

1.1.3 Open Questions

The potential for producing zinc from high-grade deposits at lower costs has renewed interest in nonsulfide zinc deposits around the world. However, because zinc production has been dominated by sulfide deposits for the past century, little is known about nonsulfide zinc deposits, and especially with respect to hypogene nonsulfide zinc deposits. There are several questions relating to the formation of hypogene zinc deposits, in particular the structurally controlled type, which are dominated by zinc silicates. These questions include:

What are the most favorable environments for the formation for zinc silicate deposits?

What role do structures play in the formation of zinc silicate deposits?

What is the ore and alteration mineral paragenesis?

What geochemical signatures do these deposits have?

What are the ore fluid characteristics of these deposits?

What are the processes related to its formation?

What geophysical and geochemical methods can be used to detect for zinc silicate deposits?

What other explorations methods can be applied to find these types of deposits?

1.1.4 The Vazante Mine and Northern Extension Deposit

The Vazante zinc silicate mine is located in the southern region of the Brasília Fold Belt near the town of Vazante, Minas Gerais, Brazil (Figure 2). It is the largest zinc producing mine in Brazil. Artisanal mining has taken place since the 1950's when the area was mined for the "calamine" (hemimorphite and smithsonite) zinc ore. It has been estimated that around 8 Mt of calamine ore was mined in the Northern Extension of the Vazante Mine (Votorantim pers. commun., 2011). In 1969 and in 1983, open pit and underground mining began, respectively (Monteiro et al., 1999).

Fig. 1.4 Location of Vazante, Minas Gerais, Brazil (modified from Encyclopedia Britannica, 2011)

The Vazante Mine has estimated reserves of 18 Mt at 19% Zn. The Northern Extension property contains additional reserves of 850 Kt of ore at 16% Zn (pers. commun., 2011). When compared to currently and historically producing SEDEX and MVT deposits, Vazante has average reserve zinc tonnages and high zinc grades (Figs. 3 & 4).

The Vazante deposit has been studied by Rigobello et al. (1988); Dardenne and Freitas-Silva (1999); Dardenne (2000); Monteiro et al. (1999, 2006, 2007); Misi et al. (2005); Cunha et al. (2007) and Rostirolla et al. (2007). Rigobello et al. (1988) and Dardenne (2000) first described the stratigraphy and host rocks as well as the structural setting of the Vazante Mine. Dardenne (2000) also described the tectonic history of the Brasília Fold Belt with respect to the Vazante region. Monteiro et al. (1999, 2006, 2007) conducted studies on the mineralization, alteration, and stable isotopes in the Vazante Mine and first proposed ideas for ore fluid models. Dardenne and Freitas-Silva (1999), Misi et al. (2005), and Cunha et al. (2007) all conducted Pb isotope dating studies in order to establish dates for the host rocks and mineralization events in the Brasília Fold Belt. They also undertook fluid inclusion studies to constrain the ore fluid salinities and temperatures of formation. Rostirolla et al. (2007) did regional studies to establish a metamorphic history of the Vazante region. A more detailed review of the previous work will be presented in Chapter 2 of this thesis.

Votorantim has developed in the last years an extensive exploration program to evaluate the extension at depth and along the structure of the Northern Extension deposit, historically known as the Mineração Areiense S/A (MASA) mine and considered to be an extension of the main Vazante orebody. This includes wide-spread drilling in this region, providing a unique opportunity to characterize the various mineralized zones and integrate the data with the previous work conducted in the Vazante mine. This knowledge generated by the integration of the data from this study in the Northern Extension with those from the Vazante Mine will further our understanding of the processes related to the formation of hypogene zinc silicate deposits, leading to guidelines for exploration in this region and for this type of deposit globally.

1.2 Thesis Objectives

The main objectives of this investigation of the Vazante Northern Extension deposit include:

- A) Determination of the major structural and lithological controls for the mineralized zones;
- B) Characterization of the mineral paragenesis for the various mineralized and alteration zones in order to understand the evolution of fluid/rock interaction during the basin formation and deformation;
- C) Identification of the critical processes responsible for the deposition of the main zinc silicate ore and the minor mineralized zones by integrating the data obtained in this study with thermodynamic data for this type of system and models proposed in previous work for similar deposits;
- D) Recognition of the relevant geological and geochemical indicators to explore for this deposit type.

This study will provide a basic understanding of the genesis of these mineralized zones and it is expected that this will lead to the generation of an exploration model that will assist in finding new deposits in the Brasília Fold Belt.

1.3 Methodology

1.3.1 Field Work and Sampling

To achieve the research objectives both field and laboratory work were undertaken. The objectives of the field work included mapping and logging the various units of the Vazante Group in the Vazante Northern Extension. Regional reconnaissance work was carried out to allow for integration of the local geology with the regional geology. Local mapping was conducted using a base topographic map provided by Votorantim, Brunton Pocket Transit, and Dakota 20 GPS at a 1:2000 scale to document the structures, rock types, mineralization, and hydrothermal alteration of the most northern exposures in the Northern Extension region. This area was chosen for detailed mapping because the open pits (referred to as Cavas 5A, 6A, and 7A) from the old mine operated by Mineração Areense S/A (MASA) allowed exposure of rock units that are normally covered by lateritic soils. The data acquired can be found in Appendix A and were integrated into the geological base map provided by Votorantim Metals.

Re-logging of drill core was conducted to examine mineralization and alteration of the host rocks in the subsurface, as well as to delineate the different stratigraphic units using less weathered samples than those found at surface (Appendix B). The re-logged drill holes were chosen based on transects perpendicular and along the major structural and mineralized trends in the Northern Extension region of the Vazante Mine.

To provide insights on the evolution of the deposit and on the critical factors related to the mineralizing event, 426 samples were selected from 30 drill holes to represent the various rock units, types of mineralization, and various degrees of alteration. These samples included representative samples of unaltered rock for comparison with the mineralized and altered zones. The sample intervals were recorded and the core was halved at the Vazante Mine.

1.3.2 Laboratory Methods

Petrographic investigation, using an Olympus BX 60 transmitted/reflected light microscope with an Olympus TH3 reflected light power source, was completed in order to identify the minerals, textures, and paragenetic relationships for ninety-nine representative samples. The thin sections are 26 x 46 mm in size, 30 microns thick, and polished to produce a reflected surface of microprobe quality. Petrographic reports were then generated to create an all-encompassing mineral paragenesis from the microscope analyses of the thin section samples (Appendix C).

A FEI MLA 650 FEG-ESEM was used to verify the identification of some rare, unknown minerals, and evaluate the variation in major elements of carbonate and willemite. Backscattered electronic images (BSEI) were taken. The samples were not carbon coated and were analyzed under low vacuum pressure at 20.00 kV. Quantax energy dispersive X-ray spectrometer (EDS) readings were used to identify qualitative information about unknown minerals.

Electron microprobe (EMP) analysis was completed at the New Mexico Bureau of Mines and Mineral Resources (NMBBMR) at the New Mexico Institute of Mining and Technology (i.e. New Mexico Tech). The analyses were conducted using a Cameca SX-100 with three wavelength dispersive electrometers with secondary electron and high-speed backscattered electron detectors. All samples were carbon coated for the EMP analyses. A beam current of 20 nA was used for willemite and sphalerite, and a beam current of 10 nA was used for carbonate analysis (Table 1.2).

<i>Mineral</i>	<i>Element</i>	<i>Standard</i>	<i>Peak counting times (s)</i>	<i>Detection Limit (ppm)</i>
<i>Willemite</i>	Cr	Chromite	20	551
	Fe	Horneblend-Kak	20	645
	Mn	Kaersuitite	20	740
	Zn	ZnSe	20	1000
<i>Sphalerite</i>	Cd	Cd	40	1021
	Fe	Horneblend-Kak	20	512
	Mn	Kaersuitite	40	576
	S	Pyrite	20	438
	Zn	Sphalerite	20	1203
<i>Carbonate</i>	Ba	Siderite	20	4397
	Ca	Calcite	20	408
	Fe	Siderite	10	1009
	Mg	Dolomite	20	262
	Mn	Siderite	20	778
	Si	Kaersuitite	20	232
	Sr	Dolomite	20	1138
	Zn	ZnSe	20	1042

Table 1.2 Table of elements analyzed by EMP with respect to each mineral, the standards, peak counting times, and detection limits.

The EMP was used to analyze the composition of each generation of willemite and to examine sphalerite and carbonate composition, allowing for a better understanding of the evolution of the hydrothermal system. The results of the petrographic and mineralogical investigation were integrated with field observations to determine the overall evolution of the deposit and can be found in Table 3.1 in Chapter 3.

Whole rock geochemical analyses of samples from each unit, alteration and mineralization zones were also completed. These analyses were done to determine the geochemical signatures related to the various styles of mineralization and alteration as well as the any possible mass changes involved in the alteration process. Of the 74 samples analyzed for

trace elements, 39 of those samples were analyzed for whole rock geochemistry using X-ray fluorescence (XRF). The geochemical analysis was carried out by the ALS Laboratory Group in Canada. Detailed information of the analytical methods is provided in Chapter 3, and the results are provided in Appendix D.

Specific statistic and isocon methods were applied to evaluate the lithogeochemical data and are described in detail in Chapter 3.

1.4 Scope of the Thesis

The organization of the thesis follows the scope described below: Chapter 1 introduces the various zinc deposit types, both sulfide and nonsulfide. It elaborates on the different types of zinc nonsulfide deposits, with emphasis on what constitutes a hypogene zinc silicate deposit. The Vazante zinc silicate deposit is briefly introduced and the objectives of this study discussed, and the methods applied to achieve the objectives are briefly outlined.

Chapter 2 presents an overview of the Tocantins tectonic province and the Brasília Fold Belt (BFB). It then discusses the stratigraphy of the BFB with emphasis on the Vazante Group sediments, which host the Vazante Mine. The issues in dating the Vazante Group sediments are examined, and finally the prominent mineral deposits of the southern BFB are reviewed.

Chapter 3 is in the form of a manuscript reporting the results of this study and their interpretations, which will be submitted to a major journal in the field of Economic Geology. It presents a brief summary of the regional geology addressed in Chapter 2 and elaborates on the geologic units investigated in the Vazante Northern Extension. The structure and mineralogy of the Northern Extension deposit are described in detail, culminating in a mineral paragenesis of the deposit. The geochemical results are integrated with the structural and mineralogical data to provide the evolution of fluid-rock interaction for the deposit. The results and interpretations

were integrated with previous work to further our understanding of nonsulfide zinc deposits and provide guidelines for their exploration.

Chapter 4 includes concluding remarks on this study and suggestions for future studies.

Chapter 1 References

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Chapter 2

Literature Review: Regional Geology, Tectonic Evolution, and Metallogeny of the Brasília Fold Belt (BFB)

2.1 Regional Geology and Tectonic Evolution

The Brasília Fold Belt is roughly 1000 km long and is part of the Tocantins Province, which is composed of three fold belts: the Araguaia Belt to the east of the Amazonia Craton, the Paraguay Belt on the southeastern margin of the Amazonia Craton, and the Brasília Fold Belt along the western edge of the São Francisco Craton (Fig. 2.1; Almeida et al., 1981; Pimentel et al., 2001; Valeriano et al., 2008; Rodrigues et al., 2010). The Paraguay and Araguaia fold belts are thrust towards the Amazonia Craton to the west; however, the central Brasília Fold Belt is thrust to the east onto the São Francisco Craton (Valeriano et al., 2008).

The Brasília Fold Belt was created through a series of tectonic events starting with continental rifting of the São Francisco Craton around 1700 Ma and ending with the formation of the Brasília Fold Belt during the Brasiliano Orogeny (Misi et. al, 2005; Martins-Neto, 2009). The continental rift system evolved into a passive margin setting along the western edge of the São Francisco Craton, allowing for the deposition of intracratonic siliciclastic sediments and platform carbonates represented primarily by the Canastra–Paranoá–Vazante groups at around 1200-900 Ma (Valeriano et al., 2008; Martins-Neto, 2009). The latter is the host of the Vazante silicate zinc deposit.

Fig. 2.1 Map of the Brasília Fold Belt (Modified from Rodrigues et al., 2010)

Subduction of oceanic crust from the Brazilide Ocean beneath the São Francisco Craton also began around 900 Ma, causing magmatism that would lead to the formation of the Goiás magmatic arc (Dardenne, 2000; Valeriano et al., 2008; Martins-Neto, 2009). Continuing subduction caused the convergence of the Goiás magmatic arc and the São Francisco Craton around 850 – 750 Ma, the start of the Brasiliano Orogeny. This collision thrust the passive margin sediments as thin-skinned nappes to the east onto the São Francisco Craton (Dardenne, 2000; Valeriano et al., 2008, Martins-Neto, 2009), and reached its metamorphic peak around 650 Ma (Martins-Neto, 2009). Dardenne (2000) also documented geochemical and isotopic evidence of a late Brasiliano collisional event around 630 – 610 Ma and interpreted the data as related to the convergence of another magmatic arc on the eastern margin of the São Francisco Craton. Finally, the cratonic sediments of the Bambuí Group were deposited and construction of the Brasília Fold Belt was completed around 590 Ma (Martins-Neto, 2009).

The central region of the Brasília Fold Belt bulges to the west because of the Pirineus Lineament, which trends NW – SE (Fig. 2.1; Almeida et al., 1981; Marini et al., 1981) and further subdivides the Brasília Belt into northern and southern zones (Dardenne, 2000). The rocks in the northern zone of the Brasília Fold Belt either remain unmetamorphosed or are metamorphosed up to the greenschist facies. Their stratigraphic relationships remain well preserved and the units consist of the Araí, Serra da Mesa, and Paranoá groups as well as the Serra da Mesa, Serra do Encosto, and Serra Dourada granites and Palmeirópolis, Juscelândia, and Indaianópolis volcano-sedimentary sequences (summarized in Table 2.1). The former mentioned granites are mineralized with tin (Pimentel et al, 1991) and the latter volcanic-sedimentary sequences host the Palmeirópolis VMS deposit. Additionally, the Araí, Serra da Mesa, and Paranoá groups host various gold occurrences and artisanal mines (Guiliani et al., 1993; Araujo, 1999; Dardenne and Schobbenhaus, 2001).

Sedimentary units	Volcanic units	Description	Age (Ma)
Paranoá Group ^{1,2}		conglomerates overlain by rhythmites with mudcracks and evaporites, marine rhythmites and quartzites, limestones, and stromatolitic dolomites	1200 – 900
	Palmerópolis, Juscelândia, and Indaianópolis Volcano-sedimentary sequences ^{1,3,4}	fine-grained amphibolites and gneiss, mica schists, metachert, and metavolcanics of varying compositions	1300 – 1170
Serra da Mesa Group ^{1,5,6,7}		quartzites, micaceous schists, and marbles	1600 – 1470
	Serra da Mesa, Serra do Encosto, and Serra Dourada granites ^{1,8}	anorogenic tin granites	1658 – 1574
Araí Group ^{1,6,7,9}		intraformational quartz conglomerates intercalated with metasiltstone on top of basal volcanics including basalt, andesite, dacite, an rhyolite	1770

Table 2.1 Summary of the characteristics of the northern Brasília Fold Belt geologic units. ¹(Dardenne, 2000); ²(Dardenne, 1978); ³(Araujo, 1999); ⁴(Dardenne and Schobbenhaus, 2001); ⁵(Fuck and Marini, 1981); ^{6,7}(Marini et al., 1984a, b); ⁸(Pimentel et al., 1991); ⁹(Pimentel et al., 2001)

The southern region of the Brasília Fold Belt, which comprises the Vazante, Canastra, Araxá, and Ibiá groups, was metamorphosed up to the greenschist facies and generally displays more intense tectonic deformation than the northern region. The Araxá, Vazante, Canastra, and Ibiá groups form a complex system of nappes that are thrust onto the Bambuí Group sediments to the east (Dardenne, 2000).

The Araxá Group is located in the very southern region of the Brasília Fold Belt, is highly deformed, and associated with numerous thrust events. It is composed of micaceous quartzites and a variety of schists including: chlorite-muscovite, biotite-garnet, staurolite, and feldspathic schists. Syntectonic meta-basalts, andesites, and rhyolites are associated with the schists in the Araxá Group (Dardenne, 2000; Pimentel et al., 2001).

The Ibiá Group lies unconformably on top of the Canastra Group and is made up of two formations: the Cubatão and Rio Verde. The Cubatão Formation consists of thick diamictites (Dardenne, 1978). The Rio Verde Formation sits on top of the Cubatão Formation and consists of calciferous phyllites with some intercalations of quartzite (Dardenne, 2000).

The Araxá and Ibiá groups have overlapping ages (1100 – 800 Ma) based on U-Pb zircon ages obtained from the syntectonic intrusives and Sm-Nd ages obtained from amphiboles (Pimentel et al., 2001). Dardenne (2000) suggests that these units represent laterally distinct sedimentary packages that were thrust onto the São Francisco cratonic margin; however, Pimentel et al. (2001) suggests that these sedimentary packages formed due to erosion from the same source.

The Canastra Group is considered to be the southern BFB equivalent sedimentary group to the Paranoá Group located in the northern BFB (Dardenne, 1978, 2000), and its age is estimated to be between 1200 – 900 Ma based on stromatolites (Dardenne, 2000) and around 1000 Ma based on Sm- Nd dating (Pimentel et al., 2001). It is composed primarily of phyllite and quartzite that has been metamorphosed up to the greenschist facies. There are 3 formations that make up the Canastra Group, which sits unconformably below the Ibiá Group and is tectonically thrust on top of the Vazante Group (Dardenne, 2000). They are from the bottom to the top: the Serra do Landim, Paracatú, and Chapada dos Pilões formations. The Serra do Landim Formation are interpreted to be the lowest section of the Canastra Group according to Freitas-Silva and Dardenne (1994); however, Madalosso and Valle (1978) have described the Serra do Landim as being the uppermost formation of the Vazante Group. The Serra do Landim comprises a pale green to gray-green calc-phyllite to calc-schist (Freitas-Silva and Dardenne, 1994; Dardenne, 2000). The Paracatú Formation is composed of gray carbonaceous phyllite with quartzite lenses (Almeida, 1969; Freitas-Silva and Dardenne, 1994; Dardenne, 2000) and hosts the Morro do Ouro gold mine located in Paracatú, Minas Gerais (Dardenne, 2000). The Chapada

dos Pilões Formation lies on top of the Paracatú Formation and is made up of intercalated phyllites and quartzites, which have been interpreted as metamorphosed rhythmites and turbidites (Dardenne, 2000).

The Vazante Group is located in the northwest region of Minas Gerais where it stretches for nearly 250 km N-S, lies tectonically below the Canastra Group; and is thrust on top of the younger Bambuí Group (Dardenne, 2000; Pimentel et al., 2001; Monteiro et al., 2007). It is primarily composed of intercalated phyllites and carbonates that have undergone metamorphism up to the greenschist facies. The age of the Vazante Group is controversial and poorly constrained due to the absence of igneous rocks and well constrained detrital zircon dating.

The Vazante Group (Fig. 2.2) is divided into 7 formations, which are from the bottom to the top: Retiro (also referred to as Santo Antônio do Bonito Formation; Cunha et al., 2007; Misi et al., 2005), Rocinha, Lagamar, Serra do Garrote, Serra do Poço Verde, Morro do Calcário, and Serra da Lapa (Dardenne, 2000). The Retiro formation consists of quartzite, conglomerate, diamictite (i.e., debris flows from glacio-marine environments), and slate (Dardenne, 2000; Cunha et al., 2007). It is host to the Coromandel phosphorite mineralization (Dardenne, 2000). The Retiro Formation grades upwards into the Rocinha Formation, which consists of pelite, siltstone rhythmites as well as phosphatic layers that host the Rocinha and Lagamar phosphorite deposits (Dardenne, 2000; Cunha et al., 2007). The top of the Rocinha Formation is a thick sequence of slate and metasiltstone that grades into carbonaceous and pyrite-bearing slate (Dardenne, 2000; Pimentel et al., 2001). These pyrite-bearing slates contain phosphorites and are host to the Rocinha phosphate deposit. The upper part of the formation contains quartzites and siltstones that host the Lagamar phosphate deposit (Dardenne, 2000). Above the Rocinha Formation is the Lagamar Formation which is a metapsamo-pelitic unit with a basal metaconglomerate. Overlaying these clastic units are dolomitic breccias, dark gray limestones, and light pink stromatolitic bioherms with columnar *Conophyton* and *Jacutophyton* stromatolites

(Dardenne, 2000; Monteiro et al. 2006; Cunha et al., 2007). Above the Lagamar Formation is the Serra do Garrote Formation, which is made up of dark gray to green-gray phyllites with localized pyritic zones (Dardenne, 2000; Cunha et al. 2007; this study).

Sitting atop the Serra do Garrote Formation is the Serra do Poço Verde Formation, which hosts the Vazante zinc silicate mineralization. The Serra do Poço Verde Formation (Fig. 2.2) can further be subdivided into four members: Lower Morro do Pinheiro, Upper Morro do Pinheiro, Lower Pamplona, and Middle Pamplona (Dardenne, 2000). The Lower Morro do Pinheiro Member forms the base of the Serra do Poço Verde Formation. It consists of light gray and pink dolomite with stromatolites intercalated with oncolitic dolarenites and intraformational dolomite breccias. The Upper Morro do Pinheiro Member is a dark gray dolomite with bird's eyes and minor carbonaceous phyllites. The Lower Pamplona Member consists of gray to pink laminated dolomites intercalated with green and maroon phyllites. The Middle Pamplona Member consists of light gray to pink dolomite with algal laminations and dolarenites with stromatolites (Dardenne, 2000).

The Morro do Calcário Formation, also known as the Upper Pamplona Member according to Rigobello et al. (1988), rests on the top of the Serra do Poço Verde Formation, is comprised of carbonaceous shale, dolarenites, breccias, and stromatolitic bioherm facies (Dardenne, 2000; this study). It hosts the Morro Agudo lead-zinc Mine (Dardenne, 2000), Fagundes zinc sulfide deposit, and Ambrósia zinc sulfide deposit (Monteiro et. al., 2006).

The upper most formation in the Vazante Group is the Lapa Formation, which sits unconformably on top of the Morro do Calcário formation. The Lapa Formation is composed of black, carbonaceous rhythmites with intercalated slates and phyllites. It also contains sericite-chlorite phyllites, carbonate bearing metasilstones with dolomite and quartz lenses (Dardenne, 2000; Monteiro et al., 2006).

There is controversy surrounding the age of the Vazante Group. The first issues stems from the age of the stromatolites, *Conophyton*, which represents a large time interval of 1.35 – 0.95 Ga. This broad age may indicate a possible stratigraphic correlation between the Vazante Group and the Paranoá Group (Cloud and Dardenne, 1973; Dardenne et al., 1979; Dardenne, 2000). Geochronological dating on sediments using $^{207}\text{Pb}/^{206}\text{Pb}$, K/Ar, and Rb/Sr methods indicate a metamorphic closing age of 750–570 Ma, giving the Vazante Group an age close to that of the ‘younger’ Bambuí Group sediments, which lie to the east (Amaral, 1968; Iyer et al, 1992;. Monteiro, 2002). In fact, Dardenne (2000) has suggested that the diamictites of the Retiro Formation may correspond to the diamictites in the Jequitai Formation of the Bamuí Group. $^{207}\text{Pb}/^{206}\text{Pb}$ dating using galenas found in the Vazante and Morro Agudo mines by Freitas-Silva and Dardenne (1997) and Dardenne (2000) suggest an age range of 1200 Ma to 650 Ma, the latter date being representative of the closing date of metamorphism in the region. Using Sm–Nd isotope dating, Pimentel et al. (2001) places the T_{DM} of the Vazante group around 2200 – 1800 Ma., an age that is representative of the basement source rocks from the São Francisco Craton. Rodrigues (2008) and Rodrigues et al. (2010) conducted U–Pb and $^{207}\text{Pb}/^{206}\text{Pb}$ analyses that provided an age range of 1350 – 630 Ma, with the latter date representing the Brasiliano Orogeny. In addition, Rodrigues (2008) and Rodrigues et al. (2010) obtained Sm–Nd ages for the basal Retiro Formation of 935 ± 14 Ma, which is younger than the rest of the overlying formations in the Vazante Group. However, it should be noted that no dates were obtained for the Serra do Poço Verde Formation, the host of the Vazante Northern Extension zinc silicate deposit.

Formation	Member	Description	Mineral Deposits
Lapa	Serra da Lapa Velosinho	Black carbonaceous slate with dolomite lenses ¹	
Morro do Calcário	Upper Pamplona	Massive, dark gray dolarenite with stromatolites and minor black phyllites. Basal unit is dark, maroon siltstones ²	Morro Agudo, Fagundes, Ambrósia Pb-Zn sulfide deposits
Serra do Poço Verde	Middle Pamplona	Massive pink to gray dolostone with algal mats and stromatolites ^{1,2}	
	Lower Pamplona	Pink dolostone intercalated with maroon and green phyllites. Contains the hydrothermal breccia and pervasive hematite and ferroan dolomite alteration veinlets ²	Vazante–Northern Extension Zn silicate deposit
	Upper Morro do Pinheiro	Dark gray dolostone with bird's eyes and algal mats with thin layers of black phyllite near the base ²	
	Lower Morro do Pinheiro	Light gray to pink dolostone with local intraformational breccias ¹	
Serra do Garrote		Dark grey phyllite, weathers to red and green. Contains localized zones of pyrite and calcite veins ²	
Lagamar	Sumidouro	Gray limestone and dolostone with stromatolitic bioherm ¹	
	Arrependido	Basal dolomitic breccia ¹	
Rocinha		Rhythmites interbedded with phosphorite bearing slates ¹	Rocinha, Lagamar phosphorite deposits
Reteiro/ St. Antônio do Bonito		Quartzite and diamictite with phyllitic intercalations Basal conglomerate ¹	Coromandel phosphorite deposit

Fig. 2.2 Stratigraphy of the Vazante Group and the mineral deposits hosted in its units (modified from ¹Dardenne, 2000; ²this study).

The Bambuí Group consists of Neoproterozoic sediments on the eastern edge of the Brasília Fold Belt and in the São Francisco Basin. The Bambuí Group sits unconformably on the granite-gneiss basement rocks of the São Francisco Craton as well as on the metasedimentary rocks of the Araí and Paranoá Groups. It comprises 6 formations, which are from the bottom to the top: Jequitaiá, Sete Lagoas, Serra da Santa Helena, Lagoa do Jacaré, Serra da Saudade, and Três Marias (Dardenne, 2000). The basal Jequitaiá Formation is composed of diamictite beds containing limestone clasts, representing glacial episodes. The Sete Lagoas Formation consists of pelitic carbonates that grade into dolomites at the top of the formation. Above the Jequitaiá Formation sits the carbonaceous pelites of the Serra da Santa Helena Formation. Sitting conformably on the Serra da Santa Helena Formation is the Lagoa do Jacaré Formation, which is composed of dark gray platform limestones. Next in the sequence are the sandy pelites that compose the Serra da Saudade Formation. The top of the Bambuí Group is made up of the Três Marias Formation, which is composed of arkoses and siltstones (Dardenne, 2000).

The age of detrital zircons found in the Bambuí Group sediments has a bimodal distribution, according to Rodrigues (2008) and Rodrigues et al. (2010). The Jequitaiá Formation has detrital zircons that represent an age of about 900 Ma; however, the Sete Lagoas Formation contains zircons as young as 610 Ma. The latter age correlates to the 650 – 600 Ma age range based on K/Ar and Rb/Sr isotope dating (Thomaz Filho et al., 1998).

The relationship between the Vazante and Bambuí Groups is not well constrained due to the overlap in detrital zircon, and other isotopic system data (1200 – 630 Ma). As previously mentioned, the passive margin sediments of the Vazante Group were thrust on top of the cratonic sediments of the Bambuí Group (Dardenne, 2000; Pimentel et al., 2001). It has been hypothesized that the Vazante sediments represent a slice of the Bambuí Group that has been thrust up atop itself and is therefore, not a separate stratigraphic group (Misi et al., 2007). Due to the tectonic complexity of the Brasília Fold Belt as well as the correlative issues between

northern and southern sedimentary packages in the BFB, this theory is not unwarranted. Chemostratigraphic investigation based on $^{87}\text{Sr}/^{86}\text{Sr}$ isotopes conducted by Misi et al. (2007) suggests a correlation between the carbonates of the Vazante and Bambuí groups. This interpretation differs from Azmy et al. (2001), who reported lower $^{87}\text{Sr}/^{86}\text{Sr}$ values indicating that the Vazante Group was, in fact, older than the Bambuí Group. Furthermore, Carbon isotope studies conducted by Misi et al. (2007) found that the $\delta^{13}\text{C}$ values for Vazante carbonates were substantially lower (+3.3 ‰ compared to +9 – 16‰) than the Bambuí carbonates. However, without ages for the Serra do Poço Verde Formation, the primary carbonate unit within the Vazante Group, the relationship between the two groups will remain uncertain and under scrutiny.

2.2 Mineral Deposits Hosted in the Vazante Group

2.2.1 Phosphate Deposits

Two phosphate mines are hosted in the Vazante Group: the Rocinha and Lagamar deposits. The Rocinha phosphate mine is located near Patos do Minas, Minas Gerais, and is hosted in the carbonate and pyrite-bearing slates of the Rocinha Formation. The phosphate ore occurs as fine phosphatic laminations and phospharenites containing phosphate pellets and intraclasts (Dardenne, 2000). The phosphate is apatite according to Da Rocha Araujo et al. (1992), and the reserves are estimated to be 400 Mt at 12 % P_2O_5 (Dardenne, 2000).

The Lagamar phosphate deposit is found in the rhythmic quartzite and siltstone sedimentary units of the upper Rocinha Formation. The deposit is almost entirely composed of phospharenite and the reserves are estimated at 5 Mt at 25% P_2O_5 (Dardenne, 2000).

A third phosphate mineralization exists in the Retiro Formation at the base of the Vazante group by the town Coromandel, from which its name is derived; however, this mineralization is currently uneconomic and poorly defined with respect to tonnage and grade (Dardenne, 2000).

2.2.2 Zinc and Lead sulfide deposits

2.2.2.1 Fagundes Zinc Deposit

The Fagundes zinc sulfide deposit is a carbonate-hosted, epigenetic lead-zinc deposit. It is currently uneconomic and therefore, poorly delineated with respect to tonnage and grade. The Fagundes deposit is hosted in the Upper Pamplona Member of the Morro do Calcário Formation about 30 km North of Paracatú, Minas Gerais (Fig. 2.2 and Fig. 2.3). In this region, the Upper Pamplona comprises dolostone with bacterial mats and stromatolite columns with localized areas containing dolrudites composed of Upper Pamplona intraclasts. The depositional environment is interpreted as a fore and back reef facies (Monteiro, 2002 and Monteiro et al., 2006). The dolostones are silicified prior to mineralization. Mineralization is stratabound and composed of pyrite, sphalerite, and late galena. The pyrite and sphalerite are found in banded, colloform, and zoned crystal habits. The galena occurs in veins and veinlets associated with pyrite and, to a lesser extent, galena. Fluid sources are interpreted as hydrothermal in origin with salinities of 5 – 22 eq. wt % NaCl and homogenization temperatures of 122 – 144 °C (Monteiro 2002, Monteiro et al., 2006, 2007; Cunha et al., 2007).

2.2.2.2 Ambrósia Zinc Deposit

The Ambrósia sulfide zinc deposit is also an uneconomic, carbonate-hosted, epigenetic lead-zinc deposit; however, unlike the Fagundes deposit, the Ambrósia deposit is controlled by a reverse fault that strikes 30° and dips 60-80° SE and has been displaced by a N20E-trending transverse-normal fault (Monteiro, 2002; Monteiro et al., 2007; Cunha et al., 2007). The mineralization is hosted in brecciated dolostones of the Upper Pamplona member of the Morro do Calcário Formation and is located 20 km Northeast of Paracatú, Minas Gerais. The deposit is uneconomic so the ore body morphology, tonnage, and grade are poorly defined. In the Ambrósia district, the

Fig. 2.3 Map of the southeastern Brasília Fold Belt with the locations of the Zn-Pb deposits in the Vazante Group (modified from Votorantim, in prep.)

Upper Pamplona is tectonically imbricated with the shales, phyllites, and dolostones of the Lower Pamplona Member of the Serra do Poço Verde Formation.

The host rocks are silicified and contain ankerite alteration (Monteiro, 2002; Monteiro et al., 2006, 2007). The mineralization is composed of pyrite, marcasite, sphalerite, galena, and coarse-grained dolomite. Veins, veinlets, and fracture fillings host the mineralization. The ore fluid salinities at Ambrósia range from 5 – 15 eq. wt % NaCl, and the homogenization temperatures range from 120 – 265°C (Monteiro, 2002; Monteiro et al., 2006, 2007; Cunha et al., 2007).

2.2.2.3 Morro Agudo Lead-Zinc Mine

The Morro Agudo lead-zinc mine has reserves at 5 Mt of 6.3% Zn and 2.9% Pb (Cunha et al., 2007). This deposit has been categorized as a MVT deposit by Rigobello et al. (1988) and Iyer et al. (1992); a SEDEX by Misi et al. (1996) as well as Freitas-Silva and Dardenne (1997); and an Irish-type by Dardenne and Freitas-Silva (1999) Cunha et al. (2000), Dardenne (2000), Misi et al. (2000), and Monteiro (2002).

The Morro Agudo mine is hosted by dolarenitic breccias the Upper Pamplona member of the Morro do Calcário Formation. The mineralization is bounded by a normal fault, interpreted as a syn-sedimentary feeder zone and conduit for ore fluids that strikes N10-20W and dips 75° S. The mineralization is both disseminated and massive along the fault zone and consists of sphalerite, galena, and pyrite associated with quartz and barite (Dardenne and Freitas-Silva, 1999; Misi et al., 2005; Cunha et al., 2007; Monteiro et al., 2007).

The Morro Agudo mineralization is divided into four ore zones: the N, M, JKL, and GHI, which are stratigraphically constrained to the Upper Pamplona Member of the Morro do Calcário Formation (Dardenne and Freitas-Silva, 1999; Misi et al., 2005; Cunha et al., 2007). The N orebody consists of fine-grained, alternating galena, sphalerite, pyrite, and chert beds. The

M orebody is irregularly shaped and composed of coarse-grained galena and sphalerite (Misi et al., 2005; Cunha et al., 2007). The JKL orebody is made up of massive fine to coarse-grained sphalerite that cements oolitic dolostone beds (Misi et al., 2005). The GHI orebody consists mainly of coarse-grained sphalerite and galena that cements angular breccia clasts, some of which are derived from the N orebody (Cunha et al., 2007).

Fluid inclusion studies conducted by Cunha et al. (2007) in sphalerite crystals show ore fluid salinities ranging from 4 – 22 eq. Wt % NaCl, and homogenization temperatures ranging from 122 – 283 °C.

2.2.3 Zn Silicate deposits

2.2.3.1 Vazante Zinc Silicate Mine

The Vazante Mine zinc silicate mineralization is hosted in a hydrothermal shear breccia found near the contact between the Lower Pamplona and Upper Morro do Pinheiro members of the Serra do Poço Verde Formation (Figs. 2.2, 2.3, and 2.4). Metamorphosed dikes are tectonically imbricated with the carbonates and hydrothermal breccias (Rigobello et al., 1988; Monteiro, et al., 1999, 2006, 2007; Cunha et al., 2007). Mineralization within the breccia is found along the Vazante fault zone that strikes N50E and dips 60-70° NW (Rigobello et al., 1988; Dardenne and Freitas-Silva, 1999; Monteiro et al., 1999; Dardenne, 2000; Monteiro et al., 2006, 2007). The fault is interpreted as a syn-sedimentary growth fault with multiple reactivations during the Brasiliano Orogeny. It began as a reverse, transcurrent fault during compression and later evolved into a normal, sinistral fault at the end of the orogenic event (Pinho, 1990; Monteiro, 1999; Dardenne, 2000). The shear zone in the Vazante Mine displays both brittle and ductile deformation, represented by brecciation and S-C foliation found within the shear zone, respectively (Monteiro et al., 1999).

Fig. 2.4 Geological NW-SE cross-section of Vazante Mine showing the mineralized zone [(1) gray dolostone; (2) sericite phyllite; slate and metamarl; (3) pink dolostone; (4) light gray dolostone, quartz sericite phyllite, (5) metabasite; (6–8) Upper Morro do Pinheiro Member: (6) dark-gray dolostone; (7) pyrite-bearing black phyllite; (8) pyrite-rich metamarl; (9) nonsulfide zinc ore; (10) hydraulic breccias; (11) limit of the Vazante Shear Zone] (from Monteiro et al., 2007).

Willemite is the main zinc ore in the Vazante mine. It occurs as pods, veinlets, and meter-wide veins within the hydrothermal breccia and is locally controlled by antithetic faults in the deposit (Monteiro et al., 1999; Dardenne, 2000; Hitzman et al., 2003; Monteiro et al., 2006, 2007). The willemite ore extends along strike for nearly 3 km and ranges in depth from the surface to over 400 m in the underground mine (Rigobello et al., 1988; (Votorantim, pers. commun., 2010).

According to Monteiro et al. (1999), small sulfide bodies consisting of Fe-poor sphalerite with minor galena are tectonically imbricated with the willemite orebodies, metabasites, and dolostones. In addition to the willemite and sulfides, franklinite, smithsonite, zincite, hematite, barite, and quartz are also found. The

relationship between willemite and sphalerite is not well understood at Vazante. Monteiro et al. (1999) and Hitzman et al. (2003) suggested coeval precipitation of willemite and sphalerite.

However, Appold and Monteiro (2009) suggest that willemite formed after sphalerite. Willemite typically occurs as radiating or prismatic crystals and displays green cathode luminescence (CL) (Monteiro et al., 2006, 2007). The willemite composition, according to EMP studies conducted by Monteiro et al. (2006), contains minor amounts of FeO (up to 0.3 wt %) and CaO (up to 0.13 %), although the calcium could be related to contamination from the carbonate host rocks. The

paragenetic sequence for the mineralization at the Vazante Mine was first described in detail by Monteiro et al. (1999) and is summarized in Figure 2.5.

The hydrothermal alteration within the Vazante district is largely controlled by the structures relating to brecciation. Siderite, ankerite, quartz and hematite are common alteration minerals found in veins and filling spaces between breccia clasts. Rare gahnite also occurs in some veinlets close to the ore mineralization (Monteiro et al., 1999). Alteration to the surrounding host rocks includes a color change from gray to pink dolostones caused by pervasive hematite alteration. Silicification of dolostone is also common (Monteiro et al., 1999; Dardenne, 2000; Monteiro et al., 2006, 2007).

Fig. 2.5 Paragenetic sequence for the mineralization in the Vazante Mine (from Monteiro et al., 2006)

Fluid inclusion studies conducted on the willemite at Vazante by Dardenne and Freitas-Silva (1999) reveal salinities of 3 – 15 eq. Wt. % NaCl and homogenization temperatures ranging

from 65 – 180 °C. Sphalerite fluid inclusion studies conducted by Cunha et al. (2007) show salinities around 15 – 23 eq. Wt. % NaCl and homogenization temperatures ranging from 201 – 232 °C.

Sulfur isotopes are limited in Vazante due to the lack of sulfur minerals within the deposit; however, Misi et al. (2005) were able to obtain sulfur isotope data from sphalerite and galena found at the Vazante mine. The isotopic ratios range from +11.8 ‰ to 16.4 ‰ which indicated that the sulfur that was sourced from seawater.

The genetic model for Vazante, like many hypogene nonsulfide zinc deposits, is not well understood nor is it complete. Given the prevalence of hematite and

willemite, the ore fluids would have to ultimately be constrained to an oxidizing

environment. Monteiro et al. (2007) first proposed that an oxygen-enriched, hot, sulfur deficient metalliferous fluid would have mixed with oxygen-depleted, cool, meteoric waters within the Vazante shear zone (Figure 5). Appold and Monteiro (2009) explained the controls on willemite deposition by fluid mixing models. Table 2 below summarizes the mechanisms proposed by Appold and Monteiro (2009) to explain the precipitation of willemite and/or sphalerite under specific conditions.

Fig. 2.6 Genetic mixing model for the Vazante Mine where a metalliferous fluid is focused through the Vazante Shear Zone and mixes with meteoric water from the surface (from Monteiro et al., 2007).

<i>Factor</i>	<i>Willemite (Wl)</i>	<i>Sphalerite (Sp)</i>
Temperature (<i>T</i>)	Precipitation not affected	As <i>T</i> decreases, Sp precipitates
pH	More sensitive to pH than Sp, as pH increases, Wl precipitates	Less sensitive to pH than Wl, as pH increases, Sp will precipitate but to a lesser extent than Wl
Salinity	A decrease in salinity precipitates Wl and Sp (favors neither)	A decrease in salinity precipitates Wl and Sp (favors neither)
Log <i>f</i> O ₂	No effect	As Log <i>f</i> O ₂ increases, sulfides converted to sulfates

Table 2.2 Summary of the factors controlling willemite and sphalerite precipitation from a fluid (Summarized from Brugger et al. (2003) and Appold and Monteiro (2009). Wl = willemite, Sp = sphalerite

Based on the factors outlined in Table 2, Appold and Monteiro (2009) interpreted the possible ore fluid as being a hot, saline, reducing, acidic, metalliferous fluid that mixed with cooler, oxidizing meteoric water. The ore would then have precipitated as a result of an increase in pH and possibly a small decrease in temperature (Brugger et al., 2003; Appold and Monteiro, 2009).

Recent work was conducted by Lemos (2011) in the Vazante Northern Extension zone. The main focus was to characterize willemite ore in order to assist in optimizing ore processing. Willemite samples from the field and drill core were crushed, categorized based on iron content, and analyzed for trace elements. Lemos (2011) found that the ore breccia containing high iron also contained higher chromium values and lower zinc values, indicating that iron and chromium were substituting for zinc. It was also found that there were no discernible differences in trace elements between iron-rich willemite breccia and iron-poor willemite breccia; however, the Northern Extension ore was determined to be depleted in the elements Ag, Cd, Ge, and Pb when compared with the main Vazante orebody. This was interpreted to be due to the smaller content in sulfide in the North Extension ore (Lemos, 2011).

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Chapter 3

Geology, Mineralogy, and Geochemistry of the Vazante Northern Extension Zinc Silicate Deposit, Minas Gerais, Brazil

3.1 Introduction

The increase in global population and in their standards of living is expected to foster the consumption of metals and in particular zinc, which has main applications ranging from galvanized alloys to fertilizer (USGS, 2011). Since the early 20th century, zinc has been mainly produced from sulfide ores of sedimentary-exhalative (SEDEX), Mississippi Valley-type (MVT), and volcanogenic massive sulfide (VMS) deposits due to development of the flotation and smelting techniques (Boni and Large, 2003). However, the potential for producing zinc from high-grade nonsulfide deposits at lower costs using hydrometallurgical techniques has renewed interest in nonsulfide zinc deposits around the world. These nonsulfide zinc deposits comprise two major subtypes: supergene and hypogene (Hitzman et al., 2003). Supergene deposits are formed by the oxidation of both zinc oxide and zinc sulfide deposits and they are typically hosted in carbonate rocks. The most common zinc nonsulfide minerals in supergene deposits are: smithsonite (ZnCO_3), hemimorphite ($\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot 2\text{H}_2\text{O}$), hydrozincite ($\text{Zn}_5(\text{OH})_6(\text{CO}_3)_2$), and sauconite ($\text{NaO} \cdot 3(\text{Zn},\text{Mg})_3(\text{Si},\text{Al})_4 \cdot (\text{OH})_2 n\text{H}_2\text{O}$) (Hitzman et al., 2003). Hypogene deposits, from now on referred to as hypogene zinc silicate deposits, are hydrothermal and not necessary derived from a pre-existing sulfide body. They comprise two categories based on their ore controls: structurally-controlled and stratiform deposits. Hypogene zinc minerals include the main ore, willemite (Zn_2SiO_4), franklinite (ZnFe_2O_4), and zincite (ZnO) (Hitzman et al., 2003). Structurally controlled deposits, such as the Beltana-Aroona willemite deposits and the Vazante Northern Extension deposits are hosted within brecciated carbonate rocks (Rigobello et al, 1988;

Monteiro et al., 1999; Dardenne, 2000; Dardenne and Schobbenhaus, 2001; Groves et al., 2003; Monteiro et al., 2006; 2007).

The Vazante Northern Extension trend is one of the largest hypogene zinc silicate deposits with estimated reserves of 18 Mt at 19% Zn in the main Vazante Mine and additional reserves of 850 Kt of ore at 16% Zn in its Northern Extension (Votorantim, pers. commun., 2011). It is located in the southern region of the Brasília Fold Belt near the town of Vazante, Minas Gerais, Brazil. Production in the area started with artisanal mining since the 1950's when the area was mined for the secondary "calamine" (hemimorphite and smithsonite) zinc ore. In the Northern Extension, it has been estimated that around 8 Mt of calamine ore were mined (Votorantim, pers. commun., 2011). In 1969 and in 1983, open pit and underground mining commenced, respectively (Monteiro et al., 1999), mining mainly the hypogene ore.

The Vazante deposit has been studied by Rigobello et al. (1988); Dardenne and Freitas-Silva (1999); Dardenne (2000); Monteiro (et al., 1999, 2006, 2007); Misi et al. (2005); Cunha et al. (2007) and Rostirolla et al. (2007). Rigobello et al. (1988) and Dardenne (2000) first described the stratigraphy and host rocks as well as the structural setting of the Vazante Mine and their tectonic setting. Rostirolla et al. (2007) conducted regional studies in order to establish a metamorphic history of the Vazante region, and identified 5 major structural events in Vazante. Monteiro (et al., 1999, 2006, 2007) studied the mineralization, alteration, and stable isotopes in the Vazante Mine and the nature of the mineralizing hydrothermal fluids. They suggested that the Vazante mineralization formed by the mixing of an oxygen-enriched, hot, sulfur deficient metalliferous fluid with oxygen-depleted, cool, meteoric water. Dardenne and Freitas-Silva (1999) also investigated the fluids associated with mineralization and concluded that the fluids had salinities of 3 – 15 Wt % eq. NaCl and homogenization temperatures ranging from 65 – 180 °C. Lead isotope investigations by Dardenne and Freitas-Silva (1999), Misi et al. (2005), and Cunha et al. (2007) revealed that the ages of the galenas to range from 1.8 Ga to 1.2 Ga,

interpreted the lead sources are probably from the São Francisco Craton and the Goiás Massif, and suggested that the lead from Vazante deposit was from the same sources as other lead-zinc sulfide deposits in the Vazante Group. However, major questions remain related to the processes by which these mineralized zones formed, whether they are associated with a major mineralizing event or represent various events of fluid-rock interaction and mineralization, and whether the processes that formed the main Vazante mine orebodies are similar to those that formed the Northern Extension. This study is focused on the characterization of the geology, mineralogy, and geochemistry of the Northern Extension of the Vazante Mine in order to further understanding of this style of mineralization.

3.2 Regional Geology

The Brasília Fold Belt is roughly 1000 km long and is part of the Tocantins Province, which is composed of three fold belts: the Araguaia Belt to the east of the Amazonia Craton, the Paraguay Belt on the southeastern margin of the Amazonia Craton, and the Brasília Fold Belt along the western edge of the São Francisco craton (Fig. 3.1; Almeida et al., 1981; Pimentel et al., 2001; Valeriano et al., 2008; Rodrigues et al., 2010). The Paraguay and Araguaia fold belts are thrust towards the Amazonia Craton to the west; however, the central Brasília Fold Belt is thrust to the east onto the São Francisco Craton (Valeriano et al., 2008).

The Brasília Fold Belt was created through a series of tectonic events starting with continental rifting of the São Francisco Craton *c.a.* 1700Ma and ending with the Brasiliano Orogeny (Misi et. al, 2005; Martins-Neto, 2009). The continental rift system evolved into a passive margin setting along the western edge of the São Francisco Craton, allowing for the deposition of intracratonic siliciclastic sediments and platform carbonates represented primarily by the Canastra–Paranoá–Vazante groups at around 1200-900 Ma (Valeriano et al., 2008; Martins-Neto, 2009). The latter is the host of the Vazante zinc silicate deposit.

Fig. 3.1 A) Geological map of Brazil with the location of the Tocantins Province. B) Map of the southeastern part of the Brasília Fold Belt, highlighting the major units and mineral deposits in the region.

Subduction of oceanic crust from the Brazilide Ocean beneath the São Francisco Craton began around 900 Ma, causing magmatism that would lead to the formation of the Goiás magmatic arc (Dardenne, 2000; Valeriano et al., 2008; Martins-Neto, 2009). Continuing subduction lead to the convergence of the Goiás magmatic arc and the São Francisco Craton around 850 – 750 Ma, the start of the Brasiliano orogeny. During this collision, the passive margin sediments were thrust as thin-skinned nappes onto the São Francisco Craton (Dardenne, 2000; Valeriano et al., 2008, Martins-Neto, 2009), and reached its metamorphic peak around 650 Ma (Martins-Neto, 2009). Dardenne (2000) also notes geochemical and isotopic evidence of a late Brasiliano collisional event *c.a.* 630 – 610 Ma, interpreting it as the latest stage of the convergence of the Goiás magmatic arc with the São Francisco Craton.

The southern region of the Brasília Fold Belt, which comprises the Vazante, Canastra, Araxá, and Ibiá groups, was metamorphosed up to the greenschist facies and generally displays more intense tectonic deformation than the northern region. The Vazante, Canastra, Araxá, and Ibiá groups form a complex system of nappes that are thrust onto the Bambuí Group sediments to the east (Dardenne, 2000). The Canastra, Vazante, and Bambuí groups are the most prominent sedimentary units in the Vazante region.

The Canastra Group is considered to be the southern Brasília Fold Belt equivalent sedimentary group to the Paranoá Group located in the northern BFB (Dardenne, 1978, 2000). The age of the Canastra Group is estimated to be between 1200 – 900 Ma based on stromatolites (Dardenne, 2000), and Pimentel et al. (2001) proposed an age of about 1000 Ma based on Sm-Nd dating. It is composed primarily of phyllites and quartzites that have been metamorphosed up to the greenschist facies. The Canastra Group sits unconformably below the Ibiá Group and is tectonically thrust on top of the Vazante Group (Dardenne, 2000). It comprises three formations from the bottom to the top: the Serra do Landim, Paracatú, and Chapada dos Pilões. The Serra do Landim Formation makes up the lowest section of the Canastra Group according to Freitas-

Silva and Dardenne (1994); however, Madalosso and Valle (1978) have described the Serra do Landim as being the uppermost formation of the Vazante Group. The Serra do Landim is a pale green to grey-green calc-phyllite to calc-schist (Freitas-Silva and Dardenne, 1994; Dardenne, 2000). The Paracatú Formation is composed of grey carbonaceous phyllite with quartzite lenses (Almeida, 1969; Freitas-Silva and Dardenne, 1994; Dardenne, 2000) and hosts the Morro do Ouro gold mine located in Paracatú, Minas Gerais (Dardenne, 2000). The Chapada dos Pilões Formation lies on top of the Paracatú Formation, and it is made up of intercalated phyllites and quartzites, which have been interpreted as rhythmites and turbidites (Dardenne, 2000).

The Vazante Group is located in the northwest region of Minas Gerais, and it stretches for nearly 250 km N-S. It is primarily composed of intercalated phyllites and platform carbonates that have undergone metamorphism up to the greenschist facies. The Vazante Group lies tectonically below the Canastra Group and is thrust onto the top of the younger Bambuí Group (Dardenne, 2000; Pimentel et al., 2001; Monteiro et al., 2007). The age of the Vazante Group is controversial and poorly constrained due to the absence of igneous rocks and well constrained detrital zircon dating.

The Vazante Group (Fig. 3.2) is divided into 7 formations, which are from the bottom to the top: Retiro (also referred to as Santo Antônio do Bonito Formation; Cunha et al., 2007; Misi et al., 2007), Rocinha, Lagamar, Serra do Garrote, Serra do Poço Verde, Morro do Calcario, and Serra da Lapa (Dardenne, 2000). The Retiro formation consists of quartzite, conglomerate, diamictite (i.e., debris flows from glacio-marine environments), and slate (Dardenne, 2000; Cunha et al., 2007). It is host to the Coromandel phosphorite mineralization (Dardenne, 2000). The Retiro Formation grades upwards into the Rocinha Formation, which consists of pelite, siltstone rhythmites as well as phosphatic layers that host the Rocinha and Lagamar phosphorite deposits (Dardenne, 2000; Cunha et al., 2007). The top of the Rocinha Formation is a thick sequence of slate and metasiltstone that grades into carbonaceous and pyrite-bearing slate (Dardenne, 2000;

Pimentel et al., 2001). These pyrite-bearing slates contain phosphorites and are host to the Rocinha phosphate deposit. The upper part of the formation contains both quartzites and siltstones that host the Lagamar phosphate deposit (Dardenne, 2000). Above the Rocinha Formation is the Lagamar Formation which is a metapsamo-pelitic unit with a basal metaconglomerate. Overlaying these clastic units are dolomitic breccias, dark gray limestones, and light pink stromatolitic bioherms with columnar *Conophyton* and *Jacutophyton* stromatolites (Dardenne, 2000; Monteiro et al. 2006; Cunha et al., 2007). Above the Lagamar Formation is the Serra do Garrote Formation, which is made up of dark gray to green-gray phyllites with localized pyritic zones (Dardenne, 2000; Cunha et al. 2007; this study).

Sitting atop the Serra do Garrote Formation is the Serra do Poço Verde Formation, which hosts the Vazante zinc silicate mineralization. The Serra do Poço Verde Formation (Fig. 3.2) can further be subdivided into four members from the bottom to the top: Lower Morro do Pinheiro, Upper Morro do Pinheiro, Lower Pamplona, and Middle Pamplona (Dardenne, 2000). The Lower Morro do Pinheiro member consists of light grey and pink dolomite with stromatolites intercalated with oncolitic dolarenites and intraformational dolomite breccias and hosts the Vazante deposit. The Upper Morro do Pinheiro Member is a dark grey dolomite with bird's eyes and minor carbonaceous phyllites. The Lower Pamplona Member consists of grey to pink laminated dolomites intercalated with green and maroon phyllites. The Middle Pamplona Member consists of light grey to pink dolomite with algal laminations and dolarenites with stromatolites (Dardenne, 2000; this study).

The Morro do Calcário Formation, also known as the Upper Pamplona Member according to Rigobello et al. (1988), rests on the top of the Serra do Poço Verde Formation, and is comprised of carbonaceous shale, dolarenites, breccias, and stromatolitic bioherm facies (Dardenne, 2000; this study). It hosts of the Morro Agudo Pb-Zn Mine (Dardenne, 2000), Fagundes zinc sulfide deposit, and Ambrósia zinc sulfide deposit (Monteiro et. al., 2006).

Fig. 3.2 Stratigraphy the Vazante region including the Northern Extension (modified from ¹Dardenne, 2000; ²this study)

The upper most formation in the Vazante Group is the Lapa Formation, which sits unconformably on top of the Morro do Calcário formation. It is composed of black, carbonaceous rhythmites with intercalated slates and phyllites, sericite-chlorite phyllites, carbonate-bearing metasilstones with dolomite and quartz lenses (Dardenne, 2000; Monteiro et al., 2006).

3.3 Geology of the Vazante Mine

The Vazante Mine (Fig. 3.3) zinc silicate mineralization is hosted in a hydrothermal shear breccia found near the contact between the Lower Pamplona and Upper Morro do Pinheiro members of the Serra do Poço Verde Formation. Metamorphosed dikes are tectonically imbricated with the carbonates and hydrothermal breccias (Rigobello et al., 1988; Monteiro et al., 1999, 2006, 2007; Cunha et al., 2007). Mineralization within the breccia is found along a fault that strikes 230 and dips 60-70° NW (Rigobello et al., 1988; Dardenne and Fritas-Silva, 1999; Monteiro et al., 1999; Dardenne, 2000; Monteiro, et al., 2006, 2007). The fault is interpreted as an early syn-sedimentary growth fault that underwent multiple reactivations during the Brasiliano Orogeny, including reverse, transcurrent fault during compression that later evolved into a normal, sinistral fault at the end of the orogenic event (Pinho, 1990; Monteiro, 1999; Dardenne, 2000). The shear zone in the Vazante Mine displays features typical of both brittle and ductile deformation, represented by brecciation and S-C foliation, respectively (Monteiro et al., 1999). The Vazante ore body is nearly 5 km long and variably 10s of meters thick, extending over 400 m below surface (Votorantim, pers. commun., 2010).

Fig. 3.3 Aerial photographs showing the location of the Vazante Mine and Northern Extension deposit, MG, Brazil. (Photo provided by Votorantim Metals)

The hydrothermal alteration within the Vazante district is largely controlled by the structures related to brecciation. Siderite, ankerite, quartz and hematite are common alteration minerals found in veins and filling spaces between breccia clasts. Rare gahnite also occurs in some veinlets proximal to the ore (Monteiro et al., 1999). Alteration in the surrounding host rocks of the breccia includes a color change from gray to pink dolostones caused by hematite alteration and silicification of dolostone (Monteiro et al., 1999; Dardenne, 2000; Monteiro et al., 2006; 2007).

Willemite (Zn_2SiO_4) is the main zinc ore in the Vazante mine. It occurs as pods, veinlets, and meter-wide veins within the tectonic-hydrothermal breccia and is controlled by antithetic

faults in the deposit (Monteiro et al., 1999; Dardenne, 2000; Hitzman et al., 2003; Monteiro et al., 2006; 2007). According to Monteiro et al. (1999), small sulfide bodies consisting of Fe-poor sphalerite with minor galena are tectonically imbricated with the willemite, metabasites, and dolostones. The main willemite ore rarely contains sulfide mineralization, but is commonly associated with specular hematite, which is the most abundant mineral associated with the ore; franklinite, smithsonite, zincite, barite, and quartz occur in minor amounts in the ore zone (Monteiro et al., 1999; 2007).

Fluid inclusion studies conducted on the willemite at Vazante by Dardenne and Freitas-Silva (1999) revealed salinities of 3 – 15 Wt % eq. NaCl and homogenization temperatures of 65 – 180 °C. Sphalerite fluid inclusion studies conducted by Cunha et al. (2007) show salinities around 15 – 23 Wt % eq. NaCl and homogenization temperatures ranging from 201 – 232 °C. Sulfur isotopic investigation is limited in Vazante due to the lack of sulfide minerals within the deposit; however, few isotopic data reported by Misi et al. (2005) yield values ranging from +11.8 ‰ to 16.4 ‰. These results were interpreted to represent sulfur that was sourced from seawater.

Appold and Monteiro (2009) proposed the formation of the Vazante deposit as being the result of mixing between a hot, saline, reducing, acidic, metalliferous fluid and cooler, oxidizing, meteoric water. The ore would then have precipitated out as a result of an increase in pH and possibly a small decrease in temperature (Brugger et al., 2003; Appold and Monteiro, 2009).

3.4 The Northern Extension

3.4.1 Geologic Units

The Northern Extension mineralization is hosted by the Vazante Shear Zone that cuts through (Figs. 3.3, 3.4, 3.5 & 3.6) the Serra do Poço Verde and Morro do Calcário formations of the Vazante Group, and this structure is truncated by the tectonic contact with the phyllites from

Fig. 3.4 Geological map of Cavas 5A, 6A, and 7A in the northernmost section of the Northern Extension (modified from Votorantim base map; this study)

Fig. 3.5 Topographic map of the Vazante Northern Extension region with locations of re-logged and sampled drillholes. “BX” is short for “breccia” and “Cava” is Portuguese for “pit” (modified from Votorantim base map; this study).

Serra do Garrote Formation. Each of these formations has been metamorphosed to sub-greenschist facies, though metamorphic assemblages are most noticeable in the Serra do Garrote Formation.

In the proximity of the zinc mineralized zones, the Serra do Garrote Formation (Fig. 3.7A) comprises a sedimentary marine sequence of laminated dark gray to black phyllites with

local zones containing chlorite alteration, pyrite boudins, and calcite. It is commonly exposed in topographic highs in the Vazante region, and it is intensely deformed by folding and faulting with the dominant folding phase (D₂) striking north-south and having associated crenulations (S₂) overprinting the S₁ foliation. The Serra do Garrote has a sharp tectonic contact with the overlying Serra do Poço Verde Formation.

Fig. 3.6 Block diagram of the Northern Extension depicting the morphology of the tectonic-hydrothermal breccia in addition to the dip and thickness of local stratigraphic units.

The four members of the Serra Poço Verde Formation were identified in the field during mapping and drill core logging: the Lower Morro do Pinheiro, Upper Morro do Pinheiro (Fig. 3.7B), Lower Pamplona (Fig. 3.7C), and Middle Pamplona (Fig. 3.7D). The Lower Morro do Pinheiro Member was not observed in the field and is

projected to the surface from the interpretation of drill logs. In drill

cores, the unit is gray to dark gray with algal layering and brecciated lenses (Fig. 3.7B). The contact between the Lower Morro do Pinheiro and underlying Serra do Garrote was not observed at depth. The Upper Morro do Pinheiro Member is composed of dark gray dolomite with bird's eyes and some algal mat layering. A few meters of fine-grained black phyllites were also observed. According to Warren (2006), these lithofacies indicate subtidal to intertidal facies. The Upper Morro do Pinheiro member typically has silica filled tension fractures and silica

selvage alteration, and occasionally dolomitic overgrowths with some veins containing pyrite and bitumen. The Upper Morro do Pinheiro is usually denoted by the presence of bird's eye structures and has gradational contact with the Lower Pamplona Member.

The Lower Pamplona Member constitutes intercalated green to maroon phyllites and pink to light gray dolomites, primarily dolarenites with some dolrudites (Fig 3.7C). These rocks suggest an intertidal to supratidal facies (Warren, 2006). The Lower Pamplona dolostone is generally identifiable in the field, as it forms well indurate outcrops that weather to beige or an orange brown color. Iron carbonate veinlets and silica-filled vugs are common throughout the dolostones in the Lower Pamplona. The phyllites exhibit recognizable North-South trending parasitic folds and crenulations, similar to those found in the Serra do Garrote Formation. In thin section, small amounts of chalcocite and trace covellite mineralization were observed in the maroon laminations from samples 043-191 and M124-297. Iron carbonate and hematite veins and veinlets are common in all rock types of the Lower Pamplona.

The Middle Pamplona Member is comprised of a massive pink and gray dolomite with moderate silica alteration in the form of veins and chalcedony-filled vugs very similar to Lower Pamplona dolomites; however, the carbonate rocks are not interbedded with phyllites and contain some algal mat layering as well as stromatolites, indicative of a subtidal environment (Warren, 2006). Collapse breccias filled with carbonates and sulfides (Fig. 3.7D) are also present and are described in the subsequent section.

The Upper Pamplona member of the Morro do Calcário Formation (Fig. 3.7E) is composed of light gray dolarenite with stromatolitic bioherms. The contact between the Morro do Calcário Formation and the Middle Pamplona Member is characterized by a dark, reddish-gray silty marker bed, which has been described by Votorantim staff to be observed in core throughout the Northern Extension region.

Fig. 3.7 Drill core samples of the geological units in the Northern Extension. A) Black phyllites with pyrite veinlets typical of the Serra do Garrote Fm. B) Upper Morro do Pinheiro Member with dark grey dolostone and bird's eyes C) Lower Pamplona Member with green and maroon phyllites interbedded with pink dolostone that contains hematite alteration veinlets D) Massive pink and gray dolostone of the Middle Pamplona Member with some collapse breccias filled with white ferroan dolomite and sphalerite. E) Massive gray dolostone (with minor black phyllites) of the Upper Pamplona Member of Morro do Calcário Formation (Photos B–E courtesy of Votorantim). Bird's Eyes=small, oval filling texture, MVT=Mississippi Valley-type, Hm=hematite.

3.4.2 Structures

The carbonate and clastic units in the Northern Extension are deformed during D_1 and exhibit an S_1 cleavage that is subparallel to bedding (S_0). These S_0/S_1 surfaces are openly folded in the

Fig. 3.8 Photograph looking to the Northeast showing the plunging antiform-synform complex in the northern wall of Cava 7A in the Serra do Garrote Fm. (Photo taken by G. Olivo)

carbonate units and formed open to tight folds in the less competent phyllite units of the Serra do Garrote (Fig. 3.8, 9A) during D_2 deformation. The fold axes have a trend and plunge of approximately $210 \rightarrow 30$ SE.

This second deformational event (D_2) generated a crenulation cleavage (S_2) that strikes SSW ranging from 200 to 225° with dips of 30 to 70 NW. S_2 is

predominantly observed in the phyllites of the Serra do Garrote exposed in Cava 7A (Fig. 3.9 A & B) and was not observed in the carbonate units in the Northern Extension.

Fig. 3.9 S_0 compositional layering with S_1 cleavage and S_2 crenulations found in phyllitic units in the Lower Pamplona Member (A) and Serra do Garrote Formation (B). (Photo A taken by P. Slezak. Photo B taken by G. Olivo)

The Northern Extension Fault Zone is controlled by two conjectural oblique dip-slip faults having strikes and dips of 210, 30° NW and 030, 55° SE. The overall trend of the ore-bearing breccia zone is bounded by these faults (Fig 4). They are observed at surface for about 600 m and are covered by lateritic soils in the southern limit of the North Zone property and truncated in the North at the tectonic contact of Serra do Pamplona Formation with Serra do Garrote Formation (Fig. 3.4). These faults appear to have been active for an extensive period of time and show evidence of multiple motions as indicated by several sets of slicken lines as well as brecciation of multiple willemite ore phases; the latter is described in the subsequent section. Regionally, these sets of NNE faults are interpreted to be formed by reactivation during the Brasiliano Orogeny of normal faults created by extension during the initial rifting of the São Francisco Craton (Valeriano et al., 2008; Martins-Neto, 2009). As they have a complex evolution, various models were proposed to interpret their geometry and movement. Valeriano et al. (2008) and Martins-Neto (2009) proposed that they were reactivated as oblique reverse faults during compression caused by the Brasiliano Orogeny. However, Rostirolla et al. (2002) interpreted them as being transverse, sinistral faults and Rigobello et al. (1988) and Dardenne (2000) reported them as both sinistral and normal faults. Slickensides (Fig. 3.10) observed in this study indicate that the latest movement is normal.

Fig. 3.10 Riedel shears with slickensides indicating the normal fault motion in the ore breccia. (Photo taken and edited by P. Slezak)

The ore-bearing tectonic-hydrothermal breccias hosted in the fault zone do not cross-cut the folded (D_2) contact with the Serra do Garrote Formation (Fig. 3.4), suggesting that they were emplaced prior to or during early D_2 deformation. Moreover, the breccia trend is subparallel to axial planes that contain the β -axis ($212 \rightarrow 11$) related to the D_2 folding event (Fig. 3.11A & B), supporting then the interpretation that the breccia formed in the early stages of the D_2 folding event.

Late sinistral and dextral transverse faults (with strikes ranging from 065 to 170 dipping 30 - 70° SW/SE; Fig. 3.11B) cut and displaced by several meters the major fault structures bounding the tectonic-hydrothermal breccia as well as the contact with Serra do Garrote and the large anticline found in the northern pit wall of Cava 7A (Fig 3.8). The secondary (supergene) calamine ore was mainly controlled by and can be found in these faults. Small NW-SE trending joints were also observed cutting the bounding faults of the tectonic-hydrothermal breccia as well as the transverse faults.

Fig. 3.11 A) Plots of the poles of S_0/S_1 compositional layering/foliation in black, S_2 crenulation cleavage in red, trend and plunges of major fold axes in green, and the average fold axis denoted by the β and plane of 212 , 79 NW. The circled red squares represent S_2 cleavages from a fault block, indicating that they may be out of place. B) Plots of the poles of the conjugate fault planes bounding the tectonic-hydrothermal breccia are outlined in blues, purples, and pinks (from lowest to highest concentration of points). In black are fault

plane poles to the later E-W transverse faults. In red solid lines is the average strike of the tectonic-hydrothermal breccia with its ranges in dip.

3.4.3 The Tectonic-hydrothermal breccias and ore zones

The Northern Extension ore zone is comprised mainly of willemite (in variable amount reaching up to 40 %) and specular hematite (varying from 1% to 50 %) with minor amounts of franklinite. These ore zones form discontinuous lenses (tens of meters in length and width) within laterally and vertically discontinuous tectonic-hydrothermal breccias, which vary greatly in thickness from a few meters to nearly 100 m (Fig. 3.6). The tectonic-hydrothermal breccia lenses within the shear zone gently plunges to the south. This structural zone has been reactivated during the evolution of the deposit and may have served as the main conduit for the hydrothermal fluids, as it hosts a variety of hydrothermal breccias types. Four main types of breccias were identified based on their overall composition and relative position to the ore lenses. Type 1 Breccia is the least altered and the most distal from the ore breccias (referred to as Type 4 Breccia). Breccia Types 2 and 3 occur between breccias 1 and 4. All of the breccias are composed mainly of gray, pink, red, and white dolostone fragments and minor phyllite fragments from the Lower Pamplona Member. Many of the clasts are rimmed by recrystallized red and/or white dolomite. The cement between clasts is composed of various proportions of dolomite, ferroan dolomite, zincian dolomite, quartz, and hematite, depending on the breccias type.

Type 1 Breccia: Weakly to moderately brecciated light gray to white dolostone units with red ferroan dolomite alteration veinlets (Figs. 3.12 and 3.13A). These breccias are commonly located between the unbrecciated host rocks and the intensively ferroan dolomite altered breccias (Type 2) and is interpreted to be formed during the initial phases of brecciation. Dolomites from veins and veinlets have 1.29 wt. % FeO and 0.13 wt. % ZnO (Fig. 3.12; Table 3.1A); the latter being lower than carbonate in the breccias proximal to the ore. The red

hydrothermal dolomites typically contain hematite inclusions; although high iron contents were observed in white hydrothermal dolomites as well.

Fig. 3.5 A) Backscattered Electronic Image (BSEI) from sample 141– 61. A) Ferroan dolomite growths in carbonate alteration veinlets from sample. The dark zones shows areas of higher iron content. (BSEI is 250 µm in diameter). B) Ferroan dolomite with hematite inclusions in dolomite alteration veinlets. The lighter zones are more iron-rich. (BSEI is 600 µm in diameter). Dol = Dolomite. Hm = Hematite.

Type 2 Breccia: Strongly altered dolostone units with substantial amounts of reddish orange to white ferroan (1.5 to 3.3 wt. % FeO) and zincian dolomite (0.3 to 1.25 % ZnO) veinlets (3mm to 2cm wide) and red dolomite alteration selvages (Fig. 3.13B; Table 3.1A). Sparry, zoned euhedral dolomite occurs in the center of the veins and hematite is found mainly on the vein margins or as small inclusions within the red dolomite. These breccias are generally proximal to the mineralized Type 4 (willemite) and Type 3 (hematite) breccias and overprint features observed in the Type 1 Breccia.

Type 3 Breccia (hematite-rich breccias): Deep red breccia composed predominantly of hematite with trace willemite (Fig. 3.13C). These breccias are commonly found in the margins of the main ore (Type 4) breccia or as isolated breccia zones (1-3 m wide) in the tectonic-hydrothermal breccias. Hematite occurs replacing carbonates from the cement and clasts and in

veinlets cross-cutting the first two breccia types, which indicates that these hematite-rich breccias formed after the major Fe–dolomite hydrothermal episode.

Type 4 Breccia (willemite ore breccia): The ore breccias are commonly found in the core of the tectonic-hydrothermal breccia structure, where the early hydrothermal breccias have been replaced by willemite (>10% to up to 50%) as well as some hematite (5 – 20%) and minor franklinite (Fig. 3.13D). The presence of hematite is not necessarily ubiquitous throughout the willemite ore zones. Willemite and hematite minerals are associated with ferroan (~1.99 wt % FeO) and zincian (~2.65 wt% ZnO) dolomite (Table 3.1A) and minor quartz alteration and are locally cut by small sulfide veinlets.

Fig. 3.6 Photographs of drill cores illustrating the various types of breccias. A) Type 1 – Light-colored, weakly brecciated dolostone with ferroan and zincian-dolomite veinlets. B) Type 2 – Strong hydrothermal ferroan and zincian-dolomite alteration in dolostone. C) Type 3 – Breccia replaced by hematite (>40% Fe). B) Type4 –Main ore breccia replaced by willemite and hematite. (Photos taken from drill hole MASA 124, courtesy of Votorantim Metals)

Willemite (0.1 to 0.75 mm) occurs as hexagonal crystal masses (Fig. 3.14A) filling in the breccia, lath-shaped crystals (Fig. 3.14B), and small, discontinuous veins that cut across many clasts in the breccia zone (Fig. 3.14C). It commonly replaces carbonates as well as quartz clasts and crystals. The lath-shaped willemite overgrows the earliest, hexagonal willemite. The small (100–200 μm wide), discontinuous willemite veins cut through both the fibrous laths and the hexagonal willemite, indicating that they formed during the last stages of mineralization. The willemite composition varies little throughout all three generations described above. Its average FeO content is 0.4 wt. %, however, various grains from generations 1 and 2 yielded about 1 wt. % FeO due to Fe contamination from hematite inclusions. Some grains contain trace amounts of chromium and rare manganese as seen in Table 3.1B.

Hematite (0.01 to 1 mm) commonly occurs as either aggregates of fine-grained blades filling in between clasts (Fig. 3.14F), or disseminated, larger crystals replacing willemite, carbonates, and quartz. Euhedral laths are also found included in willemite and in the margins of late sulfide veins.

Franklinite is most commonly found as small octahedral inclusions associated with hematite (Fig. 3.14E) in willemite-rich domains; however, it is also be found included in willemite and carbonate, as very small (1 to 10 μm) disseminated crystals in the breccia matrix and associated with hematite in the margins of the sulfide veinlets.

Small, 10 – 50 mm, galena-rich veinlets cross-cut the main willemite ore (Type 4 Breccia) and contain small amounts of sphalerite, stromeyerite ($\text{Cu}_{1-x}\text{Ag}_{1-x}\text{S}$), chalcocite (Cu_2S), and covellite (CuS) (Fig. 3.15A–C). Galena is massive within the veinlets and is altered to anglesite (PbSO_4) on the veinlet margins (Fig. 3.15A & B). Sphalerite in the Type 4 Breccia (Table 3.1C) is Cd – rich (2.88 – 3.10 wt %) and iron – poor (0.01 – 0.02 wt %), similar to the sphalerite reported by Monteiro et al. (2006) in the Vazante Mine, and is found as irregular, semi-

massive crystals within the galena. The stromeyerite forms irregular, disseminated crystals, generally alters to bladed covellite, and rarely to chalcocite (Fig. 3.15C).

Silver-bearing sulfide veinlets (10-100 mm wide) were found to cross-cut the willemite ore in one drill hole. These silver-bearing sulfide veinlets are similar in morphology to galena veinlets described above. The veinlets are primarily composed of chalcocite, native silver, stromeyerite, franklinite, hematite, and minor galena. Barite (BaSO_4) and phosphohedyphane ($\text{Ca}_2\text{Pb}_3(\text{PO}_4)_3\text{Cl}$) occur in small amounts as disseminated anhedral to subhedral crystals ranging in size from 20 – 50 μm . In back-scattered electronic images (BSEI), chalcocite shows a complex texture of light and dark gray zoning (Fig. 3.15D), with the lighter gray sections containing silver (1.1 – 1.5 % Ag) and the darker gray sections containing trace amounts or no silver.

One drill hole, VZMIF 088 (Fig. 3.5), intersected a 5 to 7 m- wide brecciated zone which contains sphalerite, pyrite, dolomite, quartz and bitumen, and are cut by galena veinlets with trace covellite (Fig. 3.15 E & F), similar to the sulfide veinlets that cut the Type 4 Breccia. This zone exhibits various stages of open filling and brecciation. Dolomite and coarse-grained pyrite grains are deformed and the fractures are filled with late quartz, carbonate and sphalerite. Unlike the cadmium-rich sphalerite found in the sulfide veinlets cross-cutting the willemite ore Breccia Type 4, the sphalerite in this zone contains minor cadmium (0.2 wt % Cd) and more iron (0.2 wt % Fe).

Furthermore, sphalerite veinlets cut collapse breccias in the Middle and Upper Pamplona members (VZMIF 141 at 16 m and MASA 124 at 97 m). Sphalerite contains little cadmium (0.2 wt. % Cd; Table 3.1) and higher iron (~ 1 wt. % Fe; Table 3.1C)), has inclusions of pyrite and is associated with sparry, euhedral ferroan dolomite (1 – 2 wt % FeO; Table 3.1C). It exhibits textural features similar to Mississippi Valley-type deposits; however their paragenetic relationships could not be established with respect to the other Northern Extension mineralizing events.

Table 3.1 EMP analyses conducted on core samples of dolomite, willemite, and sphalerite in the Northern Extension.**A)** Dolomite analysis, recalculated to % oxide

Comment	Description	CO₂	MgO	CaO	SiO₂	MnO	FeO	ZnO	SrO	BaO	Total
124-75-018	type 4 breccia	46.46	20.10	30.51	0.02	0.11	0.51	1.91	0.00	0.39	100.00
124-75-019	type 4 breccia	45.55	16.94	33.02	0.02	0.06	1.83	2.55	0.00	0.00	99.96
124-75-020	type 4 breccia	46.75	19.49	29.54	0.08	0.10	1.07	2.62	0.05	0.31	100.00
60-136B-033	type 4 breccia	46.54	19.64	29.62	0.00	0.27	1.68	2.15	0.00	0.00	99.89
60-136B-034	type 4 breccia	47.09	18.87	29.16	0.00	0.10	2.01	2.71	0.02	0.00	99.95
60-136B-035	type 4 breccia	47.18	19.76	29.25	0.00	0.08	1.44	1.91	0.07	0.31	100.00
60-136B-036	type 4 breccia	47.15	19.42	29.19	0.00	0.16	2.10	1.82	0.02	0.00	99.87
127-108.5-028	type 4 breccia	46.96	18.11	28.41	0.04	0.18	2.21	4.02	0.02	0.00	99.95
127-108.5-029	type 4 breccia	45.49	18.57	27.89	0.20	0.18	5.24	2.37	0.05	0.00	99.98
127-108.5-030	type 4 breccia	46.78	18.37	28.34	0.01	0.09	1.86	4.44	0.05	0.00	99.93
127-108.5-031	type 4 breccia	48.14	19.90	27.61	0.50	0.13	1.57	1.97	0.09	0.10	100.00
127-108.5-032	type 4 breccia	46.01	18.88	28.50	0.38	0.10	2.39	3.36	0.10	0.28	100.00
141-16-09	alteration vein	46.92	20.62	30.24	0.00	0.08	1.91	0.21	0.00	0.00	99.98
141-16-010	alteration vein in MP	46.37	21.14	30.55	0.53	0.08	0.93	0.11	0.01	0.29	100.00
141-16-011	alteration vein in MP	46.50	20.29	30.59	0.01	0.27	2.18	0.01	0.05	0.00	99.91
141-16-012	alteration vein in MP	45.74	20.78	30.08	2.27	0.08	0.80	0.15	0.00	0.07	99.97
141-16-013	alteration vein in MP	47.22	21.38	30.20	0.00	0.08	1.04	0.00	0.00	0.00	99.92
141-16-016	alteration vein in MP	46.62	21.04	31.01	0.04	0.07	1.01	0.02	0.00	0.00	99.80
141-16-017	alteration vein in MP	46.71	20.67	30.34	0.09	0.06	1.24	0.76	0.01	0.14	100.00
141-16-018	alteration vein in MP	47.15	20.05	30.12	0.03	0.07	1.89	0.63	0.06	0.00	100.00

Comment	Description	CO₂	MgO	CaO	SiO₂	MnO	FeO	ZnO	SrO	BaO	Total
141-16-020	alteration vein in MP	44.73	20.28	29.71	4.04	0.06	0.97	0.07	0.00	0.00	99.86
141-16-021	alteration vein in MP	46.44	19.88	30.10	0.02	0.06	2.15	1.25	0.05	0.00	99.95
141-16-022	alteration vein in MP	46.09	20.46	30.42	0.00	0.08	2.22	0.70	0.00	0.00	99.96
141-16-023	alteration vein in MP	46.53	20.34	30.34	0.00	0.08	1.76	0.70	0.00	0.24	99.98
141-16-024	alteration vein in MP	46.42	21.31	30.08	1.28	0.05	0.50	0.10	0.00	0.21	99.96
141-16-025	alteration vein in MP	46.67	21.29	31.16	0.13	0.08	0.47	0.09	0.00	0.02	99.92
141-16-026	alteration vein in MP	46.33	21.45	31.35	0.00	0.06	0.54	0.13	0.00	0.05	99.92
141-16-027	alteration vein in MP	46.76	20.76	30.35	0.03	0.18	1.50	0.04	0.00	0.26	99.87
141-16-028	alteration vein in MP	46.69	21.62	31.55	0.01	0.08	0.00	0.00	0.00	0.00	99.94
141-16-029	alteration vein in MP	46.43	20.39	30.28	0.00	0.19	2.32	0.00	0.02	0.36	99.99
141-16-030	alteration vein in MP	47.17	20.47	30.42	0.01	0.16	1.58	0.12	0.00	0.00	99.93
141-16-031	alteration vein in MP	47.00	20.67	31.54	0.00	0.19	0.43	0.06	0.03	0.10	100.00
141-16-032	alteration vein in MP	46.86	20.82	30.57	0.00	0.10	1.25	0.05	0.04	0.00	99.69
141-61-01	veinlet in MP	46.90	21.37	30.31	0.00	0.11	1.03	0.04	0.02	0.00	99.79
141-61-02	veinlet in MP	46.54	21.52	31.04	0.00	0.03	0.56	0.00	0.02	0.00	99.71
141-61-03	veinlet in MP	47.57	20.87	30.20	0.00	0.10	1.04	0.11	0.01	0.00	99.91
141-61-04	veinlet in MP	47.16	21.19	30.77	0.00	0.08	0.72	0.00	0.00	0.02	99.94
141-61-05	veinlet in MP	47.28	21.45	30.54	0.01	0.05	0.54	0.00	0.02	0.00	99.89
141-61-06	veinlet in MP	46.54	21.56	30.80	0.01	0.04	0.50	0.00	0.06	0.00	99.50
141-61-07	veinlet in MP	46.58	21.67	31.01	0.00	0.05	0.48	0.03	0.00	0.12	99.93
141-61-08	veinlet in MP	46.50	20.99	30.88	0.00	0.14	1.23	0.05	0.02	0.19	99.99
141-61-09	veinlet in MP	46.91	21.55	30.95	0.00	0.16	0.18	0.06	0.00	0.10	99.91
141-61-014	veinlet in MP	46.28	20.94	30.82	0.00	0.17	1.61	0.04	0.05	0.00	99.90
141-61-015	veinlet in MP	46.54	20.94	30.54	0.00	0.18	1.72	0.03	0.04	0.00	100.00

Comment	Description	CO₂	MgO	CaO	SiO₂	MnO	FeO	ZnO	SrO	BaO	Total
141-61-016	veinlet in MP	46.29	21.61	31.28	0.00	0.18	0.44	0.02	0.00	0.00	99.80
141-61-017	veinlet in MP	41.50	23.70	34.13	0.01	0.17	0.18	0.08	0.06	0.17	100.00
141-61-018	veinlet in MP	46.68	21.37	31.09	0.00	0.20	0.60	0.01	0.04	0.00	99.99
141-61-019	veinlet in MP	46.28	20.82	31.06	0.04	0.21	1.50	0.04	0.00	0.00	99.95
141-61-020	veinlet in MP	46.04	20.50	30.74	0.00	0.28	1.93	0.02	0.00	0.40	99.92
20-295-01	type 2 breccia	46.97	19.30	30.15	0.00	0.12	3.31	0.10	0.01	0.02	99.99
20-295-02	type 2 breccia	46.79	19.17	30.24	0.00	0.16	3.25	0.15	0.11	0.12	99.98
20-295-03	type 2 breccia	46.52	19.32	30.59	0.00	0.14	3.21	0.06	0.04	0.12	99.99
20-295-04	type 2 breccia	47.25	20.91	30.64	0.00	0.18	0.79	0.14	0.00	0.00	99.89
20-295-05	type 2 breccia	43.53	22.94	33.23	0.01	0.02	0.13	0.05	0.00	0.05	99.95
20-295-06	type 2 breccia	46.94	21.62	30.72	0.00	0.05	0.18	0.24	0.05	0.19	99.99
20-295-07	type 2 breccia	47.80	20.91	29.99	0.00	0.16	1.02	0.05	0.00	0.05	99.97
20-295-08	type 2 breccia	47.04	21.32	30.29	0.01	0.09	0.91	0.16	0.04	0.14	100.00
20-295-09	type 2 breccia	47.43	20.97	30.27	0.00	0.09	1.17	0.00	0.04	0.02	99.99
20-295-010	type 2 breccia	47.21	20.98	30.66	0.00	0.12	0.45	0.52	0.00	0.02	99.96
20-295-013	type 2 breccia	47.56	20.58	30.54	0.00	0.05	0.88	0.34	0.04	0.00	99.99
20-295-014	type 2 breccia	46.98	20.81	30.67	0.01	0.06	0.96	0.44	0.00	0.05	99.97
20-295-015	type 2 breccia	46.53	20.70	31.38	0.00	0.06	0.75	0.44	0.02	0.00	99.88
20-295-016	type 2 breccia	46.86	21.34	31.33	0.02	0.07	0.27	0.01	0.02	0.07	100.00
20-295-017	type 2 breccia	47.05	21.42	31.14	0.01	0.05	0.11	0.08	0.00	0.12	99.96
141-18-01	veinlet in MP	46.31	20.71	30.68	0.00	0.15	1.97	0.00	0.04	0.00	99.85
141-18-02	veinlet in MP	46.71	21.29	30.89	0.00	0.14	0.74	0.02	0.00	0.00	99.78
141-18-03	veinlet in MP	45.93	20.04	30.77	0.00	0.06	2.91	0.00	0.00	0.00	99.71

Comment	Description	CO₂	MgO	CaO	SiO₂	MnO	FeO	ZnO	SrO	BaO	Total
141-18-04	veinlet in MP	46.42	20.51	30.71	0.01	0.04	2.09	0.12	0.03	0.07	100.00
141-18-05	veinlet in MP	46.48	20.61	30.60	0.00	0.04	2.00	0.07	0.01	0.19	99.99
141-18-06	veinlet in MP	45.92	19.76	30.49	0.01	0.06	3.58	0.04	0.00	0.14	100.00
141-18-07	veinlet in MP	45.53	20.16	30.93	0.01	0.01	3.10	0.01	0.02	0.24	100.00
141-18-08	veinlet in MP	46.40	21.39	31.01	0.03	0.16	0.87	0.06	0.00	0.07	99.99

Table 3.1 B) Willemite – all willemite samples were taken from the Type 4 Breccia;

Gen. = Generation

Comment	Description	SiO₂	ZnO	Cr₂O₃	MnO	FeO	Total
101-138-03	Gen. 1	27.51	71.04	0.05	0.00	0.18	98.78
101-138-04	Gen. 1	27.17	72.41	0.03	0.01	0.11	99.72
101-138-05	Gen. 1	27.40	72.89	0.02	0.00	0.16	100.47
101-138-06	Gen. 1	27.63	72.39	0.00	0.00	0.18	100.19
101-138-07	Gen. 1	27.27	72.41	0.01	0.00	0.14	99.83
101-138-08	Gen. 1	27.35	72.67	0.00	0.00	0.56	100.59
101-138-09	Gen. 1	27.44	72.31	0.00	0.04	0.45	100.24
101-138-10	Gen. 1	26.93	72.26	0.03	0.00	0.68	99.90
101-138-11	Gen. 1	27.18	72.75	0.03	0.00	0.49	100.44
124-75-01	Gen. 1	27.34	73.05	0.00	0.00	0.20	100.60
124-75-02	Gen. 1	27.26	72.93	0.01	0.00	0.02	100.22
124-75-03	Gen. 1	27.43	72.86	0.00	0.00	0.26	100.54
124-75-05	Gen. 1	27.28	72.21	0.00	0.00	0.11	99.60
124-75-06	Gen. 1	27.45	72.79	0.00	0.01	0.13	100.37
124-75-07	Gen. 1	27.45	73.00	0.00	0.00	0.08	100.53
124-75-08	Gen. 1	27.28	73.67	0.00	0.00	0.16	101.11
124-75-09	Gen. 1	27.39	72.76	0.00	0.00	0.07	100.23
124-75-010	Gen. 1	27.51	72.77	0.04	0.00	0.13	100.45
124-75-011	Gen. 1	27.50	72.54	0.01	0.01	0.25	100.30
124-75-012	Gen. 1	27.01	71.54	0.00	0.02	0.13	98.69
124-75-013	Gen. 1	27.25	71.83	0.02	0.00	0.15	99.24
124-75-014	Gen. 1	27.48	72.48	0.00	0.00	0.11	100.07
124-75-015	Gen. 1	27.12	71.81	0.00	0.00	0.09	99.01
124-75-016	Gen. 1	27.50	72.61	0.00	0.00	0.10	100.22
124-75-017	Gen. 1	27.62	72.71	0.00	0.00	0.07	100.39
127-108.5-022	Gen. 1	27.17	70.48	0.00	0.00	1.55	99.20
127-108.5-023	Gen. 1	27.16	71.73	0.00	0.00	1.63	100.52
127-108.5-024	Gen. 1	27.22	71.43	0.02	0.00	2.17	100.83
127-108.5-025	Gen. 1	27.25	71.30	0.00	0.00	1.15	99.70
127-108.5-026	Gen. 1	27.39	71.03	0.00	0.00	1.54	99.96
127-108.5-027	Gen. 1	27.29	72.00	0.03	0.00	1.20	100.52
101-138-01	Gen. 2	27.10	71.17	0.00	0.00	0.23	98.51
101-138-02	Gen. 2	27.27	71.67	0.00	0.00	0.16	99.09
60-136B-01	Gen. 2	27.37	72.48	0.00	0.00	0.35	100.20
60-136B-02	Gen. 2	27.45	72.37	0.00	0.00	0.30	100.13
60-136B-03	Gen. 2	27.26	72.18	0.00	0.00	0.39	99.83

Comment	Description	SiO₂	ZnO	Cr₂O₃	MnO	FeO	Total
60-136B-04	Gen. 2	27.46	72.49	0.00	0.00	0.40	100.36
60-136B-05	Gen. 2	27.30	72.01	0.00	0.00	0.37	99.68
60-136B-06	Gen. 2	27.31	72.53	0.02	0.00	0.26	100.12
60-136B-07	Gen. 2	27.40	72.60	0.00	0.00	0.18	100.19
60-136B-08	Gen. 2	27.37	73.21	0.00	0.00	0.15	100.73
60-136B-09	Gen. 3	27.46	73.16	0.00	0.05	0.13	100.80
60-136B-10	Gen. 3	27.30	72.95	0.00	0.00	0.21	100.46
60-136B-11	Gen. 3	27.29	72.64	0.00	0.00	0.19	100.11
60-136B-12	Gen. 2	27.44	73.04	0.01	0.00	0.19	100.67
60-136B-13	Gen. 2	27.43	73.19	0.00	0.00	0.22	100.84
60-136B-14	Gen. 2	27.55	72.98	0.00	0.00	0.20	100.73
60-136B-15	Gen. 2	27.60	72.73	0.01	0.00	0.21	100.55
60-136B-16	Gen. 2	27.30	72.47	0.00	0.00	0.25	100.02
60-136B-17	Gen. 2	27.17	72.42	0.00	0.00	0.59	100.18
60-136B-18	Gen. 2	27.54	72.52	0.00	0.00	0.31	100.37
60-136B-19	Gen. 2	27.51	72.58	0.00	0.00	0.27	100.35
60-136B-20	Gen. 2	27.49	72.20	0.01	0.00	0.28	99.97
60-136B-21	Gen. 2	27.44	72.03	0.03	0.00	0.16	99.66
60-136B-22	Gen. 2	27.23	71.64	0.00	0.00	0.18	99.06
60-136B-23	Gen. 2	27.20	71.75	0.02	0.00	0.21	99.18
60-136B-24	Gen. 2	27.24	71.29	0.01	0.00	0.13	98.66
60-136B-25	Gen. 2	27.15	71.23	0.04	0.00	0.19	98.61
60-136B-26	Gen. 2	27.24	71.99	0.00	0.00	0.15	99.38
60-136B-27	Gen. 2	27.36	72.66	0.00	0.00	0.29	100.31
60-136B-28	Gen. 2	27.35	72.84	0.00	0.00	0.29	100.47
60-136B-29	Gen. 2	27.55	71.99	0.02	0.00	1.25	100.81
60-136B-30	Gen. 2	27.13	72.39	0.03	0.00	0.97	100.51
60-136B-31	Gen. 2	27.26	72.81	0.01	0.00	0.66	100.73
60-136B-32	Gen. 2	27.30	73.17	0.00	0.00	0.08	100.55
60-136B-33	Gen. 2	27.32	73.02	0.01	0.00	0.43	100.78
60-136A-011	Gen. 2	27.17	71.83	0.02	0.00	0.73	99.76
60-136A-012	Gen. 2	27.30	71.68	0.00	0.00	0.59	99.57
60-136A-013	Gen. 2	27.21	72.58	0.02	0.00	0.50	100.31
127-108.5-01	Gen. 3	27.22	72.96	0.00	0.00	0.34	100.53
127-108.5-03	Gen. 3	27.10	72.37	0.00	0.00	0.33	99.80
127-108.5-04	Gen. 3	27.23	72.66	0.00	0.00	0.31	100.20
127-108.5-05	Gen. 3	27.50	72.71	0.00	0.00	0.18	100.39
127-108.5-06	Gen. 3	27.27	72.42	0.00	0.00	0.22	99.91
127-108.5-07	Gen. 3	27.32	72.74	0.00	0.00	0.33	100.38

Comment	Description	SiO₂	ZnO	Cr₂O₃	MnO	FeO	Total
127-108.5-08	Gen. 3	26.98	72.45	0.02	0.00	0.31	99.75
127-108.5-09	Gen. 3	27.35	72.54	0.00	0.00	0.30	100.18
127-108.5-010	Gen. 3	27.10	72.76	0.01	0.00	0.08	99.95
127-108.5-011	Gen. 3	27.45	72.43	0.00	0.00	0.41	100.29
127-108.5-012	Gen. 3	27.21	72.15	0.00	0.00	0.41	99.77
127-108.5-013	Gen. 3	27.45	72.56	0.00	0.00	0.40	100.41
127-108.5-014	Gen. 3	27.22	72.64	0.00	0.04	0.36	100.26
127-108.5-015	Gen. 3	27.31	72.72	0.00	0.01	0.30	100.34
127-108.5-016	Gen. 3	27.51	72.12	0.00	0.00	0.36	99.99
127-108.5-017	Gen. 3	27.42	72.92	0.01	0.00	0.59	100.94
127-108.5-018	Gen. 3	27.42	72.77	0.01	0.01	0.33	100.54
127-108.5-019	Gen. 3	27.43	72.48	0.00	0.00	0.35	100.26
127-108.5-020	Gen. 3	27.22	72.30	0.02	0.00	0.33	99.87
127-108.5-021	Gen. 3	27.16	71.92	0.00	0.00	0.66	99.73

Table 3.1 C) Sphalerite analysis

Comment	Description	S	Zn	Mn	Fe	Cd	Total
60-136A-01	type 4 breccia	32.42	63.37	0.00	0.02	3.04	98.85
60-136A-02	type 4 breccia	32.44	63.59	0.00	0.02	2.91	98.95
60-136A-03	type 4 breccia	32.28	63.36	0.00	0.05	2.88	98.56
60-136A-04	type 4 breccia	32.23	63.22	0.00	0.03	3.01	98.49
60-136A-05	type 4 breccia	32.55	62.16	0.00	0.02	2.91	97.64
60-136A-06	type 4 breccia	32.19	63.59	0.00	0.01	3.01	98.80
60-136A-07	type 4 breccia	32.51	63.00	0.00	0.02	2.88	98.41
60-136A-08	type 4 breccia	32.44	63.36	0.00	0.00	3.09	98.89
60-136A-09	type 4 breccia	32.41	62.82	0.00	0.03	2.93	98.19
60-136A-010	type 4 breccia	32.39	63.00	0.00	0.07	3.10	98.55
88-68-01	sulfide breccia	32.92	66.87	0.00	0.22	0.24	100.25
88-68-02	sulfide breccia	32.89	67.26	0.00	0.23	0.22	100.59
88-68-03	sulfide breccia	32.86	66.98	0.00	0.24	0.24	100.32
88-68-04	sulfide breccia	33.07	67.16	0.00	0.21	0.19	100.62
88-68-05	sulfide breccia	32.90	67.13	0.00	0.24	0.21	100.48
88-68-06	sulfide breccia	32.91	67.07	0.00	0.21	0.17	100.36
88-68-07	sulfide breccia	33.04	67.08	0.00	0.25	0.24	100.61
88-68-08	sulfide breccia	32.64	67.49	0.00	0.23	0.21	100.56
88-68-09	sulfide breccia	32.92	67.37	0.00	0.19	0.21	100.69
88-68-010	sulfide breccia	33.02	66.85	0.00	0.19	0.21	100.27
88-68-011	sulfide breccia	33.01	67.24	0.00	0.29	0.16	100.69
88-68-012	sulfide breccia	33.02	67.23	0.00	0.20	0.25	100.70
141-16-02	alteration vein in MP	33.48	66.29	0.00	1.10	0.39	101.26
141-16-03	alteration vein in MP	32.69	66.01	0.00	1.19	0.31	100.19
141-16-04	alteration vein in MP	32.92	66.43	0.00	1.14	0.30	100.79
141-16-05	alteration vein in MP	32.84	66.27	0.00	1.17	0.33	100.62
141-16-06	alteration vein in MP	32.83	66.56	0.00	1.17	0.34	100.90
141-16-07	alteration vein in MP	32.87	66.28	0.00	1.17	0.34	100.66
141-16-08	alteration vein in MP	32.93	66.17	0.00	1.13	0.30	100.54

Fig. 3.14 Photomicrographs showing the minerals and their textural relationships in the Type 4 Breccia. A) Sample 106-122, euhedral, generation 1 willemite in a hematite matrix. Willemite is being replaced by hematite. B) Sample 060-136B, generation 2 willemite as radiating, fibrous crystal laths replacing Fe-Zn rich dolomite breccia fragments. C) Sample 060-136B, fibrous generation 3 willemite veinlets cutting generation 2 willemite. Quartz is being replaced by generation 2 willemite (PPL). D) Sample 060-136B, fibrous generation 3 willemite veinlet cutting generation 2 willemite (XPL). E) Sample 106-122, franklinite associated with generation 2 willemite in reflected light. F) Sample 106-122, hematite cutting Fe-Zn dolomite and filling in open space within the breccia. Wl = Willemite, Frk = Franklinite, Hm = Hematite. Dol = Dolomite. Qtz = Quartz.

Fig. 3.15 Photomicrographs and BSEI showing the sulfide veins and veinlets. A) Sample 060-136A, galena (replaced by anglesite) veinlets cross cutting 2nd generation willemite (XPL). B) Sample 060-136A, galena and anglesite veinlets cross cutting 2nd generation willemite (reflected PPL). Some franklinite crystals are included in the willemite. C) Sample 060-136A, sphalerite-galena veinlets with stromeyerite altering to covellite and chalcocite (reflected PPL). D) Sample 012-347A, Cu-Ag sulfide veinlets with Ag-rich intergrowths in chalcocite (lighter color). Also present willemite, franklinite, and native silver (BSEI). E) Sample 088-71, sphalerite-pyrite mineralization in hole VZMIF 088 where sphalerite is replacing pyrite (reflected PPL). F) Sample 088-72, galena in Pb-Zn sulfide veinlet cutting sphalerite-pyrite mineralization in hole VZMIF 088 (reflected PPL). Py = Pyrite, Sp = Sphalerite, Gn = Galena, Ang = Anglesite, Wl = Willemite, Frk = Franklinite, Srm = Stromeyerite, Cc = Chalcocite. Cv = Covellite, Hm = Hematite, Ag^o = Native Silver.

Based on the field and textural relationships described above, the interpreted paragenesis to the Northern Extension mineralization is presented in Figure 3.16 and summarized below:

Stage 1 (pre-ore): Early brecciation of the Serra do Poço Verde dolostones and precipitation of Fe-bearing dolomite (types 1 and 2 breccias)

Stage 2 (syn-main ore): Formation of the hematite-rich Type 3 Breccia and the willemite-rich Type 4 Breccia with multiple episodes of precipitation of willemite, hematite, franklinite, ferroan and zincian dolomites filling and replacing the previous breccias. The isolated Sp-Py mineralization in VZMIF 088 was hypothesized to be contemporaneous with the willemite ore formation because it was cross-cut by the galena-rich veinlets.

Stage 3: (post- main ore): Subsequent to the main ore stage, two distinct sulfide veinlets (i.e. Pb-rich and Ag-rich veinlets) formed and cross-cut the main ore stage minerals.

As for the isolated sphalerite and pyrite veins, they formed prior to the galena and silver-rich veinlets, but it was not impossible to determine their timing of formation relative to the Type 4 willemite breccia.

3.5 Lithogeochemistry

3.5.1 Analytical Methods

Whole rock geochemical analyses of samples from each unit, alteration and mineralization zones were conducted in order to determine the geochemical signatures related to the various styles of mineralization and alteration as well as the mass change involved in the alteration process. The geochemical analyses were carried out by the ALS Laboratory Group in Canada on 74 samples including the least altered and most representative samples of each of the local geologic units, the non-ore breccias, and the willemite ore samples.

Fig. 3.16 Paragenetic sequence of the mineralized zone in the Northern Extension. Fe-Dol = Ferroan dolomite, Qtz = Qtz, Wl = willemite, Hm = Hematite, Frk = Franklinite, Gn = Galena, Sp = Sphalerite, Py = Pyrite, Srm = Stromeayerite, Cv = Covellite, Ang = Anglesite, Cc = Chalcocite, Ag° = Native Silver, Brt = Barite, Ap = Apatite, Php = Phosphohedyphane, Chl = Chlorite

They were prepared using 4-acid digestion then analyzed for the elements Ag, Al, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cu, Cs, Fe, Ga, Ge, Hf, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, Re, S, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Ti, Tl, U, V, W, Y, Zn, Zr by inductively coupled plasma mass spectrometry (ICP-MS). The element As in addition to samples containing greater than 100 ppm Ag and greater than 10,000 ppm Pb were prepared using 4-acid digestion and analyzed using inductively coupled plasma absorption emission spectrometry (ICP-AES) to eliminate interferences and increase the upper detection limits. Mercury was analyzed by 4-acid digestion with trace vapor/atomic absorption spectrometry (AAS). Samples containing more than 10,000 ppm Zn were analyzed by titration. Standards and duplicates were used by ALS to maintain quality control and quality assurance.

A subset of 39 of those samples were analyzed for whole rock geochemistry using X-ray fluorescence (XRF), and include representative samples of the various alteration styles and of the least altered samples from the host rock types.

Major and trace elements selected from the four types of tectonic-hydrothermal breccias and their host rocks were plotted in box and whiskers diagrams using ioGAS to evaluate their variation among rock types (Fig. 3.17). Furthermore, isocons diagrams (based on Grant, 2000) were constructed to identify and compare the elemental enrichment and depletion of selected elements among the various breccia types and least altered host rocks. The mass balance equation from Grant (2000) is defined by $\Delta M = [(C_A/C_I) - 1] * 100$ where ΔM is the slope, and in this study for the various isocon plots, C_I was considered as the less altered sample and C_A the more altered sample (e.g., least altered dolostone was plotted against Breccia Type 1, and the latter was plotted against Breccia Type 2, etc.). The immobile elements necessary for the isocon line were determined to be Ce, La, Sc, Ti, Y, and Zr based on their high correlation coefficients to each other (> 0.9) as well as their repeated near linear plots in the isocon diagrams.

3.5.2 Results

The results of the whole rock geochemical analyses can be found in Appendix D. The box and whiskers plots for selected elements related to the ore-forming process (Fig. 3.17) show that the variations among the compositions of least altered samples and Type 1 and 2 breccias are minor; however, the Type 3 and 4 breccias show significant variations when compared with the least altered host rock and the Type 1 and 2 breccias. Types 3 and 4 breccias yielded the highest averages in As, Ba, Be, Bi, Fe, Ge, In, Mo, Ni, S, Sb, U, V, and W, with Type 3 being the most enriched in these elements. Breccia Type 4 has significantly higher average concentrations of Zn, Ag, Hg, Se, and SiO₂, and it also contains anomalously high concentrations of Cu and Pb. Types 3 and 4 breccias have the lowest average concentrations of Ca and Mg, which is consistent with the field and petrographic observations that hematite and willemite replace carbonate clasts and carbonate matrix.

Figures 3.18, 3.19, 3. 20 and 3.21 are isocon plots that represent the evolution of element gains and losses when a more altered breccia type is plotted against a less altered sample (e.g. Type 1 vs. Unaltered Lower Pamplona dolostone, Type 3 Breccia vs. Type 4 Breccia). The isocon line is plotted as a line of best fit through the immobile elements Ce, La, Sc, Ti, Y, and Zr. The isocon plot illustrating the unaltered Lower Pamplona dolostone with the Type 1 Breccia (Fig. 3.18) reveals that the latter is significantly enriched in Ag, Cd, Pb, Zn and moderately enriched in Bi, Co, Cu, Fe, In, Mn, Mo, Ni, P, and Sb. When the Type 2 Breccia is compared to the Type 1 Breccia (Fig. 3.19), it is shown that the Type 2 Breccia is enriched in the same suite of elements as the Type 1 Breccia, except for Bi and In, which are aligned on the isocon.

Fig. 3.17 Box and whisker plots showing the variation in composition of the least altered host rocks and various breccia types.

The Type 2 Breccia is also enriched in Ba, V, S, and W. Figure 3.20 compares the Type 3 Breccia composed mainly of hematite with the Type 2 Breccia. This graph shows that the Type 3 Breccia is enriched in the same elements as breccia Type 1 and Type 2, as well as in As, Ga, Ge, Hg, In, Pb, Se, SiO₂, U, and Zn. The Type 3 Breccia is depleted in Ca, K, and Mg compared to the Type 2 Breccia. Figure 3.21, the isocon comparing the Type 3 Breccia with the Type 4 Breccia (willemite ore) shows that the Type 4 Breccia is enriched in Ag, Cd, Cu, Hg, S, Se, SiO₂, Sr, Pb and Zn. Many of the elements previously enriched in the other breccias are aligned along the isocon and show no change or are slightly depleted compared to the Type 3 Breccia.

Fig. 3.18 Isocon plot of Type 1 Breccia vs. unaltered dolostone from the Lower Pamplona Member, showing the gains and losses during the hydrothermal event (see text for further explanation).

Fig. 3.19 Isocon plot of Type 1 Breccia vs. Type 2 Breccia showing the gains and losses during the hydrothermal event (see text for further explanation).

Fig. 3.20 Isocon plot of Type 2 Breccia vs. Type 3 Breccia showing the gains and losses during the hydrothermal event (see text for further explanation).

Fig. 3.21 Isocon plot of Type 3 (hematite) Breccia vs. Type 4 (willemite) Breccia showing the gains and losses during the hydrothermal event (see text for further explanation).

3.6 Discussion

3.6.1 Evolution of the Northern Extension

The evolution of the Vazante Group provided favorable conditions for the formation of a zinc silicate deposit as discussed below. After deposition and dolomitization of the passive margin carbonates in the Serra do Poço Verde Formation *c.a* 900–1200 Ma, tectonism began with the onset of the Brasiliano Orogeny around 850 Ma. Deformation related to the beginning of the Brasiliano Orogeny (D_1) created a regional foliation (S_1) subparallel to bedding (S_0) within the units of the Vazante Group. Continued deformation (D_2) of the region folded the S_0/S_1 foliation, resulting in an S_2 crenulation cleavage, regional folds, and the SE-striking conjugate faults of the Vazante Northern Extension. This event is most likely coeval with the formation of the thin-skinned nappes and low-grade metamorphism as described by Dardenne (2000), Valeriano et al.

(2008), and Martins-Neto (2009). These structures focused the hydrothermal fluid flow, leading to the formation of the hydrothermal breccias and ore mineralization.

The hydrothermal fluids were most likely a metalliferous, low temperature, acidic, relatively saline fluid with low S content (Appold and Monteiro, 2009), in which Zn is transported as ZnCl_4^{2-} and Fe as FeCl_3 according to Riveros and Dutruziac, (1997) and Brugger et al. (2003). These fluids would have moved through the Northern Extension Fault Zone, creating through hydraulic fracturing the Type 1 Breccia, which is characterized by weak brecciation; Fe-dolomite alteration and veinlets; substantial enrichments in Ag, Cd, Pb, Zn; and moderate enrichments in Bi, Co, Cu, Fe, In, Mn, Mo, Ni, P, and Sb. Enduring basinal fluid flow caused further brecciation and alteration, creating the strongly Fe-dolomite altered Type 2 Breccia, which exhibit similar geochemical signature as Type 1 Breccia. After the formation of the Type 2 Breccia, mixing of the basinal brine with a cooler, oxidizing, meteoric fluid in the Northern Extension may have induced further brecciation and mineralization, leading to the formation of the types 3 and 4 breccias, dominated by hypogene hematite and willemite, respectively. This interpretation is based on the fact that the main alteration minerals changed from Fe-bearing carbonate to hematite in Type 3 Breccia, denoting interaction with more oxidizing fluids. These fluids would have also added As, Bi, Ga, Ge, Hg, In, Pb, Se, SiO_2 , U, and Zn, as the Type 3 and 4 breccias are more enriched in these elements. Mixing between the basinal brine and the cooler meteoric fluids in the tectonic breccia would have diluted and cooled the system to maintain willemite precipitation, which in turn would have created a stable environment for hematite. A possible reaction for the formation of hematite from an Fe-bearing carbonate would be:

As the system became cooler and more dilute leading to increase in pH, concentrations of Zn and SiO_2 became substantial enough to precipitate out willemite in addition to hematite under the following reaction:

The production of O_2 may have kept the system oxidized enough to maintain hematite stability.

In addition, these reactions account for the elemental losses in Ca and Mg as well as the gains in Fe, Zn, and SiO_2 ; however, it is also possible for hematite and willemite to precipitate without interacting with the host carbonates, as shown in the following reactions:

This interpretation is in agreement with the models for precipitation of willemite proposed by Brugger et al. (2003) and Appold and Monteiro (2009) and summarized in Table 1. The scarcity in sphalerite is explained by the low S content in the hydrothermal fluids.

<i>Factor</i>	<i>Willemite (Wl)</i>	<i>Sphalerite (Sp)</i>
Temperature (<i>T</i>)	Precipitation not affected	As <i>T</i> decreases, Sp precipitates
pH	More sensitive to pH than Sp, as pH increases, Wl precipitates	Less sensitive to pH than Wl, as pH increases, Sp will precipitate but to a lesser extent than Wl
Salinity	A decrease in salinity precipitates Wl and Sp (favors neither)	A decrease in salinity precipitates Wl and Sp (favors neither)
Log <i>fO</i> ₂	No effect	As Log <i>fO</i> ₂ increases, sulfides converted to sulfates

Table 3.2 Summary of the factors controlling willemite and sphalerite precipitation from a fluid with temperatures ranging from 100 – 300 °C, at a pH of 4.5, and log *fO*₂ = - 40.5 (Summarized from Brugger et al. (2003) and Appold and Monteiro (2009). Wl = willemite, Sp = sphalerite

After the formation of the Type 4 Breccia, another basinal fluid containing some reduced S, base metals, and Ag^0 moved through the Type 4 Breccia and precipitated some minor sulfide upon cooling. Much later, when the willemite was exposed to weather, supergene processes

would have oxidized the willemite, creating hydrozincite, smithsonite, and other zinc-oxides in the late structures.

When compared to the research conducted by Monteiro et al. (1999, 2006, 2007) on the Vazante Mine, the Northern Extension shows many similarities. Both deposits are hosted in the carbonates of the Lower Pamplona Member, structurally controlled, dominated by willemite mineralization, and have a strong Ag, Cd, Pb, Zn geochemical signature (Monteiro et al., 1999, 2006, 2007; this study).

Unlike the Vazante Mine, the Northern Extension deposit is located closer to the surface, outcrops in the very northern region of the deposit, and shows a greater influence of brittle deformation instead of the ductile deformation recorded by Monteiro et al. (1999) in the Vazante Mine. Monteiro et al. (1999), Hitzman et al (2003), and Monteiro et al. (2006, 2007) documented sphalerite in pods that were imbricated with the willemite ore, but very little sphalerite was observed in the Northern Extension except for small amounts located in late sulfide veinlets, indicating that the ore fluid in the Northern Extension may have evolved into a cooler, higher pH fluid, or was poorer in S. In addition to the strong Ag, Cd, Pb, Zn signature, Monteiro et al. (2007) also documented gains in La, P, and Rb in the mineralized breccia; however, no substantial gains in La or P were observed in the Northern Extension, and it was observed that Rb was actually lost in the types 3 and 4 breccias in this study.

The carbonate units of the Serra do Poço Verde Formation show a decreasing $\delta^{13}\text{C}$ signature from +2 ‰ to – 2.3 ‰ at the top of the Middle Pamplona Member followed by a positive $\delta^{13}\text{C}$ excursion to +3.9 ‰ in the Morro do Calcário Formation, indicating that the Morro do Calcário may be a cap carbonate for the Sturtian snowball Earth event that occurred during the deposition of the Serra do Poço Verde Formation (Azmy et al., 2001; Misi et al., 2005). Extensive glaciation could have provided the oxygenated meteoric fluid that mixed with the basinal brine in the Vazante Northern Extension trend.

3.6.2 Comparison with Other Deposits

The Vazante Northern Extension deposit has some similarities with other hypogene zinc silicate deposits and their characteristics are summarized in Table 2. The Franklin–Sterling Hill deposit is metamorphosed to a very high grade so the original alteration and ore minerals are no longer preserved. As for all the other known zinc silicate deposits, they are hosted in carbonate rocks that formed during the Neoproterozoic to Cambrian, contain willemite and hematite as the major minerals in the ore zone, are enriched in Be, Cd, Cu, Ge, Pb and V, and are interpreted to have been formed by low temperature fluids (50 to 180 °C) of variable salinities (3-15 eq. wt %NaCl). In the Vazante Northern Extension and Kabwe deposits, brecciation is interpreted to be related to major faults (Dardenne, 2000; Kamona and Friedrich, 2007, this study); whereas the breccias at Beltana are associated with karst (Groves et al., 2003).

Deposits	Location	Size (Mt)	Grade (% Zn)	Host rocks	Host rock Age	Related Structures	Ore minerals	Alteration	T _H (°C)	Salinity (eq. wt %NaCl)	Associated Elements
Beltana¹	Australia	0.86	37.9	limestone, dolostone	Cambrian	Beltana Fault, district scale folds, breccia, karst	Willemite, coronadite, hedyphane, mimetite, smithsonite	Ferroan dolomite, hematite, quartz	50-170 (wl)	4 – 14	As, Be, Cd, Cu, Fe, Ge, Mn, Pb, Sb, V
Franklin²	U.S.A.	24	19.6	marble	Neoproterozoic	Zero Fault, district scale folds	franklinite, willemite, zincite, tephroite,	rhodonite, magnetite, calcsilicates	650-700	n/a	As, B, Co, Cu, Fe, Mn, Ni, Pb, V, W
Kabwe³	Zambia	13 ⁸	20-25 ⁸	dolostone	Neoproterozoic	Mine Club fault zone, district scale folds, minor breccia	sphalerite, willemite, galena	Quartz, hematite, smithsonite, cerussite	98-178 (sp)	11.5	Ag, Be ⁸ , Cd, Cu, Ga, Ge, In, V, Pb
Vazante-North Extension Trend	Brazil	18 ⁴	19 ⁴	dolostone	Neoproterozoic	Vazante Shear Zone, district scale folds, breccia ⁴	willemite, sphalerite, franklinite, sphalerite ^{4,5}	Quartz, ferroan and zincian dolomite, hematite ⁴	65-180 ⁶ (wl)	3 – 15 ⁶	Ag, As, Be, Bi, Cd, Cu, Ge ⁷ , Fe, Hg, In, Mo, Pb, Sb, Se, V ⁴

Table 3.3 Temperatures are taken from fluid inclusions hosted in the cited mineral, except for Franklin where the temperatures were estimated based on the equilibrium assemblage of Fe₃O₄ – Mn₃O₄ – ZnFe₂O₄.

¹ (Groves et al., 2003); ² (Fron del and Baum, 1974); ³ (Kamona and Friedrich, 2007); ⁴ (this study); ⁵ (Monteiro et al., 1999); ⁶ (Dardenne and Freitas-Silva, 1999); ⁷ (Monteiro et al., 2007), ⁸ (Boni et al., 2011).

3.6.3 Guidelines for Exploration

Based on the characteristics of the hypogene zinc silicate deposits studied in the Vazante region and those ones for other deposits described in the literature, the follow guidelines are proposed for their exploration. Hypogene zinc silicate deposits should be explored for in Neoproterozoic to Cambrian carbonate rocks that formed in epicontinental basins along shallow passive margins. These basins must have then subsequently undergone deformation during major orogenic events forming tectonic belts (e.g., Brasília Fold Belt, Zambezi Belt, and Adelaide Geosyncline). The orogenic event creates and reactivates structures suitable as ore fluid conduits and traps for fluid mixing.

On a district and local scale, shallow brittle fault zones and breccias associated with regional folds and faults should be targeted as they create a favorable environment for mixing between basinal brines and meteoric waters. Stratigraphic contacts may also be important for controlling fluid flow and mineral precipitation. With respect to Vazante, distal alteration containing enrichment in Ag, Cd, Pb, and Zn is characterized by iron-carbonates and hematite in the areas surrounding the ore breccia. Geochemical signatures that show high concentrations of Ag, As, Ba, Be, Bi, Cu, Fe, Ge, Hg, In, Mo, Ni, Pb, S, Sb, U, V, W, and Zn are indicative of hydrothermal alteration of hematite breccias proximal to the willemite dominated breccias.

3.7 Conclusions

- The Northern Extension is hosted in dolomitized, passive margin carbonates.
- The Northern Extension has undergone several phases of brittle deformation, the tectonic-hydrothermal breccia forming in Vazante Northern Extension Shear Zone, interpreted to be coeval with the D₂ folds observed in the less competent phyllitic units.

These structures acted as fluid conduits and control the hydrothermal alteration and ore deposition.

- The tectonic-hydrothermal breccia can be classified into four distinct breccia types and from the earliest to latest form:
  - Type 1 – distally located from the willemite ore, weakly brecciated with some Fe-carbonate alteration.
  - Type 2 – Strong Fe-carbonate alteration, intense brecciation.
  - Type 3 – Hematite replacement breccia, usually proximal to the Type 4 Breccia.
  - Type 4 – willemite ore breccia, containing multiple willemite generations as well as hematite and franklinite.
- The main mineralizing event contains hypogene willemite ore; however, late Pb-Zn and Ag-Cu sulfide veinlets were documented cross-cutting the Type 4 Breccia.
- The hydrothermally altered zones at the Northern Extension contains distinctly higher concentrations of Ag, Cd, Pb, Zn and the willemite breccia has additionally high concentrations of Cu, Hg, Pb, Se, and SiO₂ that correlate to losses in Ca and Mg due to replacement of carbonates in the system.
- The willemite ore is interpreted to be formed by mixing between metalliferous, low temperature, acidic, relatively saline fluid with low S content with more oxidizing meteoric fluids, leading the precipitation of abundant hematite and willemite.

Chapter 3 References

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Chapter 4

Final Remarks

4.1 Discussion and Conclusions

The Northern Extension willemite ore is hosted in dolomitized, passive margin carbonates that have undergone greenschist facies metamorphism and several phases of ductile and brittle deformation. The tectonic-hydrothermal breccia that hosts the ore is controlled by the Vazante-Northern Extension Shear Zone in the contact between the Upper Morro do Pinheiro and Upper Pamplona members of the Serra do Poço Verde Formation. This structure is interpreted to have formed during the D₂ phase along with the major folds observed in the less competent phyllitic units and acted as a conduit for the hydrothermal fluids. Four breccia types (Fig. 1) were identified in the North Vazante Shear zone and they range from the initial, weakly altered Type 1 Breccia, to the more strongly altered Type 2, to the Type 3 hematite and Type 4 willemite replacement breccias. The willemite mineralization is associated with hematite and franklinite, and is characterized by early hexagonal crystalline willemite (1st generation) that has been overgrown by later lath-shaped willemite (2nd generation), which, in turn, is being overgrown by the 3rd generation, of fibrous willemite veinlets. In addition to the hypogene willemite ore, late Pb-Zn and Ag-Cu sulfide veinlets were documented to have cut the Type 4 Breccia. The various breccia types at the Northern Extension contains distinctly higher concentrations of Ag, Cd, Pb, Zn as well as moderate gains of Bi, Co, Cu, Fe, In, Mn, Mo, Ni, P, and Sb. The willemite breccia has additionally high concentrations of Cu, Hg, Pb, Se, and SiO₂ that correlate to losses in Ca and Mg due to replacement of carbonates in the system.

Fig. 4.1: Genetic Model for the Vazante-Northern Extension

A) Stage 1

Initial brecciation from tectonism and hydraulic pumping of basinal brine, forming Type 1 Breccia

B) Stage 2

Continued brecciation from hydraulic pumping and hydrothermal alteration, forming Type 2 Breccia

C) Stage 3

Mixing of cool, oxidizing, meteoric water with basinal brine, forming Type 3 Breccia (red)

D) Stage 4

Further mixing of cool, oxidizing, meteoric water with basinal brine, resulting in dilution and pH increase, forming Type 4 Breccia (blue)

As discussed in this study, the Vazante-Northern Extension is a zinc silicate deposit, which is quite different from the other zinc deposits in the Brasília Fold Belt, particularly those in the Vazante Formation. The Morro Agudo Mine is a Pb-Zn sulfide Irish-type deposit located in the northern part of the Vazante Group and also hosted in the carbonates of the Serra do Poço Verde Formation (Dardenne and Freitas-Silva, 1999; Dardenne, 2000; Monteiro et al, 2006; 2007). There are several possible scenarios to form two deposits that contain similar metals with different ore mineralogy (sulfide vs. silicate): 1) both the silicate and sulfide deposits originate from similar basinal brines, but they interact with different fluids in the site of deposition, prompting different minerals to precipitate or 2) the original metal-bearing brine is completely different in the amount of sulfur available.

With the first scenario, both deposits would have had similar basinal fluids that were relatively warm, metalliferous, oxidizing, and acidic. These fluids may have been similar to those found in MVT, Irish-type, or SEDEX deposits (Groves et al, 2003). In the case of the Morro Agudo deposit (sulfide), the basin fluids are focused into a fault, acting as a conduit, where they interact with S-bearing, reducing fluids containing reductants such as organic matter or methane, causing reduction of the fluid and the precipitation of Zn and Pb sulfides. With respect to the Vazante-Northern Extension deposit (silicate), the basin fluid does not mix with a S-bearing, reducing fluid; rather it interacts with the low temperature, meteoric water (as proposed in Chapter 3), where dilution and pH decrease cause willemite to precipitate (Appold and Monteiro, 2009).

In the second scenario, the amount of available S present in the basinal fluid could have been substantial for Morro Agudo and negligible for the Vazante-Northern Extension, causing sphalerite to have preferentially precipitated in Morro Agudo due to reduction of the S in the site

of deposition; whereas willemite precipitated in Vazante during mineralization due to absence of reduced S and the presence of conditions ideal for the precipitation of Zn as a silicate.

When compared to the research conducted by Monteiro et al. (1999, 2006, 2007) on the Vazante Mine, the Northern Extension shows many similarities. Both deposits are hosted in the carbonates of the Lower Pamplona Member, structurally controlled, dominated by willemite mineralization, and have a strong Ag, Cd, Pb, Zn geochemical signature (Monteiro et al., 1999, 2006, 2007; this study).

Unlike the Vazante Mine, the Northern Extension deposit is located closer to the surface, outcrops in the very northern region of the deposit, and shows a greater influence of brittle deformation instead of the ductile deformation recorded by Monteiro et al. (1999) in the Vazante Mine. Monteiro et al. (1999, 2006, 2007) documented sphalerite in pods that were imbricated with the willemite ore, but very little sphalerite was observed in the Northern Extension except for small amounts located in late sulfide veinlets. In addition to the strong Ag, Cd, Pb, Zn signature, Monteiro et al. (2007) also documented gains in La, P, and Rb in the mineralized breccia; however, no substantial gains in La or P were observed in the Northern Extension, and it was observed that Rb was actually lost in the types 3 and 4 breccias in this study.

The Vazante-North Extension deposit has some similarities with other silicate deposits such as Beltana, Australia and Kabwe, Namibia (Groves et al, 2003; Kamona and Friedrich, 2007). They are hosted in carbonate rocks that formed during the Neoproterozoic to Cambrian, contain willemite and hematite as the major minerals in the ore zone, are enriched in Cd, Cu, Ge, Pb and V +/- Be, and are interpreted to have been formed by low temperature fluids (50 to 180

°C) of variable salinities (3-15 eq. wt %NaCl) (Dardenne, 2000; Kamona and Friedrich, 2007, this study). Therefore they may have been formed by similar processes.

4.2 Remaining Questions and Future Work

As previously discussed in Chapter 3, the characterization of nonsulfide zinc deposits was well established in the Vazante-Northern Extension with respect to host rocks, structures, mineral paragenesis, and geochemistry (Monteiro et al 1999; 2006; 2007; Appold and Monteiro, 1999; this study); however, open questions still remain such as:

- What geologic processes may affect the precipitation of zinc silicates over zinc sulfides?
- What are the ages of zinc mineralization in the deposit and how does this compare to the other base metal sulfide deposits found in the Vazante Group?
- Does this trend of Pb-Zn deposits in the Serra do Poço Verde Formation share a common fluid source?
- What are the different processes related to the formation of the sulfide deposits such as Morro Agudo compared to the Vazante Northern Extension?
- What are the isotopic characteristics of the willemite ore, and how it can help in identify the source of fluids and conditions of deposition?
- Why these deposits seem to be confined to a specific geological time (hosted in Neoproterozoic to Cambrian carbonate rocks)?

In order to address these questions the following future work is recommended:

- 1) Correlative studies between the ages of known nonsulfide zinc deposits with respect to specific time periods and events, such as glaciation and changes in global oxygen levels
- 2) Age dating of the Serra do Poço Verde Formation using detrital zircon analysis or another robust geochronological system
- 3) Dating of the ore deposits in the Serra do Poço Verde Formation
  - a. Age determination of the hypogene ore in the Vazante-Northern Extension using Rb-Sr and Sm-Nd dating techniques
  - b. Age determination of the sphalerite using Rb-Sr and Sm-Nd in the Morro Agudo Mine as well as the Fagundes and Ambrósia mineralizations
- 4) Fluid inclusion analysis to better compare the relationships between ore fluids in the BFB
  - a. In willemite for the Vazante Northern Extension
  - b. In sphalerite for the Morro Agudo Mine
- 5) More stable isotope analyses of the $\delta^{18}\text{O}$ from willemite to create a more robust data set of formation temperatures and fluid sources

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Appendix A Field Notes and Measurements

Field Measurements were taken using a Brunton Pocket Transit. The measurements were taken using azimuth and the “right-hand rule” for dip (e.g. when oriented along strike, the dip is measured 90° perpendicular to strike on the right-hand side). Comments were recorded with respect to compositional layering, foliations, folds, faults, etc., in addition to the locations of each measurement.

A.1 Field Measurements: Cavas 5A, 6A, 7A

<u>Easting</u>	<u>Northing</u>	<u>elevation</u> <u>(m)</u>	<u>strike</u>	<u>dip</u>	<u>dip</u> <u>direction</u>	<u>notes</u>
308039	8019190	649	224	43	NW	bx layering (S0)
308030	8019193	659	30	45	SE	fault plane
308021	8019192	670	196	30	NW	bx layering (S0)
308012	8019210	675	145	24	SW	
308012	8019210	675	140	42	SW	S1 foliation
308005	8019221	683	240	66	NW	fault
308001	8019199	686	100	16	S	bx layering (S0)
307988	8019160	698	50	40	SE	
307992	8019109	690	300	90		fault
308029	8019121	677	225	35	NW	compositional layering (S0)
308017	8019101	684	65	62	SE	fault plane
308017	8019101	684				320→55 on previous fault plane
307999	8019079	690	225	54	NW	compositional layering (S0)
307999	8019079	690	195	65	NW	S1 foliation
308028	8018993	691	250	70	NW	fault
308071	8019040	685	147	68	SW	fault
308104	8019079	683	230	35	NW	fault
308104	8019079	683	140	65	SW	fault
308126	8019069	695	116	20	SW	compositional layering (S0)
308126	8019069	695	145	52	SW	S1 foliation
308126	8019069	695	170	61	SW	fault
308159	8019081	701	275	29	S	compositional layering (S0)
308159	8019081	701	220	40	NW	fault
307990	8019171	691	65	29	SE	compositional layering (S0)

<u>Easting</u>	<u>Northing</u>	<u>elevation</u> (m)	<u>strike</u>	<u>dip</u>	<u>dip</u> <u>direction</u>	<u>notes</u>
308224	8019132	707	234	90		compositional layering (S0) and fault surface
380197	8019141	700	236	72	NW	bx foliation (S0)
308285	8019234	680	210	67	NW	Saprolite
308194	8019239	671	132	75	SW	fault
308173	8019236	670	130	56	SW	fault
308137	8019295	680	12	56	SE	fold limb
308137	8019295	680	26	74	SE	S1 foliation in fold limb
308130	8019298	686	54	31	SE	compositional layering (S0), fold limb
308128	8019298	686	106	35	SW	compositional layering (S0), fold limb
308049	8019258	688	160	34	SW	compositional layering (S0) 030→30 on preveious
308049	8019258	688				compositional layer
308061	8019305	701	189	39	NW	compositional layering (S0)
308069	8019305	708	197	70	NW	compositional layering (S0)
308092	8019318	711	34	46	SE	compositional layering (S0)
308096	8019328	716	54	75	SE	compositional layering (S0)
308118	8019342	720	45	36	SE	compositional layering (S0)
308166	8019386	731	350	90		fault
308140	8019382	738	46	50	SE	compositional layering (S0)
308106	8019381	734	200	53	NW	compositional layering (S0)
308096	8019391	736	170	41	W	fault w/ 35 ° rake
308096	8019391	736				330→29 on previous fault
308089	8019460	740	122	32	SW	compositional layering (S0)
308027	8019438	704	6	53	E	compositional layering (S0)
308013	8019336	696	305	85	NE	fault
308011	8019303	695	345	52	NE	fault
307922	8019203	700	265	33	S	compositional layering (S0)
307883	8019045	717	260	21	S	compositional layering (S0)
307892	8019049	717	60	65	SE	fault
307915	8018915	695	300	70	NE	compositional layering (S0)
307885	8018836	680	270	33	N	compositional layering (S0)
307878	8018859	678	65	85	SE	fault
307853	8018877	682	45	57	SE	fault
307853	8018877	682	103	31	SW	compositional layering (S0)
307996	8018716	680	155	39	SW	compositional layering (S0)
308039	8018769	683	75	39	SE	fault
308059	8018786	693	55	55	SW	fault
308062	8018842	697	65	90		fault

<u>Eastings</u>	<u>Northings</u>	<u>elevation</u> <u>(m)</u>	<u>strike</u>	<u>dip</u>	<u>dip</u> <u>direction</u>	<u>notes</u>
308072	8018863	702	120	34	SW	compositional layering (S0)
308096	8018917	706	65	44	SE	fault
308061	8018881	702	75	71	SE	shear zone
308032	8018917	698	130	40	SW	compositional layering (S0)
308032	8018917	698	100	80	S	S1 foliation
307931	8018838	686	90	70	S	fault
307598	8018426	637	245	19	SE	compositional layering (S0)
307596	8018429	638	315	60	NE	fault
307583	8018405	639	39	10	SE	compositional layering (S0)
307569	8018461	640	37	41	SE	compositional layering (S0)
307571	8018428	645	40	30	SE	compositional layering (S0)
307596	8018388	656	65	32	SE	compositional layering (S0)
307559	8018428	662	50	70	SE	fault
307549	8018425	666	64	45	SE	compositional layering (S0)
307540	8018481	667	190	66	E	fault
307545	8018495	666	61	26	SE	compositional layering (S0)
307532	8018544	671	315	63	NE	fault
307563	8018659	680	27	47	SE	compositional layering (S0)
307564	8018692	688	341	40	NE	compositional layering (S0)
307644	8018756	693	218	13	NW	compositional layering (S0)
307578	8018765	701	64	7	SE	compositional layering (S0)
307566	8019758	703	44	10	SE	compositional layering (S0)
307557	8018733	703	53	8	SE	compositional layering (S0)
307668	8018746	696	60	43	SE	compositional layering (S0)
307739	8018780	695	169	66	W	fault
307755	8018607	666	142	24	SW	compositional layering (S0)
307768	8018624	667	225	32	NW	fault
307781	8018626	674	205	60	NW	fault
307787	8018639	676	49	34	SE	compositional layering (S0)
307848	8018603	680	50	20	SE	compositional layering (S0)
307843	8018661	680	45	30	SE	compositional layering (S0)
307804	8018696	680	155	36	SW	fault
307758	8018660	656	185	90		fault
307754	8018681	655	200	10	NW	compositional layering (S0)
307785	8018697	673	117	33	SW	fault
307792	8018696	675	25	61	SE	fault
307770	8018695	664	129	72	SW	fault
307763	8018692	656	40	30	SE	fault
307760	8018678	653	46	70	SE	comp layering (fold limb)

<u>Easting</u>	<u>Northing</u>	<u>elevation</u> (m)	<u>strike</u>	<u>dip</u>	<u>dip</u> <u>direction</u>	<u>notes</u>
307760	8018678	653	40	30	SE	comp layering (fold limb) t→p offold axis for previous 2 measurements
307760	8018678	653	20→9			
307771	8018680	655	150	50	SW	fault
307729	8018730	666	31	41	SE	compositional layering (S0)
307705	8018670	640	55	72	SE	comp layering in shear zone
307692	8018668	628	212	34	NW	fault
307688	8018686	628	10	85	E	left fold limb (comp layering)
307688	8018686	628	172	60	W	right fold limb (comp layering)
307689	8018638	630	183	50	W	fault? Or part of previous fold
307740	8018680	645	22	48	SE	comp layering (fold limb)
307740	8018680	645	224	23	NW	comp layering (fold limb)
307710	8018646	634	90	22	S	compositional layering (S0)
307642	8018676	634	54	29	SE	fault
307635	8018666	637	20	26	SE	compositional layering (S0)
307625	8018675	656	60	30	SE	fault
307714	8018626	642	215	36	NW	fault
307717	8018606	644	210	29	NW	fault
307685	8018398	645	170	29	W	fault
307676	8018363	636	199	38	NW	fault
307660	8018313	630	195	16	NW	compositional layering (S0)
307650	8018297	627	198	35	NW	fault
307650	8018297	627	200	75	NW	S1 foliation
307586	8018332	632	40	53	SE	fault
307569	8018401	648	24	42	SE	fault
307663	8018537	628	210	35	NW	fault
307632	8018593	632	33	35	SE	fault
307632	8018593	632	215	30	NW	compositional layering (S0)
307863	8018569	728	64	20	SE	compositional layering (S0)
307832	8018332	723	216	50	NW	fault
307832	8018332	723	95	40	S	compositional layering (S0)
307749	8018385	720	216	50	NW	fault
307748	8018340	715	75	26	SE	compositional layering (S0)
307745	8018300	709	320	74	NE	compositional layering (S0)
307561	8018208	690	200	15	NW	compositional layering (S0)
307561	8018208	690	50	70	SE	fault
307689	8018682	615	185	70	W	Masa ore zone orientation

B.2 Field Measurements Cava 3A

<u>Easting</u>	<u>Northing</u>	<u>elevation</u> <u>(m)</u>	<u>strike</u>	<u>dip</u>	<u>dip</u> <u>direction</u>	<u>notes</u>
307032	8016594	677	255	20	NW	compositional layering (S0)
307000	8016564	671	225	8	NW	compositional layering (S0)
307000	8016564	671	60	54	SE	fault
306994	8016528	659	215	23	NW	strike and dip fold (N plunge?)
307020	8016546	657	239	35	NW	strike and dip fold (N plunge?)
307029	8016542	663	230	25	NW	strike and dip fold (N plunge?)
307036	8016522	665	40	90		compositional layering (S0)
307024	8016497	677	40	57	SE	strike and dip, fault
307007	8036477	583	123	16	SW	compositional layering (S0)
307031	8016416	682	45	11	SE	compositional layering (S0)
307062	8016442	685	110	46	SW	compositional layering (S0)
307072	8016430	686	20	83	SE	fault
307072	8016430	686	229	55	NW	compositional layering (S0)
307086	8016429	687	47	25	SE	compositional layering (S0)
307127	8016454	688	230	20	NW	compositional layering (S0)
307104	8016453	684	345	45	NE	strike and dip, fault
307093	8016454	682	115	27	SW	compositional layering (S0)
307087	8016487	666	359	83	E	fault
307049	8016514	668	80	19	SE	compositional layering (S0)
307060	8016528	668	335	23	NE	strike and dip, fold limb
307053	8016533	668	205	11	NW	strike and dip, fold limb
307044	8016549	670	210	50	NW	strike and dip, fold limb
307049	8016554	671	226	25	NW	compositional layering (S0)
307073	8016574	678	260	25	NW	compositional layering (S0)
307074	8016540	676	220	5	NW	strike and dip, fold limb (N plunge)
307077	8016550	678	52	31	SE	strike and dip, fold limb (N plung)
307141	8016698	677	235	23	NW	compositional layering (S0)
307154	8016659	671	247	20	NW	compositional layering (S0)
307161	8016625	673	32	35	SE	compositional layering (S0)
307171	8016636	675	40	72	SE	compositional layering (S0)
307178	8016642	677	320	73	NE	compositional layering (S0)
307185	8016649	679				82→55 Trend and plunge of fold axis
307157	8016620	676	66	40	SE	compositional layering (S0)
307136	8016628	672	260	55	NW	compositional layering (S0)
307096	8016624	666	321	28	NE	compositional layering (S0)
307052	8016607	679	28	30	SE	compositional layering (S0)

<u>Easting</u>	<u>Northing</u>	<u>elevation</u> <u>(m)</u>	<u>strike</u>	<u>dip</u>	<u>dip</u> <u>direction</u>	<u>notes</u>
307100	8016614	674				011→60 trend and plunge of fold axis
307212	8016620	698	51	0		compositional layering (S0)
307209	8016601	706	55	4	SE	compositional layering (S0)
307163	8016583	706	348	65	NE	reverse fault, ~10 m wide bx zone
307160	8016583	707	212	34	NW	strike and dip fold limb
307163	8016576	708	58	14	SE	strike and dip fold limb
307163	8016576	708				220→10 trend and plunge strike and dip fold limb
307232	8016661	666	255	48	NW	(N plunge) strike and dip fold limb
307219	8016672	665	15	35	SE	(N plunge)
307215	8016672	665	222	89	NW	compositional layering (S0)
307271	8016722	668	128	240	SW	compositional layering (S0)
307273	8016729	664	202	50	NW	compositional layering (S0)
307270	8016723	665	189	68	W	fault
307273	8016746	665	198	29	NW	compositional layering (S0)
307335	8016758	669	230	15	NW	compositional layering (S0)
307234	8016771	673	235	35	NW	compositional layering (S0)
307401	8016778	656	15	17	SE	compositional layering (S0)
307401	8016778	656	311	~90		fault
307370	8016793	654	87	32	S	compositional layering (S0)
307394	8016789	669	232	87	NW	shear zone ~1 m wide
307396	8016785	668	201	40	NW	strike and dip, right fold limb 35→29 trend and plunge of fold axis
307396	8016785	668				
307396	8016785	668	234	30	NW	strike an dip, left fold limb
307352	8016830	655	231	30	NW	compositional layering (S0)
307374	8016843	660	220	11	NW	compositional layering (S0)
307395	8016850	664	235	10	NW	compositional layering (S0)
307396	8016848	666	40	62	SE	fault
307433	8016867	672	239	38	NW	compositional layering (S0)
307474	8016860	691	219	16	NW	compositional layering (S0)
307467	8016924	676	203	26	NW	compositional layering (S0)
307498	8016932	684	57	15	SE	compositional layering (S0)
307355	8016986	632	81	3	S	compositional layering (S0)
307412	8012037	636	335	29	NE	compositional layering (S0)
307441	8017048	640	202	18	NW	compositional layering (S0)
307461	8017657	645	194	44	NW	compositional layering (S0)
307462	8017035	649	222	26	NW	compositional layering (S0)
307475	8016985	653	115	43	SW	compositional layering (S0)

<u>Easting</u>	<u>Northing</u>	<u>elevation</u> <u>(m)</u>	<u>strike</u>	<u>dip</u>	<u>dip</u> <u>direction</u>	<u>notes</u>
307484	8017000	656	185	67	W	compositional layering (S0)
307496	8016998	665	165	68	SW	compositional layering (S0)
307501	8016980	674	179	55	W	compositional layering (S0)
307532	8017018	679	29	23	SE	compositional layering (S0)
307502	8017038	670	207	24	NW	compositional layering (S0)
307575	8017086	672	120	22	SW	strike and dip of very tight fold limb
307579	8017075	681	286	55	NE	strike and dip of very tight fold limb
307576	8017143	676	204	47	NW	compositional layering (S0)
307649	8017126	714	51	68	SE	strike and dip of tight fold limb
307649	8017143	714	214	68	NW	strike and dip of tight fold limb
307649	8017143	714				210→16 T & P
307674	8017202	710	84	46	S	compositional layering (S0)
307690	8017261	701	172	34	W	compositional layering (S0)
307715	8017285	702	107	37	SW	compositional layering (S0)
307719	8017322	694	86	51	S	compositional layering (S0)
307721	8017332	691	10	8	E	compositional layering (S0)
307718	8017348	689	20	26	SE	compositional layering (S0)
307746	8017386	685	18	19	SE	compositional layering (S0)
307804	8017389	706	128	50	SW	compositional layering (S0)
307808	8017398	704	207	15	NW	compositional layering (S0)
307796	8017424	696	202	16	NW	compositional layering (S0)
307759	8017451	679	144	48	SW	compositional layering (S0)
307773	8017461	684	76	30	W	compositional layering (S0)
307711	8017359	676	179	10	W	compositional layering (S0)

Appendix B Drill Logs

The drill logs were compiled in a similar manner with the same headings as used by the Votorantim Exploration Team at Vazante, MG. All intervals are recorded in meters.

B.1 Drill Core Logs

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMSF 032	0	5.3	altered bx	Hydrothermal Breccia	brown	bx	weathered bx
VZMSF 032	5.3	38.4	dol bx	Hydrothermal Breccia	red	sheared bx	slightly withd, hm alt
VZMSF 032	38.4	52.6	dol bx	Hydrothermal Breccia	brown-red	sheared bx	hydrothermal/wthg?
VZMSF 032	52.6	53.75	dol bx	Hydrothermal Breccia	red-pink	soil	hydrothermal/wthg?
VZMSF 032	53.75	73.7	dol bx	Hydrothermal Breccia	gray	soil	hydrothermal/wthg?
VZMSF 032	73.7	94.3	dol bx	Hydrothermal Breccia	pink-violet	sheared bx	hydrothermal/wthg?
VZMSF 032	94.3	96.5	dol bx	Hydrothermal Breccia	brown	soil	hydrothermal/wthg?
VZMSF 032	96.5	97.4	phyllite	Serra do Garrote	gray	soil	hydrothermal/wthg?
VZMSF 032	97.4	103.8	phyllite	Serra do Garrote	dark gray	foliated	lesser hydrothermal alt
VZMSF 032	103.8	106.95	dol bx	Hydrothermal Breccia	pink	bx (minor shear)	
VZMSF 032	106.95	122	phyllite	Serra do Garrote	black	laminated shear	
VZMSF 032	122	157.4	dol bx	Hydrothermal Breccia	pink	bx	hm and Fe-carb
VZMSF 032	157.4	200	phyllite	Serra do Garrote	black	laminated shear	

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								brown weathered breccia
							±	broken sheared bx (red to pink, low recovery)
							x	heavily altered bx to dirt and cobbles; silica and hm rich clasts more resistant to alteration
							x	hm-rich bx
							x	altered bx
							x	well indurated bx with Fe-carb alteration
							x	brown hm-rich dirt
							x	altered phyllite (wthg?)
							x	gray phyllite, part of minor fold limb of Serra do Garrote
							x	dolomite in center of minor fold (Hydrothermal Breccia/Lower Morro do Pinheiro?)
							x	black phyllite (major fold limb)
							x	dolomite in center of major fold (Hydrothermal BrecciaLower Morro do Pinheiro?)
x							x	black shale on other side of fold limb, faulted and boudinaged

<u>Hole</u>	<u>Area</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMSF 028	Masa	0	2.3	soil		pink-brown		
VZMSF 028	Masa	2.3	3.05	bx	Lower Morro do Pinheiro?	red-gray	bx	Fe-carb alt
VZMSF 028	Masa	3.05	4.35	soil/bx	Lower Morro do Pinheiro?	brown	soil	wthg/hydrothermal alt
VZMSF 028	Masa	4.35	8.6	dt	Lower Morro do Pinheiro?	red-gray	bx	hm
VZMSF 028	Masa	8.6	11.4	dol	Lower Morro do Pinheiro?	red-gray	bx	hm
VZMSF 028	Masa	11.4	13.3	dol	Lower Morro do Pinheiro?	pink	bx	Fe-carb alt
VZMSF 028	Masa	13.3	14.4	dol	Lower Morro do Pinheiro?	gray	bx	minor hm
VZMSF 028	Masa	14.4	21.15	dol	Lower Morro do Pinheiro?	pink-red	bx	hm
VZMSF 028	Masa	21.15	25.7	soil/bx	Lower Morro do Pinheiro?	gray-brown	bx/soil	weathering/hm
VZMSF 028	Masa	25.7	39.65	dol	Lower Morro do Pinheiro?	red-pink	bx	hm
VZMSF 028	Masa	39.65	47.6	dol	Lower Morro do Pinheiro?	pink	bx	Fe-carb alt
VZMSF 028	Masa	47.6	57.2	dol	Lower Morro do Pinheiro?	gray	bx	Fe-carb alt
VZMSF 028	Masa	57.2	71.95	dol	Lower Morro do Pinheiro?	pink-gray	bx	Fe-carb alt
VZMSF 028	Masa	71.95	87.5	dol	Lower Morro do Pinheiro?	gray	bx	Fe-carb alt & minor kaolinite
VZMSF 028	Masa	87.5	108.1	dt	Lower Morro do Pinheiro?	red-gray	dolorudite/bx	some Fe-carb

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								red to gray bx with minor shear
								dolorudite w/ some bx and Fe-carb veins
								dolmitic bx w/ heavy hm and Fe-carb alteration
							x	sheared dol bx (lot of core loss)
							x	sheared gray dol bx
							x	sheared bx with increasing hm as dept increases
							x	gray to brown diret with bx from 24-24.5; lot of hm in soil
							x	pink dol w/ hm bands and alteration
							x	pink dol with gray dol clasts
							x	gray dol bx w/ fault
							x	pink and gray mottled dol bx
							x	dark to light gray dol bx; 80.4-80.6 (kaol alt)
								pink, red & gray dolorudite with some bx

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 141	0	10.25	soil	Middle Pamplona?	brown		
VZMIF 141	10.25	15.25	dol	Middle Pamplona?	gray	laminated w/ bx	
VZMIF 141	15.25	18.5	dol	Middle Pamplona?	gray	bx	
VZMIF 141	18.5	28.6	dol	Middle Pamplona?	gray	mottled	kaol at 22.1 & 24.4-24.95
VZMIF 141	28.6	34.85	dol	Middle Pamplona?	gray orange- brown	laminated	very minor silicic
VZMIF 141	34.85	47.35	soil	Middle Pamplona?			
VZMIF 141	47.35	60.55	dol	Middle Pamplona?	gray	laminated	silicic; some hm veins
VZMIF 141	60.55	62.95	dol	Middle Pamplona?	gray	dolarenite/dolorudite	
VZMIF 141	62.95	68.5	dol	Middle Pamplona?	gray	bx	minor hm veinlets
VZMIF 141	68.5	71.3	dol	Middle Pamplona?	gray	dolorudite & mottled	
VZMIF 141	71.3	79.9	dol	Middle Pamplona?	pink	laminated	Fe-carb alt
VZMIF 141	79.9	93.1	dol	Lower Pamplona	gray	laminated	Fe-carb alt w/ hm
VZMIF 141	93.1	123.25	dol	Lower Pamplona	pink/gray	laminated w/ qtz vugs & veins	silica w/ minor Fe-carb alt
VZMIF 141	123.25	153.75	dol	Upper Morro do Pinheiro	pink	bird's eyes	Fe-carb
VZMIF 141	153.75	182.65	dol bx	Hydrothermal Breccia	red	bx	Fe-carb w/ hm veins
VZMIF 141	182.65	212.6	dol/ phyllite	Upper Morro do Pinheiro	gray	laminated	
VZMIF 141	212.6	220.7	dol	Upper Morro do Pinheiro	pink	mottled	Fe-carb & minor silica
VZMIF 141	220.7	229.85	dol	Upper Morro do Pinheiro	pink/gray	mottled w/ bird's eyes	Fe-carb & minor silica

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
			x					bx 13.45-13.6
x			x					dol bx w/ minor hm & sulfides
x								dolarenite w/ kaol alt; 26-27.35 pink dolarenite w/ hm veins gray dolarenite w/ vugs at 33.23 & 34.4-34.85 soil
x?							x	gray dolarenite & massive dol
							x	gray dolarenite & dolorudite
							x	intercalated laminated dolarenite & mottled dolorudite; 63.2, 64.7, 66.8 & 71.0 are tectonic bx's
							x	mottled dolorudite & micritic dol w/ tectonic & sed bx
							x	laminated pink dol, sheared at 78, bx at 78.25 & 78.75
							x	intercalated gray dol w/ greenish-red phyllites
							x	pink & gray dol w/ silicified vugs w/ Fe-carb (hm?) alt
							x	pink dol w/ bird's eye texture; congl at 136-136.22; hm vein at 153.3
			x?			x	x	hydrothermal bx (Hydrothermal Breccia) w/ Zn mineralization
							x	intercalated gray dol & darker gray phyllites (phyllites)
							x	mottled pink dol w/ silica & Fe-carb filled vugs mottled pink dol & laminated; bird's eyes dolarenite (dk gray color)

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 012	0	65	dol	Middle? Pamplona	lt gray	laminated	slight wthg
VZMIF 012	65	89.2	dol	Middle? Pamplona	lt pink	laminated	
VZMIF 012	89.2	108.6	phyllite	Lower Pamplona	pink/green	laminated	minor silicic
VZMIF 012	108.6	113.3	phyllite	Lower Pamplona	green	laminated/bx	
VZMIF 012	113.3	123.2	phyllite	Lower Pamplona	pink/green	laminated minor bx	
VZMIF 012	123.2	127.1	phyllite	Lower Pamplona	gray	bx	highly silicic
VZMIF 012	127.1	133.9	dol & phyllite	Lower Pamplona	red	bx	minor silicic
VZMIF 012	133.9	298.15	dol & phyllite	Lower Pamplona	white/green	laminated	
VZMIF 012	298.15	336.1	dol & phyllite	Lower Pamplona	pink/green	laminated minor bx	minor Fe-carb
VZMIF 012	336.1	398	dol bx	Hydrothermal Breccia	pink/green	bx	hm veins
VZMIF 012	398	430.1	dol bx	Upper Morro do Pinheiro	pink/gray	bx	minor hm

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 127	0	20.65	soil	?	lt red-brown		wthg
VZMIF 127	20.65	24.7	soil	?	beige		wthg
VZMIF 127	24.7	34.75	soil	?	beige		wthg
VZMIF 127	34.75	87.1	dol	Lower Pamplona	red & gray	laminated	kaol, Fe-carb
VZMIF 127	87.1	112.6	dol bx	Hydrothermal Breccia (Lower Pamplona)	red & gray	bx	hm & Fe-carb alt
VZMIF 127	112.6	129.9	dol bx	Hydrothermal Breccia (Upper Morro do Pinheiro)	pink & gray	bx w/ oncolites and bird's eyes	Fe-carb
VZMIF 127	129.9	150.3	dol bx	Hydrothermal Breccia (Upper Morro do Pinheiro)	gray	bx w/ laminated & oncolite clastic intervals	minor Fe-carb

<u>Pv</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								broken dol, minor kalo and silica
							x	pink dol w/ green phyllites
							fault	marled
							x	interbedded dolarenites and phyllites
							x	
							x	red dol bx
							x	interbedded wht dolarenites and red-green phyllites
							x	pink dol w/ green phyllites
x		x	x?			x	x	pink & gray bx
								alternating pink and gray bx
<u>Pv</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
							x	calamine zone
							x	dol at 21.45; 27.75-28.0
							x	intercalated red & gray dol w/ dk red phyllites; intermittent withg zones to clay Hydrothermal Breccia, very vuggy w/ core loss; lot of hm near ore zone (107.5-109.7);
							x	sharp contact with hm and dol
							x	alternating gray & pink dol bx; uniform; oncolites in pink dol bx and bird's eyes in gray clasts

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 136	0	27.97	soil		brown		
VZMIF 136	27.97	70.05	dol/phyllite	Lower Pamplona	pink/lt gray	Algal laminated	kaol wthg/ minor Fe-carb
VZMIF 136	70.05	74.4	dol/soil	Lower Pamplona	pink/brown	vuggy	wthg to soil
VZMIF 136	74.4	108.25	dol	Lower Pamplona	pink	dolarenitic	hm & Fe-carb (minor)
VZMIF 136	108.25	117.1	dol bx	Lower Pamplona	pink	bx	hm veins
VZMIF 136	117.1	138.1	dol bx	Hydrothermal Breccia	pink & gray	bx	minor hm; silica; Fe-carb
VZMIF 136	138.1	205.75	dol	Hydrothermal Breccia	pink & gray	bx	Fe-carb
<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 143	0	74.3	soil	Lower Pamplona?			
VZMIF 143	74.3	77.05	dol	Lower Pamplona?	lt gray	algal laminated	minor Fe-carb; minor wthg
VZMIF 143	77.05	77.7	soil	Lower Pamplona?	brown		
VZMIF 143	77.7	80.23	dol	Lower Pamplona?	lt pink	algal laminated	minor Fe-carb; minor wthg
VZMIF 143	80.23	81.6	soil	Lower Pamplona?			
VZMIF 143	81.6	96.8	phyllite/dol	Lower Pamplona	red-gray to lt pink	algal laminated laminated phyllite;	trace Fe-carb veinlets
VZMIF 143	96.8	120.7	phyllite/dol	Lower Pamplona	lt gray to gray	dolarenite	
VZMIF 143	120.7	150.95	phyllite/dol	Lower Pamplona	gray/ white	laminated phyllite; marble laminated phyllite; dol has	
VZMIF 143	150.95	186.55	phyllite/dol	Lower Pamplona	gray/pink	algal laminations	trace Fe-carb veinlets

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
							x	vuggy, lt gray to lt pink dol intercalated w/ red-brown phyllite
							x	dol wthg to soil w/ vugs at 72.95-74.4
							x	pink dol w/ Fe-carb & hm veinlets; minor crackle bx
							x	pink dol bx w/ massive hm veins at 133.4-113.55 ; 114.4-115.31
							x	125.55-125.7 (fault w/ chlorite); pink and gray dol bx, specularite veins
							x	pink & gray dol bx with diamictite at 160-160.35 & 160.75-161; some silicic clasts and bird's eyes
<u>Pv</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								lt gray dol, minor bx at 76.15
								lt pink dol
								soil w/ hm
								intercalated red-gray phyllites w/ pink dol
x								white to light gray dolarenite marbles intercalated w/ gray phyllites w/ trace py
								intercalated gray shales/phyllites w/ white marble
								intercalated gray shales/phyllites w/ pink & gray dolomite

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 122	0	70.8	soil		brown		wthg
VZMIF 122	70.8	79.3	massive silicate	Hydrothermal Breccia	dark red & gray	mottled & veins	hm & wl
VZMIF 122	79.3	86.55	dol breccia	Hydrothermal Breccia	pink	dol bx	silica; hm
VZMIF 122	86.55	188.55	dol/phyllite	Lower Pamplona	pink-gray	dolarenite; laminated	Fe-carb veins
VZMIF 122	188.55	193.85	dol/phyllite	Upper Morro do Pinheiro	gray	bird's eyes	minor Fe-carb veins
<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 110	0	17.5	dol	Upper Pamplona	gray	mottled dolarenite	
VZMIF 110	17.5	17.8	soil	Upper Pamplona	orange		
VZMIF 110	17.8	34.6	dol	Upper Pamplona	gray	mottled dolarenite	kaol wthg; vuggy
VZMIF 110	34.6	107.4	dolarenite	Upper Pamplona	gray	lightly mottled	silica; trace Fe-carb
VZMIF 110	107.4	159.82	dolorudite	Middle Pamplona	dark gray	algal laminated	silica; minor Fe-carb
VZMIF 110	159.82	223.9	dolarenite	Middle Pamplona	lt pink & lt gray	mottled & algal laminated	silica; trace hm vns
VZMIF 110	223.9	344.25	phyl/dolarenite	Lower Pamplona	gray & lt gray	mottled & algal laminated	minor Fe-carb
VZMIF 110	344.25	349.9	dol	Upper Morro do Pinheiro	dark gray	bird's eyes	spotty hm
<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 020	0	42.15	destroyed	Middle Pamplona			
VZMIF 020	42.15	83.83	dolarenite	Middle Pamplona	gray	massive dolarenite laminated; minor algal mats; sed bx	
VZMIF 020	83.83	273	phyl/ dol	Lower Pamplona	black/gray		
VZMIF 020	273	335.35	dol breccia	Hydrothermal Breccia	red	brecciated	
VZMIF 020	335.35	388.55	dol	Upper Morro do Pinheiro	dark gray	bird's eyes & algal layering	

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
			±	±		x	x	dol bx replaced by hm & wl; ore similar to Vazante mine ore w/r to Ag and texture pink dol bx w/ some hm veins pink & gray dolarenite interbedded w/ ruddy brown phyllite dk gray dol w/ a few Fe-carb veins; bx at contact w/ L.P.
<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								mottled lt and dk gray dolarenite
							x?	gray, lightly mottled dolarenite
							x	dark gray dolorudite interbedded with some dolarenite
							x	light pink to light gray dolarenite w/ silicified and hm veins
							x	intercalated gray phyllites with lt gray and lt pink dolarenites; some orange areas; bx (291.8-292.8) dol with bird's eyes; vuggy, missing some intervals
<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								massive gray dolarenite w/ small sedimentary bx near contact intercalated black shale and gray dolarenite
							x	red dolomite bx (some bx phyllites) Wl ≤ 1%; high Bar (323.25-324.25)
							x	dark gray dolomite w/ bird's eyes at end is crackle breccia

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 114	0	0.8	soil	Lower Pamplona	pinkish brown		
VZMIF 114	0.8	25.55	dol	Lower Pamplona	pink	laminated with some bx	Fe-carb & silica
VZMIF 114	25.55	42.5	dol	Lower Pamplona	buff	kaol wthg	
VZMIF 114	42.5	42.75	hm	Lower Pamplona	red	vuggy hm	hm
VZMIF 114	42.75	49.55	dol	Lower Pamplona	pink	laminated vuggy	Fe-carb & hm veinlets
VZMIF 114	49.55	51	vug	Lower Pamplona			
VZMIF 114	51	51.4	soil	Lower Pamplona	brown		
VZMIF 114	51.4	54.4	vug	Lower Pamplona			
VZMIF 114	54.4	67.5	dol	Lower Pamplona	pink	laminated vuggy	Fe-carb & hm veinlets
VZMIF 114	67.5	74.75	vug	Lower Pamplona			
VZMIF 114	74.75	88.85	dol breccia	Hydrothermal Breccia	reddish gray	vuggy bx	hm and silica
VZMIF 114	88.85	94.55	dol breccia	Hydrothermal Breccia	pink to red	bx	Fe-carb & hm
VZMIF 114	94.55	115	dol	Upper Morro do Pinhero	gray	laminated, crackle bx	trace Fe-carb

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
							x	vuggy pink dolomite with silica alteration
							x	orange to buff weathered dolomite with Mn dendrites
							x	vuggy; hm
							x	pink dolomite with Fe-carb alteration & hm veinlets; bx at 50.3
							x	vuggy
					±	x	x	dol replaced by Wm & hm, vugs increase at end of run (75.0-76.0 high Ag, Cu, Pb, Zn)
							x	end of thorough Fe-carb alteration in Hydrothermal Breccia zone
							x	dark gray dol with faults and gouge; cataclasite appears after fault (downhole)

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 115	0	49.25	soil	Middle Pamplona	reddish brown		
VZMIF 115	49.25	52.55	dol	Middle Pamplona	lt gray	kharst	kaol & dissolution
VZMIF 115	52.55	62.85	dol	Middle Pamplona	pink & gray	bird's eyeys & vugs	silica alt
VZMIF 115	62.85	87.3	dol	Middle Pamplona	gray	laminated, minor bird's eyes	silica alt; minor hm
VZMIF 115	87.3	90.6	dol	Middle Pamplona	gray	bird's eye's & kharst	kaol & dissolution
VZMIF 115	90.6	94.2	dol	Middle Pamplona	gray	bird's eyes & kharst	kaol & dissolution
VZMIF 115	94.2	122.3	dol	Lower Pamplona	pink & gray	bird's eyes & bx	silica ± hm
VZMIF 115	122.3	123.85	phyllite	Lower Pamplona	brown	laminated	carb (non-ferrous)
VZMIF 115	123.85	169.2	dol breccia	Hydrothermal Breccia	pink	bx	Fe-carb & silica
VZMIF 115	169.2	205.5	dol	Lower Pamplona	pink & gray	laminated	Fe-carb & silica
VZMIF 115	205.5	212.6	dol	Lower Pamplona	red	bx & dolarenite	hm ± silica
VZMIF 115	212.6	226.05	dol breccia	Hydrothermal Breccia	red	bx	hm & silica
VZMIF 115	226.05	227.05	dol breccia	Hydrothermal Breccia	pink	bx	silicia
VZMIF 115	227.05	236.65	dol breccia	Hydrothermal Breccia	pink	bx	silica, secondary dol
VZMIF 115	236.65	244.75	dol bx	Lower Pamplona/ Hydrothermal Breccia	gray & pink	laminated w/ some bx	minor hm
VZMIF 115	244.75	274	dol bx	Lower Pamplona/ Hydrothermal Breccia	pink	lamellar w/ some bx	Fe-carb
VZMIF 115	274	300.3	dol	Upper Morro do Pinheiro	gray & pink	algal layered, some bird's eyes	Fe-carb

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								heavy silica alteration of dol
x								66.3-66.4 blk dol with qtz
								minor silica alt at 88.1
								minor silica alt
								pink dol with bird's eyes; 105.55-108.35 bx with dark layers (algal?); hm alt scattered
							x	
							x	bx w/ minor intervals of laminated dol
							x	pink & gray dol w/ minor bx and gray-brown phyllites
							x	pink dol b w/ red hm alteration
x			x	x		x	x	Hydrothermal Breccia with sulfide mineralization (*TS)
							x	
							x	Hydrothermal Breccia, minor fractures with silica overgrowths
							x	intercalated gray laminated dol w/ pink dol bx (secondary dol filling in bx)
							x	pink dol bx w/ gray spots and minor hm in bx; carb alteration at 265.7
							x	gray algal layered dol w/ pink laminated dol and minor shear bx

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 129	0	18.05	soil	Middle Pamplona	reddish brown		
VZMIF 129	18.05	26.75	dol	Middle Pamplona	lt gray	massive	Fe-carb veinlets & silica
VZMIF 129	26.75	29.3	soil	Middle Pamplona	reddish brown	massive	
VZMIF 129	29.3	48.1	dol	Middle Pamplona	gray	massive	silica
VZMIF 129	48.1	76.7	dol	Middle Pamplona	pink	motled-massive	Fe-carb, minor silica
VZMIF 129	76.7	158	dol	Lower Pamplona	gray & pink	dolarenite; vuggy	Fe-carb & silica veins
VZMIF 129	158	163.75	dol breccia	Hydrothermal Breccia	pink	mottled w/ some dolarenite	Fe-carb w/ hm
VZMIF 129	163.75	168.75	dol breccia	Hydrothermal Breccia	pink	mineralized mottling & veins	hm veins
VZMIF 129	168.75	174.8	dol breccia	Hydrothermal Breccia	pink	dol bx (no mins)	Fe-carb ± hm veinlets
VZMIF 129	174.8	187.35	dol	Lower Pamplona	pink	slightly mottled	Fe-carb veins
VZMIF 129	187.35	221	dol	Lower Pamplona	gray & pink	mottled	some Fe-carb veins
VZMIF 129	221	232.9	dol	Lower Pamplona	pink	bx	Fe-carb
VZMIF 129	232.9	250.1	dol	Upper Morro do Pinheiro	gray	bird's eye & algal laminated	trace Fe-carb, blanching

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								light gray massive dol
							x	gray dolomite w/ soil at 44.2-44.45
							x	pink dolarenite with vugs; soil at 49.9-50.25; some minor clay alt
							x	pink & gray dolomite interbedded with red-brown phyllites; some silica alteration; wthg to soil
							x	pink dolomite bx
						x	x	dolomite bx replaced by Wm & Hm (Hm in veins)
						±	x	little Zn mineralization; substantial Fe-carb alt
							x	pink dolomite thoroughly veined with Fe-carb
							x	gray and pink dolomite w/ some shear fractures & bx's, lots of mottling
							x	pink dolomite bx w/ Fe-carb veins
							x	gray dolomite w/ minor bx

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 124	0	34.35	dol	Hydrothermal Breccia overprinting Lower Pamplona	pink	algal laminated	lots of Fe-carb veining
VZMIF 124	34.35	40.1	dol/soil	Hydrothermal Breccia overprinting Lower Pamplona	pink/brown	algal laminated	Fe-carb veins, soil wth'd
VZMIF 124	40.1	47.1	dol	Hydrothermal Breccia overprinting Lower Pamplona	pink	algal laminated, vuggy	Fe-carb veins; minor wth'g
VZMIF 124	47.1	51.2	dol	Hydrothermal Breccia overprinting Lower Pamplona	red	algal laminated, w/ some bx	heavy Fe-carb alt; hm veins
VZMIF 124	51.2	59.9	dol/bx	Hydrothermal Breccia overprinting Lower Pamplona	pink	bx w/ algal layering	Fe-carb alt
VZMIF 124	59.9	62.9	dol breccia	Hydrothermal Breccia	pink	bx	Fe-carb alt; minor silicic
VZMIF 124	62.9	65.3	dol breccia	Hydrothermal Breccia	red	bx	heavy Fe-carb alt; hm veins
VZMIF 124	65.3	67.6	dol breccia	Hydrothermal Breccia	pink	bx	Fe-carb alt; minor silicic
VZMIF 124	67.6	73.15	dol breccia	Hydrothermal Breccia	red	bx	heavy Fe-carb alt; hm veins
VZMIF 124	73.15	79.45	dol breccia	Hydrothermal Breccia	reddish-gray	mottled gray and red bx	hm & W1 (Fe & silicic)
VZMIF 124	79.45	87.33	dol breccia	Hydrothermal Breccia	pink	bx	Fe-carb alt; hm veins
VZMIF 124	87.33	102.03	dol/phyllite	Lower Pamplona	pink/gray	bx	Fe-carb veins
VZMIF 124	102.03	103.85	dol	Upper Morro do Pinheiro	gray	bird's eyes	minor Fe-carb nodules
VZMIF 124	103.85	130.15	dol	Upper Morro do Pinhero	gray with some pink	bx & laminated	minor Fe-carb alt along fractures

<u>Pv</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								pink dol w/ Fe-carb alt, some hydrothermal bx and sed bx scattered throughout
								pink dol alternating w/ brown soil; some core loss
								pink dol w/ some wthg and small vugs
								red dol w/ bx similar in appearance to Hydrothermal Breccia at 47.1-49.0 (thinner than BH)
								pink dol w/ periodic small bx's (no mineralization)
								pink dol bx w/ minor hm (no wl); silicic alt → why lighter and less altered?
								red dol w/ lot of Fe-carb alt & hm shear veins (> 2cm)
								pink dol bx w/ minor hm (no wl); silicic alt → why lighter and less altered?
							x	red dol w/ lot of Fe-carb alt & hm shear veins (> 2cm)
						x	x	bx w/ hm shear veins & mottled gray Wl
							x	pink dol bx w/ minor hm (no wl); silicic alt → why lighter and less altered?
							x	pink & gray dol bx intercalated w/ reddish-gray phyllites; some black shales also present (fold limb?)
							x	gray dol w/ bird's eyes & Fe-carb nodular alt (~3-5 cm)
								gray & pink laminated dolarenite w/ dol bx scattered throughout; some pelitic layers towards end

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 134	0	17.6	soil	Lower Pamplona			
VZMIF 134	17.6	96.4	dol/dolorudite	Lower Pamplona	gray dark	algal laminated	silica vugs and veins; some Fe-carb alt
VZMIF 134	96.4	112.2	dol	Upper Morro do Pinheiro	gray	bird's eyes	trace Fe-carb veinlets
VZMIF 134	112.2	127	dol bx	Hydrothermal Breccia	red	sheared bx bird's eyes; crackle	Fe-carb alt and hm veins
VZMIF 134	127	160.6	dol	Upper Morro do Pinheiro	gray	bx	some Fe-carb alt and carb alt (in bx)
VZMIF 134	160.6	162.7	phyllite	Upper Morro do Pinheiro	black dark	laminated	
VZMIF 134	162.7	201.1	dol	Lower Morro do Pinhero	gray	algal mottled	Fe-carb veins w/ hm

Pv   Po   Cp   Sp   Ga   Cl   Wl   Shear   Observations

				±	light gray to gray dolarenite and dolorudite w/ algal layering, some minor algal mottling
				±	dark gray dol w/ some dolorudite w/ bird's eyes
			±	x	red shear bx w/ hm veins, minor Zn (high Cd)
				x	crackle bx near Hydrothermal Breccia contact, dark gray dol w/ bird's eyes
x				x	black shale at base of UMdP, contains minor Py
					dark gray dol w/ sporadic small bx lenses (~30-50 cm); mottled algal texture

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 139	0	13.6	soil	Middle Pamplona?	red-brown		
VZMIF 139	13.6	40.95	dolarenite	Middle Pamplona?	pink-gray	laminated dolarenite; some bx	minor kaol; Fe-carb w/ hm; silica alt
VZMIF 139	40.95	50.85	soil/dol	Middle Pamplona?	red-brown/ gray	laminated dolarenite; vuggy	minor Fe-carb veinlets
VZMIF 139	50.85	92.46	dolarenite/dolorudite	Middle Pamplona?	gray dark	algal dolarenite & dolorudite	trace Fe-carb veinlets
VZMIF 139	92.46	101.95	phyllite/dol	Lower Pamplona	gray/gray	laminated	wthg to kaol
VZMIF 139	101.95	149.9	dol	Upper Morro do Pinheiro	gray	bird's eys w/ minor algal layering	silica veins & filled vugs, some Fe-carb
VZMIF 139	149.9	159.15	phyllite/dol	Upper Morro do Pinheiro?	brown/gray	algal laminated; some sed bx	minor Fe-carb; chl alt
VZMIF 139	159.15	205	dol	Upper Morro do Pinheiro?	redish pink	sheared bx (splay of Hydrothermal Breccia?)	Fe-carb alt
VZMIF 139	205	220.7	dol	Upper Morro do Pinheiro?	dark gray	bx w/ bird's eyes	Fe-carb alt in bx
VZMIF 139	220.7	262.75	dol	Lower Morro do Pinheiro?	dark gray	algal laminated; crackle bx	Fe-carb
VZMIF 139	262.75	301.7	dol bx	Lower Morro do Pinheiro?	pink-gray	bx; dol	Fe-carb w/ hm veins
VZMIF 139	301.7	318.05	dol bx	Hydrothermal Breccia	red	recrystallization sheared bx	Fe-carb alt w/ hm & silica alt

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
x				±				pink-gray dolarenite w/ minor bx's w/ sulfides in silicified bx; bx at 19.5-20.55 & 25.5-28.5 alternating gray dol and red soil
±								intercalated dolarenite & dolorudite; vuggy spots in veins and fractures w/ some kaol zones intercalated gray dol w/ gray phyllites, some with light pink in phyllites gray dolarenite w/ bird's eyes & algal layering; silica vugs and Fe-carb veinlets
							x	intercalated gray-brown dol (w/ sed bx's) and red-green phyllites
							x	pink to red sheared dol bx w/ minor spots of sheared dark red phyllites; faults also present
							x	pink & gray bx (w/ bird's eyes) grading into dark gray dol w/ bird's eyes
							±	crackled gray dol w/ algal laminations & Fe-carb alt
							±	dol bx w/ red/white/gray clasts and dol overgrowths
						x		gray to mostly Hydrothermal Breccia; heavily fractures & filled w/ hm and Fe-carb alt; some Wl

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 123	0	5.7	soil	Lower Pamplona	yellow-brown		
VZMIF 123	5.7	17.7	dol/soil	Lower Pamplona	pink/brown	laminated	Fe-carb veins; kaol wthg
VZMIF 123	17.7	19.7	hm	Lower Pamplona	red	vuggy oncolites; some hm veins; minor bx;	hm
VZMIF 123	19.7	38.4	dol/soil	Lower Pamplona	pink	vuggy	carb dissolution; Fe-carb w/ hm
VZMIF 123	38.4	56.85	dol/soil	Lower Pamplona	pink	laminated	some Fe-carb veinlets
VZMIF 123	56.85	72.6	soil/hm	Hydrothermal Breccia	brown/red	vuggy	hm & dol wthd to soil
VZMIF 123	72.6	79.55	hm/silicates	Hydrothermal Breccia	red	massive hm & wl	hm
VZMIF 123	79.55	87.2	Dol bx	Hydrothermal Breccia	pink/brown	bx	Fe-carb alt
VZMIF 123	87.2	93.9	soil	Hydrothermal Breccia?	white to brown		
VZMIF 123	93.9	129.36	Do bx	Hydrothermal Breccia	pink/gray	bx	hm veins; Fe-carb alt

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								intercalated pink to ruddy brown dol w/ brown soil
								hm replacement of dol, very vuggy
								pink dol w/ thin intervals of soil; some hm veins; very vuggy (core loss)
								pink dol w/ Fe-carb & hm veinlets
							x	massive hm w/ vugs and altered to soil [vugs come after hm replacement]
						x	x	dol replaced by hm & wl (mod-high grade 15-40% Zn); very vuggy
							x	dol bx (Hydrothermal Breccia) no mineralization
								white soil that darkens in color with depth; possible elluvial horizon or hydrothermal alteration?
							±	gray & pink dol bx w/ hm veins & Fe-carb alt throughout

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 118	0	1.8	soil	Middle Pamplona	brown		
VZMIF 118	1.8	27.45	dol	Middle Pamplona	pink & gray	algal laminated w/ minor bx	minor Fe-carb alt & wthg
VZMIF 118	27.45	39.9	dol/soil	Middle Pamplona	pink	algal laminated	minor Fe-carb alt & wthg
VZMIF 118	39.9	81.55	dol	Middle Pamplona	pink	algal laminated	minor Fe-carb alt & wthg
VZMIF 118	81.55	97.05	soil	Middle Pamplona	shades of brown		supergene calmine
VZMIF 118	97.05	119.1	dol	Middle Pamplona	pink	bx; oncolites; algal layering	minor Fe-carb vns
VZMIF 118	119.1	126.62	dol	Middle Pamplona	pink	algal layering and oncolites	Fe-carb veins
VZMIF 118	126.62	135.3	dol bx	Middle Pamplona	gray	bx; stromatolites	Fe-carb veins
VZMIF 118	135.3	137.18	dol	Upper Morro do Pinheiro	dark gray	bird's eyes	
VZMIF 118	137.18	139.05	shale	Upper Morro do Pinheiro	black	laminated	calcite veinlets
VZMIF 118	139.05	162.8	dol	Upper Morro do Pinheiro	pink	laminated w/ some bx	Fe-carb veins
VZMIF 118	162.8	163.8	shale	Upper Morro do Pinheiro	black	laminated	calcite veinlets
VZMIF 118	163.8	165.2	dol	Lower Morro do Pinheiro	dark gray	mottled	hydrothermal dolomite

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								intercalated pink & gray dol (sheared); minor weathering to kaolinite in spots
								intercalated vuggy dol & soil
								intercalated pink & gray dol (sheared); minor weathering spots; very vuggy (~ 75% core loss)
					x			calamine
								pink dol w/ minor bx & some oncolites
								pink dol bx (still part of Upper Pamplona?)
								gray w/ some pink dol bx w/ stromatolites
								dark gray dol w/ bird's eyes (UMdP)
							x	black shales, similar to Serra do Garrote BUT probably blk sh at base of UMdP
							x	pink & gray dol w/ some bx zones & laminated sections
							x	black shales, similar to Serra do Garrote BUT probably blk sh at base of UMdP
								large mottled dark gray dol

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 125	0	20.95	soil	Upper Pamplona?	lt to dk brown		
VZMIF 125	20.95	29.4	dol	Upper Pamplona?	light pink	bird's eyes w/ minor bx	slight kaol withg; Fe-carb veins
VZMIF 125	29.4	31.7	soil	Upper Pamplona?	brown		
VZMIF 125	31.7	41.9	dol/phyll	Upper Pamplona?	red	algal lamellae w/ bird's eyes	Fe-carb & hm veins
VZMIF 125	41.9	64.45	dol bx	Hydrothermal Breccia?	red	bx	Fe-carb & hm veins
VZMIF 125	64.45	70.65	dol	Middle Pamplona?	white	bird's eyes w/ marbling	minor Fe-carb alt
VZMIF 125	70.65	75.65	dol bx	Hydrothermal Breccia?	red	bx	Fe-carb alt, moderate hm
VZMIF 125	75.65	82	dol	Middle Pamplona?	pink	laminated	Fe-carb alt, moderate hm
VZMIF 125	82	88.4	dol bx	Hydrothermal Breccia?	gray	bx	minor Fe-carb and hm alt
VZMIF 125	88.4	107.05	dol	Middle Pamplona?	light gray	laminated w/ minor bx	minor Fe-carb and hm alt
VZMIF 125	107.05	108.95	dol	Middle Pamplona?	red	bx, vuggy	hm veins, high Fe-carb alt
VZMIF 125	108.95	127.85	dol	Middle Pamplona?	pink & gray	laminated w/ minor bx	hm veinlets
VZMIF 125	127.85	130.3	dol bx	Middle Pamplona?	pink	bx	Fe-carb & hm veins
VZMIF 125	130.3	154.95	dol	Middle Pamplona?	pink & gray	laminated, minor bx, bird's eyes	minor Fe-carb alt

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
							x	pink dol w/ minor Fe-carb alt & soil alteration
							x	intercalated dol w/ dark red phyllites, some hm & Fe-carb veins
						±	x	hydrothermal dol bx w/ massive hm veins (5 cm w/1-2 % Zn)
							x	whit dolomite w/ Fe-carb veins, no bx, no mineralization
							x	red hydrothermal bx w/ moderate hm (less than previous bx)
							x	some bx in pink dol (not Hydrothermal Breccia)
							x	dol bx w/ little Fe-carb and hm alteration
							x	light gray dol w/ some bx, little mineralization; minor phyllite intercalations
							x	dol w/ lots of hm and vugs, lot of Fe-carb alt and veins
							x	pink & gray dol w/ some bx; Fe-carb & hm veinlets
							x	pink dol bx w/ stromatolites at end of run
							x	intercalated pink & gray dol w/ lamellae & bird's eyes, shearing w/ some hm, some minor bx

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 106	0	82.75	soil	Lower Pamplona	brown		
VZMIF 106	82.75	87.1	dol	Lower Pamplona	light pink	massive	wthg to clays; minor Fe-carb veins
VZMIF 106	87.1	88.25	soil	Lower Pamplona	brown		
VZMIF 106	88.25	104.8	dol No	Lower Pamplona	pink to white	massive w/ specks of hm	minor hm & Fe-carb alt
VZMIF 106	104.8	118.25	Recovery	Hydrothermal Breccia			
VZMIF 106	118.25	120.3	dol bx	Hydrothermal Breccia	reddish-gray	bx; vuggy	Fe-carb, hm alt
VZMIF 106	120.3	122.15	dol bx	Hydrothermal Breccia	reddish-gray	bx; vuggy	Fe-carb, hm alt, silica Wl alt
VZMIF 106	122.15	126.6	soil/ dol bx	Hydrothermal Breccia	brown		wthg w/ supergene calamine
VZMIF 106	126.6	134.2	dol bx	Hydrothermal Breccia	dark red	bx w/ hm veins	hm veins w/ some wl
VZMIF 106	134.2	149.9	dol	Lower Pamplona?	gray & pink brownish	mottled bx	minor Fe-carb & hm alt
VZMIF 106	149.9	167.25	soil/dol	Lower Pamplona?	gray	soil & dol bx	wthg to soil
VZMIF 106	167.25	211.95	dol	Lower Pamplona?	red	bx	minor Fe-carb & hm alt
VZMIF 106	211.95	217.5	dol	Upper Morro do Pinheiro	gray	bird's eyes, dolarenite	trace Fe-carb veinlets

<u>Pv</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								pink dol, very chewed up, altering to soil
								pink to white dol w/ hm specks; some spots altering to soil
								No Recovery, vugs?
					±	±		vuggy dol bx w/ some hm (low recovery)
					±	x		dol bx replaced by hm veins and Wl
x					x	x	x	Calamine in orange-brown soil (not enough soil for sample)
						x	x	dol replaced by hm, vuggy
							x	dol bx w/ gray and pink clasts, mottling
								alternating soil and gray dol bx
								red dol bx w/ Fe-carb veins & minor hm veins some algal laminated & dolarenite clasts; green phyllites
								gray dol/dolarenite w/ bird's eyes & minor bx; trace Fe-carb alt

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 155	0	48.8	No recovery				
VZMIF 155	48.8	49.05	dol	Middle Pamplona?	pink	mottled	silica & Fe-carb alt
VZMIF 155	49.05	50.28	dol	Middle Pamplona?	pink	bx	silica & hm veins (<1cm)
VZMIF 155	50.28	61.2	dol	Middle Pamplona?	pink	mottled, minor bx	silica & hm veins (<1cm)
VZMIF 155	61.2	63.65	dol	Middle Pamplona?	pink & gray	bx	mottled kaol wthg
VZMIF 155	63.65	66.15	dolarenite	Middle Pamplona?	gray	stromatolites w/ dolarenite	silica; kaol
VZMIF 155	66.15	69.15	dolarenite	Middle Pamplona?	gray	dolarenite	minor silicic alt
VZMIF 155	69.15	59.7	dol/phyllite	Lower Pamplona	gray	intercalated dolarenite & phyllite	hm banding
VZMIF 155	59.7	72.95	dol/phyllite	Lower Pamplona	light to dark gray	intercalated dolarenite & phyllite	hm alt in phyllites
VZMIF 155	72.95	75.15	phyllite	Lower Pamplona	brownish gray	laminated, minor mottling	silica alt
VZMIF 155	75.15	83.95	dol	Lower Pamplona	pink & gray	laminated	silica alt in bx
VZMIF 155	83.95	93.85	dol	Lower Pamplona	gray	laminated; bx	silica & hydrothermal dol
VZMIF 155	93.85	94.43	dol	Lower Pamplona	dark gray	bx	silicified bx
VZMIF 155	94.43	100.85	dol	Lower Pamplona	gray	algal laminated; some bx	silicified bx
VZMIF 155	100.85	108.8	dol	Lower Pamplona	gray	algal laminated; some bx	minor silicic alt
VZMIF 155	108.8	121.85	dol	Lower Pamplona	dark gray	mottled, some bx	silica & hydrothermal dol
VZMIF 155	121.85	129.05	dol	Lower Pamplona	gray	semi-massive dol	minor silicic alt & hm
VZMIF 155	129.05	130.75	dol	Lower Pamplona	brownish gray	laminated	minor silicic alt
VZMIF 155	130.75	132.65	dol	Lower Pamplona	pink & gray	laminated	hm alt
VZMIF 155	132.65	151.7	dol	Lower Pamplona	pink & gray	laminated ± bird's eyes	silica veins
VZMIF 155	151.7	191.3	dol	Lower Pamplona	pink & gray	laminated ± bird's eyes	silica veins
VZMIF 155	191.3	193.3	dol bx	Hydrothermal Breccia	red	bx	Fe-carb & hm
VZMIF 155	193.3	206.5	dol	Lower Pamplona	pink	bx; laminated	Fe-carb & hm
VZMIF 155	206.5	213.65	dol/phyllite	Lower Pamplona	light pink	laminated	

VZMIF 155	213.65	215.4	phyllite	Lower Pamplona	reddish brown	laminated	Fe-carb & hm
VZMIF 155	215.4	232.58	dol	Lower Pamplona	pink & gray	bx, minor laminations	silicic & hm alt
VZMIF 155	232.58	233.45	phyllite	Lower Pamplona	brown	laminated	chl alt
VZMIF 155	235.45	235.75	dol	Lower Pamplona	pink	wavy laminated	minor silicic
VZMIF 155	235.75	256.15	dol bx	Hydrothermal Breccia	reddish pink	bx w/ 2nd carb	Fe-carb & hm
VZMIF 155	256.15	262.85	dol	Lower Pamplona	pink	laminated	minor silicic
VZMIF 155	262.85	263.85	phyllite	Lower Pamplona	reddish brown	laminated	silica
VZMIF 155	263.85	265.85	dol	Lower Pamplona	pink & gray	laminated	hm
VZMIF 155	265.85	337.7	dol bx	Hydrothermal Breccia	reddish pink	bx	Fe-carb & hm
VZMIF 155	337.7	349.15	dol	Lower Pamplona	red	laminated w/ minor bx	silicic?; hm

Py   Po   Cp   Sp   Ga   Cl   Wl   Shear   Observations

hm filled fractures at 47.6 & 48.03

hm veins & fractures throughout; kaol alt spotty

small vugs filled w/ secondary dol

x

at 68.5-68.62 recrystallized dol w/ py; 68.7-69.15 intercalated hm alt

70.98-71.05 bx in pelite; 71.18-71.66 chl alt in phyllites; 72.15-72.95 hm alt

72.95-73.65 silica layers & bx; 74.95-75.15 hm veins, fault?

layered bx at 79; oncolites at 83; minor silica & hm fractures

hydrothermal bx at 87.05, 90.9 vert fracture; algal mats at 91.65-91.8, stylolites at 92.65

93.6-93.85 hydrothermal bx, 93.85-94 laminated/algal bx

98-99.85 bx, minor hm staining around veins

x

bx at 102.6 & py at 107.14

dark gray laminated to mottled dolarenite intercalated w/ lighter hydrothermal bx

intercalated brown-gray dol and dark gray phyllite; Fe-carb alt & minor bx's present

interlayered pink to gray dol w/ laminated & bird's eyes, multiple dark gray qtz veins

166.85-169.30 (bx w/ qtz infill, silica alt); 169.3-191.3 massive dol w/ layers of bird's eyes texture

dark red hydrothermal breccia; Fe-carb alt

dol w/ thin pelitic layers, bird's eyes @ 212.5?

x phyllite w/ Fe-carb alt

gry to mostly pink dol, various small bx's

maroon phyllite

dark pink dol

? x red to pink Hydrothermal Breccia w/ qtz, hm, & Fe-carb veins

x interlayered dol & phyllite

x

pink & gray dol

x x pink to red Hydrothermal Breccia; 295.85-298.45 heavy hm alt, Wm in bx

x intercalated laminated dol & dolomitic Hydrothermal Breccia w/ silicic alteration

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 060	0	57.05	destroyed	Lower Pamplona		laminated	
VZMIF 060	57.05	98.85	phyllite/dol	Lower Pamplona	pink & gray	phyllite/dolarenite	Fe-carb, hm veins in small bx
VZMIF 060	98.85	119.3	phyllite/dol	Hydrothermal Breccia	red	bx w/ hm veins	Fe-carb, silica alt, ± hm
VZMIF 060	119.3	122.95	dol bx	Hydrothermal Breccia	dark red	massive Wl w/ hm veins	Fe-carb, hm veins, Wl
VZMIF 060	122.95	135.15	dol bx	Hydrothermal Breccia	red	massive Wl w/ hm veins	Fe-carb, silica alt, ± hm
VZMIF 060	135.15	137.5	dol bx	Hydrothermal Breccia	dark red	massive Wl w/ hm veins	Fe-carb, hm veins, Wl
VZMIF 060	137.5	155.45	dol bx	Hydrothermal Breccia	reddish pink	bx w/ hm alt veins	Fe-carb & silica alt veins
VZMIF 060	155.45	161.75	dol	Upper Morro do Pinheiro?	dark gray	crackle bx	Fe-carb & silica veins
VZMIF 060	161.75	209	phyllite/dol	Lower Pamplona?	pink & gray	laminated phyllite/dolarenite	Fe-carb, hm veins in small bx
VZMIF 060	209	214.7	dol	Upper Morro do Pinheiro	dark gray	bird's eyes, bx near contact	graphite veins
<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 004	0	42.45	destroyed	Middle Pamplona			
VZMIF 004	42.45	64.5	dol	Middle Pamplona	gray	massive marble	silica alt & some Fe-carb veins
VZMIF 004	64.5	232.2	phyllite/dol	Lower Pamplona	Brn-red/gray	laminated dolarenite	some hm veins; some marbling
VZMIF 004	232.2	242.1	dol bx	Hydrothermal Breccia	red	bx	Fe-carb alt
VZMIF 004	242.1	250.6	dol	Lower Pamplona? or UMdP?	light pink & white	marble	minor Fe-carb alt
VZMIF 004	250.6	294.5	dol	Upper Morro do Pinheiro	gray & pink	bird's eyes & bx	Fe-carb alt
VZMIF 004	294.5	421.1	dol	Upper Morro do Pinheiro	dark gray	bird's eyes	dolomite recrystallization (hydrothermal?)

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								intercalated light pink to light gray dolarenite & red-gray phyllite; blanching proximal to Hydrothermal Breccia
							x	red & white Hydrothermal Breccia w/ Fe-carb & silica alteration
						x	x	red Hydrothermal Breccia w/ hm in shear veins; Wl
						±	x	red & pink bx ± Wl; lighter than surrounding bx
						x	x	gray-red Hydrothermal Breccia w/ high Zn & Cd, some high Ag values
						x	x	pink to red Hydrothermal Breccia
			x	±		x	x	dark gray dol w/ crackle breccia (UMdP?)
							x	fault at 17.45-167.7 (thrust? Setting UMdP on LP?)
								dark gray dol w/ bx near contact (also graphite veins) & bird's eyes

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
							x	gray dol & dolarenite w/ some Fe-carb veins w/ vugs & a lot of silica alteration
							x	white-gray dolarenite intercalated w/ red-brown phyllites
						x	x	red bx w/ Fe-carb alt; Wl w/ less massive hm; red color fades at end of bx
							x	light pink to white dolomite marble below Hydrothermal Breccia
							x	light pink dolomite w/ Fe-carb veins intercalated w/ gray dolomite w/ bird's eyes; bx from 264-267.1 (at end of bx is fault w/ chlorite)
							x	dark gray dol w/ bird's eyes & minor bx's throughout, some shear veins

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 101	0	68.2	destroyed	?			
VZMIF 101	68.2	122.58	phyllite/ dol	Lower Pamplona	gray/pink	mottled	Fe-carb veins; hm shear veins
VZMIF 101	122.58	150.5	dol bx	Hydrothermal Breccia	dark red	sheared bx laminated phyll/ dolarenite	Fe-carb alt; hm shear veins
VZMIF 101	150.5	242.1	phyllite/ dol	Lower Pamplona	gray/pink		Fe-carb alt that increases down
VZMIF 101	242.1	247.7	dol	Upper Morro do Pinheiro	gray	botryoidal & bx	dolomite recrystallization (hydrothermal?)
<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 043	0	45.5	destroyed	Middle Pamplona?			
VZMIF 043	45.5	58	dol	Middle Pamplona	pinkish gray	massive dolarenite laminated phyllite; dolarenite & dolorudite	hm veinlets
VZMIF 043	58	198.65	phyll/dA & dR	Lower Pamplona	red-brown/ gray		Fe-carb & hm alt veins
VZMIF 043	198.65	259.45	dol bx	Hydrothermal Breccia	pink	bx w/ alteration veins bird's eyes & algal layering	Fe-carb veins, minor hm
VZMIF 043	259.45	349.45	dol	Upper Morro do Pinheiro	dark gray		
<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 104	0	46	destroyed				
VZMIF 104	46	66.7	phyllite/dol	Lower Pamplona	reddish green- brown/pink & white	laminated phyllite & dolarenite	trace hm veinlets && Fe-carb alt
VZMIF 104	66.7	71.3	dol	Lower Pamplona	gray-orange reddish green- brown/pink & white	dolarenite	weathering to soil
VZMIF 104	71.3	81.2	phyllite/dol	Lower Pamplona		laminated phyllite & dolarenite	trace hm veinlets & Fe-carb alt
VZMIF 104	81.2	88.8	dol bx	Hydrothermal Breccia	red-gray reddish green- brown/pink & white	bx w/ veins	Fe-carb, slica alt
VZMIF 104	88.8	131.8	phyllite/dol	Lower Pamplona		laminated phyllite & dolarenite	trace hm veinlets & Fe-carb alt

<u>Pv</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
							x	intercalated gray phyllite & pink dolarenite w/ Fe-carb & hm veins (some sheared) increasing in density towards Hydrothermal Breccia
				x		x	x	dark red sheared dolomite Hydrothermal Breccia (lighter on margins w/ Wl & hm $\pm$ Cd & Ba
							x	intercalated pink & gray dolarenite w/ gray phyllite; Fe-carb alt decreases with depth; minor bx
							?	gray dol w/ some bx & carbonate (dol) overgrowths; no Fe-alt

<u>Pv</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
x								pinkish gray massive dolarenite w/ hm $\pm$ Py in veinlets
							x	intercalated phyllites & dolarenite (w/ dolorudite) w/ increased shear towards Hydrothermal Breccia contact; at 189 m blanching of phyllite & dolomite begins
						x	x	Hydrothermal Breccia, but with little hm veins, some minor Wl; one high 0.7% Cu interval dark gray dol w/ black phyllites (characteristic of base of UMdP) at 332.45-332.75; 339.5-339.78; 342.6-342.9; blanching at 265.65

<u>Pv</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								red-brown & green gray phyllites intercalated with pink & white dolarenite
								gray dolarenite weathering to osil in spots; vuggy
							x	red-brown & green gray phyllites intercalated with pink & white dolarenite; blanching w/in 10 m of Hydrothermal Breccia
				$\pm$		x	x	Hydrothermal Breccia w/ Fe-carb alt & some hm veins; high Wl + Cd
							x	red-brown & green gray phyllites intercalated with pink & white dolarenite; blanching & pink dol w/ in 10 m of Hydrothermal Breccia; hm & Fe-carb alt dissipate downhole

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 105	0	44	destroyed				
VZMIF 105	44	58.35	dol	Lower Pamplona	gray	mottled	Fe-carb veinlets; some weathering
VZMIF 105	58.35	81.2	dol bx	Hydrothermal Breccia	pink	vuggy bx laminated phyllite & dolarenite	Fe-carb; some small hm veinlets
VZMIF 105	81.2	96	phyllite/ dol	Lower Pamplona	dark gray/pink	sheared laminated phyllite/ boudinaged dol	some hm alt & hm stains
VZMIF 105	96	106.2	phyllite/ dol	Lower Pamplona	dark gray/pink	laminated phyllite & dolarenite	some hm alt & hm stains
VZMIF 105	106.2	167.8	phyllite/ dol	Lower Pamplona	dark gray/pink		
VZMIF 105	167.8	170.2	dol	Upper Morro do Pinheiro	dark gray	bird's eyes	trace silica
<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 015	0	41.6	destroyed				
VZMIF 015	41.6	114.65	dol	Middle Pamplona	gray	dolarenite	vuggy; silica veins
VZMIF 015	114.65	253.6	phyll/dol	Lower Pamplona	red, gray & white	laminated	trace Fe-carb veins
VZMIF 015	253.6	389.9	phyll/dol	Lower Pamplona	red, gray & white	laminated	trace Fe-carb veins
VZMIF 015	389.9	414.95	bx	Hydrothermal Breccia	red	bx	Fe-carb veins w/ hm veins
VZMIF 015	414.95	452.8	dol	Upper Morro do Pinheiro	gray	bird's eyes & algal laminated	minor blanching

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
								gray dolomite/dolorudite w/ very minor Fe-carb alt pink dol bx(distal or secondary Hydrothermal Breccia?); not sheared like Hydrothermal Breccia nor as heavily brecciated; less Fe-carb alt then next interval; some minor blanching near this Hydrothermal Breccia? (< 1 m)
							x	intercalated dark gray phyllites & pink-gray dolarenites some hm alt
x							x	intercalated gray-green phyllites & gray boudinaged dolomites & dolarenites; heavily sheared
								intercalated dark gray phyllites & pink-gray dolarenites some hm alt
x			?	?				w/ some bx 158.5-160 w/ py & hm
x								dark gray dol w/ py in some fractures

<u>Py</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>
x								gray dolarenite w/ silica & hm ± py vugs & veins
							x	mostly red-gray phyllites intercalated w/ white dolarenite (similar to wht dol in VZMIF 012)
							x	same as previous entry but with hm strains & vugs (closer to weathering surface?)
						x	x	Hydrothermal Breccia w/ some Wl; very vuggy; lot of core loss
							±	gray dolomite w/ minor blanching; vuggy; lot of core loss

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
VZMIF 088	0	45.5	destroyed				
VZMIF 088	45.5	66.7	phyll/dol	Lower Pamplona Hydrothermal Breccia?	gray-green/pink	laminated dolarenite	some hm veinlets; & Fe-carb alt in bx
VZMIF 088	66.7	72.7	dol bx	Hydrothermal Breccia?	gray	sheared bx	specularite veins; some Fe-carb alt
VZMIF 088	72.7	83.7	dol bx	Hydrothermal Breccia?	red & white	sheared bx	specularite veins; some Fe-carb alt
VZMIF 088	83.7	140.7	phyll/dol	Lower Pamplona	gray-green/pink	laminated algal	chloritic alt in phyllite
VZMIF 088	140.7	173.35	phyll/dol	Lower Pamplona	gray & white	laminated	trace Fe-carb; chlorite alt in phyll; silica alt
VZMIF 088	173.35	183.4	dol bx	Upper Morro do Pinheiro	dark gray	secondary dol overgrowths	carbonate & silica alt

<u>Pv</u>	<u>Po</u>	<u>Cp</u>	<u>Sp</u>	<u>Ga</u>	<u>Cl</u>	<u>Wl</u>	<u>Shear</u>	<u>Observations</u>

x							x	intercalated green-gray phyll w/ pink dolarenite; hm stains;
x	?	x	x				x	shear increases & color blanches w/ proximity to Hydrothermal Breccia
x							x	gray Hydrothermal Breccia w/ sulfides: py, sp & specularite instead of hm & Wl
			±				x	red & white Hydrothermal Breccia, no sulfides
							x	intercalated green-gray phyll w/ chlorite alt; light pink to gray dolarenite
							x	intercalated gray phyllite & white algal layered dolomite
								dark gray dol w/ maroon phyllite at 179.9-180.5;
								bx w/ carb overgrowths; algal laminated texture where not brecciated

<u>Hole</u>	<u>From</u>	<u>To</u>	<u>Rock Type</u>	<u>Geologic Unit</u>	<u>Color</u>	<u>Texture</u>	<u>Alteration</u>
Masa 124	0	6.8	soil	Upper Pamplona	yellow-orange		
Masa 124	6.8	32.3	phyll/dol	Upper Pamplona	blk/dark gray	evaporitic texture	
Masa 124	32.3	48.2	dolarenite	Upper Pamplona	lt gray to lt pink	dolarenite massive	silicified
Masa 124	48.2	85.45	dol	Upper Pamplona	dark gray	dolostone	silicified
Masa 124	85.45	87.35	fault	Upper Pamplona		boxworks massive	clay alt
Masa 124	87.35	96.55	dol	Upper Pamplona	dark gray	dolostone	silicified
Masa 124	96.55	96.95	fault	Upper Pamplona	orange red	minor fractures massive	Fe-carb and Hm alt
Masa 124	96.95	112.85	dol	Upper Pamplona	lt gray	dolostone dolstone w/ minor dissolution	silicified
Masa 124	112.85	115.2	dol/phyll	Upper Pamplona	gray		silicified vugs, carb dissolution, Fe-carb alt veinlets
Masa 124	115.2	128.4	phyllite	Upper Pamplona	dark gray-brown		
Masa 124	128.4	168	dol/phyll	Middle Pamplona	pinkish gray	dissolution vugs	minor Fe-carb, silicified vugs and selvages
Masa 124	168	207.7	dolorudite	Lower Pamplona	pinkish gray w/ green marls		minor Fe-carb
Masa 124	207.7	267	dol/phyll	Lower Pamplona	maroon & green phyll w/ lt gray dol		
Masa 124	267	283	dol/phyll	Lower Pamplona	pink dol and red phyll		
Masa 124	283	297.45	dol bx	Hydrothermal Breccia	red		Fe-carb
Masa 124	297.45	304	dol bx w/ phyll	Hydrothermal Breccia	pink to lt red		less Fe-carb than previous
Masa 124	304	308.9	dol bx	Hydrothermal Breccia	dark red		hematite replacement
Masa 124	308.9	326.2	dol bx w/ phyll	Hydrothermal Breccia	lt red to pink		Fe-carb and Hm replacement
Masa 124	326.2	329.75	dol bx	Hydrothermal Breccia	dark red		Hm + Wl

Masa 124	329.75	336.3	dol bx	Hydrothermal Breccia	lt pink to gray	Fe-carb
Masa 124	336.3	344.95	dol bx	Hydrothermal Breccia	lt pink	Fe-carb
Masa 124	344.95	345.5	dol bx	Hydrothermal Breccia	red bx	Fe-carb
Masa 124	345.5	352.6	dol bx	Hydrothermal Breccia	white and red bx	Fe-carb
Masa 124	352.6	354.85	dol bx	Hydrothermal Breccia	dark red	Hm replacement
Masa 124	354.85	356.65	dol bx	Hydrothermal Breccia	lt pink to lt gray	Fe-carb
Masa 124	356.65	372.9	dol	Upper Morro do Pinheiro	gray	algal layering w/ minor carb dissolution

Pv   Po   Cp   Sp   Ga   Cl   Wl   Shear   Observations

									dk gray dolarenites intercalated w/ black shale (phyllites); vermiform veinlet texture (evaporites?); 18.7-19.1 dolarenite w/ stylolites and clasts
									lt gray and pink dolarenites; 42.55-42.8 dissolution bx
									dk gray silicified dolostone w/ minor dissolution bx and Fe-veinlets; 56.8-57.24 silicified dolorudite fault w/ metoric alteration; has Fe-stained halo
									dk gray silicified dolostone w/ minor dissolution bx and Fe-veinlets
							±		Fe-alteration strong, proximal to fault
x			x						some minor faults w/ Fe-association; very silicified; "snow in the roof" bx w/ sphalerite
									gray silicified dolostone w/ minor gray phyllite and dissolution bx; stromatolites at 107 m
									phyllitic/silty marker bed b/w UP and MP
									gray dol w/ Fe-carb alt vugs and red-maroon phyllite w/ Hm alteration
									pink dol w/ porcelin white silica vugs
									pink dolarenite w/ dissolution vugs and sedimentary carbonate conglomerate; some green marls
									pink dolostone intercalated with maroon and green phyllites
									transition into Hydrothermal Breccia; Fe-carb alteration, some dolostones and marls (still in LP)

		less breccia, more bleached and cohesive dolostone unit within Hydrothermal Breccia
		Fe-carbonate bx w/ Hm-rich zones
±	x	pink dolostone intercalated with phyllites all with Fe-carb alt veinlets; dolostone is weakly brecciated
x	x	massive W1 (±Hm) in Hydrothermal Breccia (ore)
±		brecciated dolostone w/ Fe-carb alteration; bleached higher SiO ₂
		breccia w/ Fe-carb alteration veinlets
		breccia w/ Fe-carb alteration veinlets
		Fe-carbonate bx w/ silicified intervals
±		W1 + Hm replacing Fe-carbonate in hydrothermal bx (Hydrothermal Breccia)
		Fe-carbonate veinlets common in dolostone bx; end of Hydrothermal Breccia
		dark gray dolostone w/ vuggy dissolution of algal mats replaced by Fe-carb

Appendix C Thin Section Descriptions

Sample #: 012-347A

Hole #: VZMIF 012

Sample Interval: 347.8-347.95 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Disseminated Silicates (SD) in BH

Sample Photograph

Other Sample Information: Sample from Gilberto Batista. 31% Zn in sample interval

*1685 ppm Ag

minerals	Dolomite	Willemite	quartz
percentage	2	56	14
morphology	Large sparry xtals	2 xtal types: 1) Sm to lg euhedral hexagonal xtals 2) Large, fibrous laths	Anhedral around wl, subhedral in sulfide veins
texture	Being replaced by hm + frk and overgrown by wl	Hexagonal xtals massive. Fibrous xtals filling in open space	Disseminated, found in some veins
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular contacts with hm and frk. Straight edges with large, euhedral wl xtals. Some irregular contacts w/ small wl xtals	Hexagonal xtals have irregular contacts, replacing dol, qtz. Fibrous xtals replacing dol, qtz, and some granular wl. Hm + frk replacing wl (found as blebs in wl and has irregular contacts around xtal margins	Being replaced by wl, hm+frk. Qtz in veins being replaced by wl and Unknown Ag-Cu Sulfide ± sp
other (growth direction/zoning)			

minerals	Native Silver	Hematite	Frnaklinite
percentage	3	4	trace
morphology	Irregular blobs on Unknown Ag-Cu Sulfide	Euhedral xtals associated with Unknown Ag-Cu Sulfide	Euhedral xtals
texture	disseminated	disseminated	disseminated
transmitted optical properties	opaque	opaque	
reflected optical properties	Yellow with orange tarnish (happens quickly); soft Weakly? anisotropic	White, brighter than Unknown Ag-Cu Sulfide Deep carmine red internal reflections Weak to moderate anisotropy; no bireflectance (not hm)	
contact/relationships with other minerals	Irregular with Unknown Ag-Cu Sulfide, exosolution from Unknown Ag-Cu Sulfide? Straight contacts with sp and white Ag-min	Straight contact edge with Unknown Ag-Cu Sulfide. Some embayments with sp, sp found in mineral (replacing Ag-min). Straight contact with yellow Ag-min	Some xtals included in Unknown Ag-Cu Sulfide, but have straight contacts (coeval). Embayed into white Ag-min, replacing Ag.
other (growth direction/zoning)	Tarnished		

minerals	Hematite	Franklinite	Mckinstryite
percentage	5	4	12
morphology	Small laths found in more heavily sheared areas	Small round xtals associated with hm	Anhedral masses with py
texture	Disseminated	disseminated	Disseminated, vein hosted
transmitted optical properties			
reflected optical properties	Strong bireflectance		
contact/relationships with other minerals	Replacing dol, qtz, and wl. Also euhedral xtals growing on Unknown Ag-Cu Sulfide (replacing Unknown Ag-Cu Sulfide?)	See hematite	Found in later veins, straight edges with wl, replacing some qtz. Being replaced by hm + frk
other (growth direction/zoning)		Exsolution of hm from frk	Contains py

Paragenesis:

Structures: Areas with small wl and hm are associated with shearing. Fractures after main mineralization are also present and filled with Unknown Ag-Cu Sulfide. Ore mineralization was still occurring, but at a decreased rate. Hm and Frk may be on Unknown Ag-Cu Sulfide, need to view on SEM. The minerals are more likely Ag-mins, but unsure as of 3/18/2011
Paragenetic Sequence: dol→Wl + Qtz→Hm + Frk→Unknown Ag-Cu Sulfide→Ag mins→Sp?
Paragenetic Reasoning: Cross-cutting relationships and overgrowths of minerals
Sample Highlights: Substantial presence of Unknown Ag-Cu Sulfide, with lots of sulfosalts?

Sample #: 012-347B

Hole #: VZMIF 012

Sample Interval: 347.8-347.95 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Disseminated Silicate (in BH)

Sample Photograph

Other Sample Information: Same as 012-347A, but with more qtz and galena at the expense of willemite

Sample #: 012-349

Hole #: VZMIF 012

Sample Interval: 349.75-349.85 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Disseminated Silicate (SD) in BH

Sample Photograph

Other Sample Information: ~2% Zn and 12% Fe

** Similar to 125-130**

minerals	Dolomite	Hematite	quartz
percentage	42	55	3
morphology	Euhedral sparry dol	Veins and euhedral xtal laths	Anhedral replacement xtals
texture	Brecciated, being replaced by hm	Semi-massive	Veins, being replaced
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Being replaced by hm and qtz. Irregular contacts with both mins	Shredded, irregular contacts with dol and qtz	Being replaced by hm and Fe-dol in vein
other (growth direction/zoning)			

minerals	Franklinite		
percentage	trace		
morphology	Very minute blebs		
texture	Sparsely disseminated		
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Coeval with hm		
other (growth direction/zoning)	Difficult to find		

Paragenesis:

Structures: There are some dolomite veins that are orthogonal to the main shear (later even tension gashes?) The hm composes the main shear in this sample
Paragenetic Sequence: See chart
Paragenetic Reasoning: cross-cutting of minerals and irregular contacts
Sample Highlights: see 125-130

Sample #: 20-277

Hole #: VZMIF 020

Sample Interval: 276.85-277 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: No wl in sample or in drill hole

minerals	Dolomite	Hematite	quartz
percentage	70	20	10
morphology	Large euhedral xtals, some smaller 2ndary dol xtals growing on larger ones	Subhedral laths to semi-massive veins	Anhedral, follows fractures and dol xtal boundaries, associated with hm
texture	Neomorphic carbonate	Netted texture in veins (b/w specular and non specular hm). Replacement similar to	Replacement texture along dol xtal boundaries and in hm-rich zones
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Sharp contacts with dol. More irregular contacts with qtz. Embayments and hm overgrowths on dol contacts	Lath shaped overgrowths on dol and qtz	Wavy contacts with hm and dol, replaced by hm
other (growth direction/zoning)			

Structures: ~3 dol and qtz veins that run through dol and hm zones. Veins being replaced by hm when in hm and dol when in dol (after dol, but during hm events)
Paragenetic Sequence: dol→2ndary dol→qtz→hm + qtz→dol/qtz veins→hm (hm is continuous until end)
Paragenetic Reasoning: dol recrystallized and is being replaced in the center of crystals by smaller dol xtals. Qtz is replacing dol along xtal boundaries but is being replaced by hm. Hm is replacing dol as well. Dol/qtz veins cut across existing hm and dol, but have some hm laths overgrowing the veins, suggesting that hm is coeval with later qtz and the veining.
Sample Highlights: dol veins

Sample #: 020-295

Hole #: VZMIF 295

Sample Interval: 295.55-295.9 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: Large Fe-carbonate vein

minerals	Dolomite	Fe-rich dol	quartz
percentage	30	55	10
morphology	Small xtals neomorphosing to large euhedral xtals,	See dolomite	Amorphous, small to larger xtals
texture	Large xtals growing to fill in open space fractures from bx	Dol + hm filling in open space	Veins, filling open space
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Straight contacts with all mins	Straight contacts with all mins	Straight contacts with other qtz and most dol. Some irregular contacts with dol (bx fragments?)
other (growth direction/zoning)		Fe-dol is simply dolomite with interstitial hematite giving it its color.	

minerals	hematite		
percentage	5		
morphology	Massive or in euhedral laths. Laths associated with qtz		
texture	Disseminated throughout Fe-dol or in veins		
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Straight edges with dol and qtz		
other (growth direction/zoning)			

Structures: Qtz vein being cut by regular dol. Qtz vein is folded. Some qtz being replaced by dol
Paragenetic Sequence: Dol→qtz→hm
Paragenetic Reasoning: qtz contains fragments of dol and is being overgrown by hm
Sample Highlights: Sample is an example of Fe-carb alteration. Do microprobe and/or SEM analysis for further data.

Sample #: 20-323

Hole #: VZMIF 020

Sample Interval: 323.45-323.6 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Disseminated Silicate (SD in BH)

Sample Photograph

VZMIF 020

323.45-323.6

Other Sample Information: Contains Sp***

minerals	Fe-carb	Quartz	Sphalerite
percentage	75	5	10
morphology	Hydrothermal sparite, very large xtals	Anhedral grains	veinlet
texture	Rock forming, brecciated	Disseminated, being replaced by Fe-carb and Hm	Semi-massive in veinlets
transmitted optical properties			Transparent in ppl
reflected optical properties			
contact/ relationships with other minerals	Irregular, replacing qtz, being replaced by late carb and hm	Very irregular boundaries with Fe-carb and hm (these mins replacing qtz)	Irregular contacts w/ Fe-carb, cutting Fe-carb, straight contacts with Hm inclusions
other (growth direction/zoning)			Contains disseminated hm crystals

minerals	Hematite	Late Carb veinlets	
percentage	7	3	
morphology	Crystal laths, specular and nonspecular Disseminated in Sp	Fine-grained carb	
texture			
	Veinlets and disseminated	veinlets	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular with qtz and Fe-carb	Cut all other minerals, replaces Fe-carb	
other (growth direction/zoning)			

Structure: Sheared Sp in sample
Paragenetic Sequence:
Paragenetic Reasoning: Sp in a shear vein, cutting Fe-carb alteration
Sample Highlights:

Sample #: 032-157

Hole #: VZMSF 032

Sample Interval: 157.05-157.4 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Pink dolomite (DO)

Sample Photograph

Other Sample Information: Magnetite vein in bx, near contact between BH and Serra do Garrote

*V high in this sample

minerals	Dolomite	Magnetite	Hematite
percentage	35	20	25
morphology	Euhedral xtals, small in matrix, some larger neomorphosed xtals	Euhedral xtals forming massive vein	Pseudomorphs of mt. also found in thin veins running through chlorite
texture	Sparry matrix	Vein filling texture	Replacing mt, veins in chl
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight edges with chlorite. Replacement by iron oxides, embayments, xtal replacements of dol by mt. Found as euhedral xtals in chl	Fuzzy contact with hm. Irregular contacts with chl and dol	Veins are straight contacts w/ chl. Fuzzy edges w/ mt. Some irregular edges with dol and chl
other (growth direction/zoning)		2 types of mt? brn-grey and dark grey?	2 stages of hm: veins (early) and replacement of mt (later)

minerals	Chlorite	Goethite	Unknown
percentage	15	2	trace
morphology	Long fibrous xtals	Thin veins	Euhedral center of mt
texture	Sheared, vein forming	fuzzy	Being replaced by hm
transmitted optical properties	Blue in xpl		
reflected optical properties		Bluish-grey, darker than hm	Dark grey compared to hm and more grey than mt. Weakly anisotropic
contact/relationships with other minerals	Some irregular contacts with mt, straight contacts with dol and hm veins	Cloudy edges with sphalerite (oxidizing), shreddy edges with chl, (reflection of goe and chl morphology?), replacing mt	Wavy edges and embayments with hm
other (growth direction/zoning)			

minerals	Sphalerite		
percentage	3		
morphology	Hydrothermal veins and as disseminated xtals		
texture	Small veins and xtals in chl, being replaced by goe		
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular contacts with goe and chl		
other (growth direction/zoning)			

Structures: Shear vein filled with chl, sp, goe, and mt. Goe appears to be altered from chl and possibly sp.
Paragenetic Sequence: dol→mt+chl+(unknown)→hm
Paragenetic Reasoning: dol has been fractured and filled with chl and mt. The mt is being replaced by hm, as seen by the embayments, fuzzy edges, and irregular contacts b/w mt and hm.
Sample Highlights: magnetite, unknown mins, chl, high V content

Sample #: 32-177

Hole #: VZMSF 032

Sample Interval: 177.3-177.5 m

Geologic Unit: Serra do Garrote

Lithological Unit (Votorantim): Carbonaceous phyllites (FC)

Sample Photograph

Other Sample Information:

minerals	Fine-grained silicates	Carbonate (calcite?)	pyrite
percentage	70	23	4
morphology	Foliated, mostly composed of quartz with some dark, non-reflective opaques (carbon?)	Large, subhedral xtals with minor qtz associations (1%)	Small crystals in fine-grained silicates Discontinuous veinlets next to Sp (more granular than Sp)
texture	Foliated, rock matrix	Vein-forming, hydrothermal?	Foliated with silicate matrix; some found within Sp as disseminations
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Rock matrix, being cut by carbonate vein	Cutting rock matrix, next to Sp + Cpy veinlet	Veinlet xtals being replaced by Sp Within Sp and rock matrix some minor replacement
other (growth direction/zoning)			

minerals	Sphalerite	Chalcopyrite	Arsenopyrite
percentage	1	1	Very trace
morphology	Semi-massive in veinlet	disseminated throughout Sp veinlet	Very disseminated throughout Sp veinlet
texture	Veinlet-forming	Veinlet-forming, Cpy disease	Very disseminated in SP
transmitted optical properties			
reflected optical properties			Pinkish tint
contact/ relationships with other minerals	Replacing py and some cpy	Being exsolved from sp	Within Sp, smooth contacts
other (growth direction/zoning)			

Structures: Silicate rock matrix is foliated, only one observed. Carbonate veinlet cuts foliation and caused local brecciation. Pyrite is include with silicate matrix and larger xtals associated with carbonate veinlet. Sp and Py veinlets are subparallel to foliation

Sample #: 032-157A

Hole #: VZMSF 032

Sample Interval: 157.05-157.4 m

Geologic Unit: Serra do Garrote

Lithological Unit (Votorantim): Carbonaceous Phyllite (FC)

Sample Photograph

VZMSF 032

187.1 - 187.3

Other Sample Information:

minerals	Quartz	Mica and Clays	Calcite
percentage	40	24	15
morphology	Very fine anhedral grains	Very fine, subhedral laths	Very fine subhedral xtals, larger xtals in veins
texture	Foliated rock matrix	Foliated rock matrix	Foliated rock matrix and vein
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals			
other (growth direction/zoning)			

minerals	Pyrite	Sphalerite	chalcopyrite
percentage	15	5	1
morphology	Anhedral grains	Anhedral grains	Anhedral grains
texture	Disseminated, small grains. Large vein	Disseminated, larger in vein.	Cpy disease in sl, associated with some py
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Rounded grains in matrix. Blebs with sl embayments in py-vein	Wavy contacts with matrix and py, replacing py?	Mostly cpy disease in sl. Some cpy with wavy contacts in py.
other (growth direction/zoning)			

Structures: Pyrite and calcite veins. Large py vein is folded (follow small py foliation). Foliation in phyllite
Paragenetic Sequence: py→sl→cpy
Paragenetic Reasoning: Py is embayed by sl, which contains cpy disease
Sample Highlights: foliation, sulfides

Sample #: 032-187B

Hole #: VZMSF 032

Sample Interval: 187.1-187.3 m

Geologic Unit: Serra do Garrote

Lithological Unit (Votorantim): Filito Carbonação (FC)

Sample Photograph

Other Sample Information: Same as 032-187A, but with trace Pyrrhotite

minerals			
percentage			
morphology			
texture			
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals			
other (growth direction/zoning)			

Sample #: 32-199

Hole #: VZMSF 032

Sample Interval: 199.24-199.5 m

Geologic Unit: Serra do Garrote

Lithological Unit (Votorantim): Carbonaceous phyllites (FC)

Sample Photograph

Other Sample Information:

Yellow part of vein is Py, grey part is carbonate

minerals	Fine-grained siliciclastic	Carbonate	Pyrite
percentage	30	25	45
morphology	Foliated, slightly elongated	Localized in a pod/veinlet	Foliated, composed most of rock matrix
texture	Foliated rock forming matrix	Foliated, grains include some qtz and are sheared (sense difficult to tell, left lateral?)	Disseminated throughout siliciclastic mins, composed majority of rock matrix Some zones have larger eu-hedral py
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Straight edges with py, gradational to sharp contact with carbonate	Ranges from a sharp to gradational contact with dark silicates and Py	Straight contacts with all (diagenetic?)
other (growth direction/zoning)		Poor in pyrite	Some zones more rich in pyrite when associated with siliciclastics

minerals			
percentage			
morphology			
texture			
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals			
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

Siliciclastics   _____

Carb   _____

Py   _____

Sample #: 43-191

Hole #: VZMIF 043

Sample Interval: 191.1-191.3 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Pink dolomite with phyllite intercalations (DG)

Sample Photograph

Other Sample Information: Maroon phyllite is replaced by hematite, green phyllite contains very very fine chlorite

minerals	Dolomite	Chlorite?	Quartz
percentage	40	30	20
morphology	micritic	Ultra fine crystals	Subangular to subrounded grains Minor qtz cement in some veins and vugs
texture	Fine laminations with quartz-rich layers and chl dominated layers	Replacement of dol? Finely laminated with dol and dol + qtz	Disseminated grains found in lenses within dol
transmitted optical properties		Pleochroic in ppl	
reflected optical properties			
contact/ relationships with other minerals	Diffuse and fuzzy contact with chl, being replaced by chl	See dol*	Straight grain boundaries with dol and hm Later open spaced-filling qtz cement
other (growth direction/zoning)		Turns phyllite green	

Sample #: 43-264

Hole #: VZMIF 043

Sample Interval: 264.75-264.93 m

Geologic Unit: Upper Morro do Pinheiro

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information:

minerals	Dolomite	Fe-carb	Hematite
percentage	80	20	trace
morphology	Micritic boundstone with sparry carbonate cement	Sparry carbonate	Irregular crystals blebs
texture	Algal layering with dissolution features filled with carbonate cement	Veinlet	Disseminated in Fe-carb veinlet
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Primary structure in host rock	Cutting boundstone, tiny veinlet nets with hm on margins	Replacing Fe-carb
other (growth direction/zoning)			

Sample #: 43-272

Hole #: VZMIF 043

Sample Interval: 272.4-272.72 m

Geologic Unit: Upper Morro do Pinheiro

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information:

minerals	Dolomite	Carbonate Cement	Quartz
percentage	60	20	20
morphology	Intracalstic micritic rudstone	Solution filled sparite and fine grained cement in fault	Some minor med-sized qtz veins Mostly large rounded and partially recrystallized quartz grain s in fault
texture	Rudstone with solution cavity fill and replacement by carbonate cement	solution cavity fill and replacement by carbonate cement Micritic cataclastic cement in fault zone	Competent grains in cataclastic site
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight contacts with qtz and carb cement	See dol	Some recrystallized contacts with qtz other qtz grains Veins cross-cut dol
other (growth direction/zoning)			Some rotation, not cut perpendicular to shear zone,

Paragenesis:

Sample #: 043-56

Hole #: VZMIF 043

Sample Interval: 55.95-56.07 m

Geologic Unit: Middle Pamplona

VZMIF 043 55.95-56.07

Other Sample Information: Pink, massive dolarenite with py/ hm veins

minerals	dolomite	quartz	pyrite
percentage	70	10	20
morphology	Small, subedral to euhedral grains. Larger recrystallized euhedral grains in veins	occurs in irregular lenses. Some larger anhedral grains in dol matrix. Filling voids	Angular grains with botryoidal overgrowths in vein
texture	Rock matrix,	Replacing dolomite	Massive/semi massive in vein
transmitted optical properties			opaque
color ppl xpl	Clear Pastels	Clear Black and white	
pleochroism	n/a	N/a	
birefringence	3rd order	1st order	
twinning/ cleavage	Rhombohedral twinning	Undulatory extinction	
other		High relief	
reflected optical properties	N/a	n/a	
color			Light yellow
bireflectance			n/a
anisotropy			Faint color change if present
internal reflections			n/a
other			
contact/ relationships with other minerals	Being replaced by qtz. Irregular contact with py overgrowths	Irregular and blobby contact with dolomite, replacing dolomite.	Overgrowing dolomite in vein
other (growth direction/zoning)	Filling in fracture	Replacement lenses	Outward zoning

minerals	Unknown, hematite?		
percentage	trace		
morphology	Thin rims around pyrite		
texture	Rimming, replacing		
transmitted optical properties	opaque		
color ppl xpl			
pleochroism			
birefringence			
twinning/ cleavage			
other			
reflected optical properties			
color	grey		
bireflectance	weak, grey to darker grey		
anisotropy	Moderate? Blueish grey to dark grey		
internal reflections	Non observed		
other			
contact/ relationships with other minerals	Irregular with py, has small embayments, replacing pyrite. Straight contacts with dol		
other (growth direction/zoning)	Grows on outside of py		

Structures: Fracture filled in by dolomite and pyrite
Paragenetic Sequence: dol→fracture→dol recrystallization→py + hm?(slightly later than py)→qtz
Paragenetic Reasoning: Dolomite crystals are large around the edges of the fracture, suggesting recrystallization of the host rock into the vein. The py and hm are intergrown and both growing on top of the dolomite (Fig 2) and are in the center of the vein. The contacts between the pyrite and quartz are fairly straight, suggesting little interaction. There are a few specs of py in the qtz, indicating that the pyritic fluid was at an end when silicification occurred. The qtz is late, replacing dolomite.   *No qtz in fracture with dol and py*
Sample Highlights: Pyrite overgrowths with interim hematite

Sample #: 43-65

Hole #: VZMIF 043

Sample Interval: 65.66-65.87 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Pink Dolomite (DG)

Sample Photograph

Other Sample Information: maroon staining contains more hematite

minerals	Dolomite	Quartz	Muscovite
percentage	80	17	3
morphology	Micritic clasts and matrix	Subangular to subrounded grains	Flattened laths and needles
texture	Composes clasts (with mud-cracks); host mineral fabric to qtz and musc; some pressure shadows	Foliated and rotated grains indicating shear	Oriented and flattened grains indicating shear
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular contacts with hm, replacing hm	Straight edges with musc and dol	Straight edges with qtz and dol
other (growth direction/zoning)			

minerals	Hematite		
percentage	Trace		
morphology	Rounded grains		
texture	Disseminated, more concentrated in maroon zones		
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Somewhat irregular contacts with dol, replacing dol		
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

Dol   _____

Qtz   _____

Musc   _____

Hm   _____

Sample #: 43-97

Hole #: VZMIF 043

Sample Interval: 97.7—97.95 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Pink dolomite (DG)

Sample Photograph

Other Sample Information:

minerals	Fe-Chlorite	Quartz	Muscovite
percentage	85	5	3
morphology	Very fine crystalline	0.1-0.2 mm sized grains, subangular to rounded	0.3-0.4 mm crystal laths
texture	Same extinction	disseminated	disseminated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Straight contacts with all mins except hm, hem replacing all minerals	Straight contacts with all mins except hm, hem replacing all minerals	Straight contacts with all mins except hm, hem replacing all minerals
other (growth direction/zoning)			

minerals	Dolomite	Hematite	
percentage	3	4	
morphology	Rounded grains	Irregular crystals	
texture	disseminated	disseminated	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight contacts with all mins except hm, hm replacing all minerals	Straight contacts with all mins except hm, hm replacing all minerals	Straight contacts with all mins except hm, hm replacing all minerals
other (growth direction/zoning)			

Paragenesis:

Time   **Early** **Late**

Unknown Clay-silicate   _____

Dol   _____

Qtz   _____

Musc   _____

Hm   -----

Sample #: 60-136A

Hole #: VZMIF 060

Sample Interval: 136.3-136.45 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate in Hydrothermal Breccia

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Sample Photograph

Other Sample Information:

minerals	Dolomite	Willemite	Hematite
percentage	15	72	2
morphology	Large, euhedral crystals and minor amounts of small anhedral Fe-dol overgrowing euhedral dol	Small (0.1-0.2 mm) granular euhedral crystals as well as lesser amounts of larger (0.5 -1 mm) euhedral laths	Some euhedral crystal laths, mostly irregular crystals
texture	Growing in dol veins, minor amounts in late, sulfide veins	Massive	Sheared, semi-massive
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Dol has mostly straight contacts with wl, being overgrown/replaced by wl. Fe-dol is replacing dol and wl	Somewhat irregular contacts with dol filling in fractures, being replaced by Fe-dol. Lath-shaped wl overgrowing granular wl	Straight contacts with frk, replacing dol
other (growth direction/zoning)	Large dol filling vein		

minerals	Franklinite	Galena	Sphalerite
percentage	5	5	trace
morphology	Subhedral to euhedral crystals that increase in size in proximity to galena	Irregular crystals veins	Irregular xtals
texture	Disseminated with some semi-massive clusters	Vein forming	Surrounded by gn in vein and vug
transmitted optical properties			
reflected optical properties			More brown than frk
contact/ relationships with other minerals	Straight contacts with gn and hm	Has straight contacts with frk, unknown Ag min and srm. Cuts through sp and is replacing sp	Being replaced by gn
other (growth direction/zoning)	Exsolving hm		

minerals	Stromeyerite	Chalcocite	Covelite
percentage	trace	Very trace	trace
morphology	Irregular xtals	Irregular xtals	Small fibers
texture	Growing on gn	Growing on gn	Growing on srm, cc and gn
transmitted optical properties			
reflected optical properties	Slight violet tinge to gray in ppl Strong blue-indigo anisotro-	Steel blue	Blue in ppl Orange-yellow anisotropy
contact/ relationships with other minerals	Growing on gn, irregular contacts with cv and cc be- ing replaced by cv and cc	Irregular contact with cv, being replaced by cv	Replacing srm and cc, jag- ged contacts with both mins
other (growth di- rection/zoning)			

Sample #:

Hole #: VZMIF

Sample Interval: 136.3-136.45 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (SM) in the Hydrothermal Breccia (BH)

Sample Photograph

Other Sample Information: No sulfides like in 60-136A

minerals	Dolomite	Willemite	Quartz
percentage	20	60	10
morphology	Large euhedral hydrothermal dol xtals with later minor fine xtals	Large xtal laths and some smaller finer granular xtals	Large anhedral xtals
texture	brecciated	Massive, has been brecciated	Disseminated/brecciated
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Large dol xtals have irregular contacts and being replaced by qtz, wl, late fine dol and hm/frk	Lath-shaped xtals are later, growing in qtz, large dol, and granular wl. Granular wl replaced qtz and dol. Irregular contacts with hm/frk which are replacing wl	Irregular contacts with all minerals, being replaced by all minerals
other (growth direction/zoning)	Original zoning may be present, but fully replaced by wl		Original grain may be present but pseudomorphed by wl

minerals	Hematite	Franklinite	
percentage	5	5	
morphology	Sheared veins with hm xtal laths	Semi-massive amalgamations of granular xtals	
texture	Shear veins	Associated with hm	
transmitted optical properties			
reflected optical properties		Grey, lighter than hm, darker than sp	
contact/relationships with other minerals	Irregular, replacing all mins	Irregular replacing all mins,	
other (growth direction/zoning)		replacing wl on old dol clvg planes	

Sample #: 60-210

Hole #: VZMIF 060

Sample Interval: 210.18-210.38 m

Geologic Unit: Upper Morro do Pinheiro

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information:

minerals	Dolomite	Hydrothermal Carbonate	Quartz
percentage	25	30	40
morphology	Crystalline carbonate	euhedral	Euhedral
texture	Medium spar	Megaspar in vein	Megacrystalline in vein
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Host rock	Growing out from host rock, transition into quartz; brecciated	Growing out from host and transition into carbonate; sheared
other (growth direction/zoning)			

minerals	Pyrite	Sphalerite	Hematite
percentage	4	1	trace
morphology	Anhedral granular xtals	Crystalline, anhedral	Crystalline, anhedral
texture	In veinlets	In open space in breccia	Fracture filling in breccia
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight contacts with qtz, some fractures	Straight contacts with carb	Irregular contacts with carb, minor replacement
other (growth direction/zoning)			

Sample #: 60-78A

Hole #: VZMIF 060

Sample Interval: 77.95-88.15 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Pink dolomite (DG)

Sample Photograph

Other Sample Information: Fe-carbonate alteration in a minor bx in the Lower Pamplona

minerals	Dolomite	Hydrothermal dolomite	Quartz
percentage	30	45	5
morphology	Subhedral crystalline dolomite	Sparry, euhedral	Elongate, anhedral xtals
texture	Composes host rock	Vein-filling	Replacing interstices between large hydrothermal dol xtals
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight contacts with itself, fault/brecciated contact with hm and hydrothermal dol	Contains some hm inclusions, being replaced by hm at bx margins, being replaced by qtz	Replacing hydrothermal dol
other (growth direction/zoning)		Growing towards vein centers	

minerals	Hematite + Goethite		
percentage	20		
morphology	Fracture and vein forming		
texture	Continuous veinlets comprising a larger vein		
transmitted optical properties	Goe translucent with condenser lens (more orange-brown)		
reflected optical properties	Hm whiter than Goe (bluish grey)		
contact/relationships with other minerals	Replacing hydrothermal dolomite		
other (growth direction/zoning)			

Sample #: 60-78B

Hole #: VZMIF 060

Sample Interval: 77.95-88.15 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Pink dolomite (DG)

Sample Photograph

Other Sample Information: Fe-carbonate alteration in a minor bx in the Lower Pamplona

* Contains Py instead of Hm in 60-78A

minerals	Dolomite	Hydrothermal dolomite	Quartz
percentage	20	45	15
morphology	Subhedral crystalline dolomite	Sparry, euhedral	chalcedonic
texture	Host rock bx piece	Vein-filling	Replacing dolomite host rock, minor occurrences with hydrothermal dol (replacing h. dol)
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight contacts with itself, fault/brecciated contact with hm and hydrothermal dol. Being replaced by qtz	Contains some hm inclusions, being replaced by hm at bx margins, being replaced by qtz	Replacing dol host rock and hydrothermal dol
other (growth direction/zoning)		Growing towards vein centers	

minerals	Goethite	Pyrite	
percentage	15	5	
morphology	Fracture and vein forming	anhedral	
texture	Continuous veinlets comprising a larger vein	Vein forming	
transmitted optical properties	Goe translucent with condenser lens (more orange-brown)		
reflected optical properties	bluish grey		
contact/relationships with other minerals	Replacing hydrothermal dolomite	Being replaced by Goe	
other (growth direction/zoning)			

Sample #: 088-125

Hole #: VZMIF 088

Sample Interval: 125.9—126.03 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Phyllite and pink dolomite (DG)

Sample Photograph

Other Sample Information:

minerals	Dolomite	Quartz	Unknown—Chl?
percentage	20	35	45
morphology	Clast in phyllite	Subangular to subrounded	platy
texture	boundstone	laminar	Very fine
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular, brittle contact with qtz and phyllite rock	Smooth contacts with phyl- lite host rock, some qtz vein- lets growing in between carb and phyllite	Coeval with qtz and micas
other (growth di- rection/zoning)			

minerals	White Mica	Hematite	
percentage	trace	trace	
morphology	Euhedral	Irregular crystalline	
texture	Disseminated	disseminated	
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Composes host rock	Replacement of grains in phyllite	
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

Sample #: 088-164

Hole #: VZMIF 088

Sample Interval: 164.17—164.32 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Pink Dolomite

Sample Photograph

Other Sample Information:

minerals	Grey dolomite	Orange dolomite	Hematite
percentage	50	50	trace
morphology	Crystalline carbonate	Crystalline carbonate	Irregular xtals
texture	Some neomorphic vugs	Some neomorphic vugs	Disseminated in orange dol
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals		Fades into regular dol	Irregular edges with orange dol, replacing orange dol
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

Grey Dol

Orange Dol

Hm

Sample #: 88-69

Hole #: VZMIF 088

Sample Interval: 68.45-69.56 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information:

minerals	Carbonate	Quartz	Sphalerite
percentage	20	7	65
morphology	Large sparite with late fine-grained carb	Anhedral crystalline	Massive crystalline
texture	Brecciated, fine grain carb is in veinlets	Veinlets that cut sp	Massive and sheared
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Sparite is being replaced by sulfides, late fine carb is replacing sp, irregular contacts and spotty	Irregular contacts with sparite and sp, cutting these mins, replacing carb	Replacing carb, being cut by qtz, some inclusions of py and gn,
other (growth direction/zoning)			

minerals	Pyrite	Galena	
percentage	7	1	
morphology	Granular crystals	Anhedral inclusions	
texture	Fractured and disseminated	disseminated	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Minor replacement and exsolution from sphalerite	Round contacts included in sp	
other (growth direction/zoning)			

Sample #: 88-71.4

Hole #: VZMIF 088

Sample Interval: 71.46-71.62 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Disseminated Sulfide/Silicate in BH

Sample Photograph

Other Sample Information:

minerals	Pyrite	Sphaerlite	Galena
percentage	60	21	1
morphology	Euhedral cubes	Fine crystalline, appears to 'flow'	Semi massive in veinlets
texture	Forms massive sulfide	Semi-massive	Disseminated, discontinuous veinlets
transmitted optical properties			
reflected optical properties			Triangular facets
contact/ relationships with other minerals	Irregular with sp, being replaced by sp	Irregular with py, replacing py	Filling voids in sp, replacing sp?
other (growth direction/zoning)			

minerals	Carbonate	Quartz	Barite
percentage	15	3	trace
morphology	Hydrothermal carb	anhedral	Anhedral
texture	sparry	Replacing carb	Weakly associated with galena
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Jagged, irregular contacts, overgrowths and embayments with sulf; being replaced by sulfides and qtz	Being replaced by sulfides, irregular contacts and embayments	None observed, irregular contacts with all mins
other (growth direction/zoning)			

Sample #: 88-71.6

Hole #: VZMIF 088

Sample Interval: 71.62-71.78 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: Same as 88-71.4 less Py more Sp-rich

Sample #: 088-71

Hole #: VZMIF 088

Sample Interval: 70.97-71.1 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Disseminated Sulfides (in BH)

Sample Photograph

Other Sample Information:

minerals	Dolomite	Pyrite	Sphalerite
percentage	50	38	10
morphology	Dolomitic marble, large sparry xtals, los of twinning, some micrite in veins	Massive	massive
texture	Hydrothermal re-crystallization	brecciated	Vein/stringer vein; disseminated with py-disease
transmitted optical properties			Brown in ppl and xpl
reflected optical properties			Internal reflections are yellow to clear, not red
contact/relationships with other minerals	Straight contacts, growing in fractures between py	Straight contacts with dol, growing over dol. Irregular contacts with sp (from bx?), being replaced by sp	Cutting across some py, replacement of py
other (growth direction/zoning)			Occurs in semi-stringer veins after py. Contains some py-disease (NOT Cpy)

minerals	Quartz	Galena	
percentage	2	trace	
morphology	vein	Anhedral grains	
texture	chalcedonic	Disseminated in sphalerite	
transmitted optical properties			
reflected optical properties		Shows signs of anomalous anisotropy along scratches (see Uytendogaardt & Burke 1971)	
contact/relationships with other minerals	Straight edges with all mins, filling in fractures with dol in between py grains		
other (growth direction/zoning)			

Structures: Sample consists of recrystallized dolomite that was brecciated, filled in with pyrite, then brecciated again. During the pyrite fluid event, a later pulse of Zn-rich sphalerite with minor galena came through replacing some of the pyrite. Euhedral dolomite crystals are in contact with sphalerite, indicating that recrystallization started before sphalerite precipitated.
Paragenetic Sequence: See chart
Paragenetic Reasoning: see structures
Sample Highlights: Paucity of galena, evidence of 2 bx events

Sample #: 088-72

Hole #: VZMIF 088

Sample Interval: 71.85—72.08 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: Same as 088-71.4 only with slightly more Gn (~1%); note Gn is slightly later than Sp in these samples

Sample #: 088-75A

Hole #: VZMIF 088

Sample Interval: 75.19-75.36 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

VZMIF 088

75.19 - 75.36

Other Sample Information: 0.3% Zn

minerals	Fe-dolomite	Quartz	Dolomite
percentage	70	15	10
morphology	Subhedral to euhedral, sparry dolomite with hematite inclusions	Chalcedonic, cataclastic, and anhedral xtals	Euhedral xtals
texture	brecciated	In veins with dol and in between and replacing Fe-dol	In veins
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Somewhat irregular with quartz, being replaced by qtz. Being cut by dol + qtz	Replacing Fe-dol and being cut by later dol veins, straight contacts with dol in veins	Cutting Fe-dol and cataclastic and chalcedonic qtz
other (growth direction/zoning)	Some “poker chip” carbonate present with overgrowths (alternating Fe-rich zones)		

minerals	hematite		
percentage	5		
morphology	Pseudomorphing cubes (py?)		
texture	Disseminated and replacing Fe-dol and former py		
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular with Fe-dol. * no py found in sample		
other (growth direction/zoning)			

Structures: Cataclastic qtz $\pm$ carb filling in fractures caused by brecciation (and faulting). Late carbonated veins cutting Fe-dol and earlier chalcedonic qtz (replacing Fe-dol) and cataclastic qtz. Hm appears to be pseudomorphing cubic crystals, possibly Py.
Paragenetic Sequence: Py? $\rightarrow$ Fe-dol + Hm $\rightarrow$ chalcedonic qtz $\rightarrow$ bx + cataclasites $\rightarrow$ qtz + carb veins
Paragenetic Reasoning: see diagram
Sample Highlights: Possible oxidation of py to hm

Sample #: 88-75B

Hole #: VZMIF 088

Sample Interval: 75.19-75.36

Geologic Unit: Hydrthermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia (BH)

Sample Photograph

VZMIF 088

75.19 - 75.36

Other Sample Information: Similar to 88-75A, but with less sparry Fe-dol and more micritic Fe-dol. Less Hm as well. Neomorphic carbonates common.

*(slightly further from main breccia shear than 88-75A)

Sample #: 88-79

Hole #: VZMIF 088

Sample Interval: 79.15-79.38 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information:

minerals	Recrystallized carb (dol)	Fe-carbonate	Quartz
percentage	50	40	5
morphology	Large sparry xtals	Sparry xtals, but looks “dirty” in ppl (b/c of trace hm inclusions)	Megaquartz xtals
texture	Host rock, fractured	Host rock, fractured	Veinlets and disseminations
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular contacts with qtz, fades into Fe-carb, being replaced by sulfides	Irregular contacts with qtz, fades into carb, being replaced by sulfides	Spotty, wavy and irregular contacts with both carbonates, no contact observed with sulfides
other (growth direction/zoning)			

minerals	Sphalerite	Galena	Hematite
percentage	5	3	2
morphology	Semi-massive	Semi-massive to disseminated	Crystalline laths
texture	Vug filling	Veinlet and vug filling	disseminated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Some irregular contacts with gn, replacing gn, irregular contacts with hm, sp is replacing hm, and cv is overgrowing sp	Gn is replacing sphalerite in some cases, irregular contacts with hm, replacing hm to a minor extent, being overgrown by cv	Irregular and corroded contacts with sp and gn, being replaced by these mins
other (growth direction/zoning)			

minerals	Covellite	Chalcocite	
percentage	trace	Very very trace	
morphology	Euhedral crystal blades	Irregular crystals	
texture	disseminated	Very disseminated	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Growing on sp and gn, jagged contacts with these mins	Growing on sp and gn, wavy contacts with these mins	
other (growth direction/zoning)			

Sample #: 088-80

Hole #: VZMIF 088

Sample Interval: 80.8—81.04

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: Same as 088-79

Sample #: 101-127

Hole #: VZMIF 101

Sample Interval: 127.2-127.4 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Disseminated Silicate (SD) of BH

Sample Photograph

Other Sample Information: Intensely sheared

minerals	Dolomite	Hematite	quartz
percentage	70	23	5
morphology	Fine grained where dol composes rock matrix. Larger, euhedral xtals in between bx fragments and in veins	Mostly in veins, but also in disseminated euhedral laths throughout dol	Euhedral xtals found in veins
texture	Sheared breccia	Sheared breccia	Folded veins
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight contacts with qtz and chl, irregular contact with hm and wl.	Straight with qtz, wavy with dol	Straight contacts with dol, wl, and hm
other (growth direction/zoning)	Growing towards center of veins (were dol veins exist)		Qtz veinlets cut the hm indicating a small later phase of qtz

minerals	Willemite	Chlorite	
percentage	1	1	
morphology	A few granular xtals overgrowing dol and one fibrous splay overgrowing qtz	In folded veins	
texture	disseminated	Feathery texture	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight with qtz, slightly irregular with dol	Irregular contact w/ hm	
other (growth direction/zoning)			

Structures: Folded veins after shear? and general shear of sample. The chlorite and qtz veins are folded and refolded after the main shearing event. The qtz veins cut the hm shear in places.
Paragenetic Sequence: dol→hm + wl + chl→qtz
Paragenetic Reasoning: The dolostone has been brecciated and recrystallized. During recrystallization, hematite along with chl and wl were deposited in the fractures and the sample began to undergo shearing. During the late stages of shearing, qtz and dol grew into open fractures that cross cut the hm and were further folded.
Sample Highlights: shearing

Sample #: 101-138

Hole #: VZMIF 101

Sample Interval: 138.4-138.53 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (SM) of BH

Sample Photograph

Other Sample Information:

minerals	Dolomite	Willemite	Quartz
percentage	10	60	15
morphology	anhedral	Variety of crystal sizes with respect to both granular and fibrous crystal habits	Subhedral
texture	Being replaced by qtz and wl	massive	Rimmed by wl, replaced by hm. disseminated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular contacts with hm, wl, and qtz, being replaced by these mins	Irregular and convoluted contacts with other mins. replacing dol, sl, and hm but also being replaced by hm	Straight contacts with wl (rimming qtz). Has inclusions and wavy contacts of hm
other (growth direction/zoning)		Rimming some qtz grains, replacing bx clasts	

minerals	Hematite	Franklinite	Galena
percentage	10	6	4
morphology	Anhedral, located in disseminated clusters	Subhedral xtals in late fracture veins	See Sl
texture	located in disseminated clusters, being replaced by wl and dol, associated with shearing	In late cracks (late bx?) and veins associated with Wl	See Sl
transmitted optical properties			White, triangular facets, less well-polished than hm
reflected optical properties			White, triangular facets, less well-polished than hm
contact/relationships with other minerals	Very wavy, and embayed with wl and possible qtz and dol? Mostly straight contacts with sl, some replacement by sl	Occurs with gn, irregular edges with wl and dol due to fracture, little mineral replacement	See Sl
other (growth direction/zoning)			

Paragenesis:

Structures: Sample has been brecciated and the clasts subsequently replaced by wl followed by further brecciation
Paragenetic Sequence: dol + qtz → wl + hm →sl+gn→Ag-sulfosalts
Paragenetic Reasoning: Dol and qtz were early. Dol is being replaced by wl, hm, and sl. Qtz grains also exist with wl rimming textures. Wl and hm seem to be coeval because they are all replacing one another, as seen by mineral inclusions and embayed contacts with each other. Sl and gn are later minerals filling in fractures from a brittle fracture event. Sl and gn are more closely associated with Wl. The Ag-sulfosalts are after and associated with gn. They are very minute and very late.
Sample Highlights: Lots of sphalerite and willemite   Rimming and replacement textures of willemite   ***some minor late sulfides

Sample #: 101-144

Hole #: VZMIF 101

Sample Interval: 144.6-144.75 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (SM)

Sample Photograph

Other Sample Information: 2.22% Zn

minerals	Dolomite	Hematite	Fe-rich dolomite
percentage	30	50	30
morphology	Large euhedral xtals and smaller anhedral xtals	Euhedral laths	Same as dol
texture	Large dol being replaced by small dol and hm	Stringer veins, altering dol and being altered by Fe-dol	Same as dol but with hm xtals included in dol xtals
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular w/ dol and hm (b/c of replacement)	Irregular see dol	Same as dol
other (growth direction/zoning)		Some hm overgrowths	

Sample #: 104-75

Hole #: VZMIF 104

Sample Interval: 75.5-75.8

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Pink Dolomite (DG)

Sample Photograph

Other Sample Information: ** Same as 110-150

Sample #: 104-80

Hole #: VZMIF 104

Sample Interval: 80.4-80.53 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information:

minerals	Carbonate	Quartz	Pyrite
percentage	60	20	5
morphology	Megacrystalline sparite	Micro and megacrystalline	Anhedral xtals
texture	Brecciated, recrystallized	Replacing carbonate	Fractured xtals in discontinuous veins
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Being replaced by sulfides and qtz	Replacing carb, being replaced by sulf	Replacing carb and qtz, being replaced by Sp and Fe-Ox
other (growth direction/zoning)			

minerals	Barite		
percentage	12		
morphology	Crystalline, anhedral (similar to qtz)		
texture	Forms veinlets associated with sulfides		
transmitted optical properties	Low birefringence		
reflected optical properties			
contact/ relationships with other minerals	Irregular, wavy contacts with gn, replacing gn to a small extent		
other (growth di- rection/zoning)			

minerals	Sphalerite	Galena	Unknown-Chalcocite?
percentage	1	2	trace
morphology	Anhdredal blebby xtals	Anhedral xtals	anhedral
texture	Disseminated	Disseminated and in veinlets	disseminated
transmitted optical properties			opaque
reflected optical properties			Color: light blue-grey Birefl: weak to mod Anis: mod pink-grey IR: none
contact/ relationships with other minerals	Replacing Py, coeval w/ Gn (some Gn replacing Sp and vice versa)	Coeval with Sp (some Gn replacing Sp and vice versa)	Chalcocite? Replacing Sp and Py
other (growth di- rection/zoning)			

Sample #: 104-85

Hole #: VZMIF 104

Sample Interval: 85.15-85.3 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): SM in Hydrothermal Breccia

Sample Photograph

Other Sample Information: From Gilberto Batista

minerals	Dolomite (Ferroan)	Willemite	chlorite
percentage	40	27	10
morphology	Anhedral, in fractures in between wl fragments	Subhedral to euhedral xtals on breccia fragments	Fibrous xtals in anastomosing veins
texture	Fracture filling and replacing wl, minor replacement of chl. Associated with hm (being replaced by hm as well)	Replacing original dol bx fragments, but being replaced by recent dolomitization of bx fractures	Vein
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Dol is filling in fractures and creating small embayments in wl. Irregular contact with hm, hm replacing dol.	Fractured edges with dol, being replaced by dol. Hm blebs on wl with irregular contacts.	Straight contacts with dol and wl. Somewhat irregular edge with sl and hm. Altering to hm
other (growth direction/zoning)			

minerals	hematite	sphalerite	
percentage	20	3	
morphology	Euhedral xtal laths	Anhedral to euhedral xtals, associated with chl	
texture	Disseminated and veining	disseminated	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular with everything, replacing all mins	Some irregular edges with dolomite and hm, straight contacts with wl and chl	
other (growth direction/zoning)			

Structures: The sample has been brecciated under brittle conditions during which replacement of dolomite by willemite and minor hematite took place. After brecciation and wl mineralization, Fe-dolomite filled in the fractures and started to replace wl. The chlorite shear then cut the sample. The fluid contained chl as well as sl and some hm. Sl seems to be minorly diagenetic in the sample as it occurs in some of the wl breccia clasts.
Paragenetic Sequence: see chart*

Sample #: 104-86

Hole #: VZMIF 104

Sample Interval: 85.98-85.08 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate in BH

Sample Photograph

VZMIF 104 85.98-86.08

Other Sample Information:

minerals	Dolomite	Hematite	Willemite
percentage	60	15	22
morphology	Sparry and micritic dol	Euhedral laths	Subhedral granular, minor fibrous splays
texture	Sheared micritic dol and sparry vein dol. Original sparry dol being replaced by wl and hm	Small xtals in dol and shear veins b/w bx clasts	Make up bx clasts
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Most sparry dol is being replaced by wl, qtz, and hm (except for sparry dol in veins) and micritic dol is replacing wl	Replacing all mins, shreddy contacts	Replacing sparry dol and being replaced by hm and micritic dol (some straight, mostly irregular edges)
other (growth direction/zoning)		Some exsolution laths in sphalerite	

minerals	Quartz	Sphalerite	
percentage	3	trace	
morphology	Anhedral, flattened xtals	Very small, range from anhedral to euhedral in shape	
texture	Boudinaged? vein	disseminated	
transmitted optical properties	Very low 1st order (cut thin)		
reflected optical properties			
contact/relationships with other minerals	Very irregular with dol, replacing early dol and being replaced by fine-grained late dol	Some straight and curvy contacts with both wl and dol, more closely associated with wl	
other (growth direction/zoning)	flattened		

Paragenesis:

Structures: General brecciation and shearing of sample. Quartz provides evidence for shearing. Willemite/dolomite clasts show brecciation.
Paragenetic Sequence:
Paragenetic Reasoning: Dolomite occurred first as it is being replaced by willemite (second) in breccia clasts floating in hematite (third).

Sample #: 104-87

Hole #: VZMIF 104

Sample Interval: 87.5—87.63 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: Same as 104-80

Sample #: 105-133A

Hole #: VZMIF 105

Sample Interval: 113.6-113.8 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): DG—Intercalated phyllites and dolomites

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Sample Photograph

VZMIF 105 113.6-113.8

Other Sample Information: Part of dolomite marble in Lower Pamplona

minerals	Dolomite	Quartz	Fe-oxides
percentage	85	5	1
morphology	Micrite to sparry	Directional growth during shearing	anhedral
texture	Sheared, annealed, and fractured (in that order)	Chalcedonic fibers	Fracture filling
transmitted optical properties			
reflected optical properties			Bluish-grey to light purple with orange tinge
contact/relationships with other minerals	Irregular contact b/w qtz and sparry dol. Irregular and embayed contacts w/ sulfides, dol is being replaced by sulfides	Replacing sparry dol	Irregular with gn, replacing gn. Straight edges with sl. and dol
other (growth direction/zoning)			

minerals	Sphalerite	Galena	Chalcopyrite
percentage	4	5	trace
morphology	Fracture filling, anhedral to subhedra	See Sl	Anhedral blebs
texture	Semi-massive vein fill		Found in sl and on own
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight contacts with gn and Ag-SS. Replacement of early dol, but straight contacts with dol in fractures	Irregular contacts with early dol (same as sl) and Ag-SS. Straight edges with late dol and sl	Straight edges, exsolution of Cu
other (growth direction/zoning)			

Structures: Sample exhibits dolomitic brecciation and shearing followed by dolomitic annealing. Qtz has replaced some sparry dol during shearing. Later fracture filled with sulfides.
Paragenetic Sequence: dol→qtz→gn+sl+dol+cpy→Fe-ox
Paragenetic Reasoning: Dolomite is sheared and replaced by qtz. Quartz crystals are growing in open space perpendicular? to shear direction. Later brittle fracture of dolomite has been filled in by gn, sl, and dol rhombs, which are all coeval. Gn can be seen replacing dolomite cleavage planes. Cpy present in some sl, very, very minute.

Sample #: 105-113B

Hole #: VZMIF 105

Sample Interval: 113.6-113.8 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): DG—Intercalated phyllites and dolomite

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Sample Photograph

VZMIF 105 113.6-113.8

Other Sample Information: Marbled dolomite

minerals	Dolomite	Quartz	Sulfides (gn, sl)
percentage	95	5	trace
morphology	Micritic dol pieces and re-crystallized sparry dol (growing into open space from bx)	Elongated chalcedonic xtals in direction of shear and later small qtz vein	Minute blebs
texture	Micritic and sparry	Replacing dol	disseminated
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular and blobby contacts with qtz. Sharp contacts with sulfides	See dol. Not in contact with sulfides	Sharp with dol, gn has fuzzy boundary with Ag-sulfosalts, straight contacts with sl
other (growth direction/zoning)	Growing into open space left by brecciation	Xtals elongated in shear direction, some rotation	

Paragenesis:

Sample #: 105-168

Hole #: VZMIF 105

Sample Interval:

Geologic Unit: Upper Morro do Pinheiro ($\pm$ bird's eyes)

Lithological Unit (Votorantim): DO—Grey dolomite with fenestrate texture

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Sample Photograph

Other Sample Information: Sedimentary Sample

minerals	Dolomite	Quartz	pyrite
percentage	85	14	1
morphology	Micritic. Sparry euhedral xtals in vein	Subhedral grains in micrite. Chalcedonic qtz in vein	Euhedral (diagenetic?)
texture	Rock matrix. Some annealed bx around vein emplacement	Disseminated, (massive in vein)	Disseminated, some associated with microfractures
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight with all	Straight with all	Straight edges with dol and qtz
other (growth direction/zoning)	Growing towards vein center	Growing in center of vein	

minerals	sphalerite		
percentage	trace		
morphology	Very tiny blebs in micrite		
texture	disseminated		
transmitted optical properties			
reflected optical properties	Yellow internal reflections (low Fe)		
contact/relationships with other minerals	Blebby, irregular contacts with dol, minor replacement?		
other (growth direction/zoning)			

Structures: There is some brecciation around vein, but it has been healed. There are several small fractures, but all are cut by the major vein or simply end (start?) from the vein.
Paragenetic Sequence: dol→qtz→py + sl?
Paragenetic Reasoning: Dolomite makes up the host rock and contains fragments of qtz and diagenetic pyrite. A vein runs through the center of the sample and is composed of recrystallized dolomite, then quartz with some minor pyrite in the center and along fractures near the vein margins. Little replacement is present. Sphalerite most likely associated with pyrite
Sample Highlights: Sedimentary sample of UMdP

Sample #: 106-122

Hole #: VZMIF 106

Sample Interval: 121.98-122.1 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive silicate (SM) in Hydrothermal Breccia

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Sample Photograph **Not available

Other Sample Information: Not Available

minerals	Willemite	Willemite veins	Specular hematite
percentage	62	3	35
morphology	Subhedral granular	Finer, subhedral to euhedral	In interstices of Wm and as large and small veins (multiple generations)
texture	Being replaced by Hm	Cross-cutting all mins	Massive to veined
transmitted optical properties		See Wm	opaque
color ppl xpl	Clear Beige to blues, greens, & oranges, reds		
pleochroism	Faint? Light to slightly darker grey		
birefringence	Mid 1st to low 3rd order		
twinning/ cleavage			
other			
reflected optical properties	N/A		
color			Whitish-grey
bireflectance			Very weak, lighter to darker
anisotropy			Distinct, grey to greyish blue
internal reflections			Some, red
other			
contact/ relationships with other minerals	Euhedral contact w/ Wm, brecciated and irregular contact with Hm	Overgrown on all mins, smaller veins cut by faults	Hm filling space b/w Wm grains. Also multiple generations of veins (see HL)
other (growth direction/zoning)			

minerals	Hematite	Magnetite?	
percentage	Trace	trace	
morphology	Minute specs	anhedral grain	
texture	Small blebs	broken	
transmitted optical properties		opaque	
color ppl xpl	Red to ruddy brown Opaque		
pleochroism			
birefringence			
twinning/ cleavage			
other			
reflected optical properties			
color		Grey with white specs	
bireflectance		none	
anisotropy		isotropic	
internal reflections		none	
other		White specs, Hm?	
contact/ relationships with other minerals	On margins and on top of Wm and Specular Hm	Irregular boundary w/ Wm (some growing inside), some red-brown hm on edges in ppl	
other (growth direction/zoning)			

Structures: Many cross-cutting veins; micro faults; replacement of W1 by Hm   At least 3 sets of Hm veins: 1)wide, run parallel to label, appear to be related to Hm that replaces W1 ; 2)narrow, cut #1, run perpendicular to # 1; 3)run sub-parallel to #1 and cut #2
Paragenetic Sequence: W1 + Sl?→ Hm V1 + Hm→ Hm V2 + Hm V3 →W1 V1
Paragenetic Reasoning: The W1 already appears to be in place and is subhedral with smooth shared grain boundaries. The Hm associated with Hm V1 is replacing the massive W1 boundaries. The Hm V2 cut and displace Hm V1. Hm V3 cuts Hm V2 and vice versa. W1 V1 cuts all Hm veins <u>and is not</u> replaced by Hm.
Sample Highlights: Possible sphalerite, veins and faults associated with breccia   SEM– for sphalerite and quartz

Sample #: 110-150

Hole #: VZMIF 110

Sample Interval: 150.19-150.4 m

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information:

minerals	Dolomite	Fe-Carb	Quartz
percentage	90	5	5
morphology	psuedospar	Euhedral xtals	Euhedral xtals
texture	Rock matrix	Vug-filling	Vug-filling
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals		Fillings vugs in dolomite matrix	Fillings vugs in dolomite matrix
other (growth direction/zoning)			

Sample #: 110-71

Hole #: VZMIF 110

Sample Interval: 71.28-71.5 m

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information:

minerals	Dolomite	Hematite	
percentage	100	Very trace	
morphology	micrite	Subangular grains in dol	
texture	Neomorphosed ooids	disseminated	
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals			
other (growth direction/zoning)			

Sample #: 114-111A

Hole #: VZMIF 114

Sample Interval: 111.0-111.5 m

Geologic Unit: Upper Morro do Pinheiro

Lithological Unit (Votorantim): DO—Gray dolomite

Sample Photograph

Other Sample Information: Sample taken from fault

minerals	Dolomite	Cataclasite dolomite	Cataclasite matrix
percentage	35	50	15
morphology	Subhedral sparry dolomite	Mix of micrite and sparry dol; elongated xtals	Made of clay and some minor qtz
texture	Sparry, granular	Foliated cataclastic	foliated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Straight contacts, broken at xtal boundaries and space filled in with cataclasite matrix	Straight contacts, minor replacement by Fe-dol veins (veins are syntectonic)	Straight contacts with all mins
other (growth direction/zoning)			

minerals	Hematite	Quartz	
percentage	trace	trace	
morphology	anhedral	anhedral	
texture	Partial vein and disseminated	Disseminated, found in cataclasite and shear zone	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular/sheared edges, replacing cataclastic dol?		
other (growth direction/zoning)		Straight contacts with all mins	

Paragenesis:

Time   Early Late

Dol   _____

Cataclasite   _____

Fe-dol   - - - - -

Structures: Sample is in a fault zone and is a cataclasite. Cataclasite matrix fills in space in between dolomite crystals broken at crystal boundaries. Strong foliation present in dolomitic cataclasite. Fe-dol veins show some replacement, but are bent by foliation, suggesting they are syngenetic with faulting.

Sample #: 114-111B

Hole #: VZMIF 114

Sample Interval: 111.0-111.5 m

Geologic Unit: Upper Morro do Pinheiro

Lithological Unit (Votorantim): DO—Gray dolomite

Sample Photograph

Other Sample Information: Same as 114-111A. Sample is all dolomite cataclasite (dolomite crystals in a clay/carbonate $\pm$ qtz cataclasite matrix). Foliation present as well as minor neomorphism of carbonates.

Sample #: 114-111C

Hole #: VZMIF 114

Sample Interval: 111.0-111.5 m

Geologic Unit: Upper Morro do Pinheiro

Lithological Unit (Votorantim): DO –Gray dolomite

Sample Photograph

Other Sample Information: Similar to 114-111A & B. More fault bx and less cataclasite (more distal from fault)

minerals	Dolomite	Quartz	
percentage	98	2	
morphology	1)Sparry, euhedral dol 2)Micritic dol host rock	amorphous	
texture	1)Sparry dol is filling vugs and cracks 2)Micrite is part of cataclasite and host rock	Chalcedonic layers in between some sparry dol	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight contacts with all mins	Straight contacts with all mins	
other (growth direction/zoning)			

Paragenesis:

Structures: Sample is from a more “distal” location to the fault in the 111.0-111.5 m interval. The dolostone has been fractured and secondary, hydrothermal dolomite with small chalcedonic quartz intercalations is crystallizing into vugs and fractures. Some of the hydrothermal dolomite is baroque dolomite. Quartz fills the centers of some vugs, but also appears in between dolomite growth zones, indicating small siliceous “pulses”, ending with quartz.
Paragenetic Sequence: micrite→fault→spar + qtz
Paragenetic Reasoning: growth of minerals in veins
Sample Highlights: Fault bx, baroque dolomite

Sample #: 115-211

Hole #: VZMIF 115

Sample Interval: 211.67-212.1 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicated in BH

Sample Photograph

Other Sample Information:

minerals	Dolomite	Wl	Chl
percentage	65	10	4
morphology	Fine xtal dol “shreddy” looking	Granular xtals	Fibrous, Fe-rich
texture	Semi-massive, some algal layering still preserved	disseminated	vein
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular contacts with all minerals, replacing all minerals except hm/frk	Irregular contacts with hm and dol. Seems to initially replaced dol, but is now being replaced by dol. Coeval with hm?	Cuts all minerals, but is then truncated by a fault
other (growth direction/zoning)	Algal layering	Hollowed-out xtals of wl filled with hm and surrounded by hm	

Structures: Sample has both brittle/ductile brecciation/shearing as seen in broken and sheared hm. Faults truncate late chlorite, indicating that tectonism was still active even during late mineralization. Dolomite seems to be late and is very fine.

Sample #: 115-217

Hole #: VZMIF 115

Sample Interval: 217.7-217.9 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate of BH

Sample Photograph

Other Sample Information:

minerals	Dol	Hm	Frk
percentage	30	70	Very trace
morphology	Wide range of crystal sizes from small to microcrystalline (original dol?)	Euhedral crystal laths	Euhedral xtals
texture	brecciated	Massive	Very disseminated, associated with hm
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Dol is replacing itself and being replaced by hm	Irregular, replacing/overgrowing dol along non-specific and specific zones	Straight contacts with all mins, associated with hm
other (growth direction/zoning)	Preferential replacement along certain zones in dol and in specific algal layers		Contains some hm exsolution texture

Structures: Sample is both brecciated and sheared. Preferential replacement of certain dolomite zones (don't know why)

Sample #: 115-220

Hole #: VZMIF 115

Sample Interval: 220.6-220.75 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate in BH

Sample Photograph

Other Sample Information: SULFIDES PRESENT

minerals	Willemite	Quartz	Hematite
percentage	70	10	5
morphology	Euhedral granular and lath crystals	Anhedral crystals	Massive crystal laths and small disseminated crystal grains in gn
texture	massive	disseminated	Minor massive shears and disseminated in gn
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular contacts with qtz, replacing qtz. Being replaced by hm and frk. Cross-cut by gn + frk + hm + cv	Being replaced by wl and gn	Straight edges with gn, replacing wl and qtz
other (growth direction/zoning)			Being exsolved by frk

minerals	Franklinite	Covellite	Galena
percentage	5	trace	10
morphology	Granular xtals	Small shreddy xtals	massive
texture	disseminated	Very disseminated	vein
transmitted optical properties			
reflected optical properties			Triangular facets
contact/relationships with other minerals	Straight contacts with gn and hm	Shreddy contacts with gn	Straight contacts with wl, replacing qtz
other (growth direction/zoning)	Exsolving hm		

Structures: late sulfide fractures, minor brecciation associated with wl mineralization

Sample #: 115-225

Hole #: VZMIF 115

Sample Interval: 224.95-225.1 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicated of BH

Sample Photograph

Other Sample Information: Same as 141-166

Sample #: 115-289

Hole #: VZMIF 115

Sample Interval: 280.4-280.7 m

Geologic Unit: Upper Morro do Pinheiro

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information:

minerals	Fe-carb	Dolomite	Qtz
percentage	47	50	3
morphology	Selvage alteration and veins	Micrite and sparry re-crystallized dol	Anhedral in veinlets
texture	Wholesale alteration and in veinlets	Massive micrite, sparry snow-on-the-roof	veinlets
transmitted optical properties	“dirty” contains hm inclusions		
reflected optical properties			
contact/relationships with other minerals	Cutting micrite and snowy carb, but being cut by qtz and carb veinlets	Being overprinted by Fe-carb, cut by qtz + carb veinlets	Cutting host rock and alteration
other (growth direction/zoning)			

Paragenesis:

Sample #:

Hole #: VZMIF

Sample Interval:

Geologic Unit:

Lithological Unit (Votorantim):

Sample Photograph

Other Sample Information:

minerals	Dolomite	Fe-carb	Hematite
percentage	95	5	trace
morphology	Micritic stromatolite boundstone	Sparite vein with hm inclusions	Included in Fe-carb
texture	Stromatolites with some small intraformational breccias with carbonate and silica cement	Vein	Disseminated in Fe-carb vein
transmitted optical properties		Dirty looking b/c of hm inclusions	
reflected optical properties			
contact/relationships with other minerals	See Fe-carb	Cuts across boundstone, fairly straight edges (brittle?)	Blebbly and irregular, replacing Fe-carb?
other (growth direction/zoning)			

minerals	Quartz		
percentage	trace		
morphology	Subhedral crystalline		
texture	Cement filling		
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Filling lates veins w/ straight contacts in dol and fe-carb		
other (growth direction/zoning)			

Sample #: 118-164

Hole #: VZMIF 118

Sample Interval: 164.03-164.26 m

Geologic Unit: Upper?/Lower Morro do Pinheiro?

Lithological Unit (Votorantim): Marl (MG)

Sample Photograph

Other Sample Information:

minerals	dolomite	Hematite	
percentage	100	Very trace	
morphology	Massive micrite	Anhedral grains	
texture	Minor proto-stylolites; a few small recrystallized carbonate veins (non-ferrous)	Disseminated throughout rock	
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Veins cut dol, little to no shearing	Appear to be grains in rock matrix	
other (growth direction/zoning)			

Sample #: 122-73

Hole #: VZMIF 122

Sample Interval: 73.75-74.02 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (SM in BH)

Sample Photograph

Other Sample Information:

minerals	Willemite	Hematite	Franklinite
percentage	45	12	trace
morphology	1st gen. granular and 2nd gen. lath	Small anhedral xtals included in wl and large laths and needles	Subhedral xtals
texture	Semi-massive replacement 1st gen replacing carb and qtz, 2nd gen replacing 1st gen wl, carb and qtz	Replacement net-like texture and inclusions	disseminated
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Shreddy contacts with wl and carb, more jagged contacts w/ qtz and hm, being replaced by hm, replacing qtz and carb	Replacing wl, carb, and qtz, jagged contacts w/ these mins	Replacing wl, included in wl
other (growth direction/zoning)		Preferential replacement of some carbonate overgrowths	

minerals	Quartz	Carbonate	
percentage	3	40	
morphology	anhedral	Anhedral hydrothermal spar- rite Fine-grained carb in veinlets	
texture	disseminated	Hydrothermal rock-forming, being replaced Small, late cross-cutting veinlets	
transmitted opti- cal properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular and jagged contacts with all mins, replacing carb, but being replaced by wl and hm	Early stage being replaced by all mins, late stage vein- lets cutting all mins	
other (growth di- rection/zoning)			

Sample #: 122-75

Hole #: VZMIF 122

Sample Interval: 75.8-76.45 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (in BH)

Sample Photograph

Other Sample Information:

minerals	Willemite	Hematite	Franklinite
percentage	70	10	trace
morphology	1st gen. granular 2nd gen. lath-like and splays	Needle and lath-shaped xtals, oriented along veinlets	Subhedral, proximal to hm but in wl
texture	Massive	Filling veinlets in a net- texture	disseminated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Replacing qtz and carb and itself, jagged contacts with these mins Being replaced by hm and frk, also jagged contacts	Replacing wl, qtz, and carb, jagged and irregular contacts with these mins	Straight to embayed contacts with wl
other (growth di- rection/zoning)	Some 1st gen. wl xtals have been recrystallized and man- tled with more wl		

minerals	Quartz	Carbonate	
percentage	17	3	
morphology	Anhedral	Hydrothermal anhedral spar- ry Hydrothermal fin-grained late stage	
texture	disseminated	Sparry is disseminated, late stage is in small veinlets	
transmitted opti- cal properties			
reflected optical properties			
contact/ relationships with other minerals	Jagged and irregular con- tacts with wl and hm. Irregu- lar contacts with early carb, being cross-cut by late carb veinlets	Embayed contacts with qtz, jagged contacts with wl and hm. Late stage cuts all mins	
other (growth di- rection/zoning)			

Structures: Qtz and other mins cut by brittle faults. Hm seems to be more ductile and flows around minerals as it replaces them, but it's still brittle deformation

Sample #: 122-94

Hole #: VZMIF 122

Sample Interval: 94.25-94.6

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Pink dolomite (DG)

Sample Photograph

VZMIF 122

94.25-94.6

Other Sample Information:

minerals	Dolomite	Fe-carbonate	Quartz
percentage	35	25	20
morphology	Micrite forming rock	Sparry veinlets	Anhedral, veinlets
texture	Fine xtals of micrite	Veinlets	veinlets
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Being cut by qtz and carb veins, minor qtz replacement	Cutting host rock and being cut by qtz and fine-grained carb	Cutting Fe-carb and subparallel to fine-grained carbonates
other (growth direction/zoning)		Red color and hm included in xtals	

minerals	Fine-grained sheared carb	Hematite	
percentage	20	trace	
morphology	Shear vein, sparry	anhedral	
texture	Shear vein	Disseminated in Fe-carb	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Cutting Fe-carb and host rock, includes some qtz	Irregular contacts with Fe-carb	
other (growth direction/zoning)			

Sample #: 122-99

Hole #: VZMIF 122

Sample Interval: 99,63-99.8

Geologic Unit: Lower Pamplona (phyllite)

Lithological Unit (Votorantim): Pink dolomite (DG)

Sample Photograph

Other Sample Information:

minerals	Quartz	Muscovite	Carbonate?
percentage	60	10	30
morphology	Angular to subrounded grains	Euhedral laths	Fine grained micritic matrix
texture	Compos rock, oriented along foliation (fold)	Oriented along foliation	More cement in between grains
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Oriented with muscovite in foliation	Oriented with quartz in foliation	amorphous flow texture
other (growth direction/zoning)			

minerals	Hematite	Zircon	
percentage	trace	Trace	
morphology	Sub angular grains	Anhedral to euhedral grains; 20-50 microns in size	
texture	disseminated	Verry disseminated	
transmitted optical properties		High birefringence	
reflected optical properties		Gray iand zoned n ref ppl	
contact/ relationships with other minerals	Part of grains comprising phyllite	Rounded or straight contacts with musc, qtz, and hm	
other (growth direction/zoning)		Zoned, some cracked	

Paragenesis:

Time   **Early** **Late**

Qtz   _____

Musc   _____

Carb   _____

Hm   _____

Zircons   _____

Sample #: 123-46

Hole #: VZMIF 123

Sample Interval: 46.62-46.9 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: Altered rock, but not brecciated

**rock is a laminated quartz boundstone (Dunham, 1962)

minerals	Dolomite	Quartz	Muscovite
percentage	79	10	1
morphology	Small, sparry crystals	Angular to subrounded grains	Rectangular crystal laths
texture	Non planar dol; laminated with qtz due to algal layering	Laminated with dolomite	disseminated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Straight contacts with qtz and musc, sheared contact with Fe-carb vein	Straight contacts with musc and dol	Straight contacts with qtz and dol
other (growth direction/zoning)			

minerals	Fe-carbonate	Hematite	
percentage	10	trace	
morphology	Large, sparry crystals	Anhedral inclusions	
texture	Veinlet	Inclusions in Fe-carb	
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Shear contact with host rock	Irregular with Fe-carb, replacing Fe-carb	
other (growth direction/zoning)			

Sample #: 123-73

Hole #: VZMIF 123

Sample Interval: 73.17-73.3 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicates (SM) in hydrothermal breccia

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Sample Photograph

Other Sample Information:

minerals	Hematite	Specular Hm	Dolomite
percentage	25	10	3
morphology	Blebs on and around grain margins, related to specular hematite		Being replaced by Hm and Wl, faded edges
texture	Disseminated, blebby		Being replaced by Hm and Wl
transmitted optical properties		opaque	
color ppl xpl	Reddish-brown Black		Clear pastels
pleochroism	n/a		n/a
birefringence	opaque		3rd order
twinning/ cleavage	n/a		Rhombohedral clvg
other			Low relief
reflected optical properties	n/a	N/a	n/a
color		Whitish-grey	
bireflectance		Very weak, lighter to darker	
anisotropy		Distinct, grey to greyish blue	
internal reflections		Some, red	
other			
contact/ relationships with other minerals	On margins of specularite, wl, and qtz, replacing dol	In veins and in between margins of wl and qtz, replacing dol	Faded edges, in contact with Hm
other (growth direction/zoning)	Oxidation? Of specularite		

minerals	Granular willemite	Bladed willemite	quartz
percentage	45	15	2
morphology	Subhedral to euhedral granular, small to large	Large, euhedral bladed/fibrous crystals	Small subhedra grains
texture	Massive, replacing carbonates	Overgrowing existing Wl and some Hm	Amongst willemite
transmitted optical properties			
color ppl xpl	Clear *see birefringence	Clear *see birefringence	Clear White to black
pleochroism	Weak greenish tan to white	Weak greenish tan to white	n/a
birefringence	2nd to low 3rd order	2nd to low 3rd order	White to black
twinning/ cleavage	N/a	Clvg seen on fibrous splays	Undulatory extinction
other	Lower relief than qtz	Lower relief than qtz	High relief
reflected optical properties	n/a	N/a	n/a
color			
bireflectance			
anisotropy			
internal reflections			
other			
contact/ relationships with other minerals	Straight edges with qtz, overgrowing Hm and replacing dol	Growing in splays on top of granular wl and into specularite, some ruddy hm on edges	Some Hm on edges, straight contact edges with Wl
other (growth direction/zoning)	Zoned xtal growth inwards of veins. (i.e. wl is growing into vugs/veins)	Growing into hm filled vugs and fractures	Occurs in between some granular wl xtals

Structures: The sample has been brecciated, or at least fractured, creating open space in the dolomitic host rock. The wl crystals are replacing the carbonates and growing in the open space. The veins are filled with specular hematite as opposed to the ruddy hematite seen throughout the rest of the sample.
Paragenetic Sequence: dol→bx→Wl (granular) + Hm specular +qtz→ Wl (fibrous) +Hm (ruddy)
Paragenetic Reasoning: The dol is faded in the specular hm veins in which it appears, and its edges corroded by hm. The granular wl grows as small crystals in most areas along with qtz, except where there are large hematite veins and vugs, where it grows as large crystals towards the center of the open space. The specular hm is coeval with the granular wl as some wl occurs in the middle of the hm veins. The fibrous wl appears to be replacing some of the larger wl xtals on near the contacts of granular wl and specularite. The ruddy hm is later as it appears on the margins of all minerals, particularly the specular hematite.
Sample Highlights: -2 phases of wl   -open space filling of wl xtals   -coeval occurrence of hm and wl

Sample #: 124-4

Hole #: VZMIF 124

Sample Interval: 4.3-4.7 m

Geologic Unit: BH overprinting Lower Pamplona

Lithological Unit (Votorantim): Hydrothermal Breccia (BH)

Sample Photograph

Other Sample Information:

minerals	Fe-carbonate	Hydrothermal carbonate	Quartz
percentage	45	45	10
morphology	Micritic breccia fragments	Subhedral to euhedral spar-rite	Large, anhedral crystals
texture	Breccia fragments	Cement b/w breccia fragments	Associated with carb cement
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Diffuse into hydrothermal carbonate (nucleation site)	Fe-carb micrite diffuses into hydrothermal carbonate, this carbonate grows out from red Fe-carb fragments; embayed with qtz (replacing qtz)	Irregular with carbonates, being replaced by carb
other (growth direction/zoning)			

minerals	Hematite		
percentage	trace		
morphology	Anhedral xtals, mostly located as inclusions in red Fe-carb		
texture	Disseminated to miniscule veinlets		
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular contacts, replacing Fe-carbonate		
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

Fe-carb   _____

Carb Cement   _____

Qtz   _____

Hm   -----

Sample #: 124-72

Hole #: VZMIF 124

Sample Interval: 72.55-72.76 m

Geologic Unit: BH overprinting Lower Pamplona

Lithological Unit (Votorantim): Hydrothermal Dolomite

Sample Photograph

Other Sample Information:

minerals	Dolomitic host rock	Fe-carb alteration	Hematite
percentage	80	17	3
morphology	Massive micrite; sedimentary breccia replaced by micritic dolomite with carbonate cement (some neomorphic zones)	Sparry carbonate with black inclusions	Anhydrous crystal inclusions
texture	Massive; sedimentary breccia	Veinlets cross-cutting the host rock	Inclusions in Fe-carb
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	See Fe-carb; non planar dolomite	Partially sheared and partially jagged contacts with host rock	Irregular contacts with Fe-carb, replacing Fe-carb? Some inclusions in host rock as well, irregular contacts
other (growth direction/zoning)			

minerals			
percentage			
morphology			
texture			
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals			
other (growth direction/zoning)			

Paragenesis:

Time   **Early** **Late**

Dolomite   _____

Brecciation   _____

Fe-carb   _____

Hm   _____

Sample #: 124-75

Hole #: VZMIF 124

Sample Interval: 75.45-75.9 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate in BH

Sample Photograph

VZMIF 124

75.45-75.9

Other Sample Information: Interval runs 45% Zn

minerals	Dolomite	Willemite	Quartz
percentage	5	79	5
morphology	Anhedral micrite in matrix and in veins	Euhedral granular xtals	Subhedral xtals
texture	Micritic, being replaced by wl, replacing qtz	massive	Veins, minor disseminated xtals
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular, being replaced by wl and hm	Mostly straight with other wl, irregular with hm and dol (being replaced by hm)	Irregular, being replaced by dol in veins along contacts with wl
other (growth direction/zoning)			

minerals	Hematite	Sphalerite	
percentage	10	1	
morphology	Xtal laths in shear zone	Anhedral to euhedral xtals	
texture	Massive sheared vein, disseminated in wl	disseminated	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Replacing dol and wl, very minor replacement of qtz veins (most likely replacing dol in qtz veins)	Irregular and straight with hm and dol. Straight with wl. Exosolution of hm in sl	
other (growth direction/zoning)		Associated with hm in dol xtals. Dol xtals are being replaced by wl	

Structures: Sample is massive except for large shear vein/fault in middle of sample. Shearing caused some brecciation of wl. 3 vein styles present: 1) hm shear vein, 2) qtz and Fe-dol vein, and 3) qtz veins. Multiple veins see vein paragenesis below

Paragenetic Sequence: hm vein→qtz + Fe-dol→qtz

Paragenetic Reasoning: The qtz + Fe-dol vein cross-cuts the hm shear vein, but is cut by later qtz veins that cut across entire sample. Qtz veins are being altered by carbonate.

Sample #: 124-77

Hole #: VZMIF 124

Sample Interval: 77.5-77.9 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate in BH

Sample Photograph

VZMIF 124

77.5-77.9

Other Sample Information: See sample 104-86 (mid grade ~20% Zn)

Sample #: 124-83

Hole #: VZMIF 124

Sample Interval: 83.5-83.71 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: Same as 124-72** more hydrothermal breccia less sedimentary breccia fragments

Sample #: 125-130

Hole #: VZMIF 125

Sample Interval: 130.55-130.71 m

Geologic Unit: Hydrothermal Breccia(?)

Lithological Unit (Votorantim): Disseminated Silicate (unknown bx)

Sample Photograph

Other Sample Information: hematite shear zone, not in specific BH

minerals	Dolomite	Hematite (specular)	
percentage	30	70	
morphology	Large, anhedral dol crystals	Massive veins	
texture	Primary dolostone being replaced by hm.	Migmatite, breccia veins	
transmitted optical properties		opaque	
reflected optical	n/a		
contact/ relationships with other minerals	Some secondary dol replacing dol. All dol being replaced by hm	Hm is replacing dol. Hm forms a shear vein with proximal breccia.	
other (growth direction/zoning)			

Structures: Hm forms a shear vein with surrounding breccia proximal to vein. Dol and hm veins are curved and migmatized.
Paragenetic Sequence: dol→2ndary dol→hm
Paragenetic Reasoning: Dol xtals are being replaced by dolomite. All dol being replaced by hm laths. Dol xtal edges are irregular when in contact with hematite.
Sample Highlights: Migmatized dol

Sample #: 125-133

Hole #: VZMIF 125

Sample Interval: 133.3-133.48 m

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information: rock type the same as 118-132 (stromatolite boundstone)

Rest of sheet is alteration analysis only

minerals	Fe-carb	Quartz	Fine-grained carbonate
percentage	10	5	3
morphology	Sparry carbonate with hm inclusions	Crystalline quartz (subhedral)	Very small carbonate crystals
texture	Veinlets	Veinlets	veinlets
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular contacts, jagged, fine carb; being replaced by fine carb. Straight and curved edges with qtz	Grew along same fracture as Fe-carb, being replaced by fine carb	Irregular and spotty contacts with Fe-carb and qtz vein, replacing these mins
other (growth direction/zoning)			

Sample #: 127-108.5

Hole #: VZMIF 217

Sample Interval: 108.5-108.6 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (SM) in BH

Sample Photograph

Other Sample Information: 16% Zn

minerals	Dolomite	Quartz	willemite
percentage	20	6	8
morphology	2 types: 1) large, anhedral Fe-dol in veins 2) Small, subhedral dol	A few small anhedrals xtals with small dol. Mostly large euhedral xtals in veins	A few small anhedrals xtals with small dol. Mostly large euhedral xtals in veins
texture	Large dol is being replaced by dol and hm, and replacing qtz and wl Small dol is being replaced by hm	Smaller xtals compose groundmass. Large xtals make up veins, being replaced by dol	Smaller xtals compose groundmass. Large xtals make up veins, being replaced by dol
transmitted optical properties		Lower relief than wl. A few xtals have qtz overgrowths and rims	
reflected optical properties			
contact/relationships with other minerals	Small dol is corroded by hematite and being replaced by small qtz and wl	Large xtals in veins have straight edges with wl and other qtz, being slightly replaced by dol and hm	Large xtals in veins have straight edges with qtz and other wl, being slightly replaced by dol and hm
other (growth direction/zoning)		Has euhedral growth rims	

minerals	Hematite	Chlorite	
percentage	65	1	
morphology	Massive and brecciated with some small specks and laths in wl/qtz veins	fibrous	
texture	Filling interstices b/w small dol xtals.	In a few small veins	
transmitted optical properties		Blue in xpl	
reflected optical properties			
contact/relationships with other minerals	Replacing small dol and slightly replacing? xtals in veins	Slight replacement by hm, replacing dol when in contact	
other (growth direction/zoning)			

Structures: 2 large wl, qtz, and Fe-dol veins cross cut entire sample after main breccia event, as seen by there tendency to cut across breccia fragments
Paragenetic Sequence: dol→wl + qtz→hm + chl→wl + qtz + Fe-dol in veins→shreddy Fe-carb
Paragenetic Reasoning: The rock-forming dol has small spots of qtz and wl replacement, but is thoroughly being replaced by hm found in between grains and in large bx fragments. The hm, in turn, is being cut by wl, qtz, and Fe-dol veins with some slight replacement of these veins by hm. Within the veins, Fe-dol is replacing qtz and wl <u>(possible why high iron and no zinc...Fe-carb alteration)</u>. Some Fe-carb alteration on vein margins is replacing all minerals.
Sample Highlights: later wl and qtz veins with Fe-dol

Sample #: 127-108.8

Hole #: VZMIF 127

Sample Interval: 108.68-108.87 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (SM) in BH

Sample Photograph

Other Sample Information: Similar to 127-108.5 with faults instead of veins. Hm clasts in bx are sheared, faults orthogonal to shearing

minerals	Carbonate	Quartz	Willemite
percentage	15	20	15
morphology	A few original xtals being replaced by qtz and hm, mostly small, fine Fe-rich dol	Anhedral to subhedral xtals, makes up majority of non-opaques	Similar to qtz but with higher order interference colors
texture	Small Fe-dol is replacing qtz and wl	Cumulate replacement of dol, being replaced by hm	Similar to qtz but with higher order interference colors
transmitted optical properties	*sample cut thin	*sample cut thin	*sample cut thin
reflected optical properties			
contact/relationships with other minerals	Irregular contacts with qtz and wl as well as hm	Irregular contacts with hm and dol, but straight with other qtz and wl	Same as qtz
other (growth direction/zoning)			

minerals	Hematite		
percentage	50		
morphology	Massive breccia pieces with some smaller laths and interstitial hm in between dol and qtz xtals		
texture	Semi-massive net texture		
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular, jagged contacts with qtz, dol, and wl		
other (growth direction/zoning)			

Structures: A set of faults (and smaller fractures) orthogonal to the orientation of the sheared hematite bx fragments
Paragenetic Sequence: dol→qtz + wl→hm→Fe-dol
Paragenetic Reasoning: The dolomite found is relict and being replaced by qtz and wl. The qtz and wl have irregular, wavy contacts with hm, suggesting replacement by hm. Lastly, the Fe-dol is fine and also replacing the qtz and wl regions, but it is being replaced or is interwoven with hm.
Sample Highlights: fault orthogonal to shear

Sample #: 129-138

Hole #: VZMIF 129

Sample Interval: 138.0-138.18 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information:

minerals	Carbonate	Quartz	Hematite
percentage	25	72	3
morphology	Micritic to sparry	Mostly anhedral	anhedral
texture	Breccia fragment	hydrothermal	disseminated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Somewhat irregular contact with qtz, more likely b/c of change in fluid content than replacement	See carb, irregular contacts with hm, replacing hm?	Found included in qtz or being replaced by qtz
other (growth direction/zoning)		Zoned with hm; lots of secondary fluid inclusion trails	

minerals	barite	pyrite	unknown
percentage	trace	Very trace	trace
morphology	anhedral	anhedral	subhedral
texture	Disseminated	Disseminated	Some triangular faces
transmitted optical properties	Low order birefringence		
reflected optical properties			Very strong anisotropy, higher reflectance than hm
contact/relationships with other minerals	Irregular with qtz, being replaced by qtz?		Straighter contacts with qtz than hm
other (growth direction/zoning)			

Sample #: 129-165.6

Hole #: VZMIF 129

Sample Interval: 165.66-165.96 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (SM) in BH

Sample Photograph

Other Sample Information: Standard appearance of willimite and hematite shear veins

minerals	Willemite	Dolomite	Hematite
percentage	65	20	15
morphology	Small subhedral crystals to large euhedral crystals filling in void spaces all replacing dol	1) large anhedral dol (primary) being replaced by wl 2) smaller secondary dol filling in veins	Subhedral, associated with wl and replacing dol. Also filling in leftover space b/w Wl xtals
texture	Filling in open space from bx, replacing dol	Veins and being replaced by wl & hm	Replacing Wl and dol, filling in space after Wl
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight edges with other wl. Small irregularities with dol contacts (replacement). Irregular/jagged contact with hm (lots of embayments)	Irregular contacts with wl and hm (wl overgrowing dol)	Filling in spaces b/w Wl xtals
other (growth direction/zoning)			

Structures: same as 129-165   Veins associated with bx
Paragenetic Sequence: dol→Wl→Hm→late dol veins
Paragenetic Reasoning: same as 129-165
Sample Highlights: similar to 129-165, but less brecciated   Carbonate veins have larger xtals in faulted open space (See Fig)

Sample #: 129-165

Hole #: VZMIF 129

Sample Interval: 165.0-165.3

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (SM) in BH

Sample Photograph

VZMIF 129

165.0-165.3

Other Sample Information: Willimite with non specular hematite veins. Alteration appears different than the usual WI+Hm shear vein (more orange and ruddy)

minerals	willimite	dolomite	Sphalerite
percentage	60	35	2
morphology	Smaller crystals are more anhedral. Larger crystals are subhedral laths and grains around voids	Small, anhedral crystals composing veins. A few larger xtals	Disseminated, amorphous
texture	Brecciated, contains small amounts of hematite	Vein texture in between wl breccia clasts, replacing wl	Located as inclusions within wl
transmitted optical properties	Cut thin	Cut thin	opaque
reflected optical	n/a	n/a	
contact/ relationships with other minerals	Shreddy, irregular contact with Fe-carb, being replaced by Fe-carb. Irregular contact with Hm, replacing? Hm	Replacing wl, hm, and primary dol	Embayed and irregular contact with all mins,
other (growth direction/zoning)	Some minor circular zoning		Internal reflections

minerals	dolomite		
percentage	3		
morphology	Large, anhedral		
texture	In voids, being replaced by wl		
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular contact with wil- lemite, being replaced by wl		
other (growth di- rection/zoning)			

Structures: Sample is brecciated throughout and the fractures are filled with tiny, secondary carbonates, including dol and Fe-rich carbonates.
Paragenetic Sequence: dol→sl→wl→bx→2nd carbonates
Paragenetic Reasoning: The primary dolomite is being replaced by the wl in the sample. The Wl is large and subhedral, indicating growth into possible open spaces (bx?). The Sl is associated with Wl and is in the middle of many Wl samples and becoming replaced by Wl. The bx has crushed and cut the Wl and the spaces are filled in with fine carbonates.
Sample Highlights: carbonate alteration and sphalerite

Sample #: 129-167

Hole #: VZMIF 167

Sample Interval: 167.66-167.79 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Massive Silicate (SM) in BH

Sample Photograph

VZMIF 129

167.66 - 167.79

Other Sample Information: Fe-carbonate altered dolomite clasts in mineralized breccia

minerals	Willemite	Quartz	Hematite
percentage	30	20	30
morphology	Mostly fibrous xtals with some smaller anhedral xtals	Subhedrals xtals (silica alt?), a few places of later qtz filling open space	Massive in veins. Disseminated euhedral laths
texture	Filling open space, xtals grow towards center of veins and vugs. Replacing dol	Filling open space,	Veins and replacing wl and qtz
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Wl is replacing dol and filling open space. It has straight contacts with itself and qtz also with some hm. Being replaced by most of hm and cut by Fe-carb in	Straight contacts with itself and wl, replacing some dol. Being replaced by hm	Replacing most wl and qtz and dol. Straight edges with Sl. Some intergrown w/ wl
other (growth direction/zoning)			

minerals	Dolomite	Sphalerite	Fe-carb
percentage	15	trace	5
morphology	anhedral	subhedral	Small, shreddy
texture	Being replaced by wl, hm, qtz	Disseminated, but associated w/ Hm	In veins that cut everything
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular contacts with other minerals. Lot of embayments and jagged edges. Wl tends to overgrow dol	Somewhat irregular contacts with wl, mostly straight edges with Hm.	Cut everything, contacts are mottled, splotches of Fe-carb on hm, wl, and qtz. Cut through hm
other (growth direction/zoning)			Late

Structures: Sample has been brecciated and cut by hm shear veins. Silicates are replacing dol and filling in open space. Hm and Wl have intercalated growths next to hm shear vein, indicating “fluid pulses”. Fe-carbonates create a stockwork of veins that cut through all minerals.
Paragenetic Sequence: dol→wl +qtz→hm + sl→Fe-carb   *hm overlaps with wl and is intergrown w/ wl in some instances
Paragenetic Reasoning: See wl and qtz overgrowing and replacing dol. Hm is replacing wl in main shear vein and has laths growing on qtz. Sl is associated? with hm next to some wl. Fe-carb veins cut all mins and have no specific order (i.e. V1, V2, ...)
Sample Highlights: Sphalerite, Fibrous wl + qtz

Sample #: 129-247

Hole #: VZMIF 129

Sample Interval: 247.83 - 248.05 m

Geologic Unit: Upper Morro do Pinheiro

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information:

minerals	Host Dolomite	Alteration Veins	
percentage	40	60	
morphology	Micritic dolomite with sparry dol (non planar if dol)	Red and pink zoned veins of hydrothermal dolomite	
texture	Evaporitic textures and neophormism, composed mostly of (superficial?) ooids	Middle zones finer carb, outer zones larger sparry carb	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals		Jagged (brittle?) contact between veins and host rock	
other (growth direction/zoning)			

Sample #: 130-20A

Hole #: VZMIF 139

Sample Interval: 19.85-20.0

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): Pink Dolomite (DO)

Sample Photograph

VZMIF 139

19.85-20.0

Other Sample Information: Same as 139-20B

Sample #: 139-208B

Hole #: VZMIF 139

Sample Interval: 19.85-20.0 m

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): Pink Dolomite (DO)

Sample Photograph

Other Sample Information:

minerals	Dolomite	Hydrothermal Dolomite	Quartz
percentage	20	72	5
morphology	anhedral	euhedral	euhedral
texture	Host rock	Hydrothermal vein filling	Hydrothermal vein filling
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Slightly irregular edges with quartz	Slightly irregular edges with quartz. Irregular and embayed edges with sp, py, and fe-oxides, these minerals last stage formation	Slightly irregular edges with dol (rxn front?)
other (growth direction/zoning)		Growing in from wall rock	

minerals	Sphalerite	Pyrite	Fe-oxides/hydroxides
percentage	1	1	1
morphology	Anhedral xtal	Anhedral xtal	Anhedral xtal
texture	Disseminated last stage mineralization	Disseminated last stage mineralization, some 'py disease'	Alteration from py
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Irregular with dol, filling in space	Irregular with dol, filling in space, minor 'py disease' in sp-replacing sp	Altering from py
other (growth direction/zoning)			

Structures: hydrothermal carbonate vein cutting host dolomite in Middle Pamplona. Late stage sulfides present. The sulfides are associated with the Fe-rich sections (red) of the hydrothermal dolomite

Sample #: 130-20A

Hole #: VZMIF 139

Sample Interval: 19.85-20.0

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): Pink Dolomite (DO)

Sample Photograph

VZMIF 139

19.85-20.0

Other Sample Information: Same as 139-20B with no Sp

Sample #: 139-27

Hole #: VZMIF 139

Sample Interval: 27.55-27.9 m

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): Pink Dolomite (DO)

Sample Photograph

Other Sample Information: Same as 139-20B with no Sp

Sample #: 139-270

Hole #: VZMIF 139

Sample Interval: 270.33-270.7 m

Geologic Unit: breccia in Lower Morro do Pinheiro

Lithological Unit (Votorantim): Pink Dolomite (DO)

Sample Photograph

VZMIF 139

270.33-270.7

Other Sample Information:

minerals	Dolomite	Quartz	Hematite
percentage	99	1	trace
morphology	Hydrothermal dolomite overgrowths	Subhedral crystals	Very small euhedral xtals
texture	Open space filling	Open space filling	Last mineral to form
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular with hm and qtz, replacing qtz. Hm is last to form hence irregularity	Replaced by dol	
other (growth direction/zoning)			

Sample #: 141-16

Hole #: VZMIF 141

Sample Interval: 16.05-16.4 m

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): DO—Gray dolomite

Sample Photograph

Other Sample Information: Hydrothermal bx vein in Middle Pamplona...with sphalerite

minerals	Dolomite	Quartz	Ferroan dolomite
percentage	40	20	30
morphology	Hydrothermal spar	Large, euhedral xtals	Smaller anhedral to subhedral xtal (sparry micrite?)
texture	Large, crystalline	Growing out from Fe-dol vein in center of slide	One vein in center of sample, massive
transmitted optical properties		Fluid inclusion trails	
reflected optical properties			
contact/relationships with other minerals	Straight contacts with qtz. Irregular edges with sp and Fe-dol (replacing dol)	Irregular edges with Fe-dol and sp, replaced by sp	Replacing qtz and sparry dol
other (growth direction/zoning)		Xtal overgrowths w/ fluid inclusions	

minerals	Sphalerite	Pyrite/Chalcopyrite	Hematite
percentage	10	trace	trace
morphology	amorphous	Minute blebs in sp, anhedral	Found in Fe-dol
texture	Vein, minor disseminations	Cpy-disease, disseminated throughout sample	disseminated
transmitted optical properties	Yellow-brown in ppl		
reflected optical properties	Isotropic, yellow IR		
contact/relationships with other minerals	Irregular with dol and qtz (replacing these mins)	Smooth with sp	Irregular, shreddy contacts with Fe-dol, replacing Fe-dol?
other (growth direction/zoning)		Exosolution from sp	Forms reaction front b/w Fe-dol and other mins (i.e. qtz)

Paragenesis: ???

Structures: Fe-carbonate vein cuts sample in half. Quartz grows out from this vein. Sample is taken from a hydrothermal bx (not BH).
Paragenetic Sequence: dol vein→qtz ± py→dol→sph→py+sp
Paragenetic Reasoning: Vein order
Sample Highlights: Reaction front between dol and Fe-dol. Rxn front b/w qtz and Fe-dol

Sample #: 141-166

Hole #: VZMIF 141

Sample Interval: 166.6-166.77 m

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: ~32 % Zn in 166.5-166.9 m interval

See Sample 129-167

Sample #: 141-18

Hole #: VZMIF 141

Sample Interval: 18.75-18.95 m

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): DO- gray dolomite

Sample Photograph

Other Sample Information:

minerals	Dolomite	Quartz	Pyrite
percentage	87	10	2
morphology	Large sparry dol and regular rock-forming dol (minor neomorphism)	Euhedral xtals	blebs
texture	Rock-forming and secondary vein-filling	Rimming dolostone clasts	disseminated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Straight with other dol. Some minor irregularities with qtz	Straight with most dol and other qtz	Irregular with qtz, dol, and Fe-oxides. Late stage in hydrothermal dol and qtz fluid. Altering to Fe-hydroxides and oxides
other (growth direction/zoning)		Overgrowths and zones	

minerals	Fe-oxides and hydroxides		
percentage	1		
morphology	Fuzzy, low relief		
texture	Rimming py		
transmitted optical properties			
reflected optical properties	Light blue and grey		
contact/ relationships with other minerals	Fuzzy, irregular edges with py, replacing py		
other (growth direction/zoning)			

Structures: Breccia filled in with hydrothermal qtz and dol
Paragenetic Sequence: dolostone→qtz→hydrothermal dol + py→Fe-ox
Paragenetic Reasoning: Order of events in vein

Sample #: 141-61

Hole #: VZMIF 141

Sample Interval: 61.15-61.35 m

Geologic Unit: Middle Pamplona

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information: Using Wright (1992) and Embry and Klovan (1971) this is a **clast supported rudstone** with a **sparry carbonate matrix**

minerals	dolomite	Calcite?	quartz
percentage	65	24	1
morphology	Micritic dol clasts	Sparry calcite cement	Veinlets and alteration
texture	Rock forming intraclasts	matrix	Veinlets and some minor replacement of dol
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals			Replacing dol in rudstone clasts
other (growth direction/zoning)			

minerals	Fe-carbonate		
percentage	10		
morphology	Alteration veinlet		
texture	Sparry xtals with minor inclusions of hm		
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Cuts across rock, but is cut by tiny qtz veinlet		
other (growth direction/zoning)	Looks “dirty” in ppl and xpl (b/c of inclusions)		

Paragenesis:

Time   Early Late

Structures: Rock is a clast supported rudstone with sparry calcite matrix. An Fe-carbonate vein cuts across sample and looks “dirty” under microscope (possibly ankerite or siderite)

Sample #: 181-84

Hole #: VZMIF 141

Sample Interval: 84.72-84.99 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Grey Dolomite (DO)

Sample Photograph

Other Sample Information: bottom part is a massive micrite with some disseminated angular to sub-rounded quartz grains

The top part of the section is a red micrite with laminations of peloids and angular to subrounded qtz grains. The carbonate has been recrystallized to form one crystal in the micrite

minerals	Red carbonate (phyllite)	Carbonate	quartz
percentage	20	73	5
morphology	micrite	Micrite	Angular to subrounded
texture	Contains intercalated laminations of peloids and qtz grains	Some stylolites	Disseminated in carbonate, in red carbonate they are laminated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	A hummocky contact w/ carbonate		
other (growth direction/zoning)	One crystal, was formerly a "phyllite"		

minerals	peloids		
percentage	2		
morphology	Black subrounded to rounded clasts of unknown origin		
texture	Disseminated throughout red micritic carbonate		
transmitted optical properties	Opaque in XPL and PPL		
reflected optical properties	Not visible, blend in with carbonate		
contact/relationships with other minerals	Associated only with red carbonate (phyllite)		
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

Sample #: 155-117

Hole #: VZMIF 155

Sample Interval: 117.5-117.75 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim):

Sample Photograph

Other Sample Information: Sedimentary dolomite breccia with silica alteration

minerals	Dolomite	Quartz	Pyrite & Hematite
percentage	70	30	trace
morphology	Euhedral dolomite matrix with larger dolomite xtals in open space	Very fine crystals to large euhedral crystals in centers of open space	subhedral
texture	Rock matrix, some neomorphosed areas	Filling open space	Singular grain in open space
transmitted optical properties			
color ppl xpl			
pleochroism			
birefringence			
twinning/ cleavage			
other			
reflected optical properties			
color			
bireflectance			
anisotropy			
internal reflections			
other			
contact/ relationships with other minerals			
other (growth direction/zoning)	Filling open space, zoned xtals	Filling open space	Zoned with hm

Structures: Sample is part of a sedimentary breccia. Dolomite clasts are surrounded by quartz and recrystallized dolomite. Some neomorphism of dolomite has occurred. There are also tension gashes across the quartz filled vugs.
Paragenetic Sequence: dol→fracturing→neomorphism + dolomite fracture fill→qtz fracture fill→tension gashes + Py
Paragenetic Reasoning: Fracturing occurred allowing for dolomite to being to fill the void space with large, euhedral, sparry dolomite. Quartz began to fill in the rest of the fractures, filling the voids with large crystals in the center of voids along with some sparry dolomite. Pyrite is late????
Sample Highlights: Tension Gashes, dolomite overgrowths

Sample #: 155-193

Hole #: VZMIF 155

Sample Interval: 193.26-193.4 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

VZMIF 155

193.26-193.4

Other Sample Information:

minerals	Dolomite	quartz	Muscovite
percentage	95	5	trace
morphology	Micritic algal boundstone	Angular to subangular grains	Platy laths
texture	Algal laminations with qtz (+ musc) intercalations	Algal laminations with qtz (+ musc) intercalations	
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Forms rock; some unmineralized fractures	Forms rock	Forms rock
other (growth direction/zoning)			

minerals	Fe-alt		
percentage	trace		
morphology	Discontinuous veinlets with very trace hematite		
texture	veinlets		
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Overprints boundstone		
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

Fe-alt is late compared to rock-forming mins

Sample #: 155-213

Hole #: VZMIF 155

Sample Interval: 213.45-213.73 m

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Pink Dolomite

Sample Photograph

Other Sample Information: Same as 123-46. Not originally a phyllite as previously thought, just more altered carbonate

Sample #: GMN1-527 A

Hole #: Vazante
Mine

Sample Interval: Level 527; Section
12,400; Northern Ore Gallery 1

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Other Sample Information:

minerals	Fe-carbonate	Willemite	Sphalerite
percentage	25	35	20
morphology	Anhedral, large, crystalline	Euhedral laths and granular crystals	Irregular crystals
texture	“dirty” looking	Massive	Vein-forming
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Being replaced by wl, sulfides	Cross-cut and fractured by sulfides, being replaced by sp, gn, frk, and hm	Intergrown with galena, co-eval with gn, hm, and frk, cross-cutting wl and carbonate
other (growth direction/zoning)			

minerals	Galena	Franklinite	hematite
percentage	10	7	3
morphology	Irregular crystalline	Euhedral	Euhedral
texture	Vein-forming w/ sp	Disseminated in sp+gn vein, close to contacts with W1	Disseminated in sp+gn vein
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Intergrown with sp, being replaced by srm and cv	Straight contacts with gn and sp	Straight contacts with gn and sp
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

minerals	Covellite	Stromeyerite	
percentage	Trace	Very trace	
morphology	Euhedral laths	Irregular crystals	
texture	Very disseminated	Very disseminated	
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular, growing on galena	Irregular growing on galena	
other (growth direction/zoning)			

Sample #: GMN1-527 D

Hole #: Vazante
Mine

Sample Interval: Level 527; Section
12,400; Northern Ore Gallery 1

Geologic Unit: Hydrothermal Breccia

Lithological Unit (Votorantim): Hydrothermal Breccia

Sample Photograph

Other Sample Information: 527 A and B are the same with less carbonate and more willemite

minerals	Fe-carbonate	Willemite	Sphalerite
percentage	25	35	20
morphology	Anhedral, large, crystalline	Euhedral laths and granular crystals	Irregular crystals
texture	“dirty” looking	Massive	Vein-forming
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Being replaced by wl, sulfides	Cross-cut and fractured by sulfides, being replaced by sp, gn, frk, and hm	Intergrown with galena, co-eval with gn, hm, and frk, cross-cutting wl and carbonate
other (growth direction/zoning)			

minerals	Galena	Franklinite	hematite
percentage	10	7	3
morphology	Irregular crystalline	Euhedral	Euhedral
texture	Vein-forming w/ sp	Disseminated in sp+gn vein, close to contacts with W1	Disseminated in sp+gn vein
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Intergrown with sp, being replaced by srm and cv	Straight contacts with gn and sp	Straight contacts with gn and sp
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

minerals	Covellite	Stromeyerite	
percentage	Trace	Very trace	
morphology	Euhedral laths	Irregular crystals	
texture	Very disseminated	Very disseminated	
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Irregular, growing on galena	Irregular growing on galena	
other (growth direction/zoning)			

Sample #: M124-118

Hole #: MASA 124

Sample Interval: 118.18—118.32 M

Geologic Unit: Upper Pamplona (silty marker bed)

Lithological Unit (Votorantim): Marl (MG)

Sample Photograph

Other Sample Information: contact between the Upper and Middle Pamplona members

minerals	Quartz	Pyrite	
percentage	85	15	
morphology	Angular to subangular grains	Euhedral	
texture	siltstone	Replacing stratigraphy, exhalative features?	
transmitted optical properties			
reflected optical properties			
contact/relationships with other minerals	Straight contacts with py, direct replacement?		
other (growth direction/zoning)			

Paragenesis:

Time   Early Late

Qtz   _____

Py   _____

Paragenetic Reasoning: Possible that Py formed much later as a result of reducing sulfates or salts being present in unit. Py forming around voids, possible exhalative escape structures.

Sample #: M124-267

Hole #: MASA 124

Sample Interval: 267.85—267.95 M

Geologic Unit: Lower Pamplona

Lithological Unit (Votorantim): Intercalated phyllites (DG)

Sample Photograph

Other Sample Information: see 043-191 *contains trace chalcocite and covellite in green zone

Sample #: M124-97

Hole #: MASA 124

Sample Interval: 97.2—97.45 m

Geologic Unit: Upper Pamplona

Lithological Unit (Votorantim): Grey dolomite (DO)

Sample Photograph

Other Sample Information:

minerals	Dolomite	Recrystallized dolomite	Quartz
percentage	30	47	1
morphology	Subhedral crystalline	Large euhedral crystalline	subangular
texture	Pseudo-neomorphic	Vein-filling	disseminated
transmitted optical properties			
reflected optical properties			
contact/ relationships with other minerals	Host rock, being cut by re-crystallized dol	Being replaced by sp, irregular contacts	Coeval with dolomite
other (growth direction/zoning)			

minerals	Sphalerite	Pyrite	Fe-oxides (Goethite?)
percentage	15	2	5
morphology	Irregular crystalline	Irregular crystalline	Irregular crystalline
texture	Vein-filling	Disseminated and vein filling	Replacing Py
transmitted optical properties	Translucent in ppl		
reflected optical properties			
contact/relationships with other minerals	Replacing dol in vein and contains disseminated py (coeval)	Replacing dol in vein	Replacing Py and dol in vein
other (growth direction/zoning)			

Appendix D Whole Rock Geochemistry

D.1 ICP-MS Data

<i>SAMPLE</i>		<i>12-347</i>	<i>12-377</i>	<i>136-112</i>	<i>122-75</i>	<i>115-150</i>	<i>115-220</i>
Geologic		BH	BH	BH	BH	BH	BH
Unit							
Description		type 4	type 2	type 2	type 4	type 1	type 4
Ag	ppm	231	0.84	2.91	43.1	3	394
Al	%	0.08	0.19	0.13	0.04	0.34	0.02
As	ppm	42.4	5	4.4	42.5	5	96.6
Ba	ppm	1510	1980	1480	820	50	640
Be	ppm	0.76	0.11	0.16	0.98	0.05	0.48
Bi	ppm	0.03	0.02	0.01	0.02	0.08	0.06
Ca	%	3.04	17.65	7.44	1.19	19.05	0.17
Cd	ppm	178	7.75	214	59.1	278	89.2
Ce	ppm	1.56	3.59	2.54	4.21	2.64	0.74
Co	ppm	7.8	9	53.2	38.3	31.3	1.7
Cr	ppm	11	4	19	9	6	7
Cs	ppm	0.08	0.19	0.07	0.05	0.1	0.05
Cu	ppm	338	6.9	7.2	74.9	18	2650
Fe	%	3.91	2.03	3.37	3.8	1.31	1.85
Ga	ppm	5.46	0.68	1.54	1.09	1.3	1.38
Ge	ppm	0.06	0.05	0.05	0.06	0.05	0.07
Hf	ppm	0.1	0.1	0.1	0.1	0.2	0.1
Hg	ppm	8.3	0.22	0.1	1.05	0.31	8.2
In	ppm	0.082	0.01	0.079	0.828	0.01	0.061
K	%	0.03	0.08	0.01	0.01	0.02	0.01
La	ppm	0.8	1.9	2	2.5	1.7	0.5
Li	ppm	4.4	4.3	2.8	5.2	3.3	10.9
Mg	%	1.67	10.95	4.06	2.59	11.8	0.11
Mn	ppm	185	720	1040	403	529	22

<i>SAMPLE</i>		<i>12-347</i>	<i>12-377</i>	<i>136-112</i>	<i>122-75</i>	<i>115-150</i>	<i>115-220</i>
Mo	ppm	0.6	0.22	0.48	0.78	0.11	0.73
Na	%	0.03	0.05	0.03	0.01	0.01	0.01
Nb	ppm	0.3	0.6	0.3	0.2	0.8	0.1
Ni	ppm	3	2.9	13.9	7.1	9.1	1.2
P	ppm	110	80	250	140	110	240
Pb	ppm	1295	130.5	917	1750	4730	87000
Rb	ppm	0.9	3.4	0.2	0.2	0.7	0.2
Re	ppm	0.002	0.002	0.002	0.002	0.002	0.002
S	%	0.05	0.06	0.04	0.04	0.03	0.72
Sb	ppm	2.2	0.32	0.99	5.63	0.25	1.02
Sc	ppm	0.2	0.3	0.3	0.5	0.7	0.1
Se	ppm	41	1	1	38	4	39
Sn	ppm	0.2	0.2	0.2	0.2	0.2	0.2
Sr	ppm	22.3	56.3	37	34.2	63.7	85.8
Ta	ppm	0.05	0.05	0.05	0.05	0.05	0.05
Te	ppm	0.05	0.05	0.05	0.05	0.05	0.05
Th	ppm	0.2	0.2	0.2	0.2	0.3	0.2
Ti	%	0.005	0.009	0.006	0.005	0.018	0.005
Tl	ppm	0.02	0.02	0.02	0.02	0.02	0.02
U	ppm	1.5	0.6	0.4	0.7	0.6	0.7
V	ppm	21	18	97	8	33	27
W	ppm	0.2	0.3	0.3	0.2	0.1	0.2
Y	ppm	0.5	1.5	2	1	2.1	0.3
Zn	ppm	460000	4030	5440	378700	19000	489000
Zr	ppm	1.3	4.2	2.9	0.6	6.3	0.7

<i>SAMPLE</i>		<i>129-160</i>	<i>129-167</i>	<i>60-120</i>	<i>60-136</i>	<i>101-137</i>	<i>15-382</i>
Geologic Unit		BH	BH	BH	BH	BH	BH
Description		type 1	type 4	type 4	type 4	type 4	type 1
Ag	ppm	2.31	24.1	19.55	257	3.58	0.13
Al	%	1.21	0.65	0.1	0.06	0.03	0.62
As	ppm	8	68.5	54.7	49.3	68.1	5
Ba	ppm	200	150	1940	1960	470	120
Be	ppm	0.55	1.65	0.53	0.71	0.47	0.2
Bi	ppm	0.07	0.09	0.02	0.07	0.02	0.03
Ca	%	16.35	2.15	0.6	4.53	7.01	19.05
Cd	ppm	11.05	222	14.55	900	812	5.53
Ce	ppm	17.1	11.8	1.44	4.55	2.17	6.29
Co	ppm	18.4	18.5	6.4	12.1	16.8	3.5
Cr	ppm	8	30	3	8	11	4
Cs	ppm	0.74	0.15	0.14	0.05	0.05	0.5
Cu	ppm	15.7	132.5	77.6	191.5	16.6	4.6
Fe	%	1.34	12.4	13.3	7.21	1.91	0.69
Ga	ppm	3.39	6.25	1.77	3.69	4.08	1.71
Ge	ppm	0.05	0.25	0.21	0.17	0.05	0.07
Hf	ppm	0.5	0.4	0.1	0.1	0.1	0.3
Hg	ppm	0.07	0.71	2.12	0.8	0.23	0.01
In	ppm	0.033	0.285	0.677	0.086	0.008	0.006
K	%	0.54	0.01	0.01	0.01	0.01	0.35
La	ppm	8	5.2	0.9	2.6	1.7	3.1
Li	ppm	22.7	16.7	4	8.3	4.6	8.4
Mg	%	10.55	1.5	0.36	2.5	3.83	11.9
Mn	ppm	564	158	73	438	491	519
Mo	ppm	0.18	1.99	1.91	1.12	0.37	0.05
Na	%	0.03	0.01	0.03	0.04	0.01	0.02
Nb	ppm	2.1	1.4	0.4	0.3	0.2	1.2
Ni	ppm	7.1	21.3	8.3	6.6	4.3	4.7

<i>SAMPLE</i>		<i>129-160</i>	<i>129-167</i>	<i>60-120</i>	<i>60-136</i>	<i>101-137</i>	<i>15-382</i>
P	ppm	1330	2150	120	150	290	170
Pb	ppm	1225	2960	1295	34700	2920	72.5
Rb	ppm	21.5	0.3	0.3	0.2	0.2	11.6
Re	ppm	0.002	0.002	0.002	0.002	0.002	0.002
S	%	0.01	0.02	0.2	0.24	0.02	0.01
Sb	ppm	1.13	12.75	2.99	2.95	1.36	0.12
Sc	ppm	2.1	1.2	0.2	0.2	0.4	1
Se	ppm	1	37	15	41	35	1
Sn	ppm	0.4	0.4	0.2	0.2	0.2	0.2
Sr	ppm	49.7	12.1	1895	86.8	17.6	56
Ta	ppm	0.13	0.07	0.05	0.05	0.05	0.06
Te	ppm	0.05	0.07	0.05	0.05	0.05	0.05
Th	ppm	1.7	0.9	0.2	0.2	0.2	0.7
Ti	%	0.056	0.03	0.005	0.005	0.005	0.027
Tl	ppm	0.15	0.02	0.02	0.02	0.02	0.04
U	ppm	1.3	7.3	3.8	3.5	0.5	0.4
V	ppm	18	47	33	76	20	8
W	ppm	0.3	0.5	0.2	0.3	0.1	0.1
Y	ppm	9.4	2.3	0.6	1.2	1.1	1.9
Zn	ppm	3160	401200	170500	373800	382900	1470
Zr	ppm	19.9	12.9	1	0.8	0.5	9.3

<i>SAMPLE</i>		<i>125-55</i>	<i>123-73</i>	<i>139-270</i>	<i>28-47</i>	<i>124-62</i>	<i>124-72</i>
Geologic Unit Description		BH	BH	BH	BH	BH	BH
		type 3	type 4	Other	type 2	type 3	type 1
Ag	ppm	0.99	30	0.03	0.1	1.01	0.46
Al	%	0.78	0.07	0.33	0.67	0.61	0.92
As	ppm	104	90.2	5	5	115.5	13
Ba	ppm	100	150	600	170	50	30
Be	ppm	1.63	0.74	0.17	0.36	2.09	0.26
Bi	ppm	0.15	0.02	0.02	0.06	0.08	0.02
Ca	%	6.72	1.56	20	19.7	7.04	18.05
Cd	ppm	108	55.3	1.86	8.69	189	553
Ce	ppm	9.78	6.23	4.22	7.59	4.96	14.7
Co	ppm	61.9	9.5	2.7	5.8	60.3	57.4
Cr	ppm	5	12	4	6	5	8
Cs	ppm	1	0.05	0.26	0.58	0.75	0.16
Cu	ppm	9	62.5	2.1	3.3	16.2	15.9
Fe	%	43.1	15.85	0.45	0.46	41.2	2.26
Ga	ppm	3.17	1.72	0.85	1.79	3.61	3.46
Ge	ppm	0.95	0.34	0.12	0.08	0.21	0.12
Hf	ppm	0.1	0.1	0.2	0.3	0.1	0.4
Hg	ppm	0.2	1.08	0.01	0.07	0.05	0.02
In	ppm	2.94	0.231	0.014	0.011	2.89	0.064
K	%	0.04	0.01	0.16	0.39	0.1	0.01
La	ppm	3.7	3	1.9	3.7	2.8	9.2
Li	ppm	10.1	12.6	5	10.8	13.2	17.1
Mg	%	3.97	0.88	12.65	11.8	4.28	11.45
Mn	ppm	451	115	131	207	385	637
Mo	ppm	3.87	1.8	0.05	0.13	5.25	0.3
Na	%	0.01	0.01	0.02	0.03	0.01	0.01
Nb	ppm	1.4	0.5	0.9	1.4	0.2	1.4
Ni	ppm	48.5	6.1	3.5	5.4	31.5	32.3

<i>SAMPLE</i>		<i>125-55</i>	<i>123-73</i>	<i>139-270</i>	<i>28-47</i>	<i>124-62</i>	<i>124-72</i>
P	ppm	260	280	110	2700	210	380
Pb	ppm	1850	2030	99.8	187	2390	2060
Rb	ppm	2.7	0.3	6.8	16.7	3.6	0.6
Re	ppm	0.002	0.002	0.002	0.002	0.004	0.003
S	%	0.12	0.07	0.02	0.01	0.01	0.01
Sb	ppm	47.6	12.95	0.19	0.18	31	1.36
Sc	ppm	0.5	0.2	0.7	1	0.6	1.8
Se	ppm	3	29	1	1	1	1
Sn	ppm	0.2	0.2	0.2	0.3	0.3	0.3
Sr	ppm	16.8	39	58	70.8	20.3	45.1
Ta	ppm	0.05	0.05	0.05	0.09	0.05	0.1
Te	ppm	0.05	0.05	0.05	0.05	0.05	0.05
Th	ppm	0.2	0.2	0.5	1.3	0.2	1.4
Ti	%	0.005	0.005	0.017	0.026	0.005	0.046
Tl	ppm	0.02	0.02	0.03	0.07	0.04	0.02
U	ppm	7.2	3.8	0.4	0.7	15.3	1.3
V	ppm	153	138	4	6	146	23
W	ppm	1.2	0.4	0.1	0.1	1.1	0.1
Y	ppm	3.4	0.7	1.6	3.1	2	3.9
Zn	ppm	24800	324000	325	1180	12200	25700
Zr	ppm	4.2	1.1	8.2	11.3	4.2	12.7

<i>SAMPLE</i>		<i>124-75</i>	<i>124-78</i>	<i>124-83</i>	<i>139-314</i>	<i>123-127</i>	<i>101-128</i>
Geologic Unit		BH	BH	BH	BH	BH	BH
Description		type 4	type 4	type 1	type 1	type 1	type 3
Ag	ppm	5.7	37	0.25	0.07	0.1	5.59
Al	%	0.03	0.07	0.3	0.53	0.41	0.43
As	ppm	57.3	63.9	5	8	5	87.9
Ba	ppm	70	280	10	20	40	4570
Be	ppm	0.73	1.42	0.15	0.3	0.3	0.73
Bi	ppm	0.02	0.01	0.02	0.03	0.03	0.08
Ca	%	1.84	1.27	20.3	19.25	19.7	6.06
Cd	ppm	32.5	68.5	145.5	289	4.84	335
Ce	ppm	3.6	1.54	3.29	5.73	5.25	6.32
Co	ppm	12.8	9.7	19.6	65.6	1.5	14.5
Cr	ppm	5	12	3	3	6	1
Cs	ppm	0.05	0.05	0.12	0.31	0.43	0.41
Cu	ppm	18	62.5	5.6	2.5	3.8	10.4
Fe	%	6.02	12.1	1.04	1.2	0.35	25.1
Ga	ppm	1.63	3.21	1.2	1.84	1.01	2.8
Ge	ppm	0.12	0.12	0.1	0.12	0.12	0.12
Hf	ppm	0.1	0.1	0.1	0.4	0.3	0.1
Hg	ppm	0.14	1.27	0.07	0.16	0.04	0.32
In	ppm	0.532	1.935	0.012	0.139	0.006	0.077
K	%	0.01	0.01	0.01	0.02	0.21	0.01
La	ppm	1.7	0.9	2	3.6	2.4	3.2
Li	ppm	14.5	8.9	7.2	16.9	9.5	3.8
Mg	%	0.89	0.63	12.35	11.9	11.65	3.54
Mn	ppm	94	71	409	627	144	671
Mo	ppm	1.14	2.22	0.14	0.16	0.08	3.81
Na	%	0.01	0.01	0.02	0.02	0.02	0.07
Nb	ppm	0.1	0.1	0.6	1.2	1	0.2
Ni	ppm	9.3	12.8	12.3	41	2.5	10.1

<i>SAMPLE</i>		<i>124-75</i>	<i>124-78</i>	<i>124-83</i>	<i>139-314</i>	<i>123-127</i>	<i>101-128</i>
P	ppm	1030	190	80	110	110	320
Pb	ppm	1180	1290	1480	1410	314	2850
Rb	ppm	0.1	0.2	0.6	1.1	7.9	0.7
Re	ppm	0.003	0.003	0.003	0.004	0.003	0.003
S	%	0.01	0.01	0.01	0.01	0.01	0.2
Sb	ppm	3.26	11.05	0.42	0.33	0.09	13.5
Sc	ppm	0.1	0.1	0.6	1.2	0.8	0.7
Se	ppm	6	8	1	1	1	1
Sn	ppm	0.2	0.2	0.2	0.3	0.2	0.2
Sr	ppm	23.7	12.5	58.8	81.5	83.8	444
Ta	ppm	0.05	0.05	0.05	0.07	0.06	0.05
Te	ppm	0.05	0.05	0.05	0.05	0.05	0.05
Th	ppm	0.2	0.2	0.5	1	0.7	0.2
Ti	%	0.005	0.005	0.015	0.033	0.023	0.006
Tl	ppm	0.02	0.02	0.02	0.02	0.05	0.02
U	ppm	1.9	8.4	0.7	1.6	4.1	4.2
V	ppm	33	94	6	9	27	52
W	ppm	0.1	0.4	0.1	0.1	0.1	0.8
Y	ppm	1.6	0.8	2.1	3.7	2.4	1.9
Zn	ppm	486400	350000	12250	9280	542	45600
Zr	ppm	0.5	0.7	5.3	12.7	10.1	2.6

<i>SAMPLE</i>		<i>101-148</i>	<i>43-213</i>	<i>43-232</i>	<i>M124-284</i>	<i>M124-289</i>	<i>M124-300</i>
Geologic Unit		BH	BH	BH	BH	BH	BH
Description		type 2	type 1	type 2	type 1	type 1	type 1
Ag	ppm	0.41	0.06	0.03	0.1	0.18	0.18
Al	%	0.18	0.49	0.09	0.41	0.41	0.33
As	ppm	10	5	6	5	7	5
Ba	ppm	320	350	390	30	70	20
Be	ppm	0.32	0.3	0.08	0.15	0.26	0.09
Bi	ppm	0.02	0.02	0.01	0.02	0.04	0.01
Ca	%	16.6	19.45	19.65	19.1	17.25	19.3
Cd	ppm	1110	36.8	167.5	158.5	4.94	22.2
Ce	ppm	4.71	6.4	5.76	3.48	6.29	3.42
Co	ppm	36.5	17.5	27.2	15.6	6	6.6
Cr	ppm	1	2	1	4	4	3
Cs	ppm	0.07	0.51	0.08	0.16	0.32	0.17
Cu	ppm	7.3	1.8	2.6	6.2	9.1	6.7
Fe	%	1.37	0.71	1.49	0.95	2.76	0.57
Ga	ppm	2.31	1.35	0.34	1.29	1.1	0.68
Ge	ppm	0.08	0.12	0.1	0.12	0.13	0.11
Hf	ppm	0.1	0.2	0.1	0.1	0.1	0.2
Hg	ppm	0.07	0.03	0.02	0.04	0.1	0.14
In	ppm	0.017	0.006	0.006	0.005	0.006	0.005
K	%	0.01	0.23	0.01	0.08	0.2	0.04
La	ppm	2.6	3.2	3.3	1.9	2.9	1.9
Li	ppm	4	9.5	3.5	7.6	5.8	6.6
Mg	%	10.1	11.6	11.65	12	10.7	12.15
Mn	ppm	825	613	1080	541	693	578
Mo	ppm	0.14	0.05	0.1	0.11	0.32	0.11
Na	%	0.01	0.02	0.02	0.02	0.01	0.02
Nb	ppm	0.3	0.9	0.2	0.5	0.5	0.4

SAMPLE		101-148	43-213	43-232	M124-284	M124- 289	M124- 300
Ni	ppm	6.4	7.5	11.8	9.4	5.9	3.6
P	ppm	80	120	160	110	230	270
Pb	ppm	2010	656	1410	1400	1445	740
Rb	ppm	0.5	8.7	0.4	2.5	6.2	1.3
Re	ppm	0.003	0.003	0.003	0.002	0.002	0.002
S	%	0.01	0.01	0.01	0.01	0.01	0.01
Sb	ppm	1.42	0.23	0.36	0.1	0.78	0.05
Sc	ppm	0.3	0.8	0.1	0.7	0.6	0.5
Se	ppm	1	1	1	1	1	1
Sn	ppm	0.2	0.2	0.2	0.2	0.2	0.2
Sr	ppm	28.1	75.9	75.3	57.6	46.1	47.3
Ta	ppm	0.05	0.05	0.05	0.05	0.05	0.05
Te	ppm	0.05	0.05	0.05	0.05	0.05	0.05
Th	ppm	0.3	0.7	0.2	0.3	0.6	0.4
Ti	%	0.008	0.021	0.005	0.016	0.015	0.016
Tl	ppm	0.02	0.03	0.02	0.02	0.03	0.02
U	ppm	0.7	0.4	0.2	0.4	1	0.5
V	ppm	17	6	13	12	28	5
W	ppm	0.1	0.1	0.1	0.1	0.3	0.1
Y	ppm	2.2	2	3.1	1.6	3.4	1.2
Zn	ppm	107000	3660	8940	5350	1120	6170
Zr	ppm	3.3	8.4	1.5	3.7	4.7	5.4

<i>SAMPLE</i>		<i>M124-305</i>	<i>M124-321</i>	<i>M124-329</i>	<i>M124-347</i>
Geologic Unit		BH	BH	BH	BH
Description		type 3	Other-brecciated phyllite	type 4	type 2
Ag	ppm	8.82	5.35	26.1	0.31
Al	%	0.35	6.71	0.12	0.22
As	ppm	147	3.5	82	8
Ba	ppm	50	430	20	60
Be	ppm	0.87	1.92	2.38	0.1
Bi	ppm	0.08	0.1	0.01	0.02
Ca	%	1.55	1.33	0.43	17.65
Cd	ppm	50.7	11.65	10.55	628
Ce	ppm	3.78	57.7	2.27	7.41
Co	ppm	8.2	31.9	14.5	44
Cr	ppm	17	46	10	2
Cs	ppm	0.75	11.1	0.13	0.25
Cu	ppm	48.9	26.8	22.1	2.7
Fe	%	54.31	2.12	13.4	4.81
Ga	ppm	3.25	14	2.13	1.09
Ge	ppm	0.18	0.22	0.21	0.14
Hf	ppm	0.1	3.1	0.1	0.1
Hg	ppm	0.34	0.15	0.01	0.03
In	ppm	0.017	0.039	2.1	0.074
K	%	0.03	2.99	0.01	0.04
La	ppm	1.9	29.3	1	3.9
Li	ppm	3.3	78.3	5	5.7
Mg	%	0.88	3.78	0.25	10.9
Mn	ppm	357	200	80	899
Mo	ppm	9.29	0.18	2.43	0.49
Na	%	0.01	0.05	0.01	0.01

<i>SAMPLE</i>		<i>M124- 305</i>	<i>M124-321</i>	<i>M124- 329</i>	<i>M124- 347</i>
Nb	ppm	0.3	10	0.1	0.4
Ni	ppm	11.4	25.4	10.1	14.4
P	ppm	150	240	400	330
Pb	ppm	2680	702	1310	2230
Rb	ppm	1.5	107.5	0.4	1.4
Re	ppm	0.002	0.002	0.002	0.002
S	%	0.01	0.01	0.01	0.01
Sb	ppm	9.11	1.51	4.71	1.15
Sc	ppm	1.3	9.5	0.1	0.4
Se	ppm	1	1	4	1
Sn	ppm	0.2	1.5	0.2	0.2
Sr	ppm	10.4	9	5.7	75.4
Ta	ppm	0.05	0.73	0.05	0.05
Te	ppm	0.05	0.05	0.05	0.05
Th	ppm	0.2	8.1	0.2	0.3
Ti	%	0.007	0.331	0.005	0.011
Tl	ppm	0.02	0.8	0.02	0.02
U	ppm	4.7	1.7	2.9	1.5
V	ppm	49	60	34	10
W	ppm	0.4	0.8	0.2	0.2
Y	ppm	1.1	10.1	0.8	3.6
Zn	ppm	46600	8840	454200	7050
Zr	ppm	2.1	102	0.6	3.6

<i>SAMPLE</i>		<i>M124-353</i>	<i>M124-356</i>	<i>124-4</i>	<i>32-157</i>
Geologic Unit		BH	BH	BH overprint on Lp	BH?/SdG
Description		type 3	type 1	type 2	mineralized fault/vein
Ag	ppm	4.92	0.15	0.07	0.38
Al	%	0.17	0.18	0.05	0.37
As	ppm	54.7	5	5	5
Ba	ppm	30	20	50	40
Be	ppm	0.82	0.09	0.08	0.54
Bi	ppm	0.04	0.01	0.02	0.08
Ca	%	2.09	20.1	20.3	16.05
Cd	ppm	66.5	236	167.5	49.7
Ce	ppm	1.56	3.16	2.3	12.95
Co	ppm	25.4	28.6	56.7	34.5
Cr	ppm	13	2	4	33
Cs	ppm	0.3	0.09	0.06	2.81
Cu	ppm	21.9	3.1	10.7	3.1
Fe	%	59.87	0.84	1.57	13.3
Ga	ppm	5.11	0.66	0.26	1.5
Ge	ppm	0.19	0.11	0.12	0.27
Hf	ppm	0.1	0.1	0.1	0.1
Hg	ppm	0.05	0.02	0.06	0.14
In	ppm	0.613	0.047	0.014	0.151
K	%	0.01	0.02	0.02	0.03
La	ppm	0.7	2.7	1.2	6.3
Li	ppm	3.8	5.2	2	12
Mg	%	1.33	12.45	11.9	9.03
Mn	ppm	165	495	1140	778
Mo	ppm	12.7	0.07	0.45	0.54
Na	%	0.01	0.02	0.01	0.01
Nb	ppm	0.1	0.3	0.1	0.9

<i>SAMPLE</i>		<i>M124- 353</i>	<i>M124- 356</i>	<i>124-4</i>	<i>32-157</i>
Ni	ppm	30	10.9	8.1	23
P	ppm	60	380	90	110
Pb	ppm	1160	2080	2040	2580
Rb	ppm	0.3	0.5	0.6	3.6
Re	ppm	0.002	0.002	0.003	0.002
S	%	0.01	0.01	0.01	0.02
Sb	ppm	32.7	0.08	0.9	0.73
Sc	ppm	0.1	0.4	0.2	0.6
Se	ppm	1	1	1	1
Sn	ppm	1.1	0.2	0.2	0.2
Sr	ppm	11.3	56	41.8	212
Ta	ppm	0.05	0.05	0.05	0.05
Te	ppm	0.05	0.05	0.05	0.05
Th	ppm	0.2	0.3	0.2	0.2
Ti	%	0.005	0.009	0.005	0.009
Tl	ppm	0.02	0.02	0.02	0.02
U	ppm	6.8	0.8	0.2	3.7
V	ppm	60	8	15	508
W	ppm	0.5	0.1	0.2	0.2
Y	ppm	0.7	1.9	1.7	8.3
Zn	ppm	5390	6740	9800	3190
Zr	ppm	0.5	3.4	0.9	4.2

<i>SAMPLE</i>		<i>88-68</i>	<i>139-231</i>	<i>139-245</i>
Geologic		BH?	LMdP	LMdP?
Unit				
Description		Other-sulfide bx	least alt dolomite	selective Fe-carb alt selvages
Ag	ppm	44.9	0.03	0.22
Al	%	0.28	0.12	0.98
As	ppm	287	5	8
Ba	ppm	160	20	40
Be	ppm	0.09	0.15	0.41
Bi	ppm	0.02	0.01	0.04
Ca	%	7.89	20.6	18.85
Cd	ppm	508	10.55	10.2
Ce	ppm	3.41	1.84	11.25
Co	ppm	61.6	3.3	2.9
Cr	ppm	1	2	7
Cs	ppm	0.14	0.1	0.99
Cu	ppm	37.6	3.3	5.1
Fe	%	14.25	0.27	0.49
Ga	ppm	2.68	0.27	2.58
Ge	ppm	0.3	0.06	0.13
Hf	ppm	0.1	0.1	0.9
Hg	ppm	15.7	0.1	0.02
In	ppm	0.137	0.005	0.012
K	%	0.09	0.06	0.59
La	ppm	1.4	0.9	5.1
Li	ppm	3.1	4.3	18.5
Mg	%	4.49	13.15	11.05
Mn	ppm	769	194	180
Mo	ppm	1.04	0.09	0.13
Na	%	0.01	0.02	0.04
Nb	ppm	0.8	0.2	1.8

<i>SAMPLE</i>		<i>88-68</i>	<i>139-231</i>	<i>139-245</i>
Ni	ppm	38	1.6	16.9
P	ppm	50	570	3090
Pb	ppm	2960	119	176
Rb	ppm	2.5	2.2	21.5
Re	ppm	0.002	0.002	0.004
S	%	10	0.01	0.01
Sb	ppm	1.56	0.05	0.22
Sc	ppm	0.5	0.3	1.7
Se	ppm	15	1	1
Sn	ppm	0.2	0.2	0.4
Sr	ppm	71.5	65.6	79.6
Ta	ppm	0.05	0.05	0.12
Te	ppm	0.05	0.05	0.05
Th	ppm	0.3	0.2	1.5
Ti	%	0.011	0.005	0.048
Tl	ppm	0.1	0.02	0.2
U	ppm	0.5	0.3	1.8
V	ppm	3	2	9
W	ppm	0.1	0.1	0.2
Y	ppm	2.2	0.7	4.7
Zn	ppm	174300	539	754
Zr	ppm	4.8	3.8	33.3

<i>SAMPLE</i>		<i>143-124</i>	<i>155-185</i>	<i>155-214</i>	<i>43-97</i>
Geologic Unit		LP	LP	LP	LP
Description		least alt dolomite	dolomite	phyllite	red phyllite
Ag	ppm	0.02	0.06	0.28	0.06
Al	%	0.93	2.48	7.75	8.77
As	ppm	5	5	3.5	2.9
Ba	ppm	90	430	650	360
Be	ppm	0.2	0.34	1.79	2.59
Bi	ppm	0.02	0.04	0.05	0.21
Ca	%	18.7	13.45	0.23	1.24
Cd	ppm	0.16	0.29	0.08	0.03
Ce	ppm	9.81	15	87.3	82.9
Co	ppm	2.1	2.4	8.4	14.3
Cr	ppm	9	9	59	72
Cs	ppm	0.61	1.93	19.3	10.45
Cu	ppm	2.4	3.3	7.8	1.1
Fe	%	0.73	0.66	3.84	6.15
Ga	ppm	2.32	5.08	21.6	27.3
Ge	ppm	0.05	0.14	0.21	0.27
Hf	ppm	0.4	0.7	2.4	3.3
Hg	ppm	0.1	0.1	0.1	0.01
In	ppm	0.008	0.011	0.055	0.067
K	%	0.78	2.7	5.4	4.68
La	ppm	5	7.1	40.2	39.1
Li	ppm	6.3	9.1	27.4	37.8
Mg	%	11.35	8.39	1.44	2.16
Mn	ppm	312	262	18	119
Mo	ppm	0.05	0.1	0.1	0.14
Na	%	0.03	0.03	0.04	0.06
Nb	ppm	1.3	2.7	12.5	12.9

<i>SAMPLE</i>		<i>143-124</i>	<i>155-185</i>	<i>155- 214</i>	<i>43-97</i>
Ni	ppm	4.8	4.8	18.2	34.7
P	ppm	90	190	250	430
Pb	ppm	3.2	9.4	177.5	11.4
Rb	ppm	17.2	46.2	145	112
Re	ppm	0.002	0.002	0.002	0.002
S	%	0.01	0.01	0.01	0.01
Sb	ppm	0.16	0.2	0.8	0.59
Sc	ppm	1.5	2.4	13.5	17.2
Se	ppm	1	1	2	1
Sn	ppm	0.2	0.4	2.6	2.7
Sr	ppm	55.8	69.8	25.3	39.3
Ta	ppm	0.09	0.17	0.82	0.91
Te	ppm	0.05	0.05	0.05	0.05
Th	ppm	1.1	1.6	10.7	11
Ti	%	0.043	0.062	0.33	0.385
Tl	ppm	0.06	0.16	0.7	0.66
U	ppm	0.9	0.5	1.7	1.1
V	ppm	13	8	75	78
W	ppm	0.2	0.2	1.2	1.2
Y	ppm	3.8	6.5	20.8	23.7
Zn	ppm	36	24	1370	78
Zr	ppm	14.8	22.8	84.3	105.5

<i>SAMPLE</i>		<i>105-113</i>	<i>141-117</i>	<i>139-194</i>
Geologic Unit		LP	LP	LP
Description		dol-specularite vein	Fe-carb/carb and hm /py vein	selective Fe- carb alt selvages
Ag	ppm	0.15	0.06	0.07
Al	%	0.84	0.54	0.51
As	ppm	5	6	5
Ba	ppm	1350	50	130
Be	ppm	0.23	0.16	0.23
Bi	ppm	0.21	0.03	0.02
Ca	%	18.55	20	19.4
Cd	ppm	7.26	0.63	4.59
Ce	ppm	7.9	5.2	5.48
Co	ppm	3.7	2.1	2.7
Cr	ppm	5	5	3
Cs	ppm	0.66	0.32	0.62
Cu	ppm	2.1	2.6	2.3
Fe	%	0.66	0.83	0.74
Ga	ppm	1.73	1.45	1.3
Ge	ppm	0.09	0.14	0.1
Hf	ppm	0.5	0.2	0.3
Hg	ppm	0.2	0.03	0.04
In	ppm	0.007	0.006	0.007
K	%	0.74	0.38	0.25
La	ppm	3.8	2.4	2.7
Li	ppm	7.5	4.2	10
Mg	%	11.55	11.95	11.65
Mn	ppm	334	371	397
Mo	ppm	0.05	0.48	0.11
Na	%	0.03	0.03	0.02

<i>SAMPLE</i>		<i>105-113</i>	<i>141-117</i>	<i>139-194</i>
Nb	ppm	1.1	0.8	0.8
Ni	ppm	5.8	3.1	3.3
P	ppm	170	60	100
Pb	ppm	469	19.1	195
Rb	ppm	18.2	8.5	8.4
Re	ppm	0.002	0.003	0.003
S	%	0.05	0.01	0.01
Sb	ppm	0.05	0.13	0.38
Sc	ppm	1.5	0.8	0.8
Se	ppm	1	1	1
Sn	ppm	0.2	0.2	0.2
Sr	ppm	88.7	51.3	75.6
Ta	ppm	0.07	0.05	0.05
Te	ppm	0.05	0.05	0.05
Th	ppm	1	0.7	0.7
Ti	%	0.038	0.023	0.023
Tl	ppm	0.07	0.03	0.04
U	ppm	0.5	0.7	0.5
V	ppm	8	14	7
W	ppm	0.1	0.1	0.1
Y	ppm	2.7	1.7	2
Zn	ppm	523	163	1170
Zr	ppm	18.8	6.2	10.3

<i>SAMPLE</i>		<i>123-46</i>	<i>123-51</i>	<i>101-222</i>
Geologic Unit		LP	LP	LP
Description		Fe-carb selvage alt w/ no texture	Hm alt vein	mottled Fe-carb atl and veinlets
Ag	ppm	0.13	0.15	0.07
Al	%	2.22	1.43	0.4
As	ppm	9	17	5
Ba	ppm	50	40	750
Be	ppm	0.77	0.75	0.22
Bi	ppm	0.05	0.08	0.02
Ca	%	15.45	16.8	19.45
Cd	ppm	16.45	104	3.82
Ce	ppm	21.4	13.8	5.99
Co	ppm	14.3	42.6	16.5
Cr	ppm	10	7	2
Cs	ppm	1.07	0.8	0.25
Cu	ppm	5.4	10.6	9.7
Fe	%	1.14	5.11	0.95
Ga	ppm	4.75	3.72	1.25
Ge	ppm	0.13	0.11	0.06
Hf	ppm	1.2	0.7	0.2
Hg	ppm	0.69	0.07	0.06
In	ppm	0.018	0.054	0.015
K	%	0.86	0.55	0.29
La	ppm	10.1	7	3
Li	ppm	20.9	16.4	5.2
Mg	%	9.83	10.55	12.05
Mn	ppm	530	696	464
Mo	ppm	0.07	0.6	0.21
Na	%	0.06	0.02	0.01
Nb	ppm	2.9	2.1	1.1

<i>SAMPLE</i>		<i>123-46</i>	<i>123-51</i>	<i>101-222</i>
Ni	ppm	9.4	24	6.6
P	ppm	280	90	140
Pb	ppm	763	2870	59.1
Rb	ppm	27.7	18.5	7.4
Re	ppm	0.003	0.004	0.002
S	%	0.01	0.01	0.02
Sb	ppm	0.62	3.17	0.19
Sc	ppm	3.9	2.8	0.8
Se	ppm	1	1	1
Sn	ppm	0.6	0.4	0.2
Sr	ppm	44.9	28.1	72.3
Ta	ppm	0.2	0.13	0.06
Te	ppm	0.05	0.05	0.05
Th	ppm	2.9	1.9	0.5
Ti	%	0.112	0.067	0.019
Tl	ppm	0.19	0.11	0.03
U	ppm	0.6	1.6	0.4
V	ppm	14	32	11
W	ppm	0.2	0.4	0.1
Y	ppm	7.7	4.7	1.8
Zn	ppm	4070	9650	581
Zr	ppm	40.7	21.3	10.7

<i>SAMPLE</i>		<i>43-191</i>	<i>88-93</i>	<i>88-124</i>	<i>M124-199</i>
Geologic Unit		LP	LP	LP	LP
Description		green phyllite	maroon phyllite	black phyllite	pink carb w/ silica alt
Ag	ppm	0.07	0.25	0.02	0.4
Al	%	5.51	7.79	8.05	0.5
As	ppm	1.7	8.9	3.1	5
Ba	ppm	370	1050	390	40
Be	ppm	2.49	2.08	2.05	0.26
Bi	ppm	0.13	0.11	0.13	0.03
Ca	%	4.18	0.41	0.31	16.95
Cd	ppm	11.4	0.41	1.5	1.65
Ce	ppm	75.7	62.6	72.8	3.28
Co	ppm	20.9	10.1	8.2	2.5
Cr	ppm	29	71	74	8
Cs	ppm	5.26	11.8	7.69	0.24
Cu	ppm	3.6	23.7	3.8	6
Fe	%	2.35	5.5	4.9	0.83
Ga	ppm	15.2	21.7	24.2	1.38
Ge	ppm	0.21	0.19	0.2	0.11
Hf	ppm	4	3.8	3.6	0.2
Hg	ppm	0.01	0.02	0.01	0.14
In	ppm	0.045	0.056	0.054	0.005
K	%	3.86	5.56	5.75	0.39
La	ppm	39.4	28.7	33.7	1.6
Li	ppm	21.2	31.2	33	5.4
Mg	%	3.2	1.58	1.38	10.45
Mn	ppm	225	22	46	368
Mo	ppm	0.17	0.57	0.12	0.76
Na	%	0.03	0.05	0.07	0.02
Nb	ppm	25.9	12.1	13.9	0.6

<i>SAMPLE</i>		<i>43-191</i>	<i>88-93</i>	<i>88-124</i>	<i>M124-199</i>
Ni	ppm	16.2	25.5	24	2.8
P	ppm	290	400	230	60
Pb	ppm	41.3	53.3	16.4	67.1
Rb	ppm	120	118	116	8.1
Re	ppm	0.004	0.003	0.004	0.002
S	%	0.01	0.01	0.01	0.01
Sb	ppm	0.54	0.99	0.26	0.08
Sc	ppm	8.2	12.2	13.8	0.6
Se	ppm	2	1	1	1
Sn	ppm	1.8	2.3	2.4	0.2
Sr	ppm	30.1	12	17.5	46.3
Ta	ppm	0.77	0.87	0.96	0.05
Te	ppm	0.05	0.05	0.05	0.05
Th	ppm	10	9.4	10.3	0.5
Ti	%	0.27	0.38	0.405	0.017
Tl	ppm	0.58	0.67	0.59	0.04
U	ppm	1.1	2.9	1.7	0.8
V	ppm	41	101	115	19
W	ppm	1	0.8	0.9	0.1
Y	ppm	20.9	10.6	12.4	1.1
Zn	ppm	579	468	160	315
Zr	ppm	154	117	118.5	5.7

<i>SAMPLE</i>		<i>M124-250</i>	<i>139-135</i>	<i>141-16</i>
Geologic		LP	LP	MP
Unit				
Description		chalcedonic silica alt	Fe-carb selvage alt w/ qtz alt veinlets	carb-alt veinlet
Ag	ppm	0.08	0.7	0.39
Al	%	0.58	0.7	0.09
As	ppm	5	8	9
Ba	ppm	160	110	20
Be	ppm	0.21	0.22	0.1
Bi	ppm	0.02	0.02	0.01
Ca	%	15.4	15.3	17.25
Cd	ppm	2.65	3.63	58
Ce	ppm	5.18	4.86	2.52
Co	ppm	0.9	2.7	1.6
Cr	ppm	11	23	3
Cs	ppm	0.4	0.22	0.08
Cu	ppm	4.5	17.6	6.7
Fe	%	0.5	0.99	1.33
Ga	ppm	1.4	1.59	0.56
Ge	ppm	0.11	0.13	0.09
Hf	ppm	0.3	0.2	0.1
Hg	ppm	0.04	0.13	1.7
In	ppm	0.005	0.012	0.007
K	%	0.41	0.72	0.04
La	ppm	2.6	2.1	1.6
Li	ppm	5.1	3.6	1.4
Mg	%	9.39	9.61	11.05
Mn	ppm	228	249	825
Mo	ppm	0.55	2.18	0.5
Na	%	0.01	0.02	0.02
Nb	ppm	0.8	0.7	0.2

<i>SAMPLE</i>		<i>MI24-250</i>	<i>139-135</i>	<i>141-16</i>
Ni	ppm	1.4	4.5	1.5
P	ppm	60	80	90
Pb	ppm	80.6	118.5	82.2
Rb	ppm	8	9.6	1.2
Re	ppm	0.002	0.004	0.002
S	%	0.02	0.01	0.76
Sb	ppm	0.1	0.32	0.37
Sc	ppm	0.7	0.6	0.3
Se	ppm	1	1	3
Sn	ppm	0.2	0.3	0.2
Sr	ppm	55	46.9	51.1
Ta	ppm	0.06	0.05	0.05
Te	ppm	0.05	0.05	0.05
Th	ppm	0.6	0.6	0.2
Ti	%	0.022	0.017	0.006
Tl	ppm	0.03	0.05	0.02
U	ppm	0.7	1	1.4
V	ppm	28	27	15
W	ppm	0.1	0.2	0.1
Y	ppm	1.9	2.3	1.7
Zn	ppm	390	2140	12850
Zr	ppm	8.6	7.4	1.3

<i>SAMPLE</i>		<i>141-18</i>	<i>110-150</i>	<i>139-20</i>
Geologic Unit		MP	MP	MP
Description		carb-alt veinlet	least alt dolomite	carb-alt veinlet
Ag	ppm	0.03	0.01	0.09
Al	%	0.47	0.11	0.11
As	ppm	5	5	5
Ba	ppm	50	10	20
Be	ppm	0.21	0.08	0.11
Bi	ppm	0.01	0.01	0.01
Ca	%	21.1	20.1	20
Cd	ppm	0.32	0.13	2.77
Ce	ppm	6.05	1.54	2.44
Co	ppm	1.1	0.9	1.8
Cr	ppm	8	2	3
Cs	ppm	0.3	0.07	0.08
Cu	ppm	1	2.2	3.5
Fe	%	0.37	0.27	0.74
Ga	ppm	1.09	0.24	0.29
Ge	ppm	0.07	0.07	0.08
Hf	ppm	0.3	0.1	0.1
Hg	ppm	0.1	0.1	0.2
In	ppm	0.005	0.005	0.005
K	%	0.26	0.05	0.05
La	ppm	3.1	0.7	1.1
Li	ppm	4.4	3.7	1.9
Mg	%	12.55	12.9	13.15
Mn	ppm	207	324	314
Mo	ppm	0.06	0.09	0.48
Na	%	0.01	0.02	0.01
Nb	ppm	0.9	0.2	0.2
Ni	ppm	1.3	0.2	1.1

<i>SAMPLE</i>		<i>141-18</i>	<i>110-150</i>	<i>139-20</i>
P	ppm	1130	200	70
Pb	ppm	12.1	2.9	18.8
Rb	ppm	8.7	1.7	1.8
Re	ppm	0.002	0.002	0.002
S	%	0.01	0.01	0.01
Sb	ppm	0.13	0.11	0.2
Sc	ppm	0.9	0.3	0.3
Se	ppm	1	1	2
Sn	ppm	0.2	0.2	0.2
Sr	ppm	60.4	46.7	102
Ta	ppm	0.06	0.05	0.05
Te	ppm	0.05	0.05	0.05
Th	ppm	0.9	0.2	0.2
Ti	%	0.028	0.006	0.005
Tl	ppm	0.03	0.02	0.02
U	ppm	1.9	1.5	0.5
V	ppm	19	9	16
W	ppm	0.2	0.1	0.1
Y	ppm	3.8	0.7	1.6
Zn	ppm	133	17	980
Zr	ppm	10.2	1.7	2

<i>SAMPLE</i>		<i>115-67</i>	<i>129-20</i>	<i>139-68</i>	<i>32-199</i>
Geologic Unit		MP	MP	MP	SdG
Description		dolomite w/carb- qtz-py alt	fe-carb veinlets	dolomite sed bx	phyllite
Ag	ppm	0.02	0.02	0.14	1.94
Al	%	0.77	0.49	0.09	6.09
As	ppm	5	5	6	234
Ba	ppm	90	60	20	100
Be	ppm	0.31	0.14	0.08	1.61
Bi	ppm	0.08	0.02	0.01	0.39
Ca	%	17.35	20.1	14.6	0.17
Cd	ppm	0.3	0.67	1.67	1.34
Ce	ppm	7.49	3.34	1.49	46.1
Co	ppm	1.3	0.9	9.5	16.5
Cr	ppm	9	4	8	56
Cs	ppm	0.44	0.17	0.05	9.02
Cu	ppm	4.2	1.9	4.7	219
Fe	%	0.71	0.36	0.6	11.2
Ga	ppm	1.88	1.03	0.33	15.4
Ge	ppm	0.13	0.16	0.05	0.26
Hf	ppm	0.3	0.1	0.1	3.1
Hg	ppm	0.01	0.01	0.01	0.5
In	ppm	0.005	0.005	0.011	0.051
K	%	0.52	0.47	0.03	2.55
La	ppm	3.6	1.5	0.7	23
Li	ppm	5.6	4.6	1.8	26.4
Mg	%	10.5	12	9.14	0.84
Mn	ppm	289	228	188	143
Mo	ppm	0.57	0.42	0.77	14.65
Na	%	0.03	0.03	0.01	0.24

<i>SAMPLE</i>		<i>115-67</i>	<i>129-20</i>	<i>139-68</i>	<i>32-199</i>
Nb	ppm	0.9	0.5	0.2	7.6
Ni	ppm	3.2	1.3	5.7	219
P	ppm	90	60	120	510
Pb	ppm	7.3	33.9	23	71.7
Rb	ppm	11	7.2	1.1	123.5
Re	ppm	0.003	0.003	0.002	0.019
S	%	0.01	0.01	0.01	10
Sb	ppm	0.14	0.07	0.28	18.5
Sc	ppm	0.8	0.4	0.3	9.7
Se	ppm	1	1	1	15
Sn	ppm	0.2	0.2	0.2	1.9
Sr	ppm	51.4	60.5	38.7	30.9
Ta	ppm	0.06	0.05	0.05	0.64
Te	ppm	0.05	0.05	0.05	0.19
Th	ppm	0.7	0.3	0.2	9.5
Ti	%	0.024	0.013	0.005	0.283
Tl	ppm	0.06	0.03	0.03	3.45
U	ppm	0.8	0.4	1.4	8.2
V	ppm	26	3	19	187
W	ppm	0.1	0.1	0.1	0.9
Y	ppm	3	1.1	1	25.7
Zn	ppm	50	75	1090	241
Zr	ppm	8.9	4.6	1.6	115.5

<i>SAMPLE</i>		<i>118-163</i>	<i>4-407</i>	<i>101-245</i>
Geologic Unit		UMdP	UMdP	UMdP
Description		blk shale	least alt dolomite	grey dol w/ white carb alt vein
Ag	ppm	0.7	0.05	0.05
Al	%	9.08	0.33	0.12
As	ppm	7.1	7	5
Ba	ppm	3330	60	340
Be	ppm	3.91	0.19	0.17
Bi	ppm	0.4	0.02	0.01
Ca	%	0.16	20.1	16.75
Cd	ppm	1.06	0.6	10.1
Ce	ppm	72.3	3.32	2.05
Co	ppm	8.2	2.3	6.8
Cr	ppm	79	4	5
Cs	ppm	21.3	0.51	0.11
Cu	ppm	22.2	1.5	6
Fe	%	2.1	0.23	0.5
Ga	ppm	24.5	0.94	0.41
Ge	ppm	0.16	0.15	0.06
Hf	ppm	3.9	0.2	0.1
Hg	ppm	0.1	0.02	0.01
In	ppm	0.053	0.005	0.012
K	%	5.13	0.19	0.08
La	ppm	37.6	1.6	1
Li	ppm	34	10.8	3.2
Mg	%	1.29	12.7	10.35
Mn	ppm	33	498	512
Mo	ppm	0.44	0.05	0.42
Na	%	0.05	0.02	0.01
Nb	ppm	14.8	0.8	0.3

<i>SAMPLE</i>		<i>118-163</i>	<i>4-407</i>	<i>101-245</i>
Ni	ppm	32.8	4	2.6
P	ppm	180	170	160
Pb	ppm	174	14.3	27.6
Rb	ppm	211	8.8	2
Re	ppm	0.002	0.002	0.002
S	%	0.48	0.01	0.01
Sb	ppm	0.63	0.06	0.08
Sc	ppm	15.7	0.7	0.3
Se	ppm	2	1	1
Sn	ppm	3.2	0.2	0.2
Sr	ppm	23.5	99.5	72.1
Ta	ppm	1.16	0.05	0.05
Te	ppm	0.05	0.05	0.05
Th	ppm	17.6	0.5	0.2
Ti	%	0.361	0.017	0.005
Tl	ppm	1.08	0.03	0.02
U	ppm	9	0.9	0.7
V	ppm	174	5	7
W	ppm	1.6	0.1	0.1
Y	ppm	21.1	1.3	0.8
Zn	ppm	306	119	678
Zr	ppm	134	7	2.8

<i>SAMPLE</i>		<i>43-288</i>	<i>88-174</i>	<i>M124-25</i>
Geologic Unit		UMdP	UMdP	UP
Description		grey dol with Fe-carb veinlets	grey sed bx with dol overgrowths	least alt dolarenite
Ag	ppm	0.17	0.1	0.06
Al	%	0.36	0.27	0.5
As	ppm	5	7	5
Ba	ppm	120	130	40
Be	ppm	0.16	0.25	0.17
Bi	ppm	0.04	0.02	0.03
Ca	%	19.55	17.55	18.7
Cd	ppm	2.23	2.05	0.49
Ce	ppm	5.3	2.83	5.86
Co	ppm	4.2	4.7	0.8
Cr	ppm	2	7	4
Cs	ppm	0.34	0.29	0.63
Cu	ppm	5.1	8.6	2.4
Fe	%	0.6	0.36	0.37
Ga	ppm	1.05	0.65	1.21
Ge	ppm	0.06	0.12	0.1
Hf	ppm	0.2	0.2	0.3
Hg	ppm	0.2	0.01	0.01
In	ppm	0.007	0.005	0.006
K	%	0.21	0.17	0.38
La	ppm	2.3	1.3	3
Li	ppm	8.5	5.1	5.1
Mg	%	12.25	10.55	11.3
Mn	ppm	491	279	98
Mo	ppm	0.13	0.64	0.11
Na	%	0.01	0.02	0.02
Nb	ppm	0.8	0.4	0.8

<i>SAMPLE</i>		<i>43-288</i>	<i>88-174</i>	<i>M124-25</i>
Ni	ppm	3.5	4	1.8
P	ppm	430	110	120
Pb	ppm	30.7	20.6	6.6
Rb	ppm	8.1	4.6	10.8
Re	ppm	0.002	0.002	0.002
S	%	0.01	0.03	0.01
Sb	ppm	0.09	0.08	0.05
Sc	ppm	0.9	0.5	1
Se	ppm	2	1	1
Sn	ppm	0.2	0.2	0.2
Sr	ppm	88.7	56.6	54.2
Ta	ppm	0.05	0.05	0.07
Te	ppm	0.05	0.05	0.05
Th	ppm	0.7	0.3	1
Ti	%	0.017	0.013	0.028
Tl	ppm	0.04	0.02	0.05
U	ppm	0.5	0.6	1.6
V	ppm	4	8	13
W	ppm	0.1	0.1	0.1
Y	ppm	2	1.3	2.5
Zn	ppm	523	124	46
Zr	ppm	9.7	5.6	8.7

<i>SAMPLE</i>		<i>M124-42</i>	<i>M124-97</i>	<i>M124-118</i>
Geologic Unit		UP	UP	UP
Description		sed bx w/ carb b/w clasts	MVT-alt w/ sp	silty marker bed
Ag	ppm	0.04	1.38	0.11
Al	%	0.18	0.14	4.92
As	ppm	5	5	3.9
Ba	ppm	50	30	700
Be	ppm	0.07	0.05	0.54
Bi	ppm	0.02	0.01	0.09
Ca	%	12.7	18.35	0.2
Cd	ppm	0.54	124	0.58
Ce	ppm	3.97	2.61	48.5
Co	ppm	1.6	0.6	2.3
Cr	ppm	9	7	21
Cs	ppm	0.09	0.08	2.37
Cu	ppm	15.2	7.1	14.8
Fe	%	0.95	0.7	1.14
Ga	ppm	0.42	1.2	8.47
Ge	ppm	0.14	0.14	0.21
Hf	ppm	0.1	0.1	3.1
Hg	ppm	0.01	3.11	0.01
In	ppm	0.005	0.03	0.014
K	%	0.17	0.09	5.33
La	ppm	1.9	1.4	20.9
Li	ppm	1.5	2.4	8.1
Mg	%	7.93	11.2	0.31
Mn	ppm	281	397	34
Mo	ppm	0.79	0.28	0.82
Na	%	0.01	0.01	0.05
Nb	ppm	0.3	0.2	4.3
Ni	ppm	3.3	2.6	6.6

<i>SAMPLE</i>		<i>M124-42</i>	<i>M124-97</i>	<i>M124-118</i>
P	ppm	150	280	90
Pb	ppm	4.7	43.7	26.7
Rb	ppm	2.9	2.4	78.7
Re	ppm	0.002	0.002	0.004
S	%	0.02	1.27	0.39
Sb	ppm	0.06	0.39	0.42
Sc	ppm	0.4	0.3	3.6
Se	ppm	1	6	1
Sn	ppm	0.2	0.2	1.2
Sr	ppm	44.3	45	43.6
Ta	ppm	0.05	0.05	0.33
Te	ppm	0.05	0.05	0.05
Th	ppm	0.4	0.2	5.7
Ti	%	0.008	0.007	0.126
Tl	ppm	0.02	0.03	0.59
U	ppm	1.2	1.6	1.8
V	ppm	10	35	19
W	ppm	0.1	0.1	0.5
Y	ppm	1.9	1.7	12.9
Zn	ppm	50	25700	41
Zr	ppm	3.4	2.5	105

D.2 XRF Analyses

SAMPLE		32-199	141-16	141-18	143-124
Geologic		SdG	MP	MP	LP
Unit					
Rock Type		phyllite	carb-alt veinlet	carb-alt veinlet	least alt dolomite
SiO ₂	%	53.99	14.52	2.25	7.91
Al ₂ O ₃	%	11.34	0.08	0.68	1.56
Fe ₂ O ₃	%	15.69	1.62	0.43	0.91
CaO	%	0.2	25.26	28.23	25.84
MgO	%	1.49	16.63	20.96	19.61
Na ₂ O	%	0.29	0.03	0.05	0.05
K ₂ O	%	3.23	0.01	0.14	0.71
Cr ₂ O ₃	%	0.01	0.01	0.01	0.01
TiO ₂	%	0.58	0.01	0.03	0.06
MnO	%	0.02	0.09	0.02	0.03
P ₂ O ₅	%	0.101	0.012	0.211	0.013
SrO	%	0.01	0.01	0.01	0.01
BaO	%	0.04	0.01	0.01	0.01
LOI	%	11.3	38.6	45.3	42.1
Total	%	98.27	96.86	98.31	98.8

SAMPLE		110-150	139-20	139-231	118-163
Geologic		MP	MP	UMdP (LMdP?)	UMdP
Unit					
Rock Type		least alt dolomite	carb-alt veinlet	least alt dolomite	blk shale
SiO2	%	2.84	2.96	0.86	61.18
Al2O3	%	0.12	0.12	0.14	17.88
Fe2O3	%	0.33	0.89	0.33	2.98
CaO	%	28.33	27.99	29.32	0.21
MgO	%	21.25	20.93	20.95	2.3
Na2O	%	0.04	0.05	0.06	0.04
K2O	%	0.03	0.01	0.03	6.29
Cr2O3	%	0.01	0.01	0.01	0.01
TiO2	%	0.01	0.01	0.01	0.85
MnO	%	0.03	0.03	0.02	0.01
P2O5	%	0.033	0.008	0.105	0.031
SrO	%	0.01	0.01	0.01	0.01
BaO	%	0.01	0.01	0.01	0.38
LOI	%	45.5	45.4	46.4	6.55
Total	%	98.51	98.39	98.22	98.7

SAMPLE		155-185	155-214	4-407	43-97	105-113
Geologic		LP	LP	UMdP	LP	LP
Unit						
Rock Type		dolomite	phyllite	least alt dolomite	phyllite	dol-specularite vein
SiO2	%	24.99	63.99	2.3	52.32	6.2
Al2O3	%	4.28	15.27	0.47	17.8	1.33
Fe2O3	%	0.87	5.38	0.28	8.87	0.82
CaO	%	19.55	0.23	28.72	1.65	26.58
MgO	%	13.93	2.49	20.79	3.91	19.66
Na2O	%	0.04	0.05	0.05	0.06	0.06
K2O	%	2.84	6.68	0.12	7.91	0.63
Cr2O3	%	0.01	0.01	0.01	0.01	0.01
TiO2	%	0.12	0.6	0.01	0.74	0.13
MnO	%	0.03	0.01	0.05	0.01	0.03
P2O5	%	0.034	0.048	0.029	0.087	0.028
SrO	%	0.01	0.01	0.01	0.01	0.01
BaO	%	0.05	0.07	0.01	0.04	0.15
LOI	%	31.4	3.54	45.6	5.61	42.7
Total	%	98.13	98.35	98.42	99.02	98.32

SAMPLE		124-62	124-75	124-78	123-46	123-51
Geologic		BH	BH	BH	LP	LP
Unit						
Rock Type		type 3	type 4	type 4	Fe-carb selvage alt	Hm alt vein
					w/ no texture	
SiO2	%	2.1	21.54	33.85	18.09	4.76
Al2O3	%	1.14	0.05	0.13	4.06	2.68
Fe2O3	%	59.75	8.36	17.76	1.66	7.61
CaO	%	10.6	2.19	1.54	21.94	24.54
MgO	%	7.45	1.2	0.9	15.89	17.39
Na2O	%	0.02	0.02	0.02	0.1	0.04
K2O	%	0.08	0.01	0.01	0.99	0.6
Cr2O3	%	0.02	0.01	0.02	0.01	0.01
TiO2	%	0.01	0.01	0.01	0.19	0.11
MnO	%	0.08	0.02	0.01	0.07	0.1
P2O5	%	0.056	0.194	0.042	0.062	0.025
SrO	%	0.01	0.01	0.01	0.01	0.01
BaO	%	0.01	0.01	0.03	0.01	0.01
LOI	%	16.7	3.58	2.57	35.1	39.2
Total	%	98.02	37.18	56.88	98.17	97.06

SAMPLE		101-128	101-245	43-191	88-93
Geologic		BH	UMdP	LP	LP
Unit					
Rock Type		type 3	grey dol with white carb alt vein	green phyllite	maroon phyllite
SiO2	%	12.38	19.92	58.17	58.98
Al2O3	%	0.96	0.2	10.34	16.53
Fe2O3	%	42.25	0.68	3.27	7.9
CaO	%	9.37	24.07	5.65	0.47
MgO	%	6.53	15.84	5.33	2.91
Na2O	%	0.11	0.01	0.06	0.11
K2O	%	0.02	0.05	4.46	6.95
Cr2O3	%	0.01	0.01	0.01	0.01
TiO2	%	0.01	0.01	0.46	0.72
MnO	%	0.12	0.06	0.02	0.01
P2O5	%	0.082	0.034	0.065	0.091
SrO	%	0.04	0.01	0.02	0.01
BaO	%	7.24	0.03	0.03	0.12
LOI	%	14.45	37.4	10.7	3.86
Total	%	93.56	98.3	98.57	98.66

SAMPLE		88-124	88-174	M124-25
Geologic		LP	UMdP	UP
Unit				
Rock Type		black phyllite	grey sed bx with dol overgrowths	least alt dolarenite
SiO2	%	58.6	14.45	3.6
Al2O3	%	17.63	0.48	0.88
Fe2O3	%	7.06	0.51	0.54
CaO	%	0.43	25.81	29.61
MgO	%	2.63	17.03	18.82
Na2O	%	0.13	0.01	0.01
K2O	%	7.67	0.1	0.31
Cr2O3	%	0.01	0.01	0.01
TiO2	%	0.75	0.01	0.04
MnO	%	0.01	0.04	0.01
P2O5	%	0.056	0.028	0.033
SrO	%	0.02	0.01	0.01
BaO	%	0.03	0.01	0.01
LOI	%	3.75	40	44.6
Total	%	98.77	98.48	98.46

SAMPLE		M124-42	M124-97	M124-118
Geologic		UP	UP	UP
Unit				
Rock Type		sed bx w/ carb between clasts	MVT-alt w/ sp	silty marker bed
SiO2	%	32.63	3.32	76.68
Al2O3	%	0.31	0.25	10.33
Fe2O3	%	1.36	1.09	1.58
CaO	%	19.76	28.88	0.25
MgO	%	13.12	20.8	0.65
Na2O	%	0.01	0.02	0.07
K2O	%	0.15	0.03	7.08
Cr2O3	%	0.01	0.01	0.01
TiO2	%	0.01	0.01	0.27
MnO	%	0.03	0.06	0.01
P2O5	%	0.035	0.074	0.025
SrO	%	0.01	0.01	0.02
BaO	%	0.01	0.01	0.07
LOI	%	30.8	41.3	1.61
Total	%	98.2	95.82	98.64

SAMPLE		M124-199	M124-250	M124-284	M124-289
Geologic		LP	LP	BH	BH
Unit					
Rock Type		pink carb w/ silica alt	chalcedonic silica alt	type 1	type 1
SiO2	%	12.52	22.7	1.51	7.98
Al2O3	%	0.9	1.06	0.72	0.74
Fe2O3	%	1.21	0.72	1.44	4.15
CaO	%	25.75	22.77	29.15	26.98
MgO	%	17.6	15.57	19.82	17.88
Na2O	%	0.01	0.01	0.04	0.02
K2O	%	0.33	0.37	0.03	0.16
Cr2O3	%	0.01	0.01	0.01	0.01
TiO2	%	0.02	0.03	0.02	0.01
MnO	%	0.05	0.03	0.08	0.1
P2O5	%	0.018	0.017	0.029	0.054
SrO	%	0.01	0.01	0.01	0.01
BaO	%	0.01	0.02	0.01	0.01
LOI	%	40.3	35.4	45.3	40.9
Total	%	98.72	98.71	98.14	98.99

SAMPLE		M124-300	M124-305	M124-321	M124-329
Geologic		BH	BH	BH	BH
Unit					
Rock Type		type 1	type 3	brecciated red phyllite	type 4
SiO ₂	%	1.71	7.49	62.83	20.95
Al ₂ O ₃	%	0.63	0.63	13.31	0.2
Fe ₂ O ₃	%	0.84	77.65	2.92	20.92
CaO	%	29.36	2.2	1.83	0.52
MgO	%	20.28	1.6	6.3	0.3
Na ₂ O	%	0.03	0.02	0.07	0.01
K ₂ O	%	0.02	0.04	3.49	0.01
Cr ₂ O ₃	%	0.01	0.03	0.01	0.02
TiO ₂	%	0.02	0.01	0.57	0.01
MnO	%	0.08	0.07	0.02	0.02
P ₂ O ₅	%	0.063	0.039	0.056	0.083
SrO	%	0.01	0.01	0.02	0.01
BaO	%	0.01	0.01	0.04	0.01
LOI	%	45.4	3.61	6.68	0.94
Total	%	98.43	93.4	98.15	43.99

<i>SAMPLE</i>		<i>M124-347</i>	<i>M124-353</i>	<i>M124-356</i>
Geologic Unit		BH	BH	BH
Rock Type		type 2	type 3	type 1
SiO2	%	2.08	1.8	0.69
Al2O3	%	0.39	0.31	0.31
Fe2O3	%	7.37	85.6	1.16
CaO	%	27.22	3.1	29.68
MgO	%	18.74	2.45	19.9
Na2O	%	0.02	0.01	0.04
K2O	%	0.03	0.01	0.01
Cr2O3	%	0.01	0.03	0.01
TiO2	%	0.01	0.01	0.01
MnO	%	0.13	0.05	0.04
P2O5	%	0.08	0.022	0.086
SrO	%	0.01	0.01	0.01
BaO	%	0.01	0.01	0.01
LOI	%	42.5	5.08	46.2
Total	%	98.59	98.48	98.12

D.3 ICP-MS Correlation Matrix

The 48-element analysis ICP-MS data for each sample was placed in a correlation matrix in MS Excel 2010 using the Data Analysis function

	Ag	Al	As	Ba	Be	Bi	Ca	Cd	Ce	Co
Ag	1									
Al	-0.12873	1								
As	0.251367	-0.03983	1							
Ba	0.22628	0.214831	0.061843	1						
Be	0.026392	0.751596	0.214511	0.287583	1					
Bi	-0.01283	0.692163	0.271005	0.334459	0.680511	1				
Ca	-0.33746	-0.50112	-0.49984	-0.36118	-0.72884	-0.43087	1			
Cd	0.2346	-0.21269	0.215968	0.145021	-0.11428	-0.11728	-0.03789	1		
Ce	-0.1252	0.976522	-0.07056	0.187849	0.745205	0.629547	-0.50132	-0.18283	1	
Co	-0.07366	-0.05614	0.303785	-0.0584	0.119717	0.036102	-0.09343	0.474649	-0.02424	1
Cr	-0.05784	0.919543	0.035384	0.214417	0.777761	0.690488	-0.59341	-0.18612	0.886668	-0.0517
Cs	-0.09708	0.914235	-0.0203	0.300092	0.746198	0.674468	-0.47466	-0.1836	0.889515	-0.04537
Cu	0.821524	-0.05813	0.229538	0.074563	0.010688	0.053023	-0.25973	0.021296	-0.06711	-0.09325
Fe	0.008073	-0.05579	0.556707	0.07007	0.311156	0.161255	-0.46175	0.058103	-0.05733	0.31899
Ga	-0.03816	0.967157	0.046699	0.254947	0.816453	0.685309	-0.60508	-0.11102	0.952336	-0.01398
Ge	-0.0508	0.23489	0.407537	-0.05331	0.419605	0.340094	-0.38601	-0.01944	0.250933	0.337077
Hf	-0.11695	0.965531	-0.0374	0.196004	0.729502	0.686248	-0.49663	-0.21167	0.955108	-0.06251
Hg	0.551153	-0.12314	0.595105	0.079253	-0.07231	-0.0707	-0.2347	0.193127	-0.12934	0.15554
In	0.015506	-0.10351	0.364488	-0.05411	0.410277	0.05019	-0.36044	-0.00483	-0.10314	0.379286
K	-0.12217	0.95946	-0.11411	0.206959	0.661306	0.577798	-0.48097	-0.23735	0.946333	-0.14431
La	-0.12394	0.972729	-0.0712	0.199888	0.755377	0.643917	-0.49461	-0.16635	0.997124	-0.00443
Li	-0.04421	0.780382	-0.024	0.079127	0.658295	0.523563	-0.421	-0.14369	0.758067	0.11387
Mg	-0.36194	-0.43454	-0.53368	-0.36299	-0.69151	-0.40045	0.992934	-0.06764	-0.4382	-0.10025
Mn	-0.16529	-0.40165	-0.0588	-0.01186	-0.44167	-0.27591	0.460364	0.43159	-0.36707	0.548044

	Ag	Al	As	Ba	Be	Bi	Ca	Cd	Ce	Co
Mo	-0.00087	0.058382	0.635117	0.00669	0.250396	0.390608	-0.43215	-0.03027	0.009456	0.125899
Na	-0.03527	0.549586	0.310289	0.246065	0.331717	0.676605	-0.29805	-0.12793	0.480986	-0.1045
Nb	-0.10852	0.884804	-0.07964	0.175062	0.734575	0.58883	-0.44042	-0.18489	0.930169	-0.02221
Ni	-0.07205	0.400333	0.567399	-0.02174	0.369761	0.673075	-0.33043	0.015917	0.34397	0.292145
P	-0.04845	0.012545	0.00552	-0.09314	0.085302	0.0637	0.006218	-0.06636	0.033927	-0.09078
Pb	0.869933	-0.10838	0.20618	0.124047	-0.01639	0.014692	-0.23239	0.19965	-0.10495	-0.03414
Rb	-0.1203	0.970803	-0.03038	0.268483	0.753917	0.738819	-0.47576	-0.23252	0.947853	-0.10305
Re	-0.07602	0.297546	0.427448	-0.06684	0.191334	0.539654	-0.18026	-0.04779	0.245687	0.073584
S	0.061321	0.142654	0.771584	-0.03572	0.05027	0.366592	-0.1971	0.114166	0.093341	0.195267
Sb	-0.00066	-0.03808	0.513568	0.021118	0.344079	0.259043	-0.40014	0.045483	-0.04851	0.38626
Sc	-0.11983	0.981804	-0.0372	0.216022	0.759671	0.692855	-0.47846	-0.19358	0.961022	-0.0471
Se	0.71822	-0.14246	0.409487	0.200867	0.108758	0.025843	-0.48335	0.348151	-0.12721	0.014048
Sn	-0.10012	0.969162	-0.00697	0.242221	0.784795	0.698892	-0.54617	-0.18558	0.952749	-0.04329
Sr	0.014102	-0.10907	0.059112	0.350481	-0.07906	-0.06746	-0.12052	-0.02932	-0.10912	-0.07417
Ta	-0.09893	0.983663	-0.03933	0.248309	0.785676	0.692846	-0.51243	-0.18833	0.966938	-0.04859
Te	-0.02443	0.239817	0.488224	-0.05372	0.169446	0.55716	-0.20531	-0.05051	0.180765	0.006142
Th	-0.11226	0.973466	-0.03142	0.267006	0.780422	0.747257	-0.48484	-0.19787	0.955518	-0.06193
Ti	-0.11775	0.98687	-0.04421	0.182145	0.740942	0.662071	-0.4828	-0.20223	0.966846	-0.04727
Tl	-0.07377	0.676161	0.349203	0.095988	0.490796	0.771163	-0.39621	-0.14857	0.616163	-0.02774
U	0.013567	0.179938	0.470897	0.175887	0.589483	0.465026	-0.50243	0.007829	0.14186	0.230339
V	0.001128	0.290387	0.20792	0.121048	0.432142	0.4479	-0.35506	-0.03508	0.29748	0.229243
W	-0.04485	0.781313	0.222672	0.374142	0.877684	0.719525	-0.65028	-0.1056	0.782423	0.188608
Y	-0.15309	0.902076	0.048925	0.141616	0.67936	0.752839	-0.41938	-0.17742	0.919416	0.011399
Zn	0.634092	-0.22455	0.402831	0.137553	0.18477	-0.11957	-0.54802	0.30277	-0.20256	0.019367
Zr	-0.12889	0.952672	-0.02705	0.187715	0.719994	0.697469	-0.47367	-0.21593	0.951092	-0.05924

	Cr	Cs	Cu	Fe	Ga	Ge	Hf	Hg	In	K
Cr	1									
Cs	0.886469	1								
Cu	-0.01298	-0.03926	1							
Fe	0.045646	-0.02354	-0.01524	1						
Ga	0.944134	0.894628	-0.02574	0.059066	1					
Ge	0.242223	0.209715	-0.05917	0.529606	0.262185	1				
Hf	0.864917	0.831246	-0.04654	-0.0869	0.918726	0.203407	1			
Hg	-0.0997	-0.09789	0.450022	0.059439	-0.05044	0.078248	-0.12018	1		
In	-0.06614	-0.07536	-0.01704	0.57201	-0.03272	0.569227	-0.12986	-0.00442	1	
K	0.855924	0.843745	-0.06151	-0.10171	0.912943	0.187211	0.941922	-0.12289	-0.13267	1
La	0.882156	0.892787	-0.06622	-0.06426	0.948548	0.234911	0.957026	-0.13229	-0.10918	0.931993
Li	0.716017	0.723866	0.012793	-0.03565	0.739191	0.23405	0.752469	-0.10944	-0.01827	0.649819
Mg	-0.54057	-0.41245	-0.2734	-0.4929	-0.54907	-0.39505	-0.43472	-0.25924	-0.3822	-0.42398
Mn	-0.41457	-0.36228	-0.18971	-0.06407	-0.41409	-0.13045	-0.40334	0.023768	-0.13255	-0.43477
Mo	0.163105	0.063546	0.044061	0.757809	0.124527	0.308234	0.065726	-0.00211	0.306087	-0.0226
Na	0.51032	0.453473	0.002367	-0.02194	0.506563	0.112125	0.565015	-0.06894	-0.14465	0.458603
Nb	0.785763	0.78671	-0.05626	-0.07184	0.8708	0.211624	0.921481	-0.10291	-0.10331	0.853922
Ni	0.429651	0.366585	0.0114	0.245306	0.401263	0.359516	0.408402	0.043409	0.144183	0.258763
P	0.041488	-0.00995	-0.01041	-0.04984	0.032084	-0.00467	0.043447	-0.08238	-0.01559	-0.01594
Pb	-0.06593	-0.08222	0.937984	0.007023	-0.06575	-0.04187	-0.10046	0.38884	-0.01026	-0.10727
Rb	0.88625	0.942488	-0.04869	-0.08802	0.926441	0.187526	0.950429	-0.11697	-0.12655	0.931544
Re	0.287505	0.208659	0.024647	0.045536	0.259058	0.118591	0.356208	-0.06279	0.002208	0.21457
S	0.142725	0.129451	0.083839	0.093443	0.13973	0.202026	0.161544	0.584585	-0.0355	0.068675
Sb	0.019347	-0.02152	0.002189	0.832643	0.04848	0.703141	-0.06111	-0.01987	0.745457	-0.10593
Sc	0.930827	0.921569	-0.05436	-0.05319	0.976214	0.202975	0.92479	-0.11455	-0.1189	0.911651
Se	0.005667	-0.10696	0.481809	0.054054	-0.00768	0.045847	-0.12024	0.473072	0.069505	-0.15712

Sn	0.929964	0.927637	-0.03824	0.038112	0.974408	0.219161	0.92989	-0.10494	-0.07986	0.919506
	Cr	Cs	Cu	Fe	Ga	Ge	Hf	Hg	In	K
Sr	-0.11876	-0.08484	0.015975	0.071593	-0.09779	0.038471	-0.10746	0.075543	0.044689	-0.10547
Ta	0.926386	0.925341	-0.03974	-0.06024	0.96972	0.202895	0.958353	-0.10274	-0.10634	0.928037
Te	0.286362	0.207008	0.064139	0.062817	0.222075	0.134244	0.270401	-0.00919	-0.02817	0.129312
Th	0.903475	0.934088	-0.04432	-0.08082	0.946569	0.189223	0.954946	-0.11225	-0.12314	0.916506
Ti	0.921834	0.896352	-0.04941	-0.07964	0.9646	0.199352	0.959019	-0.11562	-0.13019	0.926967
Tl	0.648654	0.628344	0.023204	0.001612	0.628231	0.192407	0.693165	-0.04692	-0.08167	0.574257
U	0.287994	0.254029	-0.00838	0.668678	0.262344	0.438729	0.161221	-0.05132	0.664596	0.097749
V	0.489647	0.371062	0.000168	0.34384	0.327926	0.439347	0.256726	-0.06448	0.26928	0.221067
W	0.759199	0.781451	-0.01547	0.400782	0.819924	0.534141	0.730002	-0.09887	0.34864	0.70082
Y	0.818006	0.830984	-0.06579	-0.0582	0.865171	0.246351	0.89086	-0.12676	-0.11549	0.838586
Zn	-0.07478	-0.17769	0.438804	0.108422	-0.07925	0.030888	-0.20628	0.41495	0.29743	-0.22351
Zr	0.842448	0.820562	-0.05297	-0.09224	0.901024	0.204521	0.995855	-0.12151	-0.13415	0.927676

	La	Li	Mg	Mn	Mo	Na	Nb	Ni	P	Pb
La	1									
Li	0.767795	1								
Mg	-0.43052	-0.34572	1							
Mn	-0.35032	-0.30406	0.438956	1						
Mo	0.010319	0.005408	-0.45066	-0.16306	1					
Na	0.481787	0.410585	-0.27187	-0.19551	0.474312	1				
Nb	0.943941	0.676551	-0.38342	-0.342	-0.01576	0.400061	1			
Ni	0.354258	0.349032	-0.31769	-0.07764	0.672583	0.810054	0.288536	1		
P	0.027645	0.17526	-0.00461	-0.18895	-0.02521	0.07335	0.021646	0.059442	1	
Pb	-0.10235	-0.01454	-0.25201	-0.09912	-0.00086	-0.06138	-0.09417	-0.0576	-0.0326	1
Rb	0.953113	0.729038	-0.41347	-0.4094	0.0733	0.557886	0.89343	0.411938	0.018661	-0.10491
Re	0.252605	0.205395	-0.17723	-0.09986	0.594079	0.850526	0.220828	0.893308	0.056899	-0.05763
S	0.096515	0.053911	-0.20369	0.038805	0.441788	0.560071	0.075939	0.715634	-0.02409	0.03069
Sb	-0.05519	0.020534	-0.4228	-0.09106	0.686783	0.106121	-0.06598	0.409344	0.018186	-0.00122
Sc	0.959865	0.770107	-0.41133	-0.37521	0.048077	0.528179	0.872633	0.395823	0.024136	-0.1006
Se	-0.12437	-0.04929	-0.50429	-0.17565	0.089982	0.016971	-0.11895	0.064468	0.079293	0.512132
Sn	0.951768	0.71077	-0.48621	-0.4107	0.153809	0.516623	0.876198	0.413263	0.016128	-0.08695
Sr	-0.10816	-0.11301	-0.13728	-0.06618	0.018571	0.032863	-0.09421	-0.04922	-0.04649	0.010299
Ta	0.971358	0.771434	-0.44605	-0.39107	0.044878	0.514451	0.918892	0.380583	0.013065	-0.08666
Te	0.187764	0.170274	-0.19896	-0.11902	0.632386	0.837382	0.140197	0.908554	0.096514	-0.02608
Th	0.96326	0.739391	-0.4224	-0.39154	0.063478	0.541524	0.904663	0.414029	0.026874	-0.09606
Ti	0.966014	0.81114	-0.41242	-0.38667	0.047048	0.554132	0.898072	0.40754	0.026053	-0.09969
Tl	0.623732	0.520942	-0.35742	-0.28188	0.500116	0.907897	0.548214	0.876889	0.04891	-0.06788
U	0.148458	0.195612	-0.51978	-0.27021	0.61087	0.220281	0.110375	0.448141	0.082979	-0.00746

	La	Li	Mg	Mn	Mo	Na	Nb	Ni	P	Pb
V	0.300029	0.280554	-0.3687	-0.03037	0.287424	0.241025	0.236656	0.396033	-0.05485	0.018022
W	0.784713	0.617311	-0.61378	-0.30556	0.324567	0.423271	0.726631	0.442246	0.018043	-0.03325
Y	0.923981	0.662979	-0.36977	-0.27948	0.165251	0.652266	0.8532	0.570077	0.071556	-0.11967
Zn	-0.20226	-0.07711	-0.58285	-0.23352	0.046756	-0.16212	-0.18973	-0.07423	0.109333	0.454434
Zr	0.955672	0.736546	-0.41342	-0.39142	0.077414	0.579969	0.934476	0.429846	0.053232	-0.10953

	Th	Ti	Tl	U	V	W	Y	Zn	Zr
Th	1								
Ti	0.960667	1							
Tl	0.695212	0.673228	1						
U	0.216054	0.144762	0.311176	1					
V	0.295613	0.276435	0.324732	0.517459	1				
W	0.787572	0.747312	0.541921	0.610395	0.464279	1			
Y	0.912779	0.878854	0.783766	0.202234	0.380202	0.742074	1		
Zn	-0.19935	-0.20836	-0.14084	0.151795	0.014327	-0.07581	-0.249	1	
Zr	0.952015	0.945359	0.71122	0.162011	0.25551	0.728373	0.906297	0.22608	1