GEOMETRIES AND GENESIS OF BRECCIAS WITHIN THE HALOKINETIC KALUKUNDI DIAPIR AT
THE MASHITU MINE, KATANGA, DEMOCRATIC REPUBLIC OF CONGO

by
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ABSTRACT

The Mashitu Cu-Co deposit is located within the western part of the Kalukundi breccia complex in the Democratic Republic of Congo (DRC). The Kalukundi breccia complex, similar to others in the Congolese Copperbelt, consists of clasts and megaclasts of Neoproterozoic sedimentary rocks ranging from millimeters to hundreds of meters in diameter contained in a quartz-chlorite-dolomite matrix. The Congolese Copperbelt breccia complexes remain poorly understood because mining has traditionally focused on mineralized megaclasts within the breccias and the matrix to the breccias has undergone recessive weathering.

The Mashitu open pit mine exploited typical Cu-Co mineralized megaclasts as well as supergene mineralized breccia matrix material. The breccias exposed at the Mashitu mine, together with data from exploration diamond drill cores beneath the open pit, presented an exceptional opportunity to generate detailed geological maps and a three-dimensional model of the internal geometry of a Congolese Copperbelt breccia complex and allowed for improved understanding of its genesis.

Textures of the breccias in outcrop and in drill core, together with a variety of petrographic data on a suite of representative samples, formed the basis for characterization of different clast, matrix, and breccia types. Clasts are less than 1 meter in diameter while megaclasts or blocks, range in size from >1 meter to 100’s of meters in diameter; megaclasts commonly display stratigraphic coherence but are commonly broken. Clast and megaclast size is broadly related to the strength of the dominant rock types; sand-rich, silicified, and carbonate-rich units display the most coherence while shale- or clay-rich rock types are commonly disrupted and disaggregated. Spatial analysis of megaclasts within the breccia complex exposed at Mashitu indicates stacking of megaclasts (blocks). Clast geometry in the breccia complex displays a fractal pattern.

Currently the clast to matrix or ‘block’ to breccia ratio exposed at Mashitu is approximately 5:1. The distinctive geometry, presence of clasts of stratigraphy hundreds to
thousands of meters above their apparent depositional position, and mineralogy of the breccia matrix supports hypotheses presented by earlier workers that the Congolese breccia complexes represent the remnants of salt diapirs probably formed in the late Neoproterozoic; later replacement by carbonate minerals and dissolution of halite and anhydrite within these diapiric structures led to the complex breccia bodies observed today in the Congolese Copperbelt.

Mashitu contains mineralized megaclasts typical of the Congolese Copperbelt. It also contains lithologies and breccia matrix containing a supergene assemblage of supergene black Cu-Co-Mn-Fe-oxide and malachite that have not been reported from elsewhere in the district. Much of this supergene assemblage replaced former carbonate minerals in carbonate veins cutting clasts or in breccia matrix. Supergene mineralized breccia material is best developed beneath mineralized megaclasts. The distribution of mineralized zones in breccia indicates that metals were derived from such megaclasts. The supergene mineralized breccia zones at Mashitu represent a new style of orebody in the Congolese portion of the Central African Copperbelt.
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CHAPTER 1
INTRODUCTION

The Central African Copperbelt (CACB) is located within the Lufilian fold belt, an arcuate zone of variably deformed and metamorphosed sedimentary rocks of the Neoproterozoic Katangan Supergroup in the southern Democratic Republic of Congo (DRC), north-western Zambia, and south-eastern Angola (Figure 1.1). The Central African Copperbelt hosts the world’s largest accumulation of sedimentary rock-hosted copper and cobalt, in addition to significant deposits of zinc, lead, gold, nickel and uranium (Hitzman et al., 2012). Copper-cobalt orebodies in the DRC portion of the Central African Copperbelt, referred to as the Congolese Copperbelt (CCB), consist largely of Neoproterozoic Roan Group megaclasts (blocks) of 100’s of meters to kilometers in diameter contained within multi-kilometer scale breccia complexes.

The breccia complexes in the CCB have been recognized for decades though their genesis has been contentious. Some workers have considered the breccias to be tectonic and/or sedimentary due primarily to their location within anticlines or along apparent thrust faults (Demesmaeker et al., 1963; François, 1973; Grujenschi, 1978; Wendorff, 2000a, 2000b, 2003; 2005c; Cailteux and Kampunzu, 1995). Other workers have ascribed a salt tectonic model for their origin (François, 2006; DeMagnée and François, 1988; Kampunzu and Cailteux, 1999; Jackson et al., 2003; Hitzman et al., 2012; Schuh et al., 2012). The salt required for these diapiric structures is believed to have been derived from thick evaporite beds originally present in the Lower Roan Group (Jackson et al., 2003; Hitzman et al., 2012).

Brecciated rocks within the diapiric complexes are recessively weathered and were referred to by early workers as undifferentiated and brecciated Roan Group (François, 2006). Despite their ubiquity in the CCB and their importance in understanding the geology of this important mineral district, there are few good descriptions of the internal features of the breccia complexes or of the geometry of blocks within them other than those contained in Cailteux
(1983), Schuh et al., (2012), and Broughton, (2014). Only Cailteux (1983) and Schuh et al. (2012) presented cross sections through the breccia complexes though neither constructed three-dimensional models of the breccias and their included clasts. Broughton (2014) described the textures and mineralogy of breccias from several areas throughout the Central African Copperbelt but did not utilize his breccia classification scheme to produce a model of breccia geometry.

![Simplified geological map of the Central African Copperbelt showing the location of the Mashitu deposit in the northwestern portion of the arcuate Lufilian fold belt.](image)

Figure 1.1: Simplified geological map of the Central African Copperbelt showing the location of the Mashitu deposit in the northwestern portion of the arcuate Lufilian fold belt. Modified from Jackson et al., (2003), Hitzman et al., (2012), and Broughton, (2014).

This study examines the western portion of the Kalukundi diapiric breccia complex exposed in the Mashitu open-pit mine, operated by Eurasian Resources Group (Figure 1.2). The Mashitu mine is located approximately 25 kilometers east of Kolwezi in the western portion of
the Katanga Province in southern DRC (Figure 1.1). The Mashitu open pit was approximately 1.5km in length, 700m wide and 85m deep when field mapping was completed. The mine exploits traditional copper-cobalt mineralized megaclasts within a breccia complex as well as a new style of supergene orebody developed within the breccias themselves and in a lithology, that is not typically mineralized at other deposits. Exposures in the pit presented a unique opportunity to study one of the most important, but poorly understood, aspects of the geology of the Congolese Copperbelt: the breccia complexes that host the mineralized megaclasts. Improved understanding of the Mashitu breccia-hosted orebody allows for development of an exploration model for similar supergene orebodies within the diapiric breccia complexes throughout the Katangan portion of the Central African Copperbelt.

Figure 1.2: Geological map of the western margin of the Kalukundi diapir breccia complex showing the location of the Mashitu deposit (outline in red), modified from François et al. (1974).
1.1 SCOPE OF THIS STUDY

This thesis consists of two papers (Chapters 2 and 3) being readied for publication, as well as this introductory chapter, a conclusions chapter, and a series of appendices. Chapter 2 addresses the geometries and genesis of breccias and megaclast types at the Mashitu deposit. Chapter 3 focuses on the breccia-hosted supergene Cu-Co mineralization at Mashitu.

This study utilizes geological mapping, petrographic studies, and two- and three-dimensional modelling to describe the characteristics and geometries of the breccias and megaclast types at the Mashitu deposit and based on these data propose a genetic model for their formation. The three-dimensional geological model together with geochemical assay data from exploration diamond drillholes and blast holes provide a means to determine the relationship between the distribution of copper and cobalt grades within the deposit and the geometry of megaclasts within the breccia complex. These data are utilized to demonstrate that Mashitu represents a new style of supergene orebody in the Congolese Copperbelt and to propose an exploration strategy for this deposit type.

1.2 METHODS

Geological mapping at Mashitu was undertaken during two field seasons (2014-2015) and was combined with logging of exploration drill core from the pit area. The fieldwork together with petrographic studies allowed classification of different types of breccia. Detailed geological pit mapping, at a scale of 1:500, focused on the exposed block and breccia geometries. Initial mapping of the pit exposures enabled establishment of a rock and breccia classification system that was refined through petrographic studies. This classification represents an extension of lithostratigraphic classification developed by previous workers in the CCB for the Neoproterozoic Katangan Supergroup (Cailteux, 1994). Two hundred and twenty exploration drill cores (~25,000m) were logged either on site or from drill core photos utilizing this rock classification scheme.
Geological data from pit mapping and core logging were integrated to produce 25 east-west trending cross-sections and two north-south trending cross-sections using Encom MapInfo Discover software. A simplified rock classification framework was established to subdivide the major rock and breccia types at Mashitu for a three-dimensional geological model developed using Aranz Leapfrog Geo 3D software. Blast hole assay geochemical data were used to build a three-dimensional model of copper and cobalt mineralized zones for comparison with the breccia and megaclast geometries established from the three-dimensional geological model.

A representative suite of clast and breccia matrix samples was obtained from both drill cores and the pit exposures for petrographic analysis. These studies, undertaken at the Colorado School of Mines, focused on determining mineralogy and the contact relationships between different breccia and clast types. Petrographic analysis included transmitted and reflected light microscopy to examine important textural and paragenetic relationships (Craig, 2001) and automated mineralogy by QEMSCAN® (Quantitative Evaluation of Minerals by Scanning electron microscopy) to produce false-color field image scans of polished thin-sections and epoxy mounts.

QEMSCAN® is a fully automated SEM-based analysis system which utilizes electron-beam instrument analysis to obtain quantitative mineralogical and textural data based on automated point counting. The tool utilizes a Carl Zeiss EVO50 SEM platform, four Bruker energy dispersive detectors, and proprietary software (iMeasure - iDiscover) to produce false-color mineral maps from backscatter electron signals and EDS spectra. Mineral identification is based on the BSE value and elemental intensities. QEMSCAN® allowed for better textural analysis than traditional petrographic techniques and was well suited to the often highly weathered and/or supergene-altered fine-grained sediments and breccia matrix material present at Mashitu. The statistical data produced were used to quantify mineral abundance, grain-size, and mineral associations.
FE-SEM (Field-Emission Scanning Electron Microscopy) was utilized on a selection of the fine-grained breccia samples. Analyses were conducted at the Colorado School of Mines using a TESCAN MIRA3 LMH Schottky field emission-scanning electron microscope which features a TESCAN motorized retractable annular, single-crystal YAG backscatter electron detector (BSE) and a Bruker XFlash® 6/30 silicon drift detector for energy-dispersive X-ray spectrometry (EDS). The instrument provides topographical and elemental information at magnifications of 10x to over 300,000x at a spatial resolution down to the nanometer scale.

X-Ray Diffraction (XRD) analyses of samples of different breccia matrices were undertaken at the Colorado School of Mines to identify the mineralogy of this fine-grained, commonly supergene weathered material. Determination of total organic carbon (TOC) on samples of dark matrix (black) breccia material collected from the pit during the first field season was undertaken to assess the presence of former hydrocarbon material.
CHAPTER 2
GEOMETRIES OF HALOKINETIC BRECCIAS AND MEGACLASTS AT THE MASHITU DEPOSIT, KATANGA, DEMOCRATIC REPUBLIC OF CONGO: EVIDENCE FOR THE INTERNAL GEOMETRIES OF SALT DIAPIRS IN THE CONGOLESE COPPERBELT

2.1 INTRODUCTION

Cu-Co orebodies in the Congolese Copperbelt (CCB) consist largely of megaclasts of Neoproterozoic Roan Group sedimentary rocks within multi-kilometer scale breccia complexes in the cores of anticlines that are considered to have formed due to salt movement (Jackson et al., 2003). Although some megaclasts in these breccia complexes represent orebodies, the geometry of megaclasts within the breccias has been relatively poorly described. Cailteux (1983) and Schuh et al. (2012) include cross sections through different examples of the breccias though neither of these publications offered a three-dimensional model of the breccias and the entrained clasts. Broughton (2014) described the textures and mineralogy of breccias from several areas throughout the Central African Copperbelt but did not utilize his breccia classification scheme to produce a model of breccia geometry.

Geological maps of the CCB illustrate the distribution of the Roan Group megaclasts within the breccia complexes. However, the breccia complexes themselves have undergone recessive weathering and are generally referred to as undifferentiated Roan Group breccia (François, 2006). The breccia complexes contain megaclasts (blocks) of sedimentary rocks from deeper in the stratigraphic sequence than rocks adjacent to the complexes as well as lesser blocks of sedimentary rocks from the adjacent stratigraphic sequences. Previous workers (Cailteux, 1983; Schuh et al., 2012; Broughton, 2014) described breccia matrices as dominantly composed of quartz, “clay”, and carbonate minerals, where clasts within the breccia range from millimeters to kilometers in size. Commonly smaller clasts (<1m) are rounded to sub-rounded,
whereas larger clasts or megaclasts may be more elongate and show shapes suggestive of large blocks of disarticulated sedimentary rocks with clast edges parallel to bedding planes.

This study utilized the exceptional exposures of the breccia and megaclasts in the Mashitu open pit, located within the western part of the Kalukundi diapir in the Democratic Republic of Congo, together with data from drillcores in the pit area to characterize the location and geometry of megaclasts, as well as the types and distribution of breccias. The improved understanding of the genesis of the CCB breccia complexes obtained from this study may be applied to other breccia complexes in the Congolese Copperbelt, and to elsewhere in the world to better understand the internal geometry of salt diapirs and the process of halokinesis.

2.2 REGIONAL GEOLOGICAL SETTING

The Central African Copperbelt (CACB) is located within the Lufilian fold belt, an arcuate zone of variably deformed and weakly metamorphosed Neoproterozoic sedimentary rocks of the Katangan Supergroup that encompasses southern Democratic Republic of Congo (DRC), northwestern Zambia, and southeastern Angola (Figure 2.1).

The Neoproterozoic Katangan Supergroup comprises, from base to top, three major lithostratigraphic successions; the Roan, Nguba and Kundelungu groups with an estimated thickness of 5-10 km (Batumike et al., 2009; Bull et al., 2010, 2011). The Roan Group of the Congolese Copperbelt is subdivided into four subgroups: the R.A.T. (Roches Argilleous Talcose or ‘talcy argillaceous rocks’) Subgroup (R-1), Mines Subgroup or Series (R-2), the Dipeta Subgroup (R-3), and Mwashya Subgroup (R-4) (Francois, 1973, 1974, 2006; Cailteux, 1994; Cailteux et al., 2005a, b; Kampunzu et al., 2005) (Figure 2.2). Katangan Supergroup sedimentary rocks were deposited within a rift basin on the Congo craton (Buffard, 1988; Kampunzu et al., 1991, 1993; Cailteux et al., 1994, 2005) that underwent compression during the Lufilian orogenic event resulting from the convergence of the Congo and Kalahari cratons (Cailteux et al., 2005).
The basal unit of the Roan Group exposed throughout most of the Congolese Copperbelt is the R.A.T. Subgroup. It contains generally reddish, hematitic, commonly indistinctly stratified siltstone and fine-grained sandstone with very minor dolostone (François, 1973). Unweathered R.A.T. Subgroup rocks consists of diagenetic magnesian chlorite and dolomite with variable amounts of both detrital and diagenetic quartz; it commonly is devoid of or contains very little talc (Cailteux et al., 2005a). Talc within the R.A.T. Subgroup appears to be largely confined to weathered rocks and may be in part a secondary mineral (Cailteux, 1983; Cailteux et al., 2005a). The composition of this unit has been interpreted as indicative of an
evaporative depositional environment and/or extreme metasomatism (Cluzel, 1985; Moine et al., 1986; Kampunzu et al., 2005). The thickest intact sequence of R.A.T. Subgroup rocks that has been described is the 235m section from the Kolwezi mining district (François, 1973, 1974; Cailteux et al. 2005a).

Figure 2.2: Lithostratigraphy of the Katangan succession in the Congolese Copperbelt, based primarily on Cailteux et al. (1994).
Four lithological packages within the R.A.T. Subgroup have been recognized (Cailteux et al., 2005a). The stratigraphically lowest comprises red colored and strongly hematitic, chlorite-rich, irregularly bedded siltstones and argillites that contain minor dolomite. This is overlain by red colored, irregularly bedded, chlorite-rich siltstone that grade upward into strongly hematitic and dolomite-rich siltstone, sandstone, and shale and then into a siltstone-dominated package that displays little obvious bedding. The top of the R.A.T. Subgroup sequence adjacent to the overlying Mines Subgroup carbonate rocks is commonly occupied by lithologically similar rocks that lack hematite and display a green color. These rocks, commonly termed “R.A.T. grise or grey R.A.T. Subgroup unit” appear to be diagenetically or hydrothermally altered variants of the typical hematitic R.A.T. Subgroup clastic rocks (Cailteux, 1994). Cailteux et al. (2005a) noted that R.A.T. Subgroup rocks are rarely exposed in continuous intact sequences and more commonly occur as separated blocks or megaclasts within breccia bodies.

The Mines Subgroup is subdivided into three major units: the Kamoto, Shales Dolomitiques or S.D., and C.M.N. (Calaire à Minerai Noir) or Kambove formations. The lowermost portion of the Kamoto Formation, the D. Strat. (Dolomites Stratifiées) unit, marks a major lithological change from the underlying R.A.T. Subgroup rocks (Cailteux, 1994). The D. Strat. unit contains finely bedded impure and variably silicified algal dolostone, commonly with casts after evaporite minerals and centimeter-sized elliptical siliceous nodules. The overlying R.S.F. (Roches Siliceuses Feuilletées) unit is lithologically similar to the D. Strat. unit but displays reduced bed thicknesses and a lack of nodules (François, 1974; Cailteux et al., 1994). In many locations, there is a progressive increase in the degree of silicification from the D. Strat. unit to the top of the R.S.F. unit. The R.S.F. unit is overlain by the R.S.C. (Roches Siliceuses Cellulaires) unit that forms the top of the Kamoto Formation. The R.S.C. unit is composed of pervasively silicified, massive to stromatolitic dolostone with abundant casts after evaporite minerals and minor non-silicified siltstone interbeds.
The transition from the R.S.C. unit to the overlying S.D. Formation is generally abrupt with silicified dolostone changing up-section to fine-grained, parallel-stratified, locally nodular and dolomitic siltstone and variably carbonaceous shales. The lower portion of the S.D. Formation contains finely laminated dolomitic sandstone and shales that give way up-section to dolomitic shales, black carbonaceous shales, and lesser fine-grained sandstone.

A marine regression following deposition of the S.D. Formation resulted in formation of sub-tidal to evaporitic inter- to supra-tidal dolostone in the lower part of the C.M.N. or Kambove Formation (Cailteux et al., 1994; Hitzman et al., 2012). A second transgression during deposition of the upper C.M.N. resulted in a return to either sub- or intertidal locally evaporitic and silicified carbonate sediments or dolomitic siltstone.

The base of the overlying Dipeta Subgroup comprises hematitic, argillaceous dolomitic siltstone, sandstone, and locally conglomerates of the R.G.S. (Roches Gréso-Schisteuses) unit. The R.G.S. unit represents an abrupt sea level regression or basin-ward shift of facies to clastic rocks that are lithologically similar to those of the R.A.T. Subgroup. The upper portions of the Dipeta Subgroup contain regressive and transgressive cycles of evaporitic and stromatolitic dolostone with deeper water dolomitic shales; they are lithologically similar to the rocks of the Mines Subgroup (Hitzman et al., 2012; Schuh et al., 2012). Rocks of the Dipeta Subgroup are overlain by a heterogeneous sequence of dolomitic shales and siltstone, carbonaceous siltstone, and minor sandstone of the deeper water Mwashya Subgroup.

The Roan Group in the CCB is overlain by sedimentary rocks of the Nguba and Kundelungu groups that locally have a combined thickness of several kilometers. The contact between the Mwashya Subgroup and the overlying Nguba Group is marked by the Grand Conglomérat unit, a regionally persistent succession of turbidites, debris flows, and diamicrites that has been traditionally interpreted as a Sturtian-age (c. 715 Ma) glacially-derived sequence (Binda and Van Eden, 1972; Wendorff and Key, 2009; Master and Wendorff, 2011). The Grand Conglomérat unit is commonly overlain by massive carbonate rocks (cap carbonate) of the
Kakontwe Limestone Formation (Cailteux et al., 2007). The remainder of the Nguba Group consists of dolomitic sandstone and siltstone (Batumike et al., 2006, 2007). A generally thin diamicrite, the Petit Conglomérat unit, occurs at the base of the Kundelungu Group and is believed to be time-equivalent to the 635 Ma Marinoan glaciogenic event (Hoffmann et al., 2004; Master and Wendorff, 2011). The uppermost Kundelungu Group comprises argillaceous to arkosic sandstone and conglomerates (Batumike et al., 2006, 2007).

2.3 ROLE OF SALT TECTONICS

In the Congolese Copperbelt, all exposed R.A.T. Subgroup through Dipeta Subgroup rocks of the Roan Group are known only as blocks or megaclasts (“écailles” - fish scales in French) that occur within stratiform to discordant diapiric breccia complexes (François, 1973, 1974). These ‘megabreccias’ locally contain blocks of Nguba and Kundelungu group rocks (François, 1974, 1986; de Magnée and François, 1988). Although the breccia complexes of the DRC Roan Group have been recognized for decades their genesis has been contentious.

François (1973) noted that Roan Group rocks may have contained evaporites and that evaporitic layers could have provided a locus for deformation and décollement during the latest Neoproterozoic to early Cambrian Lufilian orogenic event. He thus interpreted the breccias as tectonic. Many subsequent publications dealing with the geology of the Congolese Copperbelt adhered to this tectonic model of breccia formation facilitated by evaporites (François, 1974, 1993, 1995; De Magnée and François, 1988; Bell, 1989; Cailteux and Kampunzu, 1995; Kampunzu and Cailteux, 1999). Other authors have proposed a sedimentary origin for the breccias. Bartholomé et al. (1972) interpreted breccia within the upper part of the R.A.T. Subgroup at Kolwezi as conglomerate deposited on an erosional surface. Grujenschi (1978), proposed a sedimentary “wildflysch” model for the megabreccias which was expanded upon by Wendorff (2000a, b, 2003, 2005a, b) to include breccia formation as olistostromes.
Broughton (2014), noted a depositional model for formation of the Congolese Copperbelt breccias based on textural observations and their close association with evaporitic rocks. He demonstrated that the location of similar breccias in the Zambian Copperbelt at the boundaries between successive shallowing-upwards sequences, many of which contain anhydrite, indicates the breccias are genetically related to evaporitic rocks as originally suggested by Francois (1973). Jackson et al. (2003) noted the similarity of the Congolese breccias to those in other salt tectonic provinces and concluded that the breccias resulted from halokinesis (salt tectonics). The salt required for halokinesis is believed to have been present within the R.A.T. and Dipeta subgroup sequences (Hitzman et al., 2012).

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Megabreccia containing Mines Subgroup blocks was emplaced upon a specific stratigraphic level of the Kundelungu Group, the Ku 2.1 unit (François in Demesmaeker et al., 1963; and 1973), indicating that salt movement occurred during deposition of the upper Kundelungu Group. Subsequent work by Selley et al. (2010) suggests that much of the Kundelungu Group sedimentation occurred in mini-basins between diapirically rising salt walls and domes. Systematic variations in the thickness of the Grand Conglomérat unit on opposite limbs of megabreccia-cored anticlines in the Congolese Copperbelt suggest that diapirc movement of evaporites was underway by early Nguba Group time (Hitzman et al., 2012). Jackson et al. (2003) proposed that salt was extruded along structures in the Katangan basin
during the latest Neoproterozoic-early Cambrian Lufilian orogenic event. Though it is likely that evaporitic breccia did serve to lubricate structures the geologic evidence indicates that the diapiric breccias were already present prior to the Lufilian orogenic event.

Although breccias that are lithologically similar to those in the Congolese Copperbelt occur within the Upper Roan Subgroup of the Zambian Copperbelt (Selley et al., 2005; Broughton, 2014) they appear stratabound and are generally unrelated to structures suggesting they represent relatively thinner evaporite sequences that did not undergo significant halokinesis. The apparent transition from a thick-skinned (i.e. basement involved) geometry in Zambia to a thin-skinned structural style in the DRC is attributed to the thicker evaporitic sequences that were present in the DRC that led to increased salt diapirism (Hitzman et al., 2012; Woodhead, 2013).

Figure 2.3: Geological map of a portion of the Congolese Copperbelt showing the location of the Mashitu deposit within the Kalukundi diapir or breccia complex. The breccia complexes (pale blue regions) were originally mapped as undifferentiated Lower Roan Group rocks (Ri) that include the R.A.T. and Dipeta subgroup rocks and breccias. KAL = Kalukundi diapir, TF = Tenke-Fungurume diapir, KK = Kakanda diapir. Modified from François et al. (1974).
Although large (> several hundred meters in length) megaclasts of Roan Group sediments were mapped within the Kalukundi diapir (François, 1974) geological mapping did not differentiate clasts of R.A.T. Subgroup or Dipeta Subgroup R.G.S. unit rocks (Figure 2.3). The inability of previous workers to differentiate megaclasts of R.A.T. Subgroup and Dipeta Subgroup R.G.S. unit blocks within the breccias is undoubtedly due to their recessive weathering along with that of the breccia matrix.

2.4 GEOLOGY OF MASHITU MINE

A detailed geological pit map (1:500) of the Mashitu pit (Figure 2.4), twenty-five east-west trending, 1:1000scale cross-sections (XS) (50m line spacing), and two north-south trending cross-sections (LS) were constructed from pit exposures and data from drill cores (Figure 2.5). A three-dimensional geological model of megaclast and breccias types was produced using Aranz Leapfrog Geo 3D software (Figure 2.6).

2.4.1 MASHITU STRATIGRAPHY

Geological mapping of the Mashitu open pit together with drill core logging allowed subdivision of rocks of the R.A.T. Subgroup into individual sections of intact R.A.T., broken R.A.T., and brecciated R.A.T. subgroup rocks, as well as intact, broken, and brecciated Dipeta Subgroup R.G.S. unit rocks (Table 2.1). The mine area also contains the Kamoto, S.D., and C.M.N. (or Kambove) formations. Stratigraphically higher portions of the Roan Group and rocks of the Nguba and Kundelungu groups were not recognized in the pit area but are present beyond the margins of the Kalukundi diapir. Clasts are defined as sedimentary rocks <1 m in diameter, and blocks or megaclasts are largely intact sedimentary rocks >1m in diameter.
Figure 2.4: Geological map (1:500) of the Mashitu open-pit mine and the geological legend established at Mashitu for this study.
Figure 2.5: Mashitu topographical survey map of the open-pit at the time of mapping. Green lines represent 3m high pit bench levels. The locations of the studied drillholes and the cross-sections (XS and LS) developed to produce the three-dimensional geological model for Mashitu are represented by black dots and black lines respectively.
2.4.1.1 R.A.T. SUBGROUP

Three major R.A.T. Subgroup lithologies are present at Mashitu based on dominant rock type, color, bedding thickness, and brecciation style. These are best observed in drillhole DH MDF07 to the east of the open-pit drilled to a final depth of ~315m that intersected a relatively intact ~250m thick sequence of R.A.T. Subgroup rocks below the Mines Subgroup (Figure 2.7). This intersection represents a thicker sequence than the previously described R.A.T. Subgroup sequence of 235m section from the Kolwezi mining district (François, 1973, 1974; Cailteux et al. 2005a).

The three R.A.T. Subgroup lithologies in this drillhole comprise from bottom to top; clay-rich (R1Cl), sandstone-rich (R1Sst), and siltstone-rich (R1Slt). These subdivisions correspond broadly to those defined for the R.A.T. Subgroup sequence at Kolwezi (Cailteux et al., 2005a). Where no contact information or distinctive rock characteristics were observed, rocks of the R.A.T. Subgroup were mapped as undifferentiated (R.A.T. u).
Table 2.1: Rock Classification for Lithologies observed at the Mashitu deposit based primarily on Cailteux et al. (1994) (2005a).

<table>
<thead>
<tr>
<th>CCB Roan Group</th>
<th>CCB Subgroup</th>
<th>CCB Formation</th>
<th>CCB Unit</th>
<th>Mashitu Lithological Subdivision codes</th>
<th>CCB or Mashitu Lithological Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3</td>
<td>R.3 (Dipeta)</td>
<td>R.3.1</td>
<td>R.G.S.</td>
<td>R.G.S.</td>
<td>Brecciated Lower Dipeta Roches Gréso-Schisteuses unit</td>
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</tr>
<tr>
<td>R2</td>
<td>R.2 (Mines)</td>
<td>R.2.2 (C.M.N. Fm.) #</td>
<td>C.M.N.x</td>
<td></td>
<td>Brecciated C.M.N. Formation</td>
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<td></td>
</tr>
<tr>
<td>R1</td>
<td>R.1 (Roches Argileuses Talqueuses - R.A.T.)</td>
<td>R.1.3</td>
<td>S.D.x</td>
<td>Shales Dolomitiques (dolomitic shales)</td>
<td>Brecciated S.D. Formation</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>R.1.2</td>
<td></td>
<td>R.S.C.</td>
<td>Roche Silicieuses Cellulaires (siliceous rocks with cavities)</td>
<td>Brecciated C.M.N. Formation</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>R.S.F.</td>
<td>Roche Silicieuses Feuilletées (laminated and silicified rocks)</td>
<td>Brecciated C.M.N. Formation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D. Str.</td>
<td>Dolomie Stratifiée (stratified dolomite)</td>
<td>Brecciated C.M.N. Formation</td>
</tr>
</tbody>
</table>

# R2Up: Upper Mines Subgroup (S.D. and C.M.N. Formations)
* R2L: Lower Mines Subgroup (Kamoto Formation)
Clay-rich R.A.T. Subgroup unit (R1Cl)

The clay-rich R.A.T. Subgroup lithology is the dominant R.A.T. Subgroup type exposed in the northern portion of the pit at Mashitu. It occurs as megaclasts within both monomict and polymict breccia that range in size from 10’s of meters to ~300m; this lithology also constitutes a large proportion of the smaller R.A.T. Subgroup clasts within the polymict breccia bodies. Rocks of the clay-rich R.A.T. Subgroup lithology are typically lilac-grey, pale to dark mauve, or salmon-pink in color. The unit contains interbedded argillite and siltstone with rare thin sandstone (Figure 2.8a). Larger blocks of the unit display a continuum from intact, though commonly poorly bedded and strongly folded, argillite to strongly broken or fractured zones resembling ‘crackle-breccia’, grading to intensely brecciated zones on block margins. Clasts derived from such brecciated block margins became assimilated into the surrounding monomict R.A.T.-derived breccia and/or polymict breccia bodies.

The mineralogy of the unit comprises quartz and Mg-chlorite with abundant hematite and white mica (muscovite, illite) and more rarely, kaolinite, alkali feldspar, and magnesite (Figure 2.8b). Thus, despite the fact true clay is not the major constituent of the rock, megascopically the rock appears to be clay-rich, hence the designation. Carbonate minerals, dominantly dolomite and more rarely magnesite are rare in weathered examples. Both specular hematite and carbonate minerals occur as possible pseudomorphs after evaporite minerals. Where weathered this unit commonly contains abundant supergene malachite in veins and as clast-coatings on clasts in broken or brecciated zones (Figure 2.8c).

Sandstone-rich R.A.T. Subgroup unit (R1Sst)

The contact of the clay-rich R.A.T. Subgroup lithology with the overlying sandstone-rich R.A.T. Subgroup lithological unit at Mashitu was not observed in pit exposures. However, in drill core, a gradual transition from the clay-rich unit to the sandstone-rich unit occurs with the appearance of pale-colored sandy interbeds within a section of indistinctly bedded
Figure 2.7: Downhole geological log of diamond drillhole MDF07 located 500m east of the Mashitu open-pit that represents a 250m intersection of essentially intact R.A.T. Subgroup rocks.
mauve-colored argillites. The sandstone-rich R.A.T. Subgroup unit comprises interbedded beige to pale-pink dolomitic sandstones with thick, well-bedded brick-red (strongly hematitic) siltstones. Weakly weathered examples of the unit contain abundant quartz, Mg-chlorite, dolomite, and hematite with minor amounts of detrital feldspar and lesser rutile, tourmaline, zircon and monazite (Figure 2.8d).

Three-dimensional modelling of the pit exposures and examination of drillcore indicates that this unit is the dominant R.A.T. Subgroup lithology at Mashitu. The sandstone-rich R.A.T. Subgroup unit occurs as large megaclasts up to 100’s of meters in diameter; it is generally the least brecciated R.A.T. Subgroup lithology at the mine.

The base of the unit is marked by a distinctive buff to salmon-pink coarse sandstone horizon with pink, purple or red silty laminations that locally contains rip-up clasts of alkali-feldspar and muscovite- an alkali feldspar-rich purple shales. This horizon may be analogous to the ‘grès ocellés’ marker unit noted by Cailteux et al., (2005a) at the base of their R1.3 R.A.T. unit at Kolwezi (Figure 2.8e). Above this basal sequence the unit is comprised of brick-red strongly hematitic semi-massive to thickly bedded siltstones containing abundant specular hematite and minor black-oxides as both fracture-fill and infill of former pseudomorphs after evaporite minerals. This sequence grades upwards to paler-colored interbedded dolomitic siltstones and sandstones, containing conformable breccias horizons.

The uppermost portion of the unit contains bedding-parallel (conformable) breccia horizons (R1Sstcx) typically 10’s of mm to less than 1m thick that may represent former evaporitic or perhaps calcrete layers (Figure 2.8f). The collapse breccia horizons are composed of quartz and Mg-chlorite with minor dolomite and anhydrite, the latter as inclusions within quartz. Soft-sediment deformation, micro-faulting and collapse patterns have been recognized above the R1Sst conformable breccias horizons. Carbonate pseudomorphs, possibly after anhydrite or gypsum in semi-massive dolomitic siltstones, occurring above or below the conformable breccia horizons suggests a sabkha-type environment of deposition. It is probable
that the interbedded former evaporite horizons underwent dissolution leading to the
development of the collapse breccias.

Megaclasts of the sandstone-rich R.A.T. Subgroup lithology exposed in the Mashitu pit display less brecciation on their margins compared to the margins of the clay-rich R.A.T. Subgroup lithology. The margins of sandstone-rich R.A.T. Subgroup lithology megaclasts are commonly broken but display a sharp transition to breccia. The abundant dolomite in the sandstones may explain its less-brecciated nature. The sandstone-rich R.A.T. Subgroup unit at Mashitu appears similar to Cailteux et al.'s (2005a) R1.3 sequence at Kolwezi which contains the grès ocellés marker.

Siltstone-rich R.A.T. Subgroup unit (R1Slt)

A conformable contact between the sandstone-rich R.A.T. Subgroup lithological unit and overlying siltstone-rich R.A.T. Subgroup unit was observed in drill core. However, in many instances a thin polymict breccia was noted at the contact suggesting this zone was structurally weak facilitating separation of the R.A.T. Subgroup sequence during transport of megaclasts in the diapir. The siltstone-rich R.A.T. Subgroup lithology at Mashitu typically occurs as megaclasts up to 100’s of meters in diameter that directly underlie Mines Subgroup megaclasts. The siltstone-rich R.A.T. Subgroup lithology consists of thickly-bedded to semi-massive brick-red or reddish-brown siltstone with rare thin (<1cm) wispy buff-colored interbedded sandstones (Figure 2.8g). Rocks of this lithology contain quartz, Mg-chlorite, and hematite with minor white mica (muscovite or illite) and alkali feldspar as both detrital grains and diagenetic growths in the groundmass. Unweathered examples of the unit contain abundant dolomite as fine-grained cement, pseudomorphs after evaporite minerals, and fracture-fills in broken to brecciated zones (Figure 2.8h). Weathered and broken to brecciated portions of the siltstone-rich R.A.T. Subgroup lithology contain malachite and/or black Fe-Mn (Cu-Co) oxide minerals in fracture-fills and in vugs after leached pseudomorphs of evaporite minerals.
The uppermost portion of the siltstone-rich R.A.T. Subgroup unit is commonly brecciated suggesting it may have contained a thick evaporite sequence that underwent dissolution resulting in more intense disaggregation of the siltstone-rich R.A.T. Subgroup unit. Megaclasts of the siltstone-rich R.A.T. Subgroup lithology display a continuum from intact block cores comprising to broken or ‘crackle-breccia’-like zones of variable lateral continuity. The broken zones on margins of megaclasts transition to strongly disaggregated matrix- to clast-supported breccia. The siltstone-rich R.A.T. Subgroup unit at Mashitu would probably be included in Cailteux et al.’s (2005a) R1.3 sequence at Kolwezi.


The stratigraphically uppermost portion of the R.A.T. Subgroup sequence is distinctive in that it displays a green rather than red color (Cailteux, 1994) and is referred to as the grey R.A.T. (R.A.T. Gr) unit. It conformably underlies rocks of the Mines Subgroup. The grey R.A.T. at Mashitu is dominantly a dolomitic siltstone to sandstone and ranges in thickness from approximately 5m to 10’s of centimeters. It contains quartz, Mg-chlorite, and dolomite (in less weathered examples) with minor rutile, apatite, and sulfides. Where weathered, it may contain malachite as well as iron- and copper-bearing oxide minerals. It is generally more deformed than other R.A.T. Subgroup lithologies. The grey R.A.T. Subgroup lithology is believed to represent the uppermost portion of the R.A.T. Subgroup sequence that underwent reduction with conversion of hematite to sulfides during diagenesis and the brine-related alteration associated with the sulfide-mineralizing event (Hitzman et al., 2012).
Figure 2.8: Examples of R.A.T. Subgroup unit rock types identified at the Mashitu deposit: a) Polished thin-section of unweathered clay-rich R.A.T. Subgroup unit (R1Cl) from DH MDF07. b) Automated mineralogy false-color image area annotated in Fig 2.8a of unweathered R1Cl from DH MDF07 containing abundant magnesite. c) Automated mineralogy false-color image of a polished thin section of weathered R1Cl from a DH MNWD001 containing abundant Mg-chlorite and white-mica laths with supergene Cu-Co minerals as patchy groundmass replacement. d) Automated mineralogy false-color image of a polished thin section of unweathered sandstone-rich R.A.T. Subgroup unit (R1Sst) containing abundant coarse quartz and dolomite from DH MDF07. E) R1Sst marker horizon from DH MNWD033 considered equivalent to the “grés ocellés” horizon (Cailteux et al., 2005). f) R1Sst unit conformable breccia horizon after dissolution of evaporite from DH MNWD034. g) Example of siltstone-rich R.A.T. Subgroup (R1Slt) from DH MNWD054 in the north pit contains abundant dolomite-filled pseudomorphs after evaporite minerals with dolomite veins. h) Polished thin section of unweathered R1Slt from DH MDF07 containing abundant fine-grained quartz, Mg-chlorite and dolomite, with dolomite fracture-fill.
2.4.1.2 MINES SUBGROUP

The Mines Subgroup (or Mines Series) is subdivided into three formations: the Kamoto, S.D., and C.M.N. or Kambove formations. Although these formations are commonly further subdivided into a number of units, only those of the Kamoto Formation were utilized during mapping and logging. The Kamoto Formation at Mashitu is lithologically similar to that described from throughout the Congolese Copperbelt. The siltstones and dolomitic siltstones of the S.D. Formation at Mashitu is generally highly weathered and was not been subdivided; it was mapped as undifferentiated S.D. Formation (S.D. Formation) or brecciated S.D. Formation (S.D. x). Drilling indicates a maximum preserved thickness of 160m of the S.D. Formation in the mine area. Talc-goethite-quartz-rich clasts after weathered C.M.N. Formation dolostones were observed overlying the S.D. Formation along the upper margin of a large buried Mines Subgroup megaclast in the open pit. It appears that the C.M.N. Formation at Mashitu was largely disaggregated during halokinesis resulting in entrainment of small fragments and/or assimilation of C.M.N. Formation-derived material into the polymict breccia.

2.4.1.3 DIPETA SUBGROUP

Dipeta Subgroup rocks are not exposed within the Mashitu pit. However, exploration drill cores from below the pit intersected megaclasts interpreted to represent the basal unit of the Dipeta Subgroup, the R.G.S. (Roches Gréso Schisteuses) (R-3.1). At Mashitu, the R.G.S. unit comprises weakly hematitic, pale purple or mauve colored argillaceous dolomitic siltstones and white to pale green colored sandstones containing abundant alkali feldspar, quartz, dolomite, Mg-chlorite and muscovite (Figure 2.9). These apparent R.G.S. unit rocks are lithologically similar to those of the sandstone- and siltstone-rich R.A.T. Subgroup lithologies. Differentiation of the R.G.S. unit from R.A.T. Subgroup lithologies at Mashitu was established using differences in the mineralogy, primarily the abundance of alkali feldspar.
Figure 2.9: Brecciated R.G.S. unit purple argillites and siltstones and R.G.S. unit pale sandstones (a) from cores drilled along the western margin of the Mashitu deposit (MSPD052). The QEMSCAN® image (b) of a polished thin-section (c) taken from this drillcore shows a siltstone clast with abundant alkali-feldspar and muscovite and minor low Mg-chlorite compared to R.A.T. Subgroup lithologies. Dolomite and coarse euhedral quartz occurs on the margin of the argillaceous fragment.

2.4.1.4 SUPRA-R.G.S. UNIT LITHOLOGIES

The upper portions of the Dipeta Subgroup comprising evaporitic and stromatolitic carbonate units and shales and siltstones of the overlying Mwashya Subgroup, were not observed within or proximal to the Mashitu pit. Rocks of the younger Nguba and Kundelungu groups are not present in pit exposures or drill cores from the pit area. One drillhole ~200m northwest of the Mashitu deposit (MNWD035) interpreted to be outside of the Kalukundi diapir intersected the Grand Conglomérat unit diamicite and overlying thinly-bedded dolomitic siltstones and shales of Nguba Group.
2.4.1.5 BRECCIA TYPES

Mashitu contains a variety of breccia types that were characterized based on textures and contact relationships observed during mapping as well as petrographic and mineralogical analysis in the laboratory. Five different breccia types were defined. The primary division was differentiation of monomict from polymict breccia. Additional subdivision was based on matrix color, matrix mineralogy, clast to matrix ratio, and internal fabric (Table 2.2).

Table 2.2: Breccia type classification framework established for the breccia complex exposed at Mashitu.

<table>
<thead>
<tr>
<th>Type</th>
<th>Mashitu Breccia Classification Terms</th>
<th>Breccia Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monomict Breccia</td>
<td>Dark Matrix Polymict Breccia</td>
<td>dPtx</td>
</tr>
<tr>
<td>Polymict Breccia</td>
<td>Pale Matrix Polymict Breccia</td>
<td>pPtx</td>
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<tr>
<td></td>
<td>Specular hematite-rich Polymict Breccia</td>
<td>shPtx</td>
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<tr>
<td></td>
<td>Polymict Breccia Undifferentiated</td>
<td>ptx</td>
</tr>
<tr>
<td>Monomict Breccia</td>
<td>Pale Matrix Monomict Breccia</td>
<td>pMtx</td>
</tr>
<tr>
<td></td>
<td>Specular hematite-rich Monomict Breccia</td>
<td>shMtx</td>
</tr>
<tr>
<td></td>
<td>Monomict Breccia Undifferentiated</td>
<td>mtx</td>
</tr>
</tbody>
</table>

**Monomict R.A.T. Subgroup-derived breccia**

Monomict R.A.T. Subgroup-derived breccia, included in the unit “R.A.T. breche” of earlier workers (François, 1974), is one of the most common breccia types exposed in the northern pit at Mashitu. It is a clay-like to granular textured matrix-supported breccia containing sub-angular to rounded clasts of R.A.T. Subgroup lithologies from millimeters to several centimeters in diameter. Clasts were derived from immediately adjacent megaclasts of R.A.T. Subgroup rocks. Thus, in the northern portion of the mine most monomict breccia contains clasts of clay-rich R.A.T. Subgroup rocks whereas siltstone- and sandstone-rich R.A.T.
Subgroup lithologies are more common in monomict breccias in the central and southern portion of the open pit. Clasts in these breccias typically range in color from pale pink to beige and the matrix varies from white to salmon-pink in color. The overall color of this breccia varies depending on the type of R.A.T. Subgroup fragments contained and on the degree of weathering. Monomict breccia adjacent to megaclasts of siltstone-rich R.A.T. Subgroup rocks that dominantly contain clasts of this lithology are brick-red to dark pink in color whereas monomict breccia appears more pale-pink to white with a sandier appearance adjacent to megaclasts of sandstone-rich R.A.T. Subgroup. Monomict R.A.T. Subgroup-derived breccia matrix is composed of Mg-chlorite, quartz, muscovite, and hematite. Specular hematite is commonly abundant in matrix between closely spaced clasts and where alignment of specular hematite laths defines a distinctive stretched fabric (Figure 2.10).

Figure 2.10: (a) Specular hematite rich monomict breccia from drillhole MNWD001 with area of automated mineralogy false color image by QEMSCAN® (b) shown in black box. Clasts of <1mm are probably composed of strongly weathered clay-rich R.A.T. Subgroup unit siltstone or argillite composed of quartz-Mg-chlorite-muscovite/illite.

There is a continuum from broken R.A.T. Subgroup megaclasts, to those that display a “crackle breccia” appearance, to the monomict R.A.T. Subgroup-derived breccia, first a clast-supported breccia and then matrix-supported breccia. The mineralogy of breccia matrix indicates it was largely, probably solely, derived from intense fragmentation of R.A.T. Subgroup lithologies. The largest volume of monomict breccia at Mashitu is spatially associated with the clay-rich R.A.T. Subgroup unit likely due to its low structural competence (Figure 2.11).
Figure 2.11: Monomict R.A.T. Subgroup-derived breccia on the northeast pit wall of the Mashitu open pit. A) Annotated image of monomict R.A.T. subgroup-derived breccia showing the distribution of clay-rich R.A.T. Subgroup blocks (R1Cl) and breccia matrix (mtx). B) Image of the irregular contact zone between a highly-broken to brecciated clast of clay-rich R.A.T. Subgroup unit (R1Clx) and paler colored monomict breccia matrix (mtx).

**Polymict breccia**

Polymict breccias are the most distinctive breccia type at Mashitu. They display irregular geometries and commonly form centimeter- to tens-of-meters-scale injections and vein- or dyke-like bodies. Injections of polymict breccia into megaclasts commonly occur along lithological contacts such as bedding planes and are particularly common along lithological contacts in the R.A.T. Subgroup, along the lower and upper boundaries of the silicified Kamoto Formation, and between the S.D. and the C.M.N. formations (Figure 2.12). The most common clast types present within polymict breccia at Mashitu are R.A.T. Subgroup rocks, R.G.S. unit sandstones, and C.M.N. Formation dolostones.

Rounded to sub-angular megaclasts or blocks and generally rounded clasts of various rock types occur throughout polymict breccia zones and may display a banded appearance giving the unit a pronounced fabric (Figure 2.13). The polymict breccia matrix contains Mg-chlorite and quartz with variable amounts of white mica (muscovite), specular hematite, goethite, and talc. Significant dolomite may be present in less weathered polymict breccia matrix.
Polymict breccia is subdivided on both matrix composition and color. Matrix with a high content of supergene Fe-Mn (Cu-Co) oxide minerals ranges from dark brown to black in color. Breccia matrix dominated by quartz and/or dolomite is generally pale colored. Supergene Fe-Mn (Cu-Co) oxides are most common in matrix-supported, clast-poor polymict breccia that contains abundant Mg-chlorite, clays, and rare talc (Figure 2.14a). Hypogene sulfides were not observed in polymict breccia.

Pale matrix polymict breccia is typically clast-rich, well cemented, and has a granular textured matrix composed dominantly of dolomite and quartz with lesser Mg-chlorite, white mica, and specular hematite (Figure 2.14b and c). This breccia type was observed in the northeastern part of the pit and is common in core from exploration drillholes below the limit of supergene weathering.

Specular hematite-rich polymict breccia is most common along the margins of dark matrix polymict breccia bodies and as irregular bodies within the polymict breccia. It displays a distinctive bright pink or silver-grey to purple color and contains 4-10% fine-grained to coarse grained (centimeter length) disseminated laths of specular hematite. Specular hematite-rich breccia is typically clast-supported and displays a well-developed fabric represented by the alignment of hematite laths parallel to bounding megaclasts, pale or dark polymict breccia.
zones, or trains of elongated millimeter-size clasts (Figure 2.14d and e). Contacts between specular hematite-rich breccia and pale or dark polymict breccia bodies are often irregular and indistinct and do not display distinctive cross-cutting relationships.

Figure 2.13: Dark matrix polymict breccia (dPtx) zone on the north wall of the central pit area at Mashitu that contains clasts of brecciated C.M.N. Formation (C.M.N. x) and broken to monomict brecciated siltstone-rich R.A.T. Subgroup unit blocks (R1Sltx). The color variations are related to the types of entrained clasts, the degree of weathering, and/or variations in the content of black-oxide minerals (dark). These color variations highlight a distinctive fabric (white-dashed lines).
Figure 2.14: Examples of breccia types identified at the Mashitu deposit (page 38). a) Automated mineralogy false-color image of dark matrix polymict breccia from DH MNWD014 in the northern pit at Mashitu. The polymict breccia contains clasts of R.A.T. Subgroup rocks (quartz (31%) -Mg-chlorite (22.8%)-muscovite (9%)-bearing) and R.G.S. unit rocks (K-feldspar (29%)-quartz-muscovite-bearing). The polymict breccia matrix contains abundant Mg-chlorite, together with supergene malachite and black Cu-Co oxide minerals. b) Example of unweathered pale matrix polymict breccia from drillhole MDF07 that contains clasts of various clay-rich R.A.T. Subgroup unit rocks (R1Cl). c) Automated mineralogy false-color image of pale matrix polymict breccia from drillhole MDF07. The breccia matrix contains coarse dolomite grains (2%) together with Mg-chlorite (41%) and quartz (39%). The mineral composition of the sub-rounded clasts of clay-rich R.A.T. Subgroup unit rocks entrained in the breccia are similar to the matrix. The clasts also contain dolomite, commonly removed from more weathered examples. d) Specular hematite-rich monomict breccia containing abundant quartz-Mg-chlorite-muscovite in both clasts (<5mm in diameter) and matrix from DH MNWD022 in the north pit. The matrix contains abundant specular hematite (dark color) and scan area for fig 2.14e. (e) Automated mineralogy false-color image of polymict breccia from drillhole MNWD022 (area in figure 2.14d) showing the contact of specular hematite-rich polymict breccia and pale matrix polymict breccia. The latter zone in the upper scan area shows a clast of R.G.S. unit K-feldspar-quartz-dolomite-bearing rock contained in a coarse-grained quartz (>30%) -Mg-chlorite (>16%) -dolomite (>15%) matrix. The contact with specular hematite-rich polymict breccia is represented by the presence of abundant specular hematite grains (>15%) aligned sub-parallel to the breccia margin and appears to grade inwards (lower scan area) to a more coarse-grained quartz-dolomite-specular hematite and Mg-chlorite rich breccia matrix that contains mostly clasts of R.A.T. Subgroup-derived rocks.
2.5 GEOMETRIES OF MEGACLASTS AND BRECCIAS

Geological mapping, exploration diamond drillhole data and two- and three-dimensional modelling were utilized to establish the geometries and distribution of the various breccias and megaclast types at the Mashitu deposit. The modelling indicates that Mines Subgroup rocks form the dominant megaclast type at Mashitu followed by the sandstone-rich R.A.T. Subgroup unit (Figure 2.15). Polymict breccia is the most common breccia type. Regions of R.A.T. Subgroup-derived monomict breccia represents approximately 10% of the breccia body at Mashitu but does not include the brecciated margins of individual megaclasts of R.A.T. Subgroup unit rocks. The megaclast to breccia ratio in the Mashitu mine area of the Kalukundi breccia complex is approximately 5:1.

Previous workers interpreted the breccias at Mashitu as a series of cross-cutting, steeply-dipping to sub-horizontal ‘cataclasite’ (fault related) bodies. Mapping conducted in the present study provided no evidence for preserved fault structures within the breccias or along block margins. Instead the monomict breccias were found to form carapaces on large blocks or megaclasts and generally grade from containing dominantly sub-angular clasts closer to the intact zone, commonly termed broken, that grade to dominantly sub-rounded clasts on carapace margins. The polymict breccias form complex three-dimensional bodies surrounding multiple clast types as well as injections at a variety of scales into and through blocks (Figure 2.16).

Polymict breccias commonly display fabrics parallel to entrained block margins and to elongated, commonly highly broken blocks or bodies of monomict breccia. These textures are believed to be due to entrainment of blocks of sediment within mobile evaporite minerals, dominantly halite. The entrainment of monomict fragments into polymict breccia bodies indicates that brecciation of the blocks was initiated during halokinesis and continued during dissolution of salt and development of the polymict breccia (Figure 2.17).
Figure 2.15: North-south trending sections LS01 and LS02 (1:1000) illustrating the volume of Roan Group megaclasts relative to breccia at Mashitu and the apparent staking of fragments of the lower Roan Group stratigraphy. The location of these section-lines is shown on Figure 2.4. LS01 lies 100m west (in front of) LS02. The pit surface contour is shown as a solid black line in the upper portions of the sections. Black vertical lines represent drillhole traces. Areas in white are overburden at the top of the sections and represent areas outside the bounds of available exploration drillhole data along the base of the sections.
The different polymict breccia types do not display consistent cross-cutting relationships. The dominant matrix-supported polymict breccia zones are commonly irregularly bounded by specular hematite-rich, clast-supported polymict breccia in areas of restricted space between blocks or megaclasts. Such specular hematite-rich polymict breccias are commonly laterally discontinuous and may even form clasts within the matrix-supported polymict breccia. Matrix-supported dark or pale polymict breccia may grade into more clast-rich to almost clast-supported polymict breccia adjacent to megaclasts. Generally, polymict breccias are increasingly matrix-supported and more clast-diverse away from clast margins but there are also examples of matrix-supported, highly polymictic breccia immediately adjacent to blocks.
Clasts in the polymict breccias are aligned sub-parallel to their long-axis and are distributed as ‘trails’ within the polymict breccia forming bands or a pronounced fabric. In some cases, such trails contain clasts that have been subjected to en-echelon style fragmentation with geometries that suggest a direction of movement. The relatively intact appearance of such clast trails indicates either little movement of clasts during salt dissolution or deformation post-salt dissolution.

Figure 2.17: Clast of pink to reddish monomict R.A.T. Subgroup-derived breccia within a matrix-supported dark matrix polymict breccia from the southern pit at Mashitu that dominantly contains small (<5mm) clasts of R.A.T.- and R.G.S. subgroup unit rocks and <2mm C.M.N. Formation fragments. The clast-rich red to pink monomict breccia may be derived from the siltstone-rich R.A.T. Subgroup unit located below a Mines Subgroup megaclast. The dark matrix polymict breccia contains abundant black Cu-Co oxide minerals.

Preliminary investigations for this study at Mashitu considered the distribution of megaclast or block types to be somewhat chaotic representing complex mixing of rock types as megaclasts from different portions of the stratigraphic sequence. However, geological modelling demonstrates that the original Roan Group stratigraphy is largely preserved in the breccia complex. Apparently more ductile (shale-dominant) units such as portions of the R.A.T. Subgroup and the R.G.S. unit of the Dipeta Subgroup, and the dolostone-rich C.M.N. Formation (containing abundant talc), were most deformed and brecciated (Figure 2.18). More competent units such as the sandstone-rich R.A.T. Subgroup unit, the silicified Kamoto Formation, and the
S.D. Formation tend to form large blocks.

Figure 2.18: Image showing an injection of polymict breccia between clay-rich R.A.T. Subgroup (R1Cl) megaclasts on the northern pit wall at Mashitu. The polymict breccia contains clasts of R.A.T. Subgroup rocks (R1Cl and R1Slt), C.M.N. Formation dolostones, and R.G.S. Dipeta Subgroup unit sandstones. The dominantly dark matrix polymict breccia zone (dPtx) displays a banded fabric in places parallel to clast margins and contains zones of specular hematite-rich polymict breccia (shPtx).

The distribution of R.A.T. Subgroup units in the northern and central portion of the Mashitu deposit appears to reflect the macro-scale, stratigraphically-ordered disaggregation of the R.A.T. Subgroup stratigraphic sequence during halokinesis. Clay-rich R.A.T. Subgroup unit megaclasts representing the lower portion of the R.A.T. Subgroup stratigraphic sequence are present on the northern pit wall whereas sandstone-rich R.A.T. Subgroup unit megaclasts occur in the central pit and are succeeded to the south by siltstone-rich R.A.T. Subgroup unit megaclasts (Figure 2.19).

Figure 2.19: The northern portion of cross section LS01 (Fig. 2.5) showing the distribution of R.A.T. Subgroup unit blocks. The red arrow shows direction of stratigraphic way-up for the R.A.T. Subgroup units at Mashitu. It appears that the stratigraphy was disarticulated with blocks being moved to the south. The legend for lithologies is shown on Figure 2.4.
The margins of these megaclasts were broken and brecciated during halokinesis leading to the progressive formation of R.A.T. Subgroup-derived monomict breccias followed by, or simultaneous with, injection of polymict breccia.

The large Mines Subgroup megaclast or block, which dominates the central pit at Mashitu, is largely intact but is broken by a series of polymict breccia injections resulting in what appear to be entirely separate blocks in the geological map of pit exposures (Figure 2.4) but which can be seen to form a largely coherent whole in the three-dimensional model (Figure 2.6).

This large megaclast is also cut by polymict breccia along the Mines Subgroup R.S.C. unit – S.D. Formation contact. Historic geological mapping (François, 1974) together with sparse recent drill holes suggest the edge of diapir lies within several hundred meters of the western edge of the Mashitu deposit. Mapping and modeling at Mashitu suggests that the orientation of megaclasts becomes steeper towards the diapir edge. Such changes in geometry suggests that the diapir edge may have served as a buttress for salt. Thus, megaclasts within the salt and proximal to the diapir edge may have undergone more intense folding, deformation, and brecciation than megaclasts towards diapir centers (Figure 2.20).

Figure 2.20: Intense folding and deformation of Mines Subgroup megaclasts along the western part of the Mashitu deposit approximately 200m from the margin of the Kalukundi diapir shown on cross section XS14 (Fig. 2.5). Polymict breccia injections occur between the R.S.C. unit and the S.D. Formation of the Mines Subgroup megaclast. The legend for lithologies is shown on Figure 2.4.
Megaclasts of R.A.T. Subgroup, Mines Subgroup, and Dipeta Subgroup R.G.S. unit rocks were identified by drilling below the current pit floor. However, the paucity of deep drillhole intersections (>100m) restricted detailed determination of their geometries. The largest megaclast at Mashitu, some 600m long (north-south) and 500m wide, is present in the subsurface and consists of a relatively intact ~350m thick right-way-up stratigraphic sequence that comprises from base to top; a thin siltstone-rich R.A.T. Subgroup unit, grey R.A.T. Subgroup rocks, Kamoto Formation, and a ~160m thick sequence of the S.D. Formation (Figure 2.21).

![Megaclast Diagram](image)

**Figure 2.21**: The southern portion of north-south section LS01 (Fig. 2.5) showing a buried megaclast of stratigraphically intact Mines Subgroup beneath the central and south pit areas at Mashitu. The S.D. and Kamoto formations are dominantly intact. C.M.N. formation rocks have undergone more intense weathering, brecciation, and assimilation into the polymict breccia. Polymict breccia injections at the base of the Mines Subgroup and along weak lithological contacts within the Mines Subgroup are common. Blocks of Dipeta Subgroup R.G.S. unit rocks are common in the polymict breccia; some may be derived from the upper portions of the buried Mines Subgroup megaclast. Deeper blocks of these younger rocks (and C.M.N. formation) suggest that another Mines Subgroup megaclast is present below the base of drilling at Mashitu. The legend for lithologies is shown on Figure 2.4.

The C.M.N. Formation appears to be missing or is represented by monomict breccia above the S.D. Formation. However, the polymict breccia that surrounds and cuts this megaclast contains abundant C.M.N. Formation fragments. Another buried megaclast is thought
to occur beneath the southern portion of the Mashitu pit where megaclasts of Dipeta Subgroup R.G.S. unit siltstone, argillite and sandstone are present near the surface. These blocks were probably derived from the upper portions of a deeply buried Roan Group megaclast.

2.6 DISCUSSION

As demonstrated by the geological map of the Mashitu mine area, polymict breccia at Mashitu carried large (tens to hundreds of meters in length) megaclasts of lithified Roan Group sedimentary rocks upward in the Kalukundi diapir to the stratigraphic position of the lower Kundelungu Group. Mapping demonstrates that the megaclast geometries are not chaotic but represent en-echelon stacking of largely stratigraphically intact sequences. At least three repeated sequences of right-way-up Roan Group fragments separated by polymict breccia are present at Mashitu.

Ductile (shale-dominant) units such as portions of the R.A.T. Subgroup and the R.G.S. unit of the Dipeta Subgroup, and the dolostone-rich C.M.N. Formation (comprising abundant talc) were the most disrupted during halokinesis and thus represent the most common clast types within the polymict breccia. More competent units such as the sandstone-rich R.A.T. Subgroup unit, the silicified Kamoto Formation, and the S.D. Formation formed large blocks surrounded and intruded by polymict breccia. The morphologies of the different rock units at varying scales indicates that brecciation resulted in a fractal pattern.

Polymict breccias commonly display fabrics parallel to entrained block margins and to elongated commonly highly broken blocks or bodies of monomict breccia. These textures appear to have resulted from entrainment of sedimentary rock blocks within a mass of mobile evaporite minerals, dominantly halite. The entrainment of monomict fragments into polymict breccia bodies indicates that brecciation was initiated during halokinesis and continued during dissolution of salt and development of the polymict breccia.
The matrix of the polymict breccia at Mashitu is currently composed of Mg-chlorite, quartz, and dolomite. Samples from deep drill holes indicate that unweathered polymict breccia contains significantly more dolomite than is present in polymict breccia from the present-day surface. If the polymict breccia did undergo upward movement, as the geologic evidence suggests, it must have originally been composed primarily of halite, probably with lesser anhydrite to allow for ductile movement. Thus, the polymict breccia (resistate) observed today at Mashitu must represent a very small portion, probably less than five percent, of the original volume of the halite-dominant material. The brecciation observed in the rock is thus probably a combination of breakage and deformation during halokinesis and fragmentation during salt dissolution and collapse.

Breccias similar to those at Mashitu are present throughout the Congolese Copperbelt. In the Tenke-Fungurume diapir to the east of Mashitu, isoclinal antiforms or piercement structures occupied by similar breccias have been interpreted as salt walls and the breccias interpreted as insoluble residue from dissolution of mobile salt (Jackson et al., 2003; Schuh et al., 2012). In the Kolwezi mining district, to the west of Mashitu, large, broken and locally folded, but stratigraphically intact, stacked sheets of lower Roan Group stratigraphy have been interpreted as having been extruded from salt diapirs that reached the surface during deposition of the lower Kundelungu Group sediments (Jackson et al., 2003). Long-lived passive dissolution likely occurred after this time whenever groundwater could access the diapirs; up to and including present day. No breccias in the Congolese Copperbelt are known to presently contain halite or significant anhydrite. However, somewhat similar breccias containing abundant anhydrite within their matrix have recently been found in similar-aged Neoproterozoic sedimentary sequences at the Kansanshi copper deposit in the Zambian Copperbelt (Hitzman and MacIntyre, pers. comm. 2015).

Breccias similar to those in the Congolese Copperbelt are found in the Flinders Range, Australia. These Neoproterozoic breccias, termed the Callanna Group, occur in diapiric
structures. They contain blocks of sedimentary rock from deeper in the stratigraphic sequence than that at which they are exposed in a largely carbonate matrix. They are interpreted to have formed as a resistate derived from a halokinetic evaporite sequence in which halite and other evaporite minerals underwent dissolution or replacement (Hearon, 2013; Hearon et al., 2015 and references therein) and to be analogous to diapirs in the Gulf of Mexico derived from the Jurassic Louann salt (Hearon, 2013; Hearon et al., 2015).

A modern analogue for the process that formed the polymict breccia at Mashitu is observed in the Zagros Mountains of Iran where active salt glaciers derived from diapiric salt bodies are mantled by a dissolution-derived carapace (Warren, 1999). These carapaces contain fragments or rafts of rocks transported by the salt from lower in the stratigraphic section as well as sediment deposited atop the salt glaciers that itself can become brecciated and form a poorly-sorted polymict rubble in a fine-grained, largely calcareous matrix (Talbot and Jarvis, 1984; Warren, 1999).

2.7 CONCLUSIONS

The distinctive geometry, presence of clasts of stratigraphy hundreds to thousands of meters above their apparent depositional position, and mineralogy of the breccia matrix supports hypotheses presented by earlier workers that the Congolese breccia complexes represent the remnants of salt diapirs probably formed in the late Neoproterozoic. The salt required for halokinesis is believed to have been present within the R.A.T. and Dipeta subgroup sequences. Dissolution of halite and anhydrite within these diapiric structures led to the complex breccia bodies observed today in the Congolese Copperbelt.

The current block to breccia ratio observed in the pit and in drillcore at Mashitu is approximately 5:1. However, the halokinetic polymict breccia volume must represent a relatively small amount of the original material (salt) that was present prior to dissolution and replacement by carbonate-minerals. The original block to breccia ratio within diapiric structures such as that
exposed at Mashitu could have been close to 1:100. Thus, the halokinetic breccias represent resistsate after salt loss. Monomict and some polymict breccias probably formed from both disaggregation of megaclasts during upward transport and from collapse during salt dissolution following halokinesis. The spectrum of breccias exposed in the Mashitu pit and in drill core from the mine area indicate a long-lived, multi-phase process of brecciation.

Implementation of a block and breccia classification, together with detailed mapping and three-dimensional geological modeling as undertaken at Mashitu, provides significant insights into the internal geometry of the Kalukundi breccia complex. A similar methodology could be applied in other breccia complexes in Congolese Copperbelt and perhaps elsewhere such as the Flinders Range in South Australia to better understand the internal geometry of halokinetic breccias. This study demonstrates that the geometry of megaclasts as well as their stratigraphic orientation should be considered when interpreting models for salt movement in ancient and existing salt diapirs. In the Congolese breccia complexes a better understanding of megaclast geometry and orientation may enable better prediction of the location of potentially mineralized megaclasts.
CHAPTER 3

HALOKINETIC BRECCIA-HOSTED SUPERGENE CU-CO MINERALIZATION AT THE MASHITU DEPOSIT IN THE KALUKUNDI DIAPIR, KATANGA, DEMOCRATIC REPUBLIC OF CONGO: A NEW DEPOSIT STYLE IN THE CENTRAL AFRICAN COPPERBELT

3.1 INTRODUCTION

The Central African Copperbelt of southern Democratic Republic of Congo (DRC), northwestern Zambia, and southeastern Angola hosts the world’s highest-grade accumulation of sedimentary rock-hosted copper and cobalt in addition to significant deposits of zinc, lead, gold, nickel and uranium (Hitzman et al., 2012; Broughton, 2014). Copper-cobalt orebodies in the DRC portion of the Central African Copperbelt, referred to as the Congolese Copperbelt (CCB), consist primarily of 100’s of meters to kilometers in diameter megaclasts (blocks) of Neoproterozoic metasedimentary rocks within multi-kilometer scale breccia complexes. Jackson et al., (2003) recognized the breccia complexes as former salt diapirs formed after halokinesis (salt movement).

The Mashitu deposit is located within the western part of the Kalukundi diapiric (halokinetic) breccia complex. It exploited traditional supergene copper-cobalt mineralized megaclasts within the breccia complex as well as a new styles of supergene mineralization that occurred within a lithology that is not typically mineralized at other Congolese deposits as well as within the breccias themselves.

New data on the compositional variation of different breccia matrices and the geometry of megaclasts within the exposed and drilled breccia complex at Mashitu has improved understanding of the genesis of the Congolese Copperbelt diapiric breccia complexes. Integration of a three-dimensional geological model of clast and breccia morphologies at Mashitu together with a three-dimensional model of both copper and cobalt grades from
geochemical assay data from exploration diamond drillholes and blast holes allowed spatial analysis of metal grades to different lithologies. These data indicate that Mashitu contains a previously undescribed style of supergene mineralization in the Congolese Copperbelt.

3.2 REGIONAL GEOLOGY

The Central African Copperbelt is located within the Lufilian fold belt, an arcuate zone of variably deformed metasedimentary rocks of the Neoproterozoic Katangan Supergroup that comprises, from base to top, three major lithostratigraphic successions; the Roan, Nguba and Kundelungu groups with an estimated combined thickness of 5-10 km (Batumike et al., 2009; Bull et al., 2010, 2011) (Figure 3.1 and 3.2).

The Roan Group is subdivided into four subgroups: the R.A.T. (Roches Argilleux Talcose or ‘talcy argillaceous rocks’) Subgroup, Mines Subgroup or Series, the Dipeta Subgroup, and Mwashya Subgroup (Francois, 1973, 1974, 2006; Cailteux, 1994; Cailteux et al., 2005a, b; Kampunzu et al., 2005). Rocks of the R.A.T., Mines and Dipeta subgroups in the Congolese Copperbelt occur only as megaclasts within diapiric breccia complexes.

The R.A.T. Subgroup (R-1) forms the basal unit of the exposed Roan Group in the Congolese Copperbelt. It contains generally reddish, hematitic, commonly indistinctly stratified siltstones and fine-grained sandstones with very minor dolostones (François, 1973). The thickness of the unit is unconstrained as the R.A.T. Subgroup is everywhere truncated along its lower contact against breccia (Cailteux et al., 2005a).

The overlying Mines Subgroup is subdivided into three major units: the Kamoto, Shales Dolomitiques or S.D., and C.M.N. (Calaire à Minerai Noir) or Kambove formations. The lowermost portion of the Kamoto Formation, the D. Strat. (Dolomites Stratifiées) unit, contains finely bedded impure and variably silicified algal dolostone, commonly with casts after evaporitic minerals and centimeter-sized elliptical siliceous nodules. The overlying R.S.F. (Roches Siliceuses Feuilletées) unit is lithologically similar to the D. Strat. unit but displays reduced bed thicknesses, lacks nodules, and contains abundant evaporite casts (François, 1974). It is overlain by the R.S.C. (Roches Siliceuses Cellulaires) unit, which is composed of pervasively silicified, massive to stromatolitic carbonate rocks with abundant casts after evaporite minerals.
and minor non-silicified siltstone interbeds.

The transition from the top of the Kamoto Formation (R.S.C. unit) to the overlying S.D. Formation is generally abrupt, with silicified carbonate rock adjacent to fine-grained, parallel-stratified, locally nodular and dolomitic siltstone and variably carbonaceous shale (François, 1974). The S.D. Formation was followed by deposition of massive to algal laminated carbonate rocks of the C.M.N. (or Kambove) Formation that also commonly display casts after evaporite minerals.

Figure 3.2: Lithostratigraphy of the Katangan succession in the Congolese Copperbelt, based primarily on Cailteux et al. (2005a).
The base of the overlying Dipeta Subgroup comprises hematitic and/or dolomitic siltstone and sandstone of the R.G.S. (Roches Gréso-Schisteuses) unit that are lithologically similar to rocks of the R.A.T. Subgroup. The upper Dipeta Subgroup contains stromatolitic and laminated algal carbonate units and dolomitic shale and siltstone that are lithologically similar to rocks of the Mines Subgroup (Hitzman et al., 2012; Schuh et al., 2012).

Rocks of the Dipeta Subgroup are overlain by a heterogeneous sequence of dolomitic shale and siltstone, carbonaceous siltstone, and minor sandstone of the Mwashya Subgroup. In the Congolese Copperbelt rocks of the Roan Group are overlain by sedimentary rocks of the Nguba and Kundelungu groups, which have a combined thickness of several kilometers.

3.3 LITHOLOGIES AT MASHITU

Geological mapping at Mashitu established that the pit area primarily contains rocks of the R.A.T. and Mines subgroups of the Roan Group with lesser rocks of the Dipeta Subgroup. The pit also contains a variety of breccia types (Figure 3.3).

3.3.1 R.A.T., MINES AND DIPETA SUBGROUP ROCKS

R.A.T. Subgroup lithologies are the dominant Roan Group rocks present at Mashitu. The R.A.T. Subgroup contains three dominant lithological units: clay-rich, sandstone-rich, and siltstone-rich. Megaclasts (blocks) of R.A.T. Subgroup lithologies at Mashitu commonly display a continuum from intact block cores, to broken or fractured rocks resembling crackle-breccia on block margins, which often grade irregularly outward to monomict brecciated zones.

The uppermost, reduced grey R.A.T. Subgroup unit conformably underlies the Mines Subgroup at many locations. Grey R.A.T. Subgroup rocks are comprised of dolomitic sandstone containing quartz, dolomite, and Mg-chlorite with minor amounts of rutile and apatite. It ranges in thickness from 10’s of centimeters to less than 5m. The grey R.A.T. Subgroup unit very rarely forms individual clasts in the breccia complex.
Figure 3.3: Geological map (1:500) of the Mashitu open-pit mine showing the distribution of major Roan Group megaclasts and breccia.
The Mines Subgroup lithostratigraphy at Mashitu is similar to that elsewhere in the Congolese Copperbelt (François, 1973, 1974; Cailteux et al. 2005a). Rocks of the Lower Dipeta Subgroup R.G.S. unit occur as clasts and megaclasts at Mashitu but were only recognized in exploration diamond drill cores. While all of the lithologies at Mashitu have undergone intense weathering within approximately 150m of the present-day land surface, less silicified rocks (R.A.T. Subgroup, S.D. Formation, Kambove Formation, and the R.G.S. unit of the Dipeta Subgroup) are the most intensely weathered.

3.3.2 MONOMICT R.A.T. SUBGROUP-DERIVED BRECCIA

Monomict R.A.T. Subgroup-derived breccia is the dominant breccia type exposed in the northern pit at Mashitu. Monomict breccia is typically matrix-supported with sub-angular to rounded clasts ranging in size from millimeters to several centimeters in diameter within a clay-like to granular matrix. Clast color typically ranges from pale pink to beige within a white to peach-colored matrix composed of Mg-chlorite, quartz, and abundant potassium-bearing minerals (muscovite, kaolinite, illite or phengite). Specular hematite-rich monomict breccia represents a fine grained, clast-rich to clast-supported breccia that contains abundant specular hematite (up to 5%) and displays a distinctive stretched fabric caused by alignment of specular hematite laths parallel to the margins of entrained clasts. The mineralogy of the monomict breccia closely resembles that of the clay-rich R.A.T. Subgroup unit. The close association between the monomict breccia and blocks of clay-rich R.A.T. Subgroup unit rocks in the northern pit at Mashitu suggests this rock type was the chief protolith for the monomict R.A.T. Subgroup-derived breccia.
3.3.3 POLYMICT BRECCIA

Polymict breccias are the most distinctive breccia type exposed at Mashitu and represent a halokinetic or diapiric (salt-related) breccia. Polymict breccia displays irregular geometries and commonly forms injections and vein- or dyke-like bodies ranging in scale from centimeters to tens of meters. Injections of polymict breccia into megaclasts typically occur along lithological contacts within and between the Mines and R.A.T. subgroup units. Rounded to sub-angular blocks or megaclasts (>1m) and clasts (<1m) of various rock types occur throughout polymict breccia zones. Alignment of coarse quartz, muscovite and/or specular hematite grains sub-parallel to the edges of entrained clasts or megaclasts often produces a banded appearance (fabric) within the polymict breccia matrix. The most common clast types within the polymict breccia at Mashitu are R.A.T. Subgroup rocks, R.G.S. unit sandstones, and strongly weathered fragments of C.M.N. Formation carbonate rocks. R.A.T. Subgroup, Mines Subgroup, and to a lesser degree Dipeta Subgroup megaclasts are surrounded and intruded by polymict breccia at Mashitu. The polymict breccia matrix is dominantly composed of quartz, Mg-chlorite, muscovite, specular hematite or goethite, and alkali feldspar; dolomite is common in unweathered polymict breccia matrix. Other minerals present in the breccia matrix include rutile, tourmaline, and talc. Sub-divisions of the polymict breccia are based on matrix composition and/or color, attributable to the presence or abundance of dolomite and/or quartz (pale), specular hematite (dark), and/or supergene Fe-Mn (Cu-Co) oxides (dark).

Pale matrix polymict breccia is typically clast poor, well cemented, and displays a granular textured matrix, probably due to the presence of abundant medium- to coarse-grained quartz and dolomite. It is composed dominantly of quartz, Mg-chlorite, muscovite, hematite, dolomite, and alkali feldspar. In many cases, the pale matrix polymict breccia is found below the limit of supergene weathering and represents the unweathered equivalent of dark polymict breccia in the near surface. Dark colored polymict breccia in unweathered zones is invariably specular hematite rich. Specular hematite-rich polymict breccia commonly occurs along the
margins of dark matrix polymict breccia bodies. It is typically clast-rich and displays a distinctive bright pink or silver-grey to purple color banded fabric containing 4-10% fine-grained ‘disseminated’ to coarse flaky laths of specular hematite.

3.4 DISTRIBUTION AND STYLE OF SUPERGENE MINERALIZATION AT MASHITU

The Mashitu deposit contains several styles of mineralization. A number of the large Mines Subgroup megaclasts are well mineralized, similar to those at many other deposits throughout the Congolese Copperbelt. These rocks contain hypogene sulfides, dominantly chalcopyrite, and more common supergene mineralization assemblages of chalcocite, malachite, copper oxide minerals, heterogenite, and black Cu-Co-rich “wad.” In addition to this typical style of mineralization, Mashitu also contains mineralized R.A.T. Subgroup rocks and mineralized polymict breccia.

3.4.1 MINERALIZED MINES SUBGROUP ROCKS

Hypogene sulfides were only observed in deep (>150 m) unweathered Mines Subgroup megaclasts. Unweathered megaclasts of the Kamoto Formation contain a supergene mineral assemblage of chalcocite with copper and cobalt carbonate and oxide minerals. Some the Kamoto Formation megaclasts contain only minor copper and cobalt with original sulfide and supergene copper and cobalt mineral sites occupied by iron oxides indicating leaching of both hypogene and supergene copper and cobalt minerals.

In buried, weakly weathered megaclasts at Mashitu the lowermost S.D. Formation contains blebby to disseminated supergene chalcocite replacing hypogene chalcopyrite. In the southern Mashitu pit S.D. Formation rocks contain supergene copper minerals but elsewhere in the deposit the S.D. Formation rocks have been intensely leached and contain only residual black Fe-Mn(-Co) oxide minerals as thin veinlets and patchy replacements.
Supergene sulfides in hypogene sulfide sites were not observed in rocks of the C.M.N. Formation at Mashitu. However, intensely weathered portions of C.M.N. Formation in buried megaclasts locally display replacement of a supergene talc-goethite assemblage by black Fe-Mn (Cu-Co) oxides intergrown with coarse-grained, subhedral to euhedral quartz. Weathered clasts of C.M.N. Formation rocks in polymict breccia in the pit exposures contain abundant supergene black Cu-Co-oxide minerals and/or malachite.

3.4.2 SUPERGENE MINERALIZATION OF R.A.T. SUBGROUP ROCKS

Brecciated clay-rich R.A.T. Subgroup rocks and monomict breccia contain malachite in several portions of the Mashitu deposit, locally in concentrations that allow economic extraction. The malachite occurs in veins, open-space fillings, and as pervasive replacement of groundmass or matrix (Figure 3.4 a, 3.5 b and 3.5c). It forms lath-shaped crystals and cluster-style growths and is commonly spatially associated with euhedral quartz that may be replacing dolomite (Fay et al., 2011) (Figure 3.4 b). QEMSCAN® mineral mapping shows fine-grained supergene cobalt oxide minerals as coatings on malachite-quartz intergrowths or as wispy veins in both weathered R.A.T. Subgroup rock units and in monomict breccia. These fine-grained supergene copper and cobalt minerals are interpreted from XRD data to represent combinations of heterogenite, tenorite, and unidentified Cu-Mn-Fe-oxide minerals.

The sandstone-rich R.A.T. Subgroup sequence at Mashitu locally contains abundant fine black-oxides as both fracture-fills and replacements of former carbonate pseudomorphs after evaporite minerals. Malachite and chrysocolla also occur in patchy replacements and fracture-fills in originally dolomitic beds. Siltstone-rich R.A.T. Subgroup rocks are rarely well mineralized although vugs or leached pseudomorphs after evaporite minerals that may have contained carbonate minerals prior to weathering locally host blebby supergene black Fe-Mn (Cu-Co) oxide minerals, malachite, and quartz.
Figure 3.4: QEMSCAN® automated mineralogy false-color images showing supergene copper and cobalt minerals at Mashitu; black areas represent voids (background). a) Malachite veinlets and pervasive replacement after carbonate-minerals are present in a sample of the clay-rich R.A.T. Subgroup unit from the north pit (DH MNWD001). b) Clast of R.A.T. Subgroup siltstone with a leached core after dolomite that contains malachite and Cu-Co oxide minerals from polymict breccia sample in drillhole MNWD014 from the north pit at Mashitu.

3.4.3 SUPERGENE MINERALIZED POLYMICT BRECCIA

Black copper-cobalt oxide minerals with occasionally visible malachite dominate mineralized zones in polymict breccia. This fine-grained assemblage occurs as pervasive matrix replacement in clast-poor matrix supported dark polymict breccia. Although significant volumes of polymict breccia at Mashitu contain copper and cobalt, there is no evidence that the matrix of the breccia contained hypogene sulfides. The polymict breccias do contain clasts of Kamoto
and S.D. formation rocks with copper, cobalt, and iron oxides and copper carbonate minerals that have replaced hypogene sulfides (Figure 3.6 A). Such clasts could have served as a copper source for mineralization of the matrix of these breccias but a sufficient number of such mineralized clast types (<1m) were not recognized to account for the supergene minerals present in the breccia matrix.

Figure 3.5: Supergene mineralized breccias from Mashitu. A) Specular hematite-rich polymict breccia containing abundant malachite veinlets sub-parallel to the irregular contact with dark polymict breccia. B) Monomict breccia containing pervasive matrix replacement by malachite and black copper-cobalt oxide minerals. C) Monomict breccia derived from clay-rich R.A.T. Subgroup unit rocks with the breccia matrix pervasively replaced by black Cu-Co oxide minerals (tenorite and heterogenite) with malachite. Note that some clast edges have also been partially replaced with this supergene mineral assemblage.

Malachite occurs as pervasive fine-grained matrix replacement and or replacement of submicron grains contained in the dark breccia matrix. Fine-grained supergene copper and cobalt minerals interpreted from XRD analysis contain a complex mixture of copper, cobalt, manganese, and iron-bearing oxide minerals including tenorite, heterogenite, and cuprite with variable amounts of unidentified Mn-Cu-oxide and/or Fe-Mn-Cu-oxide mineraloids as pervasive matrix replacement in clast-poor matrix supported dark polymict breccia (Figure 3.6 C). The mineralized polymict breccia is invariably dark colored and lacks significant dolomite suggesting
it underwent carbonate, as well as evaporite mineral (anhydrite), dissolution during weathering.

Initial observations of the distinctive black color and fine-grained sooty dark polymict breccia matrix suggested the dark color resulted from the presence of residual hydrocarbons. Measurement of total organic carbon in 15 samples of clast-poor dark polymict breccia matrix material was undertaken to confirm whether organic material was present. LECO total organic carbon (TOC) values were low (<0.6%) for all samples indicating an absence of hydrocarbons. The analyses indicated, however, that all of the breccia samples contained in excess of ~6 wt.% carbonate.

Weakly weathered polymict breccias at Mashitu (Figure 3.6 B) contain abundant carbonate minerals, many of which appear to have replaced evaporite minerals. Dissolution of carbonate by acidic fluids generated during supergene weathering of sulfides within Mines Subgroup megaclasts would have significantly increased permeability and porosity of the breccia matrix. In the mineralized polymict breccia the resulting space within the breccia matrix is occupied by supergene Fe-Mn-Cu-Co oxide and minor copper carbonate minerals.

Very fine grained matrix polymict breccia generally contains an increased amount of supergene black-oxide minerals compared to breccias with a coarser grained matrix, probably due to its lower porosity and permeability. However, malachite may be present along the margins of the fine-grained matrix breccias as vein-like bands parallel to the breccia fabric suggesting such zones represent more permeable paths for groundwater flow (Figure 3.5 A). Fine-grained supergene copper and cobalt mineral distribution in such sample types show a closer textural relationship or association with Mg-chlorite and/or muscovite/illite rich zones around clasts compared to the abundant quartz grains (some euhedral supergene quartz) or quartz-rich micro-clasts (<1mm) in the breccia matrix (Figure 3.7).
Figure 3.6: Polymict breccia examples at Mashitu: A) Polymict breccia with clasts of the R.S.F. unit of the Kamoto Formation containing malachite and copper oxide minerals. B) Unmineralized pale matrix polymict breccia representing unweathered halokinetic breccia with a dolomite-rich matrix. This type of breccia appears to be the protolith for weathered, dark polymict breccia that may be mineralized. C) Dark matrix supported polymict breccia whose dark color is largely the result of abundant supergene Cu-Co oxide minerals within the breccia matrix.

Figure 3.7: QEMSCAN® automated mineralogy false-color scan of polymict breccia from the north pit DH MNWD014) showing supergene copper and cobalt minerals at Mashitu. Black areas represent voids. The dark matrix polymict breccia contains abundant Cu-Co oxide minerals as a pervasive matrix replacement; there is a spatial association of the oxide minerals with Mg-chlorite.
3.5 SPATIAL DISTRIBUTION OF MINERALIZED ZONES

In addition to the typical styles of mineralized Mines Subgroup rocks found in the Congolese Copperbelt, Mashitu locally contains economic mineralized material within both R.A.T. Subgroup rocks and polymict breccia. Such mineralized zones are found beneath virtually all of the Mines Subgroup megaclasts though the grade of such zones is highly variable; in some areas assay data is lacking beneath mineralized Mines Subgroup megaclasts.

In the northern portion of the Mashitu pit historic drill data indicate that a megaclast or block of Mines Subgroup rocks was present at the original land surface prior to mining (Figure 3.8). Drilling indicated this block contained little copper and cobalt. However, copper and cobalt are present in both R.A.T. Subgroup rocks and polymict breccia beneath this Mines Subgroup megaclast suggesting derivation from the overlying Mines Subgroup block (Figure 3.9a and b). Copper and cobalt are concentrated in veins in R.A.T. Subgroup rocks and as replacements of the matrix of polymict breccia suggesting they replaced carbonate minerals.

![Figure 3.8: Three-dimensional geological model of the northern portion of the Mashitu mine area illustrating geology and copper distribution from diamond drill hole assay data (to a maximum depth of 150m) showing the pre-mining location of a former megaclast containing Mines Subgroup rocks (R2L) and a thin sequence of siltstone-rich R.A.T. Subgroup unit (R1Stt) overlying the north pit area. Metals leached during supergene weathering were deposited in the underlying clay-rich R.A.T. Subgroup rocks (R1Cl), monomict breccia (mtx) and polymict breccia. Legend for lithologies is shown on Figure 3.3.](image)
A large Mines Subgroup megaclast in the central portion of the Mashitu deposit contains supergene copper carbonates and cobalt and copper oxides after hypogene sulfides typical of many Congolese deposits (Figure 3.10). Supergene copper and cobalt mineralized polymict breccia is also present directly beneath the megaclast. Drill data indicates similar distributions of copper and cobalt within and beneath Mine Subgroup blocks throughout the Mashitu deposit with supergene mineralized material occurring in both former carbonate-bearing R.A.T. Subgroup rocks and polymict breccia. Blocks of siltstone-rich and/or sandstone-rich R.A.T. Subgroup rocks beneath mineralized Mines Subgroup megaclasts in the central and southern portions of the Mashitu deposit are generally only weakly mineralized, presumably due to their lower carbonate mineral content.
3.5.1 ELEMENTAL DISTRIBUTION IN SUPERGENE MINERALIZED ZONES

Multi-element ICP geochemical assay data from 220 diamond drillholes at Mashitu were reviewed to determine the distribution of elevated Cu (>1%), Co (>0.2%), and other elements in mineralized zones within R.A.T. Subgroup rocks and polymict breccia. Higher Cu-Co grades are correlated with increased manganese (0.5% - 2.5%), zinc (>100ppm – 200ppm), lead (>30ppm – 700ppm), barite (>200ppm), and uranium (>50ppm). Iron, although recognized as an important constituent of Cu-Co supergene mineralized zones, is present at similar levels in unmineralized zones and reflects the abundance of specular hematite in R.A.T. Subgroup rocks.

Metal distribution in the supergene mineralized zone in R.A.T. Subgroup rocks and polymict breccia from the northern pit at Mashitu reflects metal mobility in the system (Figure 3.11). Barium, copper, cobalt, manganese, and zinc are present to approximately 90m below the base of the Mines Subgroup megaclast that is believed to have been the metal source at this location. Unusual relative to many other deposits in the Congolese Copperbelt (e.g. Fay et al., 2011), cobalt appears to have been somewhat more mobile than copper. Copper,
Figure 3.11: Multi-element ICP geochemical data from exploration diamond drillhole MNWD002 located in the northern pit. This drill hole intersected the base of a partially leached Mines Subgroup megaclast and then passed down into R.A.T. Subgroup rocks and polymict breccias. Geochemical data indicate that significant copper and cobalt are present to approximately 90m below the base of the Mines Subgroup megaclast and that cobalt has migrated slightly further down section than copper. Barium, manganese, and zinc have also been highly mobile and are concentrated with cobalt. Lead is relatively immobile and uranium is variable with most remaining near the Mines Subgroup megaclast but some migrating downward and concentrated in the highest copper zone and near the lower fringe of the supergene dispersion zone.
dominantly as malachite, is concentrated in broken and brecciated clay-rich R.A.T. Subgroup rocks both above and below a large clast of intact clay-rich R.A.T. Subgroup rock suggesting that fracture permeability was critical for supergene groundwater flow. Cobalt, largely as heterogenite, together with barium, manganese, and zinc, and to a lesser degree uranium, are concentrated lower in polymict breccia. Zinc is the most mobile of the elements while lead is the least mobile. Uranium is concentrated in Mines Subgroup rocks relative to the underlying R.A.T. Subgroup unit rocks and breccia although locally concentrations of up to 10 ppm do occur in brecciated clay-rich R.A.T. Subgroup and polymict breccia zones ~60m down hole.

3.6 CONCLUSIONS

Malachite is the most common supergene copper mineral within broken and brecciated clay-rich R.A.T. Subgroup rocks and monomict breccia. It occurs in veins, open-space fillings, and less commonly as pervasive replacement of groundmass or matrix. Its distribution suggests that copper most commonly precipitated due to interaction with carbonate minerals and that fracture permeability was critical for supergene mineralization of this rock type.

Weakly weathered polymict breccias at Mashitu contain abundant dolomite. Mineralized polymict breccia is invariably dark colored due to the abundance of copper ± cobalt-oxide minerals and mineraloids and lacks significant dolomite. These relationships suggest carbonate minerals were also important in supergene mineralization of the polymict breccia. It is probable that dissolution of carbonate minerals by acidic fluids generated during supergene weathering of sulfides within Mines Subgroup clasts significantly increased permeability and porosity of the breccia matrix allowing groundwater to more easily flow downward.

The distribution of Cu-Co supergene mineralized R.A.T. Subgroup rocks and polymict breccias indicate that copper and cobalt were derived from leaching of near-surface, hypogene mineralized Mines Subgroup megaclasts. Downward moving metal-bearing acidic groundwater derived from oxidation of sulfides dissolved carbonate in underlying rocks and replaced it with a
supergene Cu-Co carbonate and oxide mineral assemblage. Mineralized zones within R.A.T. Subgroup rocks and polymict breccia at Mashitu represent a previously unrecognized type of deposit in the Central African Copperbelt. Future exploration in the Congolese Copperbelt should include testing beneath seemingly barren Mines Subgroup megaclasts present in breccia complexes. Exploration should focus on determining if such barren megaclasts once contained hypogene sulfides and if chemically suitable (carbonate bearing) rock might be present beneath them.
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CONCLUSIONS

This study examined the western portion of the Kalukundi diapiric breccia complex that is exposed in the Mashitu open-pit mine. These exposures, together with data from exploration diamond drill cores beneath the open pit, presented an exceptional opportunity to generate for the first time a three-dimensional model of the internal geometry of a Congolese Copperbelt breccia complex based upon a detailed characterization of different breccia types from both mapping and petrographic data.

Spatial analysis of megaclasts within the breccia complex at Mashitu indicates the pit area contains at least three large Roan Group fragments separated by polymict breccia. The distribution of these megaclasts are not chaotic but represent en-echelon stacking of largely stratigraphically intact sequences. The map pattern of megaclasts towards the edge of the breccia complex suggests they may have been aligned sub-parallel to the breccia complex margin and there is suggestion from available drill data that megaclasts became more deformed through both folding and breakage along this contact. Regional mapping within the Kalukundi breccia complex (François, 1974), though it failed to accurately portray the complexity present due to the recessive weathering of the R.A.T. Subgroup lithologies and the different breccia types, supports this hypothesis. More steeply-dipping Mines Subgroup megaclasts occur proximal to the inferred breccia complex margin to the north of the Mashitu deposit while flatter lying Mines Subgroup megaclasts are present to the east towards the center of the breccia complex.

The polymict breccia bodies at Mashitu contain clasts from lower in the stratigraphic section and have a mineralogically unusual matrix composition indicating they were derived from salt diapirs as suggested by previous workers (e.g. Jackson et al., 2003). The absence of
halite or significant anhydrite in the breccias indicates mineral dissolution during weathering. The polymict breccias at Mashitu represent resistate derived from salt diapirs as is observed today in the Zagros Mountains of Iran. The improved understanding of the genesis of the CCB breccia complexes obtained from this study may be applied to other breccia complexes in the Congolese Copperbelt as well as elsewhere in the world to better understand the internal geometry of salt diapirs and the process of halokinesis.

The Mashitu deposit exploits typically mineralized Mines Subgroup rocks as well as unusual zones of mineralized R.A.T. Subgroup rocks and polymict breccia. The supergene mineralized polymict breccia material mined at Mashitu displays a dark color due to the presence of black Cu-Co-Mn-Fe-oxide minerals together with malachite within the breccia matrix. Unweathered polymict breccia at Mashitu is generally pale color, contains abundant dolomite, and lacks copper or cobalt. Weathering removed carbonate minerals in the polymict breccia and where an overlying mineralized Mines Subgroup megaclast was present resulted in supergene mineralization. Dissolution of carbonate minerals probably also significantly increased the permeability and porosity of the breccia matrix.

The supergene mineralized breccia zones at Mashitu represent a previously unrecognized type of deposit in the Central African Copperbelt. Their recognition suggests that exploration beneath apparently barren Mines Subgroup blocks in breccia complexes throughout the Congolese Copperbelt may be warranted. The most favorable sites for similar supergene mineralized zones appear to areas that originally contained carbonate-bearing lithologies.

This study indicates that the geometry of the blocks in such breccia complexes and their stratigraphic orientation should be considered when interpreting models for salt movement in ancient and existing salt diapirs. Improved understanding of the geometries of Mines Subgroup megaclasts within this former salt diapir structure, together with an appreciation of metal sources and potential metal sinks such as carbonate-bearing lithologies, will be fundamental for discovery of similar types of supergene deposits.
REFERENCES CITED


APPENDIX A: GEOLOGICAL MAPPING AND CROSS-SECTIONS

Figure A-1: Mashitu topographical survey map of the open-pit at the time of mapping. Green lines represent 3m high pit bench levels. The locations of the studied drillholes and the cross-sections (XS and LS) developed to produce the three-dimensional geological model for Mashitu are represented by black dots and black lines respectively. Section line locations in WGS 84 Universal Transverse Mercator Zone 35 South coordinate system are included on the individual sections that follow in figures A-4 to A-30. All sections were produced on a scale of 1:1000.
Figure A-2: Simplified geological pit map of the Mashitu deposit (1:500) and simplified stratigraphic legend utilized to develop simplified two-dimensional geological cross-sections and the three-dimensional geological model.
Figure A-3: Lithostratigraphy developed for the Mashitu deposit two-dimensional and three-dimensional geological modelling and drillhole geological and assay logs.
Figure A-4: North-south section LS01 on Easting 380368m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-5: North-south section LS02 on Easting 380468m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-6: West-east section XS01 on Northing 8822615m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-7: West-east section XS02 on Northing 8822565m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-8: West-east section XS03 on Northing 8822515m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-9: West-east section XS04 on Northing 8822465m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-10: West-east section XS05 on Northing 8822415m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-11: West-east section XS06 on Northing 8822365m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-12: West-east section XS07 on Northing 8822315m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-13: West-east section XS08 on Northing 8822265m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-14: West-east section XS09 on Northing 8822215m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-15: West-east section XS10 on Northing 8822165m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-16: West-east section XS11 on Northing 8822115m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-17: West-east section XS12 on Northing 8822065m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-18: West-east section XS13 on Northing 8822015m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-19: West-east section XS14 on Northing 8821965m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-20: West-east section XS15 on Northing 8821915m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-21: West-east section XS16 on Northing 8821865m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-22: West-east section XS17 on Northing 8821815m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-23: West-east section XS18 on Northing 8821765m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-24: West-east section XS19 on Northing 8821715m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-25: West-east section XS20 on Northing 8821665m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-26: West-east section XS21 on Northing 8821615m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-27: West-east section XS22 on Northing 8821565m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-28: West-east section XS23 on Northing 8821515m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-29: West-east section XS24 on Northing 8821465m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure A-30: West-east section XS25 on Northing 8821415m as shown on Figure A-1. Lithology colors are shown on Figure A-3. A) Detailed geological section with drillhole traces. B) Simplified geological section with drillhole traces showing drillhole assays for copper.
Figure B-1: Simplified geological map of the Mashitu pit draped on the open-pit topographical surface with 3m benches displayed in Leapfrog Geo software and as utilized to develop the three-dimensional geological model for Mashitu. (Plan view with north to left). Legend for lithology colors is shown on figure A-3.

Figure B-2: Three-dimensional view of cross-section locations developed through the Mashitu deposit shown with the topographical pit surface map. View to north-east (042).
Figure B-3: Three-dimensional geological model constructed in Leapfrog Geo software for the Mashitu deposit using the simplified geological map of the Mashitu pit and 27 two-dimensional cross-sections to produce block or megaclast meshes based and using the simplified geological lithostratigraphic framework to establish the distribution and geometries of blocks and breccia types at Mashitu. View to north-east (042).

Figure B-4: Three-dimensional geological model constructed in Leapfrog Geo software for the Mashitu deposit showing the distribution and geometries of blocks and breccia types at Mashitu and using the simplified geological lithostratigraphic framework. View to north-northwest (343). Legend for lithology colors is shown on figure A-3.
## APPENDIX C: PETROGRAPHIC DATA

Table C-1: Locations of pit and drill core samples collected at the Mashitu deposit during 2014 and 2015 field seasons and studied using a combination of QEMSCAN® automated mineralogy, SEM-FE and transmitted light petrographic analysis.

<table>
<thead>
<tr>
<th>Source</th>
<th>Easting (m)</th>
<th>Northing (m)</th>
<th>Elevation (m)</th>
<th>Depth_From</th>
<th>Depth_To</th>
<th>Sample Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit</td>
<td>380487</td>
<td>8820910</td>
<td>1429.5</td>
<td></td>
<td></td>
<td>2014_423</td>
</tr>
<tr>
<td>Pit</td>
<td>380401</td>
<td>8820201</td>
<td>1413.0</td>
<td></td>
<td></td>
<td>2015_059_S3</td>
</tr>
<tr>
<td>Pit</td>
<td>380419</td>
<td>8820998</td>
<td>1431.3</td>
<td></td>
<td></td>
<td>2014_315b</td>
</tr>
<tr>
<td>Pit</td>
<td>380525</td>
<td>8820588</td>
<td>1417.0</td>
<td></td>
<td></td>
<td>2015_252</td>
</tr>
<tr>
<td>DH_MDF02</td>
<td>380465</td>
<td>8820261</td>
<td>1454.9</td>
<td>279.60</td>
<td>279.75</td>
<td>MDF02_S2</td>
</tr>
<tr>
<td>DH_MDF07</td>
<td>381307</td>
<td>8820395</td>
<td>1462.4</td>
<td>36.95</td>
<td>36.98</td>
<td>MDF07_S1</td>
</tr>
<tr>
<td>DH_MDF07</td>
<td>381307</td>
<td>8820395</td>
<td>1462.4</td>
<td>162.95</td>
<td>163.15</td>
<td>MDF07_S10</td>
</tr>
<tr>
<td>DH_MDF07</td>
<td>381307</td>
<td>8820395</td>
<td>1462.4</td>
<td>213.55</td>
<td>213.62</td>
<td>MDF07_S14</td>
</tr>
<tr>
<td>DH_MDF07</td>
<td>381307</td>
<td>8820395</td>
<td>1462.4</td>
<td>277.10</td>
<td>277.30</td>
<td>MDF07_S17</td>
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<tr>
<td>DH_MNWD001</td>
<td>380516</td>
<td>8820917</td>
<td>1484.2</td>
<td>47.00</td>
<td>47.05</td>
<td>MNWD001_S1</td>
</tr>
<tr>
<td>DH_MNWD001</td>
<td>380516</td>
<td>8820917</td>
<td>1484.2</td>
<td>81.50</td>
<td>81.60</td>
<td>MNWD001_S4</td>
</tr>
<tr>
<td>DH_MNWD004</td>
<td>380515</td>
<td>8820665</td>
<td>1485.2</td>
<td>121.90</td>
<td>121.98</td>
<td>MNWD004_S2</td>
</tr>
<tr>
<td>DH_MNWD014</td>
<td>380466</td>
<td>8821015</td>
<td>1478.6</td>
<td>52.80</td>
<td>52.90</td>
<td>MNWD014_S2A</td>
</tr>
<tr>
<td>DH_MNWD014</td>
<td>380466</td>
<td>8821015</td>
<td>1478.6</td>
<td>52.80</td>
<td>52.90</td>
<td>MNWD014_S2B</td>
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<tr>
<td>DH_MNWD022</td>
<td>380416</td>
<td>8820665</td>
<td>1479.9</td>
<td>70.26</td>
<td>70.50</td>
<td>MNWD022_S1</td>
</tr>
<tr>
<td>DH_MNWD033</td>
<td>380365</td>
<td>8820921</td>
<td>1475.7</td>
<td>80.40</td>
<td>80.55</td>
<td>MNWD033_S1</td>
</tr>
<tr>
<td>DH_MSPD052</td>
<td>380217</td>
<td>8820517</td>
<td>1463.8</td>
<td>72.96</td>
<td>73.10</td>
<td>MSPD052_S2</td>
</tr>
<tr>
<td>DH_MSPD052</td>
<td>380217</td>
<td>8820517</td>
<td>1463.8</td>
<td>104.62</td>
<td>104.72</td>
<td>MSPD052_S3</td>
</tr>
<tr>
<td>DH_MSPD052</td>
<td>380217</td>
<td>8820517</td>
<td>1463.8</td>
<td>128.20</td>
<td>128.40</td>
<td>MSPD052_S4</td>
</tr>
<tr>
<td>DH_MSPD055</td>
<td>380615</td>
<td>8820816</td>
<td>1482.8</td>
<td>92.85</td>
<td>92.95</td>
<td>MSPD055_S2</td>
</tr>
<tr>
<td>DH_MSPD063</td>
<td>380663</td>
<td>8820816</td>
<td>1480.2</td>
<td>64.20</td>
<td>64.35</td>
<td>MSPD063_S1</td>
</tr>
<tr>
<td>DH_MSPD063</td>
<td>380663</td>
<td>8820816</td>
<td>1480.2</td>
<td>9.40</td>
<td>9.50</td>
<td>MSPD083_S2</td>
</tr>
</tbody>
</table>
Table C-2: QEMSCAN® automated mineralogy and petrographic studies on samples collected at the Mashitu deposit during 2014 and 2015 field seasons. Representative samples are organized by rock type (lithocode) and follow in the same order.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Lithocode</th>
<th>Scan ID</th>
<th>Sample Type</th>
<th>Sample Prep</th>
<th>Scan Scale</th>
<th>XRD</th>
<th>Sample Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014_423</td>
<td>shPtx-R.G.S.</td>
<td>2014_423 Area 1</td>
<td>Hard BX</td>
<td>Mount</td>
<td>5 μ</td>
<td>dPtx and shPtx irregular contact</td>
<td></td>
</tr>
<tr>
<td>2014_059_S3</td>
<td>dPtx</td>
<td>2015_059_S3</td>
<td>Hard Breccia</td>
<td>Mount</td>
<td>20 μ</td>
<td>Dark matrix polymict Breccia from Salive North pit area containing a block of monomict R.A.T. derived breccia</td>
<td></td>
</tr>
<tr>
<td>2014_315b</td>
<td>dPtx</td>
<td>2014_315b</td>
<td>Soft BX</td>
<td>Mount</td>
<td>30 μ</td>
<td>Mashitu north NW-40w clast poor black oxide mineral-rich with fine quartz grains</td>
<td></td>
</tr>
<tr>
<td>MNWD014_S2A</td>
<td>dPtx</td>
<td>MNWD014_S2A</td>
<td>Hard Breccia</td>
<td>Thin Sections</td>
<td>5 μ</td>
<td>Clast of possible R.G.S. sandstone with euheudal vug after dolomite filled with Cu-Co supergene minerals</td>
<td></td>
</tr>
<tr>
<td>MNWD014_S2B</td>
<td>dPtx</td>
<td>MNWD014_S2B</td>
<td>Hard Breccia</td>
<td>Thin Sections</td>
<td>30 μ</td>
<td>Dark polymict matrix supported breccia with &lt;2-20mm rounded mixed clasts</td>
<td></td>
</tr>
<tr>
<td>MNWD014_S2B</td>
<td>dPtx</td>
<td>MNWD014_S2B Area 1</td>
<td>Hard Breccia</td>
<td>Thin Sections</td>
<td>5 μ</td>
<td>Micro-clasts with dark matrix polymict breccia zone showing fabric and alteration of ptx</td>
<td></td>
</tr>
<tr>
<td>MNWD014_S2B</td>
<td>dPtx</td>
<td>MNWD014_S2B Area 2</td>
<td>Hard Breccia</td>
<td>Thin Sections</td>
<td>5 μ</td>
<td>Altered (rimmed) clast surrounded by supergene euheudal quartz with ptx zone</td>
<td></td>
</tr>
<tr>
<td>MDF02_S2</td>
<td>pPtx</td>
<td>MDF02_S2</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>15 μ</td>
<td>pPtx (pale-grey green) contact with purple R.G.S. siltstone or Dijeta</td>
<td></td>
</tr>
<tr>
<td>MDF07_S1A</td>
<td>pPtx</td>
<td>MDF07_S1A</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>15 μ</td>
<td>mixed R.A.T. subgroup + R.G.S. clasts in competent clast rich matrix supported</td>
<td></td>
</tr>
<tr>
<td>MNWD022_S1</td>
<td>pPtx</td>
<td>MNWD022_S1</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>10 μ</td>
<td>Spicular-hematite rich polymict breccia with well defined fabric and rounded clasts</td>
<td></td>
</tr>
<tr>
<td>MISP003_S1</td>
<td>pPtx</td>
<td>MISP003_S1</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>30 μ</td>
<td>Polymict to monomict clast-rich breccia with well defined fabric and rounded clasts</td>
<td></td>
</tr>
<tr>
<td>MISP003_S1</td>
<td>pPtx</td>
<td>MISP003_S1 Area 1</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>5 μ</td>
<td>R.A.T. derived clast within possible monomict breccia with pronounced fabric in matrix around clasts</td>
<td></td>
</tr>
<tr>
<td>MISP003_S2</td>
<td>pPtx</td>
<td>MISP003_S2</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>5 μ</td>
<td>Contact of specular hematite rich band at margin of breccia and larger R.A.T. derived clast</td>
<td></td>
</tr>
<tr>
<td>MISP005_S1</td>
<td>pMtx</td>
<td>MISP005_S1</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>15 μ</td>
<td>Contact of pMtx and possible R15SII-derived breccia</td>
<td></td>
</tr>
<tr>
<td>MNW001_S1</td>
<td>shMtx</td>
<td>MNW001_S1</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>10 μ</td>
<td>YES fine-grained matrix-supported monomict breccia with 70% clasts (&lt;3mm); R1C1 derived</td>
<td></td>
</tr>
<tr>
<td>2015_252</td>
<td>R.G.S.</td>
<td>Rock</td>
<td>Thin Section</td>
<td>10 μ</td>
<td>YES well-rounded chlitico pale-green to white nodules or clasts of R.G.S. sandstone from dPtx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MISP005_S3</td>
<td>R.G.S.</td>
<td>MISP005_S3</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>15 μ</td>
<td>YES pale green-white R.G.S. sandstone brecciated in situ</td>
<td></td>
</tr>
<tr>
<td>MISP005_S4</td>
<td>R.G.S. x</td>
<td>MISP005_S4</td>
<td>Hard Breccia</td>
<td>Thin Section</td>
<td>15 μ</td>
<td>YES breccia of purple R.G.S. siltstone and R.G.S. pale-green sandstone</td>
<td></td>
</tr>
<tr>
<td>MDF07_S1</td>
<td>R.A.T. Gr</td>
<td>MDF07_S1</td>
<td>Rock</td>
<td>Thin Section</td>
<td>10 μ</td>
<td>Grey R.A.T. cross-cut by fine malachite veinslets oblique to bedding</td>
<td></td>
</tr>
<tr>
<td>MISP005_S2</td>
<td>R15SII</td>
<td>MISP005_S2</td>
<td>Rock</td>
<td>Thin Section</td>
<td>15 μ</td>
<td>Pale brick-red to pink R.A.T. lithology siltstone with leached uggly evaporitic horizons</td>
<td></td>
</tr>
<tr>
<td>MISP005_S2</td>
<td>R15SII</td>
<td>MISP005_S2</td>
<td>Rock</td>
<td>Thin Section</td>
<td>10 μ</td>
<td>Crackle breccia or broken R15SII siltstone with alteration oblique to bedding and x-cutting dolomite fracture-fill</td>
<td></td>
</tr>
<tr>
<td>MNW004_S2</td>
<td>R15SII</td>
<td>MNW004_S2</td>
<td>Rock</td>
<td>Thin Section</td>
<td>30 μ</td>
<td>YES brick-red siltstone with mal-dolite veins and evaporitic pseudomorphs</td>
<td></td>
</tr>
<tr>
<td>MNW003_S1</td>
<td>R15SII</td>
<td>MNW003_S1</td>
<td>Rock</td>
<td>Thin Section</td>
<td>10 μ</td>
<td>R15SII marker horizon gross ocellars with argillaceous, rip-up frags interbedded with sandstone and siltstone</td>
<td></td>
</tr>
<tr>
<td>MDF07_S10</td>
<td>R15SII</td>
<td>MDF07_S10</td>
<td>Rock</td>
<td>Thin Section</td>
<td>20 μ</td>
<td>YES buff-pink coarse graded sandstone with uggly zones (leached)</td>
<td></td>
</tr>
<tr>
<td>MNW001_S4</td>
<td>R1Cl</td>
<td>MNW001_S4</td>
<td>Rock</td>
<td>Thin Section</td>
<td>30 μ</td>
<td>YES pale-red to purple (illiac) clay-rich argillaceous R.A.T. with mal-blk-ox-spoc hematite veinslets</td>
<td></td>
</tr>
<tr>
<td>MNW001_S4</td>
<td>R1Cl</td>
<td>MNW001_S4 Area 1</td>
<td>Rock</td>
<td>Thin Section</td>
<td>5 μ</td>
<td>YES clay-muscovite rich bedding parallel band in R1Cl with abundant specular hematite</td>
<td></td>
</tr>
</tbody>
</table>
| MDF07_S17   | R1Cl | MDF07_S17 | Rock | Thin Section | 20 μ | R1Cl unweathered: Brick red pass clay-rich siltstones with thin evaporic horizons and red hem suggesting
Figure C-1: Sample of polymict breccia in contact with specular hematite-rich polymict breccia from the central part of the north pit at Mashitu. The sample highlights the typical irregular nature of the contact between various polymict breccia types at Mashitu. The topmost images show the hand sample collected in the pit that was mounted in epoxy and polished prior to QEMSCAN® automated mineralogy and SEM-FE analysis. A) QEMSCAN® automated mineralogy false-color mineral map of the scan area A shown in on the epoxy mount image. The image clearly shows the irregular contact between the specular hematite-rich polymict breccia containing large grains of specular hematite in a quartz-Mg-chlorite-muscovite rich matrix that grades to a more fine-grained dark matrix quartz-Mg-chlorite rich matrix containing abundant supergene black copper-cobalt oxide minerals containing abundant micro-clasts of quartz-rich rocks and or euhedral supergene quartz grains that contain anhydrite inclusions. B) Separate QEMSCAN® automated mineralogy false-color mineral map of a clast of R.G.S. sandstone showing abundant quartz-Mg-chlorite that contains numerous accessory minerals including zircon, rutile and monazite. Note that supergene copper-cobalt oxide minerals occur only in the polymict breccia on the rims of the clasts showing that permeability and porosity is a fundamental control on supergene mineralization. C) SEM-FE image of specular hematite grain and surrounding muscovite laths within the pale colored specular hematite-rich polymict breccia portion of the sample showing the distinctive fabric that is common in this breccia type.
Figure C-2: Sample of polymict breccia from the south pit area at Mashitu containing large blocks up to 10cm in diameter of monomict breccia. The monomict breccia is R.A.T. Subgroup-derived, based on the dominant mineralogy (Mg-chlorite-quartz-muscovite). The presence of strongly hematitic (red) R.A.T. Subgroup derived clasts can be observed in the sample photograph however in QEMSCAN® the monomict breccia clasts and matrix contain a similar mineralogy and are differentiated only by the abundance of quartz and Mg-chlorite respectively. Supergene copper-cobalt oxide minerals are best developed in the fine-grained polymict breccia matrix indicating that permeability and porosity was a more fundamental control on supergene mineralization that the presence of former carbonate minerals in both breccia types.
Figure C-3: Sample of fine-grained dark matrix polymict breccia sample mounted in epoxy and collected from the northwest corner of the Mashitu North pit area and analyzed using QEMSCAN® automated mineralogy. The breccia represents a matrix-supported, fine-grained clast-poor example that contains abundant copper oxides in the black matrix (Cu-Mn-Fe-oxide minerals). Trails of micro clasts are dominantly quartz-rich and may represent either R.G.S unit or R.A.T. Subgroup unit fragments or supergene euhedral quartz grains. Note the fabric or banded-appearance in the sample with alignment of quartz grains and the patchy matrix replacement of the matrix by Cu-oxide minerals that may represent preferential replacement of layers in the breccia possibly resulting from the original mineralogy (perhaps former carbonate-mineral bearing banding after layered evaporite minerals).
Figure C-4: Clast of possible R.A.T. Subgroup unit siltstone rock contained within polymict breccia from drillcore MNWD014 in the north pit area at Mashitu. The clast contains a large rhomb-shaped void possibly after dissolution of dolomite. In the QEMSCAN® automated mineralogy false-color mineral map of the sample, the void-space represented by the former dolomite rhomb is partially filled with malachite and black Cu-Co oxide minerals. Abundant Mg-chlorite occurs in the breccia matrix closely associated with Cu-Co oxide minerals. K-feldspar occurs throughout the matrix, perhaps derived from entrained R.G.S. unit clasts or associated potassic alteration of the matrix.
Figure C-5: Sample of polymict breccia from drillcore MNWD014 in the north pit area at Mashitu and the QEMSCAN® automated mineralogy false-color mineral map of the matrix area. 1) Clast of the K-feldspar-rich R.G.S. unit rock contained within the polymict breccia zone that is surrounded by Mg-chlorite rich matrix with abundant Cu-Co oxide minerals. 2) Clast of the muscovite-rich R.G.S. unit rimmed by K-feldspar. Matrix contains supergene euhedral quartz and Cu-Co bearing black oxide minerals.
Figure C-6: Sample of unweathered pale matrix polymict breccia from drillhole MDF02 from below the central pit area at Mashitu. The QEMSCAN® automated mineralogy false-color mineral map of the sample clearly shows the variation in matrix composition of the polymict breccia associated with the dominant clast type entrained. The left portion of the QEMSCAN® automated mineralogy false-color mineral map of the sample shows abundant potassium-feldspar and coarse dolomite associated with the R.G.S. clasts. The right side of the sample contains abundant clasts of quartz-Mg-chlorite and muscovite rich R.A.T. Subgroup unit rocks.
Figure C-7: Sample of pale matrix polymict breccia from drillhole MDF07 east of the open pit area containing an intact sequence of R.A.T. Subgroup rocks (top image). The polymict breccia injects clay-rich R.A.T. Subgroup unit rocks (R1Cl) that display intact to brecciated zones. The polymict breccia matrix is pale colored due to the absence of supergene black oxide minerals at this depth (213.5m). Clasts within the breccia are sub-rounded and dominantly derived from R1Cl nit as they contain abundant Mg-chlorite-quartz-muscovite with minor amounts of dolomite (central image). QEMSCAN® automated mineralogy false-color mineral map of the breccia matrix composition dominantly resembles that of the main clast components but also contains abundant dolomite and specular hematite and minor K-feldspar. The latter may represent potassic alteration or entrainment of R.G.S. unit clasts from below the drillhole intercept.
Figure C-8: Sample of specular hematite-rich and pale matrix polymict breccia from drillhole MNWD022 in the north pit area at Mashitu (left image). The sample clearly shows the distinctive fabric typical of this breccia type highlighted by the alignment of specular hematite grains sub-parallel to the margin of the pale matrix polymict breccia although the contact is irregular and indistinct and does not show a cross-cutting relationship. QEMSCAN® automated mineralogy false-color mineral map of the sample (right) shows that the pale color of matrix attributed to abundant dolomite. Grey fabric defined in center of drillcore sample contains abundant specular hematite. Sub-rounded clasts of R.G.S. unit and clay-rich R.A.T. Subgroup unit are discernable.
Figure C-9: Sample from drillhole MSPD063 to the northeast of the central pit area at Mashitu was interpreted as pale polymict breccia but QEMSCAN® automated mineralogy shows the clasts and matrix are dominantly composed of quartz-Mg-chlorite (a). b) Sample is located at margin of a buried R.A.T. Subgroup megaclast containing siltstone (R1Slt) and sandstone-rich units (R1Sst) and therefore contains clasts of both, composed of dominantly quartz-Mg-chlorite. Detrital tourmaline may also be more common in R1Sst. c) Area shown by yellow box contains abundant muscovite, throughout the upper portion of the sample it is developed in the breccia matrix and displays alignment parallel to clast margins. Abundant muscovite - K-feldspar suggests intense potassic alteration. d) subtle fabric is developed in the center of the sample highlighted by the alignment of sub-rounded clasts in the upper portion of the sample. This zone is separated from a large clast of R1Sst by a zone of abundant specular hematite displaying a similar alignment.
Figure C-10: Weakly weathered monomict breccia in contact with brecciated clast of R1Sl t or R1Sst unit from drillhole MSPD055 from the northeast of the central pit area at Mashitu. QEMSCAN® automated mineralogy false-color mineral map (right) of the polished thin section (left) displays minor dolomite preserved in the breccia matrix that is dominantly composed of Mg-chlorite-quartz but indicates some replacement of a primary carbonate (dolomite) +/- evaporite mineral rich matrix.
Figure C-11: Specular hematite-rich monomict breccia from drillhole MNWD001 in the north part of the Mashitu pit containing abundant <5mm diameter clasts of clay-rich R.A.T. Subgroup unit (R1Cl) (left image). QEMSCAN® automated mineralogy false-color mineral map (right) of the polished thin section area shown in black (left) indicates a quartz-Mg-chlorite-muscovite rich breccia matrix, derived from the same clasts that show similar mineralogy. However, the matrix also contains abundant laths of specular hematite developed as rims on clasts and scattered in the matrix-poor breccia. K-feldspar occurs as rims on clast margins indicating perhaps more intense potassic alteration of clast rims. Minor Mn-Co-Fe-oxide minerals (+/- heterogenite) occur as patchy matrix replacement and on both R1Cl clast margins, and on the margins of specular hematite laths. The latter indicates supergene mineralization occurred after hematite growth. Accessory minerals include tourmaline, rutile and zircon.

Figure C-12: Well-rounded clast of R.G.S. unit sandstone from the north pit area; a common constituent of matrix-supported polymict breccia at Mashitu. The clasts are typically white to pale-green in color and exhibit coarse quartz grains and black copper-oxide or Fe-oxide minerals as patchy groundmass replacement (left). QEMSCAN® automated mineralogy false-color mineral map (right) of the polished thin section shows the mineralogy is dominantly quartz-Mg-chlorite – muscovite - K-feldspar (Compare to sample of R.G.S. from DH MNWD052 S3)
Figure C-13: Sample of R.G.S. sandstone unit rock from drillhole MSPD052 along the western part of the Mashitu central pit area that displays a somewhat brecciated appearance. QEMSCAN® automated mineralogy false-color mineral map (bottom) of the polished thin section area (black box on top image) highlights the ‘brecciated’ nature of the sandstone that varies from parched of coarse-grained quartz- k-feldspar – Mg-chlorite-muscovite and minor dolomite to clast-like zones of quartz-muscovite-k-feldspar rich zones. Black areas represent voids. Accessory minerals include zircon and rutile.
Figure C-14: Sample of R.G.S. argillite and R.G.S. sandstone rocks from drillhole MSPD052 along the western part of the Mashitu central pit area that displays a somewhat brecciated appearance (top left). QEMSCAN® automated mineralogy false-color mineral map (top right) of the polished thin section area (bottom left) displays the ‘brecciated’ nature of the sandstone that contains mixed clasts of R.G.S. unit purple argillite and pale green sandstone ‘sandy’ matrix that may represent former carbonate minerals +/- evaporite minerals that is composed of coarse-grained quartz- k-feldspar – Mg-chlorite-muscovite and coarse dolomite as a rim to the argillite clasts of fine-grained quartz-muscovite-k-feldspar. Black areas represent voids. Accessory minerals include zircon and rutile.
Figure C-15: Grey R.A.T. Subgroup unit from drillhole MDF07 east of the Mashitu pit (left). A) represents the upper contact of grey R.A.T. Subgroup unit with the overlying D. Strat unit: base of the Kamoto Formation (Mines Subgroup). B) represents the subtle 'contact' represented by a redox change between reduced grey R.A.T.- and oxidized red R.A.T. - (Siltstone-rich R.A.T. or R1Slt) subgroup units in drillcore. C) QEMSCAN® automated mineralogy false-color mineral map of the grey R.A.T. Subgroup unit is composed of abundant quartz and Mg-chlorite. Malachite veinlets are common throughout this reduced upper portion of the R.A.T. Subgroup sequence. Remnant diagenetic dolomite is preserved as inclusions in quartz but was dominantly removed by later supergene weathering.
Figure C-16: Siltstone-rich R.A.T. Subgroup unit from drillhole MSPD052 on the western margin of the Mashitu central pit area that shows preserved vuggy (leached) evaporite-like horizons interbedded with the fine-grained former dolosiltstone (top) and polished thin section (bottom left). Carbonate minerals (dolomite?) have been weathered out. QEMSCAN® automated mineralogy false-color mineral map (bottom right) shows that leached white interbeds contain abundant quartz and specular hematite. Cu-Co oxide minerals have also formed patchy replacement in these former carbonate-bearing layers. Mg-chlorite-quartz with minor muscovite supports R1Slt unit interpretation.
Figure C-17: Broken siltstone-rich R.A.T. Subgroup unit (R1Slt) from drillhole MSPD063 located to the northeast of the central pit at Mashitu (left). QEMSCAN® automated mineralogy false-color mineral map (right) shows a composition dominated by Mg-chlorite, dolomite and quartz. Minor hematite, muscovite, minor k-feldspar with accessory minerals including tourmaline and rutile are present. Muscovite and minor alkali feldspar are more commonly associated with fine sandy interbeds. Specular hematite occurs within euhedral quartz infill of vugs and fractures. Quartz is secondary infilling former carbonate-filled pseudomorphs after evaporite minerals. Majority of fracture fill or veining is composed of dolomite.
Figure C-18: Siltstone unit occurring as interbeds within the sandstone-rich R.A.T. Subgroup unit (R1Sst) containing white colored spots representing former pseudomorphs after evaporite minerals and cross-cutting veinlets of malachite from drillhole MNWD004 located in the north pit at Mashitu (top). QEMSCAN® automated mineralogy false-color mineral map (bottom center) of the polished thin section (bottom right) shows a composition dominated by Mg-chlorite (clinochlore) and quartz. Minor hematite and k-feldspar with accessory minerals including tourmaline and rutile are present. Euhedral quartz and malachite represent the veinlets and void filling after former carbonate-minerals removed during supergene weathering.
Figure C-19: Grès Ocellés marker unit in sandstone-rich R.A.T. Subgroup unit (R1Sst) from drillhole MNWD033 in the north pit at Mashitu (left). QEMSCAN® automated mineralogy false-color mineral map (right) of the area outlined in black on the sample (left) shows the unit is composed of quartz, Mg-chlorite, with minor alkali feldspar and contains darker fragments, most likely related to more argillaceous lithology. Abundant specular hematite occurs in the groundmass of the marker horizon suggesting more porous horizon for fluids mobilizing iron from the strongly oxidized R.A.T. Subgroup rocks.
Figure C-20: Weakly weathered intact sandstone-rich R.A.T. Subgroup unit from the relatively intact sequence of R.A.T. Subgroup rocks from drillhole MDF07 located east of the Mashitu open pit (A). B) QEMSCAN® automated mineralogy image of weakly weathered sandstone-rich R.A.T. Subgroup unit of the area marked by a black outline in (A). Sample represents a coarse-grained quartz rich horizon with minor leaching. The presence of former carbonate minerals was indicated in hand-sample. QEMSCAN® verified the presence of minor dolomite associated with coarse quartz grains which are not considered to represent diagenetic or detrital quartz. Magnesian and potassic alteration resulting in Mg-chlorite and white mica +/- K-feldspar respectively. Quartz likely replaced much of the former dolomitic groundmass.
Figure C-21: Weathered clay-rich R.A.T. Subgroup unit rock from drillhole MNWD001 in the north pit at Mashitu (A). A polished thin section (B) shows fracture fill and somewhat pervasive replacement of the groundmass by malachite and specular hematite. C) QEMSCAN® automated mineralogy false-color mineral map of the polished thin section that shows the malachite may have replaced former dolomite or magnesite in the matrix or as fracture-fill. Black areas represent weathered voids (background). D) shows a zoomed in area of the R1Cl rock matrix that contains abundant muscovite developed along what are probably more argillaceous interbeds that show the supergene copper-cobalt oxide minerals and malachite are more common in the quartz-muscovite- Mg-chlorite rich zones of this rock (top area). Specular hematite form rounded micro scale patches possibly infilling former pseudomorphs after evaporite minerals.
Figure C-22: Unweathered clay-rich R.A.T. Subgroup unit from drillhole MDF07 (A) located to the east of the Mashitu open pit and representing a relatively intact sequence of R.A.T. Subgroup rocks. B) Polished thin section of the clay-rich R.A.T. Subgroup unit showing finely interbedded 'siltstone and carbonate-bearing beds with possible pseudomorphs after evaporite minerals filled by specular hematite. C) QEMSCAN® automated mineralogy false-color mineral map of the polished thin section shows the R1Cl unweathered unit contains abundant Mg-chlorite and quartz in argillaceous zones and dominantly magnesite-quartz in dolostone interbeds. Specular hematite and magnesite occur as infill of pseudomorphs after former evaporite minerals. Minor alkali feldspar occurs in the fine-grained groundmass but may represent potassic alteration.
APPENDIX D: X-RAY DIFFRACTION ANALYTICAL DATA

X-Ray Diffraction (XRD) analyses of samples of different breccia matrices and R.A.T. Subgroup unit rocks were undertaken at Colorado School of Mines. Whole-rock XRD analysis was conducted using Cu-Kα radiation Scintag XDS-2000. Prepared powder samples of ~5µm grain size were scanned from 4° to 60° at 1° per minute. Diffractogram patterns produced were interpreted to determine the mineralogy of the various samples (Moore and Reynolds, 1997).

MDI-Jade-2010 Software for Powder XRD Pattern Processing was used for improved mineral phase identification and quantification of mineral weight percentages per sample. Mineral phase identification and weight percent mineral abundance (Table D-2) were calculated using MDI-Jade Software Search/Match (S/M) together with WPF refinement (Rietveld) processing.

Table D-1: Location and description of samples selected for analysis by XRD

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<th>Northing (m)</th>
<th>Elevation (m)</th>
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Figure D-1: Location of pit samples analyzed by XRD from the Mashitu deposit.
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<td>14.14</td>
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<td>15.15</td>
<td>68.10</td>
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<td>68.10</td>
<td>3.00</td>
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Table D-2: Mineral abundance (wt.%) by XRD calculated using MDI-Jade software.
APPENDIX E: TOTAL ORGANIC CARBON DATA

Total Organic Carbon (TOC) analysis was utilized to rule-out the presence of organic or hydrocarbon-derived material within the black halokinetic breccia material exposed in the Mashitu pit. Determination of LECO TOC and Percentage Carbonate was performed by GeoMark Research Ltd. on 15 samples of dark matrix breccia material collected from the pit during the 2014 field season. Percent Carbonate was ~6 wt.% to ~24 wt.% for many of the breccia samples. Three samples contained >39 wt.% carbonate and represent breccia matrix material comprising a higher proportion of clay-rich R.A.T Subgroup unit or Shales Dolomitiques Formation (SDu) derived clasts. The selected samples contained no organic carbon. LECO TOC values were low for all samples; <0.06 wt.%. Therefore, the distinctive fine-grained sooty appearance and black color characteristic of this breccia matrix type is attributed to common occurrence of supergene black Fe ± Mn (Cu - Co) -oxide minerals.

Table E-1: Summary of sample locations and TOC analysis results for dark matrix clast-poor polymict breccia samples collected in the Mashitu open pit.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Pit Location</th>
<th>Easting</th>
<th>Northing</th>
<th>Pit Area</th>
<th>Percent Carbonate (wt%)</th>
<th>Leco TOC (wt%)</th>
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<tr>
<td>CSM-WPT-315a</td>
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<td>380418.63</td>
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Figure E-1: Location of samples analyzed for TOC from the polymict breccia zones in the north pit area at Mashitu.