Paper 20

Exploration Under Total Cover: A Case Study from Northwest Botswana

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ABSTRACT

Total cover (100% cover) presents both a challenge and an opportunity. A challenge, in the sense that mineralization is not visible at the surface and that the cover greatly reduces the effectiveness of traditional geochemical sampling techniques, and an opportunity in that a large deposit may be hidden beneath the cover. With partial cover it is still possible to answer many of the geological questions vital to assessing the prospectivity of an area. In this sense, total cover represents one of the last frontiers of mineral exploration.

Exploration companies have a history of utilizing soil geochemistry and other traditional geochemical methods to great effect in a variety of non-covered plays. However with thick cover, the effectiveness of surface samples remains unproven, yet there is a requirement in covered exploration for an unambiguous method of 'direct detection'.

There are few existing case studies for exploration of total covered plays, with the majority focused on gold exploration in Western Australia. The lack of a known test bed (mineralized deposit with total cover) means trailing many techniques, often with considerable expense, in order to identify a reliably unambiguous method of 'direct detection'. This paper serves as a case study of the exploration methods used and their relative effectiveness in the thick Kalahari cover of northwest Botswana. Many of these methods were not fully established and required development of both the technique and technologies required to effectively undertake the method.

Ultimately, the effectiveness of exploration under cover will always be at loggerheads with both project deadlines and budgets. Balancing the quality of data with cost is key to efficient and effective covered exploration. Establishing early in the project regolith composition and stratigraphy as well as the regional water regime (including water table) is important for both program design and data interpretation. A staged exploration program with 'exit' decision points is vital, with early decision points reachable with limited boots on the ground. Key geophysics and geochemical sampling programs should be undertaken in campaigns, reducing the requirements for big logistical footprints in country and allowing for staged appraisal (linked to decision points) following each campaign until the ground is proven effectively unprospective or an economic intercept is established. Due to variability in the regolith of covered environments many more case studies will be needed to establish a measured approach to undercover exploration.

INTRODUCTION

The Central African Copperbelt (CACB) of Zambia and the Democratic Republic of Congo (DRC) contains some of the largest reserves of copper and cobalt on Earth. The numerous deposits which constitute the Copperbelt are hosted in the Neoproterozoic Katangan Supergroup, and although they show marked variations in age, textures, alteration, metals, grades and tonnages, they are all ascribed to the sediment-hosted stratiform copper (SHSC) category of ore deposits.

The Katangan Supergroup was deposited in an intracontinental rift basin and now crops out over large portions of northern Zambia and southern DRC, but the limits of the basin are poorly constrained. Given the economic significance of the basin, in recent years several authors have attempted to better define the extents of the basin and possible lateral equivalents.

Between 2013 and 2016, an FQM-Tsodilo Resources Ltd. partnership investigated the potential of what de Wit (2009) and Hitzman, (2012) postulated to be an extension of the CACB in northern Botswana. The area represented a geological province about which almost nothing was known, due in part to a ubiquitous thickness of Kalahari Supergroup sands. Hitherto, this transported regolith had prohibited systematic exploration of the area. The potential presented by a possible extension of the Katangan Supergroup coupled with very low exploration maturity made for a potentially very lucrative exploration play.

The project required that we refine or develop many techniques to suit the unique circumstances of exploring for SHSC mineralization under the Kalahari. These included airborne gravity, airborne EM, hydrogeochemistry and various regolith-sampling methods. This was done in parallel to an effort that attempted to appraise the prospectivity of a package of Katangan rocks, which bore a strong resemblance to those in the Domes region of Zambia. The project was an expensive endeavour, requiring new approaches to managing risk and decision-making. In short, the project required us to adopt and develop very different approaches to exploration.

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GEOLOGICAL BACKGROUND

Generic Features of Sedimentary-Hosted Cu Deposits

Sediment-hosted stratiform copper deposits form some of the largest economic accumulations of copper in the Earth's crust. Examples include the Paleoproterozoic Udokan deposit in Russia; the Mesoproterozoic White Pine deposit in Michigan, USA; the Neoproterozoic CACB of Zambia and DRC; the Permian Kupferschiefer of Germany and Poland; and the Carboniferous deposits of Dzhezkazgan, Kazakhstan.

Sediment-hosted stratiform copper deposits are accumulations of vein and disseminated copper sulphides commonly found in organic/reduced shales, sandstones or carbonates. They are aerially extensive, often covering several km^2, with a thickness in the order of metres to tens of metres. Cu grades vary from about 1 to 5%, with some deposits exceeding 10%. Accessory metals may include including Cu, Ag, Au, Co, U, Pb and Zn. Mineralization typically forms around syn- and post-sedimentary structures on basin margins or flanking basement domes where stratigraphic successions are draped over paleo-topographic highs and where fluids are focused beneath impermeable rock units (Hitzman et al., 2005).

The deposits form where large volumes of basin brines are displaced by thermal convection (Brown, 2014), contrasting densities (Koziy et al., 2009), meteoric recharge (Brown, 2008), gravity compaction (Swenson et al., 2004) or a combination of these. Brines are typically bittern, having precipitated halite, or hyper-saline from the dissolution of evaporates, of low to moderate temperatures and enriched in cations (Selley et al., 2005). Oxidized pore fluids flowing through terrigenous redbeds promote the decomposition of mafic and other minerals, and the liberation of metals, which are transported in complex with Cl^- and SO_4^{2-} (Brown, 2009). Brines deposit these metals as sulphide minerals at strong redox boundaries such as a reduced shale overlying a redbed sandstone or an accumulation of hydrocarbons in a trap structure (Sverjensky, 1987).

The formation of the earliest sediment-hosted copper deposits coincided with the oxygenation of the Earth's atmosphere in the Paleoproterozoic; oxygen being a prerequisite for the formation of redbeds. The temporal distribution of deposits shows clustering around periods of Supercontinent break-up, halite accumulation and global ice ages (Hitzman et al., 2010). Fertile basins typically formed in restricted seas occupying intracratonic basins at low latitudes (Brown, 2014).

The Geology of Northwest Botswana

Xaudum Corridor

The present-day surface of northwest Botswana (Figure 1) is dominated by ENE-trending linear dunes of Kalahari Supergroup sediments, described in Geological Background. Shales and sandstones of the Karoo Supergroup were intersected in several drill holes but are present as isolated remnants. Precambrian rocks crop-out at three locations in northwest Botswana: magnetite ironstone in the town of Shakawe, carbonates at the Mohembo ferry crossing, and the prominent Tsodilo Hills quartzites approximately 40 km SSW of Shakawe. Outcrops of sandstone and quartzite are also present along the Okavango River in Namibia's Caprivi Strip.

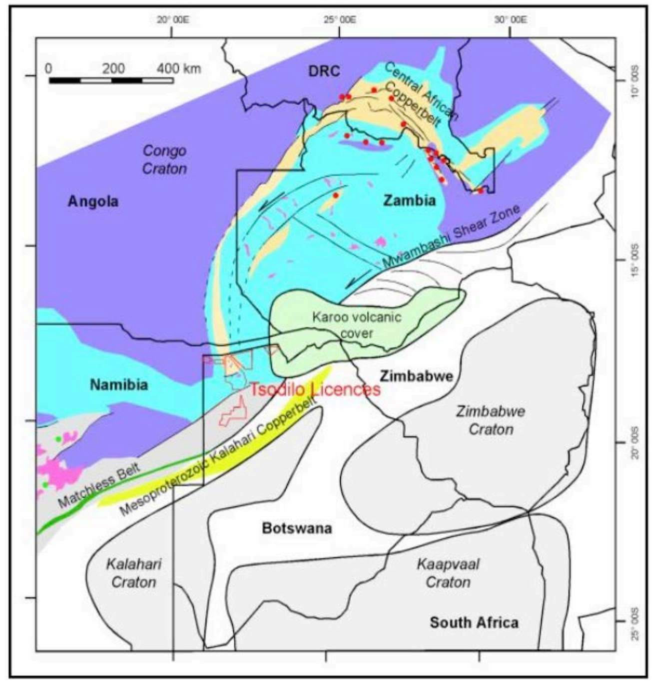

Figure 1: Interpreted extension of the Zambian/Congolese Copperbelt into northern Botswana (adapted from Hitzman, 2012).

Data available prior to commencing this project included a 1:500,000 Geological Survey of Botswana geological map and 250 m-spaced airborne magnetic data. The near-ubiquitous Kalahari cover had long precluded the creation of accurate basement geological maps. Airborne magnetic data attested to tight, north-south oriented folds and structures, with stratigraphy wrapping around at least two north-south trending dome-like structures.

Key and Ayres (2000) divided the rocks into the Xaudum Group, which included sandstones, siltstones and cherty-carbonates, and the Tsodilo Group quartzites, which locally contain kyanite, muscovite and/or magnetite.

Mapeo et al., (2000) dated a sample of arkosic sandstone from northwest of Tsodilo Hills, obtained a detrital zircon age of 1.02 Ga, and concluded it to be part of the Neoproterozoic Ghanzi-Chobe Supergroup. Singletary et al., (2003) summarized the geochronological data of northern Botswana and speculated that the Tsodilo Hills Group may correlate to the Chuos Formation of Namibia.

De Wit (2009), Gaisford (2011), Hitzman (2012) and Masters (2013) identified components of the Katangan Supergroup in the Shakawe area of northern Botswana based upon detrital mineral age constraints and stratigraphic associations.

Post Mineral Geology

There are two distinctive post-mineral cover sequences deposited in the Ngamiland district: discrete occurrences of the Karoo Supergroup, and wide spread Kalahari Supergroup cover. The Karoo Supergroup of Botswana unconformably overlies Archaean and Proterozoic rocks (Diskin et al., 2010). While covering up to 70% of the landmass of Botswana, the Karoo is typically confined to four sub-basins within the Kalahari Karoo Basin (Segwabe et al., 2008). Principally, the known occurrences consist of a package of glacially derived basal tillites termed the Dwyka Group (lower Karoo) and an overlying sequence of dark-coloured shales with interspersed siltstones, sandstones, and occasional coal seams (Johnson et al., 1996). There are also occurrences of the upper Karoo, including sandstones and mudstones of the Lebung Group, as well as large expanses of the Stormberg Group (flood basalts and dolerite dykes).

The geological units of the Kalahari Supergroup have been comprehensively described by Haddon (2005). The units applicable to the Ngamiland of NW Botswana include basal conglomerates, clays, silcretes, calcretes and unconsolidated sands.

A paper on the Kalahari borehole stratigraphy from the Tsodilo Hills area by Linol et al., (2009) reports a sequence of carbonates, varying in thickness from 30–60 m, overlain by unconsolidated aeolian sands. The report attributes calcrete formation to lacustrine processes and pedogenesis. A distinct basal breccia is common in the interface horizon between the Kalahari and underlying sequences, where calcrete "veins" dissect the bedrock. There are a number of ages postulated for the Kalahari calcretes, however Cooke and Verhagen (1977) reported Upper Pleistocene ages of 45,000 to 22,700 and 11,000 to 9,800 years for calcretes from the Kwihabe Valley of north-western Botswana.

Paleo-redox horizons within the upper sand sequences are locally rich in hematite and goethite. Multiple horizons represent a regressing water table. Lancaster (1980) described the dunes of the northern Kalahari to be 25 m high and 1.5 to 2 km apart and extending as far as 200 km in length.

Correlations to the Zambian CACB

The Katangan Basin, or CACB of Zambia and the DRC, is one of the world's largest resources of copper and cobalt ores, and a significant source of other metals (Kirkham, 1989). The basin is typically divided into five different structural terranes which from north to south are the Katanga High, Synclinorial Belt, Domes Region, External Fold and Thrust Belt and the Foreland basin in the north (e.g. Selley et al., 2005; Kampunzu and Cailteux, 1999) with each domain characterized by different styles of mineralization, alteration, metamorphism and deformation.

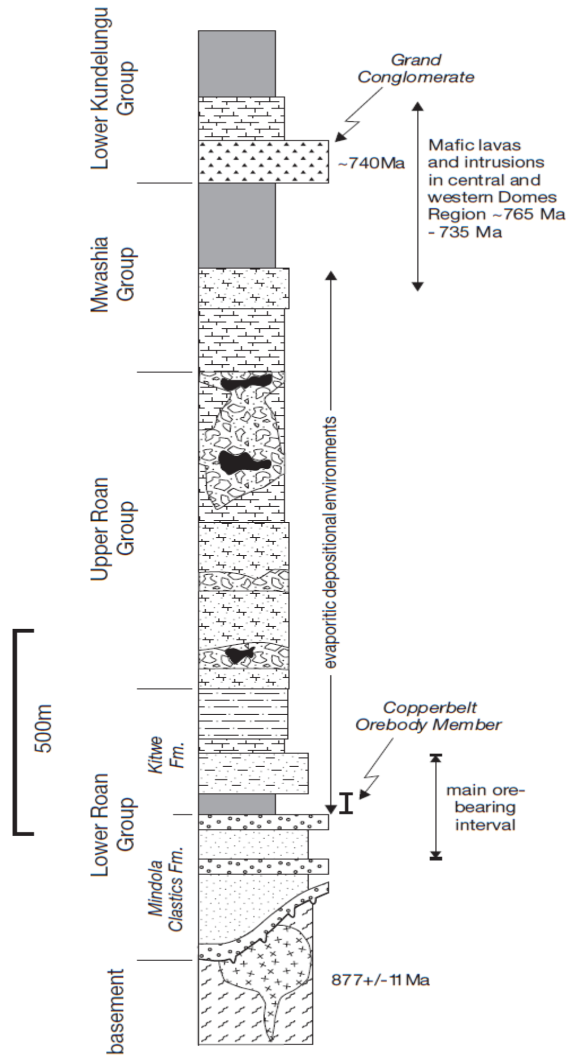

Figure 2: Idealized stratigraphic column of the Katangan Supergroup (Selly et al., 2005).

Depositional ages of the Kantangan Supergroup (Figure 2) span from the Nchanga granite c. 880 Ma (Armstrong et al., 1999) to the c. 573 Ma Biano Group (Master et al., 2005). The Kundelungu and Nguba Groups can be easily correlated between the Zambian and DRC portions of the CACB (e.g. Cailteux et al., 1994) by the Sturtian and Marinoan glacial diamictites – the Grand and Petit Conglomerates respectively. The blanket nature of the Upper Katangan stratigraphy is attributed to sag-phase basin evolution (Selley et al., 2005). Below the Nguba, the Upper Roan and Mwashya stratigraphy includes carbonates, minor clastics and dissolution features after evaporites. These rocks were deposited on a shelf setting during a post-rifting thermal sag phase and are intruded by 765–735 Ma basalts related to a minor extensional event. The Lower Roan, including the Kitwe and Mindola Clastic Formations, comprise immature continental arkoses, which record rift initiation and climax. Lower Roan sedimentation was compartmentalized in normal fault-controlled sub-basins and displays abrupt lateral facies changes (Selley et al., 2005). In Zambia the Ore Shale records a widespread transgression at the top of the Mindola Clastics Formation. Localized variations in sedimentary facies in the Lower Katangan rocks make regional correlations more difficult than in the Upper portions of the stratigraphy. In Zambia, the basal Roan Group unconformably overlies basement rocks, in contrast to the DRC where the base of the Katanagan Supergroup has not been observed. Peak metamorphism to upper greenschist–lower amphibolite facies was coincident with Lufilian basin inversion and the emplacement of the Hook Granites at ≈600 to 500 Ma (Katongo et al., 2004).

Prior to the commencement of the project in 2013, existing drill cores from northern Botswana showed clear visual similarities to those from the Domes Region of Zambia. These similarities included basement comprising granites and quartz-biotite schists; a mixed carbonate-siltstone package; and a glacial diamictite containing banded ironstones and overlain by a clean limestone. Stratigraphically this package resembles the Mwashya to Kakontwe Groups or Upper Katangan Supergroup. The sediment-basement interface showed varying degrees of ductile strain and possible 'blotchy' feldspar alteration similar to the Domes region. Several sulphide-bearing (pyrite + pyrrhotite) shales contained large kyanite porphyroblasts which were visual indistinct from the Sentinel and Enterprise deposits, located on the south edge of Zambia's Kabompo dome. Gabbro intrusions had been intersected in drill cores. All rocks had been subject to moderate ductile strain and upper greenschist to lower amphibolite facies metamorphism.

The drill cores and exposures available at the beginning of the project provided evidence to support the hypothesis that a significant mineral system exists. The gabbro intrusions provided evidence of a thermal input; minor salt breccias, K-feldspar alteration and kyanite implied that saline brines could have existed in the basin, and Godfroid and Goswell (2013) observed reductants in the form of carbonaceous shales. Some components considered necessary for the creation of giant sediment-hosted copper camps were not initially observed in the rocks of northern Botswana, such as Mg- and Na-alteration assemblages (e.g. Selley et al., 2005) typical of the Copperbelt. Although redbed sandstones were not observed in drill core they were identified near Andara, Namibia, by Masters (2013).

The package of rocks we examined in northern Botswana contained evidence to suggest a possible extension of the Katangan Basin geologically similar to the Domes region of Zambia. This coupled with the ubiquitous post-mineral (Kalahari) cover and low exploration maturity presented an opportunity where a world-class sediment-hosted copper camp may have being lying undiscovered.

Climate and Vegetation of the Project Area

The southern part of the Kalahari Basin falls within the borders of Namibia, Botswana, Zimbabwe and South Africa and is characterised by semi-arid to arid conditions. Seasonal precipitation of 600 mm per annum has been recorded in northern Botswana (Thomas et al., 2003). Significant temperature ranges occur seasonally, with variation of -10°C in winter and up to 45°C in summer (van Rooyen and Bredenkamp, 1996). Despite significant season rainfall, evaporation rates are very high, and in the summer months can be up to six times greater than the precipitation (Meyer et al., 1985).

Regionally the Kalahari plateau plays host to a varied selection of savanna vegetation adapted to survive the seasonal erratic rainfall associated with the Kalahari. Haddon (2005) reported that in excess of 400 species of plant life exist on the Kalahari plateau and described the general vegetation of northern Botswana to be broad-leafed deciduous forests. Plant species typically show adaptation for survival in the semi-arid conditions of the Kalahari. Local to the project area, Chatupa et al., (1996) described the Ngamiland vegetation to include species of deciduous trees, low scrub and tussocky grass. Vegetation of the Kalahari is controlled, in part, by climatic variation and type and availability of micronutrients in the soils.

METHODOLOGY

Examples of successful technical discoveries of blind deposits made beneath cover are limited. Pertinent examples include the Osborne and Eloise Cu-Au deposits (Cloncurry district, Queensland). Furthermore, no examples exist of successful discoveries of large sediment-hosted copper deposits in covered terranes.

A conceptual model was constructed that attempted to represent the mappable and detectable attributes of the style of mineralization we were to target (Figure 3). The model utilized our knowledge of the system at the start of the program and formed the basis around which the exploration program was designed.

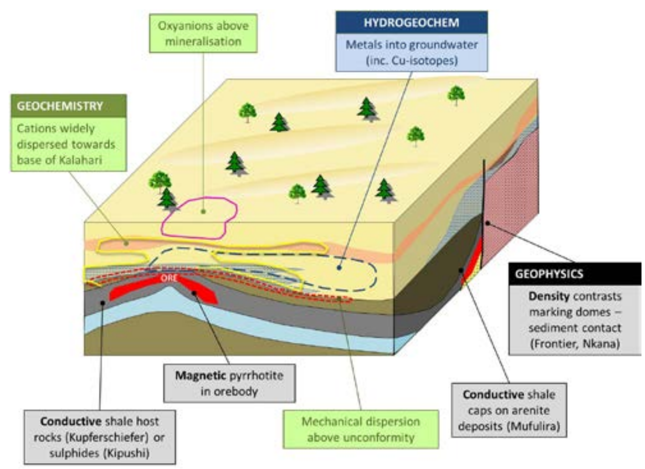

Figure 3: Cartoon diagram of the mappable and detectable attributes of the target mineralization style.

Historical Data

Drilling and Geochemical Data

The government data archives for the area include: (1) regional soil geochemical data; (2) lithostratigraphic borehole sections from regional government drilling; (3) cadastral map data for mineral occurrences, geological map interpretations, drill hole locations, water sources, roads, towns, parks, wildlife reserves and hunting concessions; and (4) government reports on projects undertaken in the Ngamiland area.

Data were also available from private exploration companies, particularly Tsodilo Resources LTD, who had undertaken extensive exploration for iron, diamonds and base metals since 2000. Although mainly shallow, spatially confined and generally focused on iron ore potential of the Rapitan banded iron formation (BIF) a total of 187 boreholes, totaling 50,845 metres (pre–2013) were available for review. A suite of geochemical data from the drill holes was also available.

Geophysical Data

Regional, yet low-resolution, government airborne magnetics flown between 1996 and 1997 by Compagnie Generale de Geophysique (CGG) and regional Bouger gravity data sets were available, but were too low resolution for mapping and geological interpretation purposes. In additional good quality Landsat and digital terrene model (DTM) data was available. High-resolution ground magnetic data was available over part of the project area from Tsodilo Resources LTD. This data, along with drilling data, would prove crucial for initial development of geological maps, and for gaining an understanding of the types of lithologies and structural styles we were to encounter. Government airborne electromagnetic (EM) data is confined to the periphery of the Okavango Delta, flown with the objective of mapping the geometry of the underlying aquifer system beneath the deltas surface expression, as well as mapping salinity *(*Kgotlhang, 2008*).* Finally, Slingram EM data was available, with low resolution and low depth penetration data.

Geochemical Techniques

The variations in thickness (5 to 90 m) and stratigraphy of the Kalahari sequence posed a significant barrier to exploration. At the outset of the project it was not known if a buried mineral deposit would generate a surface geochemical signal though the Kalahari cover. The only viable approach therefore was the trial and error testing of traditional geochemical techniques. The conceptual targeting of sediment-hosted copper deposits remains generally poorly understood and the added complexity of post-mineral cover requires a form of direct detection to provide context and build confidence in geochemical vectoring techniques.

The basis of geochemical sampling (Figure 4) was grid drilling shallow boreholes though the Kalahari sequence. A total of 220 diamond holes were drilled (totaling 13,652 m), on a 2 x 2 km grid, recovering the entire Kalahari sequence and a 6 m bedrock 'tail'. In order to achieve >90% recovery of the Kalahari Sequence a number of different drilling methods were trailed. Initially reverse circulation (RC) drilling was tested, however the combination of wet, unconsolidated and highly porous Kalahari sands resulted in a loss of borehole pressure into the surrounding porous sands, and the clogging of drill-bit hammers. Secondly, Sonic drilling, while achieving 100% recovery with no contamination in the Kalahari sands, failed to penetrate the increasingly competent and crystalline silcretes and calcretes. While highly effective the method was ultimately unsuitable as it was unable to achieve the vital bedrock samples, requiring a diamond drill rig to re-enter the borehole and complete a 'diamond tail' at a later date.

The combination of sample quality, low contamination risk and speed of completion were all factors in the decision to use diamond drilling for the geochemistry grid. While the core samples could be considered 'over-kill' for the intended purpose of geochemical sampling, the additional textural and geological information provided by whole core, yielded invaluable geological information about the Kalahari sequence.

Profile and Bedrock Sampling

Successful discoveries of covered deposits such as Boddington (Anand, 2005), Jaguar (Anand et al., 2009), DeGrussa (Noble et al., 2017) and Eloise (Robertson et al., 2003) has demonstrated that significant lateral and vertical geochemical dispersion plumes can form in post-mineral cover, typical driven by weathering of primary sulphides in the bedrock and hydromorphic mobility through the cover sequence.

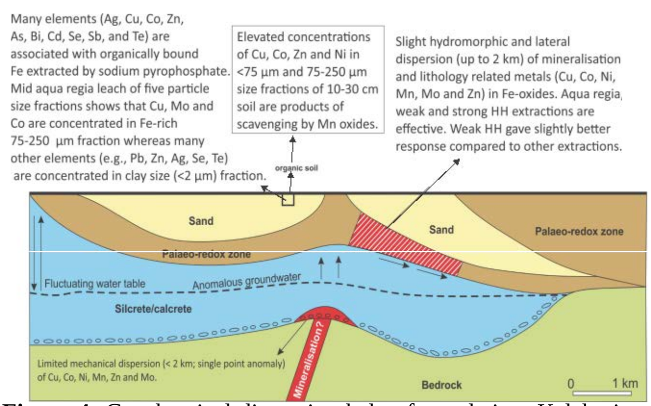

Figure 4: Geochemical dispersion halo of metals into Kalahari post-mineral cover in the project area (Anand et al., 2016).

The geological variability of the Kalahari sequence required careful sampling consideration and was constrained by lithology. Analysis with two different leach methods was undertaken. Initially the consolidated Kalahari sands were sampled using 2 m composites and subjected to a standard lab aqua regia leach. Later in the program the entre drill hole cover sequence (post-mineral cover and bedrock) was resampled and analyzed using a more aggressive four acid leach.

The importance of the 'interface horizon' has been identified by a number of previous workers. The Eloise volcano massive sulphide (VMS) discovery in Western Australia (Robertson et al., 2003) is an example of such; discovered by drilling across the interface horizon and identifying mechanical dispersion down paleo-slope of the deposit.

The interface between bedrock and Kalahari sequence in northwest Botswana is well defined with metamorphosed and deformed Neoproterozoic rocks overlain by un-deformed silcretes and calcretes of the Kalahari Supergroup. The base of the Kalahari is characterized by thin, laterally extensive breccia sequence with clasts of bedrock cemented into the overlying silcretes and calcretes. Weathering of the bedrock is limited with little variation in the depth of oxidation observed between drill holes - indicative of long term reduced conditions beneath the water table. Anomalies along the interface horizon can either be driven mechanically, with brecciated clasts moving down the paleo surface via gravity, or hydromorphically, in solution by the groundwater (Salama, 2015). To this end a good understanding of both the paleo-topography of the interface horizon and the groundwater regime in the area is important to vector to anomaly sources.

Thickness isopachs and contour surfaces of the Kalahari sequence and interface horizon were developed from the drilling data. Variability is limited, with major changes in Kalahari thickness typically associated with structural controls and recessive or resistant geological units within the bedrock. However, the hummocky nature of the base of the Kalahari appears to have limited mechanical dispersion of mineralization along the unconformity, thus reducing the secondary footprint.

Soil Sampling

Historically, a number of soil surveys were undertaken in the project area with different scopes. Walker (2005) collected soil geochemistry data over a ground magnetics and gravity anomaly in 2005 for base metal exploration. The results of this survey were deemed inconclusive due to the thick cover. The Geological Survey of Botswana undertook a regional geochemical mapping project (Project No. NDP7/MR217) focused on determining trace element concentrations in the O and A horizons of the soil. Their report concluded that there was a lack of element accumulation in the soils due to thick cover, despite variable sample depths and size fractions (Chatupa et al., 1996).

Early in the program, soil geochemistry data were collected over two conceptual targets, both of which have significant Kalahari cover.

Hydrogeochemistry

A two-stage hydrogeochemical sampling program was undertaken. Initially available drill holes in the immediate target district (both recent and historic) were sampled. Sampling within the district-drilling grid was intended to provide a camp-vectoring tool. Secondly, a wider, regional sampling program took place, focused on existing boreholes, wells and seeps. The sampling techniques used for these samples corresponded to the method described by Gray et al., (2012).

Within the target district a sample density of 2 km was achievable, increasing up to 10 km with regional samples. The water sources vary considerably, but correspond to: (1) Recent diamond drilled boreholes, cased with PVC, capped with PVC, and flushed; (2) historic commercial and government reverse circulation and diamond drill holes, both cased (including PVC and steel) and uncased, typically uncapped; (3) village water sources, typically metal taps from PVC tanks connected to PVC lined boreholes; (4) privately dug or drilled wells or boreholes on farmland, typically unlined and uncapped. Multiple re-samples were collected at ‘control’ drill holes intended to test variation at different depths below the water table in the drill hole stream.

Drilling mud and equipment degradation represents a significant potential source of chemical contamination, particularly with recently drilled boreholes. To minimize potential contamination a program of flushing boreholes with 5000 liters of water to remove remnant drilling mud and pumping boreholes to allowing the groundwater regime to recharge over six to eight weeks, before sampling. There is little or no equipment available for these applications, flushing boreholes with up to 100 m of hydraulic head above the water table requires significant adaptation of existing equipment. A mobile, vehicle mounted, pumping rig was developed and composed of a mobile generator, wind able heavy-duty water hose and a narrow gauge Grundfos MP1 pump.

A piezometer was used to collect water table data and establish the regional groundwater regime. Understanding the regional water table has far reaching applications, firstly hydromorphically driven anomalies, either at surface or within the cover, will be controlled largely by the direction of hydraulic head. Therefore geochemical vectoring in this environment relies on an understanding of hydraulic process of the area.

Geophysical Techniques

With the unknown effectiveness of geochemical tools to vector though the Kalahari cover, the use of geophysics is vital, especially in the absence of an empirical dataset. Two airborne geophysical surveys were undertaken, including; regional scale EM and gravity surveys.

Electromagnetic (EM)

Airborne EM data was collected early in the project using Spectrem Air’s time-domain system. A total of 18,500 line kilometres were flown on E-W lines oriented perpendicular to the general strike of the Tsodilo Group rocks. Regional line spacing was 1,000 m; line spacing over the rocks believed to be Katangan was 500 m; and a high priority area characterized by apparently complex deformation around dome was flown at 200 m line spacing.

The rationale for flying EM—and flying it at relatively close spacings was threefold: (1) Tsodilo Resources LTD had previously identified mineralized conductive carbonaceous shales from drilling, the preferred copper host unit or a trap above arenite-hosted deposits (e.g. Mufulia, Zambia); (2) FQM had previously success using time domain EM to map carbonaceous shales including Frontier (DRC), Mwinilinga (Zambia) and Trident (Zambia); (3) to provide key geological information, which in combination with existing geophysics could be used to build a robust geological model for the area; and (4) for mapping depth of cover, allowing for the early identification of unexplorable areas of deep cover. As the project progressed, point (4) would prove to be the key area elimination tool.

Gravity

An airborne gravity survey was also undertaken using an aero plane-mounted gravimeter. Flight lines were spaced 1,000 m apart and oriented ENE-WSW, with tie lines flown at 1,000 m spacing and oriented N-S. The key objective of the gravity survey was to map basement architecture (Figure 5)—in particular paleo- highs (e.g. hidden domes)—which will have controlled fluid flow in the basin and may have focused ascending basin fluids into ore deposits. It was also anticipated that the technique would aid the overall geological interpretation of basin. Previous ground gravity surveys in Zambia have demonstrated that the contrast between low-density granitic-composition basement and high-density dolomitic carbonates and hematitic sandstones of the Katangan Supergroup, can be mapped effectively. The technique would image deeper features than magnetic or EM surveys.

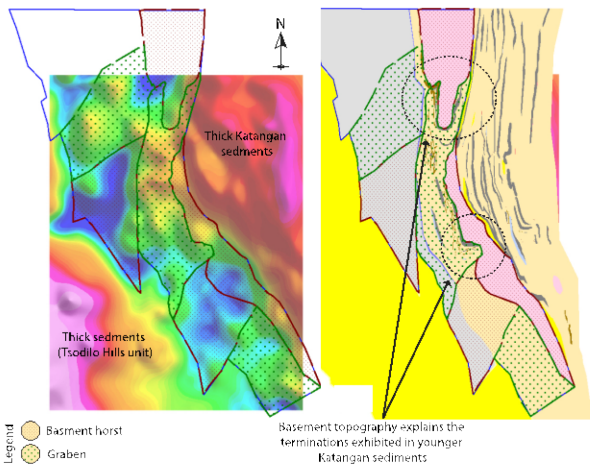

Figure 5: Airborne gravity data interpretation demonstrating the ability of the technique to basin architecture in comparison to mag and EM inferred geology.

Geochronology

The FQM-Tsodilo Resources Ltd. partnership collected collected 16 core, outcrop and stream sediment samples at the earliest stage of the project. The samples were sent to the GEMOC laboratory at Macquarie University for U-Pb age analysis via LA-ICPMS and Hf-Lu isotopes via LA-MC-ICPMS. Combined with published data and data from unpublished Masters Theses we accumulated a dataset of 822 zircon and 35 apatite ages.

Geochronology Results

Eight samples of granite and quartz-biotite schist interpreted to be pre-Katangan basement contained rounded zircons with U-Pb zircon ages of between 2,737.7 ± 6.6 Ma and 2,548 ± 65 Ma (weighted averages). No younger age zircon grains were present in these rocks. In many locations the contact between Katangan metasediments and the underlying basement displayed ductile shearing and possible potassium feldspar alteration. We attempted to address these uncertainties by sampling a suite of different rocks and textures but all samples returned the same Neoarchean ages. ƐHf plots of zircons in the pre-Katangan basement rocks tend to plot above CHUR (CHrondrite Uniform Reservoir) with ƐHf > 0.

Witbooi (2011) identified a population of eight zircons in a sample of metabasalt, with a weighted average age of 743 ± 62 Ma. Three other metabasalt samples dated by ourselves and Gaisford (2010) returned five zircon age populations of 592 ± 9.7 Ma to 519.7 ± 6.8 Ma.

Detrital zircons in metasedimentary rocks from around Shakawe—believed to belong to the Katangan Supergroup—returned dominantly Neoarchean ages (c. 2.65 Ga) with lesser populations of 2.1–1.9 Ga and 1.1–0.9 Ga age grains.

Five samples of Tsodilo Hills Group quartzite have been dated, producing 284 zircon grain ages. Our data and data from Mapeo et al., (2008) show six distinct detrital zircon age populations at approximately 3.42 Ga, 2675 Ma, 2206 Ma, 2068 Ma, 2029 Ma and 1988 Ma.

Mapeo et al., (2000) carried out SHRIMP zircon dating on 25 detrital grains in a sample of arkosic sandstone from west of the Tsodilo Hills Group. Age populations included 1019 ± 7 Ma, 1088 ± 44 Ma, 2043 ± 16 Ma and 2055 ± 14 Ma.

Geochronology Interpretation

Zircons in the pre-Katangan basement beneath Shakawe returned ages of approximately 2.5–2.7 Ga. This contrasts with typical ages for basement to the Katangan Supergroup in Zambia and the DRC, of between 1980 ± 7 and 1874 ± 8 Ma (Rainaud et al., 2005). The positive ƐHf values of the basement rocks tentatively suggest they are derived from juvenile mantle, possibly from a mantle plume (Belousova et al., 2010) and resemble data from the Domes region of NW Zambia (pers. comm, D.G. Wood, 2017).

The ages of metabasalt intrusions into the Katangan rocks around Shakawe coincide with two significant magmatic events in Zambia and the DRC: the 765 to 740 Ma Mwashia extension (Armstrong et al., 1999) and coincident with the Hook Granite suite and Lufilian orogeny at 570 to 520 Ma (Milani et al., 2015).

Detrital zircons in Katangan metasedimentary rocks reflect those in the underlying basement, with Neoarchean ages dominating. Samples taken more distal to the basement highs show a decreasing proportion of Neoarchean zircons and an increasing component of younger, Mesoproterozoic zircons.

The Tsodilo Hills Group—considered by some to be equivalent to Zambia's Lower Roan Group—has a very different distribution of zircon ages to the metasedimentary rocks around Shakawe. Airborne magnetic maps appear to show deformation fabrics in the THG, which are absent in the rocks around Shakawe. We therefore interpret the THG to be significantly older than Neoproterozoic; possibly Paleoproterozoic.

Conceptual Drilling

Conceptual target core drilling commenced early in the exploration program and initially focused on building geological understanding of the area through the drilling of a "Stratigraphic Section Line". The section was oriented east–west across the sub-basin to the east of the basement high. The intention of this drilling fence was to provide information on the stratigraphy and structure of the area as well as testing an "embayment" style target in the basement high. The eight holes of the stratigraphic section line varied from 400 to 970 m deep.

Following the completion of the initial phase of stratigraphic drilling and the EM survey, drilling was briefly paused for interpretation of the newly acquired geological data. After refinement of the geological model, a series of geophysics-based targets were ranked for sequential diamond drill-testing. The majority of the targets focused on the combination of EM and magnetic datasets and the identification of structural anomalies and metasedimentary-basement unconformities in coincidence with highly conductive packages of rock.

Ultimately, this ongoing conceptual drilling allowed us to develop a robust geological understanding of the Xaudum district and northwest Botswana.

Equipment Innovations

Exploring beneath total cover requires the development of new, or the adaptation of existing, techniques and equipment. Exploring beneath Kalahari cover poses a number of challengers to the adoption of equipment used in more traditional settings, namely: (1) lithological variation in Kalahari sequence, from consolidated calcretes and silcretes at the base of the formation to the unconsolidated composition of the upper horizon of the Kalahari sands; (2) considerable variation in cover depth, from 10-100 m; and (3) moisture variation though the Kalahari sequence.

The Kalahari geochemistry drilling commenced with a RC drill rig with the intention of recovering samples quickly and cost-effectively. However, the RC drilling was unable to recover adequate samples of unconsolidated Kalahari sand and could not penetrate the aquifer in the unconsolidated sand at the base of the Kalahari. A trial of a sonic drill rig—designed for drilling tailings, mineral sands and other unconsolidated media – proved effective but expensive. Ultimately diamond drilling with a heavy, viscous, drilling mud proved to be the most effective method and was utilized for the remainder of the program. In order to ensure consistent high recovery, a number of innovations to core lifting springs and prototypes were tested to aid the recovery of loosely consolidated materials. To this end, having a flexible drilling contractor willing to work and innovate with the client is very important. The second area of major innovation occurred in the development of a pumping rig to flush boreholes prior to hydro geochemical sampling. To undertake this work, existing equipment had to be incorporated into a submersible electric pumping rig capable of entering the 6 cm plastic casing, and mounted on a light vehicle.

RESULTS

Geochemical Vectoring

There was little compelling evidence of metal anomalism in surface samples over the project area, from either standard soil samples collected during exploration activities or by research projects conducted by Salama et al., (2016). The average 60 m of Kalahari cover combined with a variable depth of water table resulted in the lack of a meaningful dispersion mechanism from paleo-redox horizons to surface.

While inefficient and expensive profile grid drilling is a highly effective exploration method in these environments. Vertical and lateral migration of metals can be identified and mapped though the analysis of cover mediums. Thick crystalline calcretes and silcretes have not prevented the dispersions of elements from bedrock to cover, most likely because the dispersion occurred pre- or syn-formation. Paleo-redox horizons are also really important metal scavengers in the Kalahari sequence, recording the original water table and redox front. Anomalous Cu, Co and Mo were identified from four acid leached analyses of paleo-redox samples, while Salama et al., (2016) (Figure 4) identified the hydromorphic dispersion of Cu, Ni, Co, Zn and As, using weak aqua regia and multiple hydroxylamine hydrochloride leaches.

Hydrogeochemistry was useful on two fronts: (1) as a vector to mineralization, and, (2) as pre-Kalahari geological mapping tool. Despite concerns of contamination from recent drilling activates, the enrichment of major ions (Mg, Na, Ca, K and SO_4) versus Cl demonstrated the interaction of groundwater with bedrock. The groundwater is typical of reducing, neutral to sub-alkaline shallow groundwater composition (Figure 6), however a second group of oxygenated, acidic (pH of 2.8 to 6) waters correspond to a signature similar to that of mine acid drainage (Figure 6).

The highly acidic samples are associated with elevated metal anomalism (Cu, Co, Cd, U, As, Zn) however this is a false positive most likely associated with Fe buffering and the waters themselves likely under saturated in relation to baseline chemistry. In comparison to other case studies (Leybourne et al., 2008, Downey et al., 2013) the groundwater from the project areas are not highly anomalous in any of the pathfinder elements (Cu, Co, Ni, As, Mo) with anomalous Cu occurring above 10 ppb (max Cu concentration = 96 ppb). While this may reflect the lack of a large ore body in the area, it could be also be due to the relatively short recharge time between flushing, pumping and sampling.

Mapping chrome and vanadium rich mafic units (typically gabbros) in the bedrock was particularly effective. There are several examples of false positives within the hydrogeological dataset, including the Namasere and Kajaja targets. These targets have a multi-element signature composed of Cu, Cd, As, Cr, V and Pb. The strong Cr and V element of these anomalies normalizes the signature to a mafic source, as opposed to hydrothermal mineralization (ground-truthed from available drill core).

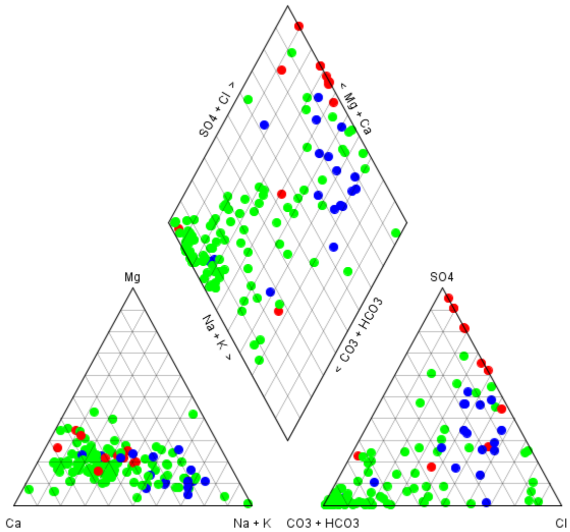

Figure 6: Piper Diagram (Red = acidic oxygenated, Green = Alkaline/Neutral reducing, Blue = Neutral reduced).

Geophysics

As an area reduction tool, the airborne EM proved vital in reducing the area from a district (14,500 km^2) to camp scale (1200 – 2000 km^2). The benefits of quickly focusing from district to camp scale targeting—by eliminating areas of thick cover and identifying domains of favorable stratigraphy—offset the relatively large cost of undertaking the survey.

The EM was extremely successful in mapping the Katangan metasedimentary rocks, i.e., carbonaceous shale units. CDI sections were also very successful in establishing the nature of the interface contact as well as the basement architecture and structure of the Katangan metasedimentary rocks.

FUTURE APPLICATIONS

Geochemical Sample Mediums

Exploration under total cover currently, to some extent, relies on the adaptation of existing geochemical tools or the expensive, yet effective, use of grid drilling. Realistically, in the long term exploration of covered targets will only be viable with the development of new indirect and direct detection geochemical tools, combined with geophysics.

There are a number of geochemical techniques, which have shown promise as potential 'cover busting' tools. Perhaps the technique with the greatest potential and upside is hydrogeochemistry and the rapidly developing use of stable isotopes.

Hydrogeochemistry

As an exploration tool, aqueous geochemistry of ground and surface waters, as well as stream sediments, has successfully been utilized in exploration (Leybourne, 2007). Groundwater has the potential to be a 'cover busting' tool, due to the deep percolation of ground waters through porous mediums and along fractures and faults, deep into the earths crust. Leybourne (2007) concluded the increasing interest in hydrogeochemistry to be result of the ongoing advances in analytical techniques and the increasing availability of inductively coupled plasma mass spectrometers (ICP-MS), while newer ICP-MS instruments allow routine multi- element analyses with low detection limits (sub-parts per trillion for many elements). There are detailed case studies for a number of deposit types, including: porphyry; VMS; sedimentary-hosted uranium; SEDEX; vein gold; and kimberlite intrusions (Leybourne et al., 2007). However there has been a lack of hydrogeochemical research in relation to sedimentary-hosted copper deposits, on which this paper is focused.

There are a number of different sampling techniques, the majority of which involve sampling pre-existing boreholes or water sources with bailers or pumps. An overview of the various methods has been outlined in detailed by Leybourne et al., (2007) and Gray et al., (2012).

One of the most comprehensive case studies is that of the Spence porphyry Cu deposit (Chile), in which groundwater elemental concentrations were used to vector to mineralization obscured beneath 30-180 m of Miocene piedmont gravels (Leybourne et al., 2008). The downstream signature of the deposit is Cu poor, yet are elevated in Se (up to 800 μg/l), Re (up to 31 μg/l), Mo (up to 475 μg/l) and As (up to 278 μg/l) in comparison to background water (Leybourne et al., (2008). This secondary footprint elevated in anions is a product of the groundwater chemistry, with the differential behavior of the metals/metalloids occurs because the former group dissolves as anions, enhancing their mobility, whereas the base metals dissolve as cations and are lost from solution most likely through adsorption to clay surface exchange sites and through formation of secondary copper chlorides, carbonates, and oxides (Leybourne et al., 2008).

Isotopes in Hydrogeochemistry

Although currently underutalized in hydrogeochemistry and exploration in general, light stable isotopes (e.g., O, H, C, and S) can be used to provide context and interpretation of (1) water sources; (2) mixing between multiple water sources; and (3) water-sulphide interactions (Cameron and Leybourne 2005; de Caritat et al., 2005; Kirste et al., 2003; Leybourne and Cameron 2006, 2008). As an exploration vector isotopes can offer an important contextual interpretative tool. This is particularly useful when integrating element concentration data where pH values are buffered and/or mineralization is deeply buried.

Case studies in literature are limited and although applicable there are currently no examples relating to sedimentary-hosted copper deposits. The main focused of the work to date has been the identifying water compositions and sources. Of particular interest as vectors to minerslization are S and Cu isotopes. Perhaps the premier example in literature is the use of sulphur isotopic composition of groundwater at the Spence porphyry copper deposit (Chile). Pueyo et al., (2001) demostrated the use of $\delta^{34}S$ to differentiate sulphur sources and vector mineralization with groundwater $\delta^{34}S$ values decreasing from values typical of regional waters and salars (Pueyo et al., 2001; Rech et al., 2003; Rissmann, 2003) to those typical of porphyry copper mineralization as waters flow into and through mineralization (Leybourne and Cameron 2006). Similarly de Cariat et al., (2005) reported that the S and O isotopic composition of dissolved sulphate from the Broken Hill SEDEX deposit in Australia could be utalised to vector to mineralization and yield a larger footprint than Zn, Pb, Cu concerntrations in groundwater.

Cu isotopes have great potential as direct vectors to copper mineralization, with studies concluding Cu isotopes and systems are a proxy for natural water-deposit interaction (Kimball et al., (2009). The premier example in the context of exploration is the Pebble porphyry Cu-Au-Mo deposit (Alaska, USA). Downey et al., (2013) measured the Cu isotopic composition of groundwater's and natural waters (e.g., ponds and seeps), reporting that $\delta^{65}Cu$ signatures could be used to vector to zones of active weathering sulfides. A trend in $\delta^{65}Cu$ weighting is also evident in the samples with samples collected proximal to mineralization producing elevated $\delta^{65}Cu$ signatures.

Soil and Gaseous methods

The detection of buried mineralization using soil mediums requires mobilization of at least one ion of interest through the cover. The key mechanisms for migration correspond to the source location, i.e., above (vadose) or below (phreatic) the water table. The use of gases and vapours as a vector to mineralization has been experimented with for the past 50 years (Klusman. 2009). An outline of the processes of gases migration are provided by Cameron et al., (2004) and include: (1) barometric pumping, cycles of low and high barometric pressure force air into the earth through porosity and fractures, and withdraw air mixed with gases from the rocks; (2) seasonal air and gas exhaustion from the vadose zone, during climatically colder periods, warmer air within the earth is exhausted and replaced by denser colder air; (3) migration as bubbles and bubble-generated aerosols, provides a mechanism for advective movement through the saturated zone.

More recently research has been driven, primary by a small number of academics focused on exploration of porphyry deposits through the Atacama post-mineral cover (Chile) and Nickel deposits though sedimentary cover of the Yilgarn Craton (Australia). Townley et al., (2007) provided field directions for the ORE HOUND GOCC® passive collector devices, which includes burial between 30 to 40 cm depth, for between 70 to 120 days. The principle objective of soil gas collection is the detection of ions and gases from source to surface.

There are a number of case studies from Western Australia demonstrating the effectiveness of ions and hydrocarbon adherence on ORE HOUND GOCC® collectors. Noble et al., (2013) reported results from the North Miitel Ni deposit (Yilgarn Craton, Australia), concluding that gaseous driven migration of Ni through the cover sequence at North Miitel had occurred and that soil gas mediums were viable exploration vectoring mechanisms.

Biogeochemistry

Biogeochemical and biogeobotanical prospecting methods are potentially important tools for the exploration of buried mineralization. Plant species, termed metallophytes, accumulate high levels of metals in proportion to metal content in the soil (Nkoane et al., 2005). The mechanics of metal uptake by plant roots were described by Kabata-Pendias and Pendias (1984) and include: (1) cation exchange by the root network; (2) transport inside cells by chelating agents and other carriers; and (3) rhizospheric effects. With post-mineral cover, the interaction of deep tapping root networks with anomalies associated with surface soils, zones within the post-mineral cover (e.g., paleo-redox horizons) or mineralization in the bedrock can provide a mechanism for metals to mobilize to the current paleo-surface. All parts of the plant antimony can be sampled, including roots, stems, leaves, and flowers. In Botswana a number of case studies have been undertaken to develop a biogeochemical toolbox for exploration through shallow Kalahari cover. Cole and Le Roex (1978) successfully used *Helicrysum Leptolepis* (Compositae family) to identify copper mineralization through shallow Kalahari cover in the Ghanzi area of northwest Botswana and *Ecbolium Lugardae* (Acanthaceae family) to vector copper mineralization though deeper Kalahari sand cover in Ngwako Pan area, Ngamiland (northwest Botswana). Most recently, Nkoane et al., (2005) demonstrated the uptake of metals from soils for two species of metallophytes; *Helichrysum candolleanum* and *Blepharis diversispina* in the Francistown area (Selkirk, Nakalakwana, Thakadu and Malaka) of the Botswana Kalahari.

Perhaps the most interesting biogeochemical work to-date has been undertaken by Lintern et al., (2013) who presented the first recorded case of particulate Au within natural specimens of living biological tissues from Eucalyptus trees growing above a zone of gold mineralization at the Freddo Gold Prospect (Kalgoorie, Western Australia). Gold imaged in leaves was derived from a zone of gold mineralization at 35 m depth and buried beneath 30 m of post-mineral sediments. Lintern et al., (2013) postulated the model for Au mobility to be the absorption and transport of Au from mineralization, through the root network and vascular system of the plant as ionic gold at sub-toxic concentrations. Reducing and precipitation of Au within the cells of the plant occurs. This essentially provides the evidence of process between the abiotic and biotic geochemistry.

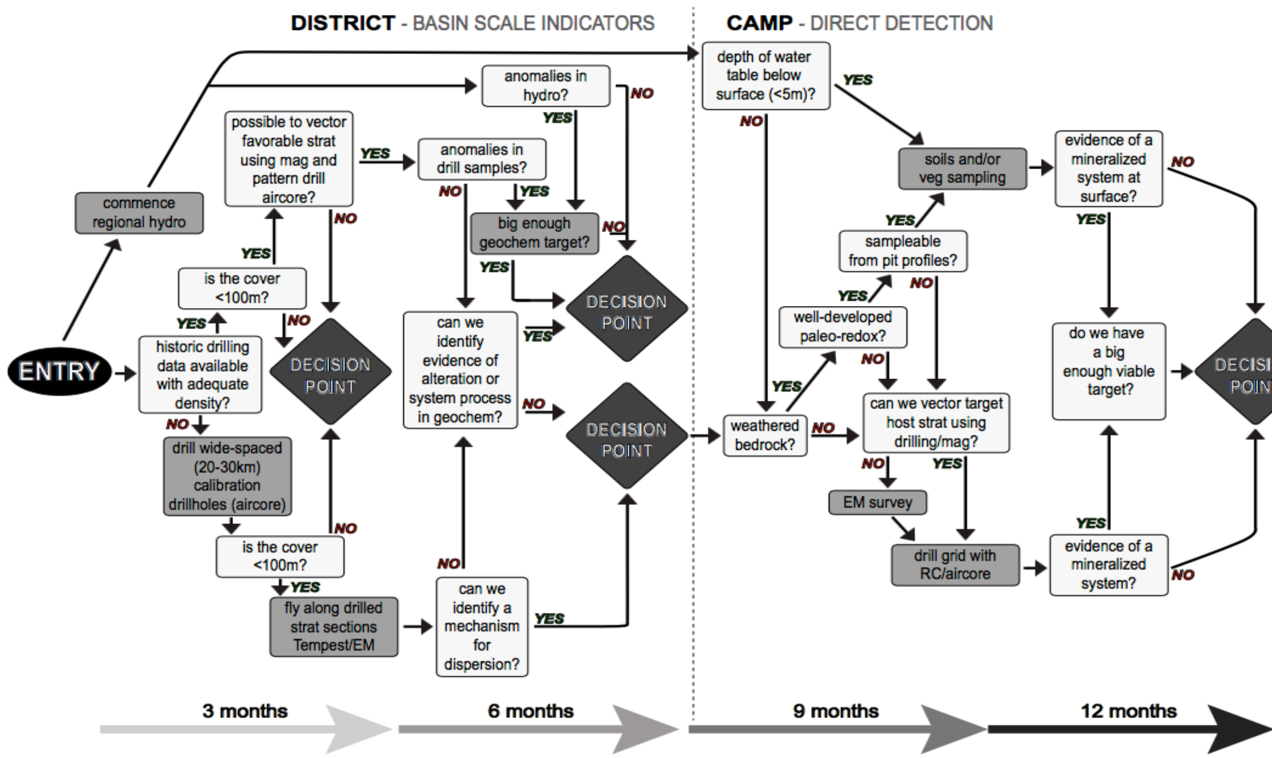

Figure 7: Undercover exploration decision flow chart.

Decision Tree – Flow Chart

One of the key outcomes from this case study is that effective decision-making in the covered environment is aided by the adherence to an established framework. To date the project has provided many lessons that will benefit mineral explorers attempting exploration projects in covered terranes elsewhere in the world. The project will no doubt continue to yield important lessons as further 'blind' exploration targets are tested in what is a world-class metallogenic belt.

Figure 7 is a sedimentary-hosted copper deposit specific flow chart for an approach to undercover exploration. This model relies on a minimal footprint approach with campaign style exploration, which reduces the upfront costs. Key information such as regional groundwater regime and types of vegetation are important to understand before choosing appropriate exploration tools and can have a significant impact on the geochemical mobility of elements through cover.

Ultimately, exit points are key to maintaining a realistic approach to undercover exploration. When considering exploration of covered terranes elsewhere in the world, it should be noted that even projects with exceptional geological attributes might be deemed 'unexplorable' if techniques prove less effective than those utilized in northern Botswana and discussed in this paper. Terranes, which cannot be explored effectively or economically, should be identified early, with early expenditures kept to a minimum to mitigate risk.

While at more advanced exploration stages the strict adherence to exit points will eliminate the risk of becoming lost in a project where tangible results are hard to come by and unknowns remain. The flow chart also aims to provide the reader with the favoured exploration techniques and tools based on the experiences from this case study and for a number of geological and post-mineral cover scenarios.

DISCUSSION

As geologists, we are most comfortable exploring in the traditional residual regolith environment (e.g., shallow soils or saprolite). The conundrum of post-mineral cover requires a change of mindset and an understanding of the mechanics of geochemical dispersion and secondary detection footprints.

Geochemical datasets in covered environments are complex. Whereas in shallow regolith settings, where single datasets (e.g., soil, and rock chips) are used, the variability of the cover profiles results in several uniquely different layers within the cover and bedrock profile (e.g., surface, bulk cover and interface horizon), which have to treated independently and then layered to identify evidence of geochemical plume development or coincident anomalism. This requires the interrogator to transfer 2D single layer thinking to a 3D setting. Having an understanding of the mobility of metals/metalloids and the differential behavior resulting from variations in groundwater chemistry and cover composition and porosity, as well as the different mechanisms for mobility through cover are important when choosing suitable geochemical tools and interpreting results.

While the techniques listed in the future applications chapter of this paper have proved effective on the vectoring of known analogs of mineralization, there are precious few examples of covered deposits discovered without the need for expensive grid grilling techniques. Of the geochemical tools currently being developed for the covered environment, hydrogeochemistry is by far the most advanced, while having the greatest potential. However there are still few detailed studies in literature which industry use to build confidence in a technique.

CONCLUSIONS

The continuing decline in discoveries of world-class mineral deposits demonstrates the need for explorers to extend their search space below cover. The paper serves as an example that may assist future explorers in working more effectively in such environments. However, extensive work is needed to develop new techniques, both geochemical and geophysical. The exploration program in northern Botswana is an example of effectively identifying high quality drill targets beneath transported cover in a greenfield environment. However, the true endowment of the belt will not be ascertained until all of these targets have been drilled. Ultimately some of the experimental techniques yielded important lessons that can be applied to future exploration projects in similar covered terranes.

- EM was the most effective area reduction technique utilized in this study, it allowed for the focusing in on prospective camps (belts of potential host rocks (shales)) and the identification of areas of deep cover (>100 m), which are likely unexplorable.

- Grid drilling (particularly diamond drilling) is an effective approach to covered exploration, yet it is expensive and generally inefficient.

- There are a number of emerging geochemical methods, including hydrogeochemistry, biogeochemistry and soil gas, all of which could have a significant impact vectoring in the undercover environment and mitigate the requirement for grid drilling.

- Hydrogeochemistry was an effective geochemical vector and pre-kalahari geology mapping tool.

- Lateral and vertical migration of metal ions from bedrock sources though the cover Kalahari cover (both interface and unconsolidated sand horizons) sequence has taken place.

- This case study demonstrates that in areas of thick Kalahari cover (average 60 m), surface geochemical sampling is largely ineffective or that a mechanism for dispersion has yet to be discovered.

- The reader should pay close attention to advancements in stable isotope geochemistry, particularly in hydrogeochemistry, as a potentially powerful undercover vectoring tool.

- Ultimately, success in the undercover environment, particularly ‘total cover’, relies on both technology, and perhaps more importantly, on the ability of geologists to adapt their thinking to this new environment where geological data density is poor and secondary dispersions and footprints are important.

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