Geological and metallurgical characteristics of banded iron formation associated detrital iron mineralisation in Central West Africa

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ABSTRACT

Recent exploration has identified the presence of detrital iron deposits (DIDs) associated with banded iron formation (BIF) units in the north-west of the Congo Craton, Gabon. The regional geology comprises a complex of granitoids and gneisses assigned to the Archaean Chaillu Complex, within which older slivers of lower amphibolite-grade greenstones are preserved including muscovite-biotite-garnet-bearing felsic schist, amphibolite and BIF. These units are typically overlain by several metres of residuum comprising colluvium, eluvium and duricrust. The residuum is overlain by a regionally extensive loess cover from 2 m to 10 m thick.

The DIDs occur within the weathered residuum as mostly unconsolidated gravels with lesser canga (CAN) duricrust draped over deeply weathered hematite. Head grades are in the range of 45 to 52 per cent Fe. Fresh BIF, located from 30 to 50 m below surface, is comprised of magnetite-quartz±amphibole. The detrital iron gravels are comprised of rod- and plate-shaped clasts of hematite (martite)-maghemite-goethite composition, in a ferruginous sand to clay-sized matrix. The DID form ridges and plateaus that coincide with magnetic highs defined using high-resolution ground magnetic surveys.

The field relations and petrography indicate that the detrital iron accumulations are the result of weathering (including enrichment) and erosion of primary BIF. This includes removal of quartz, further oxidation and re-cementation of BIF to form ferruginous caprock. This cap and the *in situ* oxidised BIF were subsequently disaggregated and liberated, and further weathered to form the detrital iron accumulations.

Metallurgical test work on bulk detrital iron samples has shown this material can be upgraded to lump and fines iron ore products with grades of 62 to 65 per cent Fe using simple scrubbing and wet screening, followed by dense media separation of the -1 mm fraction, with overall mass yields from 75 to 85 per cent. The test work indicates a high ratio of lump to fines products, sometimes exceeding 50:50.

INTRODUCTION

The north-western portion of the Congo Craton in Cameroon, Gabon and the Republic of Congo (ROC) comprises Archaean rocks of the Chaillu and Ntem blocks, which are dominated by a complex of tonalite-trondhjemite-granodiorite (TTG) rocks and gneisses (Schlüter, 2008, and references therein). This basement is partly obscured by the Palaeoproterozoic Francevillian Supergroup and by Phanerozoic cover of the Congo Basin.

Within the Archaean TTG complex, large rafts of greenstone belts occur, comprised of metasedimentary and metavolcanic units, and, in many cases, extensive banded iron formations (BIFs). Regionally, these BIFs can be grouped into those of the Ntem Block and those of the Chaillu Block, north and south of the Francevillian basins respectively (Figure 1).

Known iron mineralisation in the Ntem Block includes the Nkout, Mbalam, Nabeba, Avima, Badondo and Belinga

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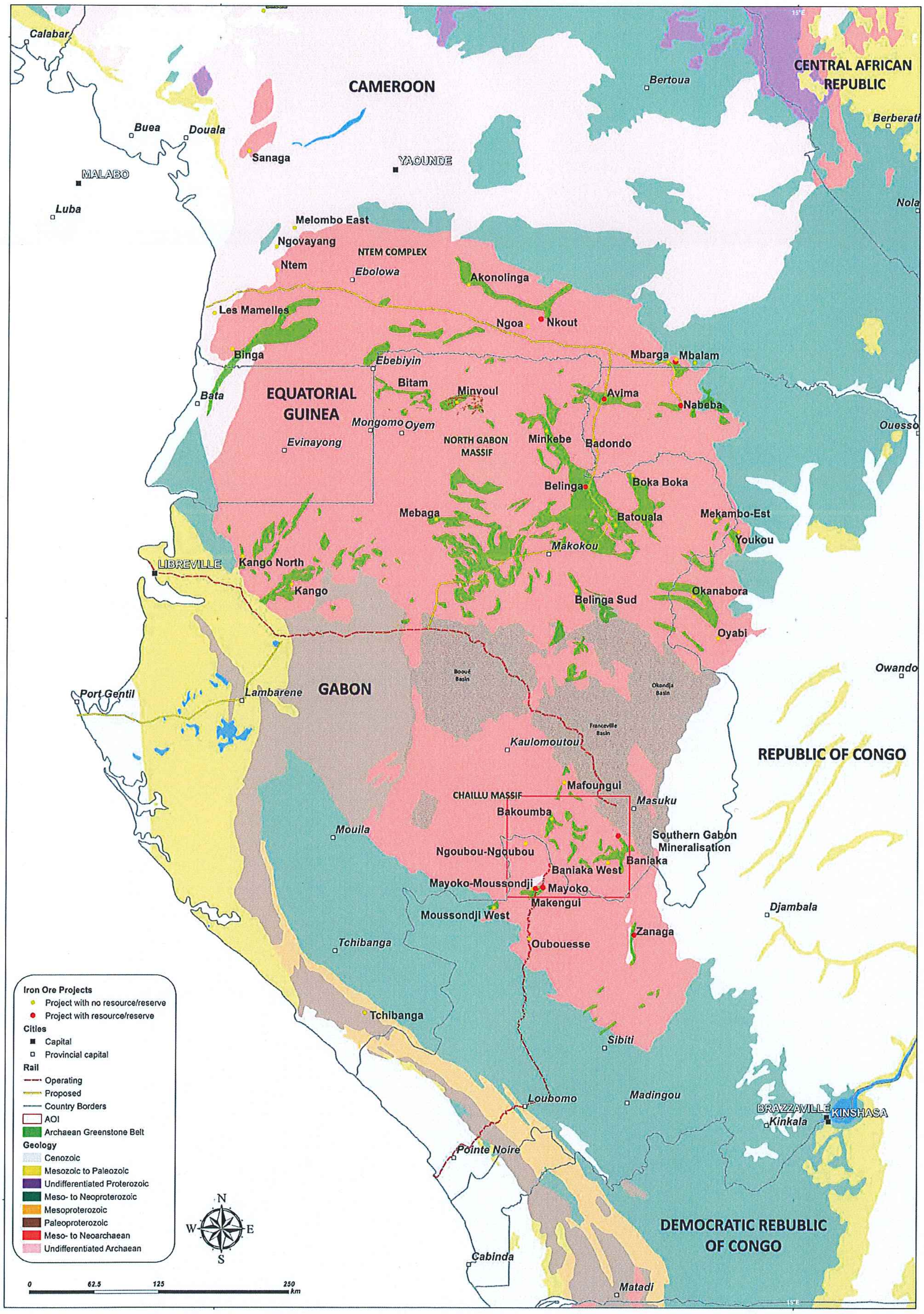

FIG 1 – Regional overview of the geology of Central West Africa, indicating greenstone belts and location of known iron ore deposits.

Projects (Figure 1). Projects are characterised by pronounced linear magnetic features, coinciding with outcropping BIF mineralisation over strike lengths of several tens of kilometres. Most of these projects have extensive resources (several billion tonnes) in primary BIF at grades of between 30–35 per cent Fe, and some have significant components of higher grade oxidised resources (Table 1). The projects are clustered around the ROC/Gabon/Cameroon triple border and will rely on the development of rail infrastructure either through Southern Cameroon or Gabon, and access to existing or planned deep-water port facilities in Cameroon or Gabon.

In the Chaillu Block, the Mayoko-Moussondji, Mayoko and Zanaga projects are the main iron ore projects in the ROC (Figure 1, Table 1). Like those in the Ntem Block, these deposits are characterised by pronounced linear magnetic highs along several tens of kilometres of strike length, coincident with outcropping BIF mineralisation. Each of these projects record significant primary BIF resources with components of oxidised higher grade mineralisation (Table 1). Successful exploitation of this southern cluster of deposits will depend on the re-establishment of the historic Mayoko-Pointe Noire Railway, and upgrades to the deep-water port at Pointe Noire.

A series of new iron prospects have recently been studied in southern Gabon, focused on a series of linear magnetic anomalies immediately south of the Francevillian basins. Mapping has shown these anomalies outline a series of greenstone belts, comprised of gneiss, amphibolite and BIF. The principal iron ore deposits occur as residual detrital iron deposits (DIDs) deposits preserved on top of underlying oxidised BIF and the upper supergene parts of the oxidised BIF. This paper summarises the geology and metallurgy of the DID and underlying oxidised deposits, focused on the Magnima, Baniaka and Kopa belts.

GEOLOGY OF THE PROJECT AREA

Overview

The study area is in the south-east of Gabon, near the provincial capital of Franceville (Figure 2). Regional scale mapping work (Martini, Makanga and Gnangamoukoula, 2001; Thomas, Makanga, Chevallier, 2001; Thiéblemont *et al*, 2009a, 2009b) identified two Mesoarchaean complexes of granitoids and gneisses. To the west, the Chaillu Complex occurs, dominated by a variety of tonalitic granitoids. These units are delineated to the east by an important sinistral shear zone, the Magnima shear that marks the western boundary of the Magnima greenstone belt and its along-strike continuation into the ROC (Figure 2). To the east of the Magnima shear, deformed orthogneisses and migmatitic units occur, which are ascribed to the Gabon Migmatite Complex. Within this complex, several discrete belts of mafic gneisses and metavolcanics occur, ascribed to the Belinga Group (greenstone belts) (Figure 2). Detailed mapping work confirmed five greenstone belts; from west to east, the Moussondji, Mayoko, Magnima, Baniaka and Kopa belts. These belts all have structural (sheared) contacts with the Chaillu Complex or Gabon Migmatite Complex. The greenstone belts are comprised mainly of amphibolite-grade mafic and intermediate gneisses derived from mafic and felsic volcanic and sedimentary protoliths and include laterally continuous 10–100 metres thick BIF units. To the north, metasedimentary and volcanic rocks of the 2.2–2.0 Ga Francevillian Group overly the Mesoarchaean units (Figure 2). Several E-W oriented magnetic lineaments were confirmed to be due to small dolerite/microgabbo dykes intruding both the Mesoarchaean and Francevillian units.

TABLE 1

Summary of iron resources in the study region.

Project	Resource	Source
Nkout	22 Mt @ 62.60 %Fe and 105.0 Mt @ 51.10 %Fe	Afferro website (6/10/2014)
Avima	580 Mt @ 60.00 %Fe	Core website (not dated)
Mbalam	153.8 Mt @ 62.88 %Fe	SNL database (20/05/2015)
Nabeba	363.1 Mt @ 61.92 %Fe	SNL database (20/05/2015)
Mayoko-Moussondji	Resource grades at 42 %Fe 42.5 Mt @ 44.4 %Fe	SNL database (31/10/2014) EQX ASX release 25/11/2014
Mayoko	Resource grades at 36 %Fe 74 Mt @ 46.1 %Fe (transported ore) 10 Mt @ 56.1 %Fe (caprock) 80 Mt @ 43.6 %Fe (eBIF)	SNL database (31/12/2014) Exxaro 2014 Mineral Resource and Ore Reserve Report
Belinga	349 Mt @ 64 %Fe	Sims, 1977
Zanaga	Resource grades at 31 %Fe	SNL database (31/12/2015)

EQX: Equatorial Resources Ltd; ASX: Australian Securities Exchange.

Geology of the banded iron formation units

Petrography

The petrography described below is based on a series of internal reports to Genmin Limited on various samples from the Baniaka project (ALS, 2016; Crawford, 2015, 2016; Townend, 2013, 2016; Townend and Townend, 2016). The BIFs occur as 10 to 100 metres thick units within a succession of amphibolites, paragneisses and orthogneisses. The paragneisses typically have quartz-muscovite-biotite-garnet mineral assemblages. The orthogneisses have a quartz-microcline-sodic plagioclase-muscovite-biotite ± clinozoisite ± tourmaline assemblage and, in several cases, intrude the BIF. Fresh BIF is comprised of alternating layers of quartz and magnetite, with individual layers rarely thicker than two millimetres. In least altered BIF, magnetite grains underwent minor hematite replacement along grain boundaries and fractures, while quartzose bands react via development of yellow-orange films of Fe-oxy-hydroxides on grain boundaries (Figure 3). Locally, BIF contains significant amphibole of hornblende, grunerite and occasionally actinolite. These amphibole-rich BIFs are composed of thin polygonal bands of quartz, interlayered with bands dominated by grunerite/actinolite in which thin bands or streams of magnetite occur. Other minerals found associated with the mafic bands are biotite, stipnomelane, epidote-clinozoisite and chlorite. The quartz-rich layers in some BIFs have polygonal textures with straight grain boundaries and 120° triple junctions, with uniform extinction suggesting equilibrium crystallisation in low strain conditions. Others show unstable, frilly margins with locally, undulate extinction indicating recrystallisation of quartz under conditions of strain.

Quartz-muscovite-biotite-garnet assemblages in felsic gneiss, the mafic amphibole-biotite±garnet assemblage in BIF and amphibolite, and pervasive recrystallisation of quartz in BIF suggest pressure–temperature (PT) conditions to have been in the lower amphibolite facies (500–550°C at 3–5 kbar). Some retrograde crystallisation of chlorite after biotite and sericite after K-feldspar indicates some retrogression to greenschist facies.

Structure

The Magnima greenstone belt defines a narrow linear belt of mafic and intermediate gneisses and BIFs that show upright tight folding along shallow north-plunging axial planes.

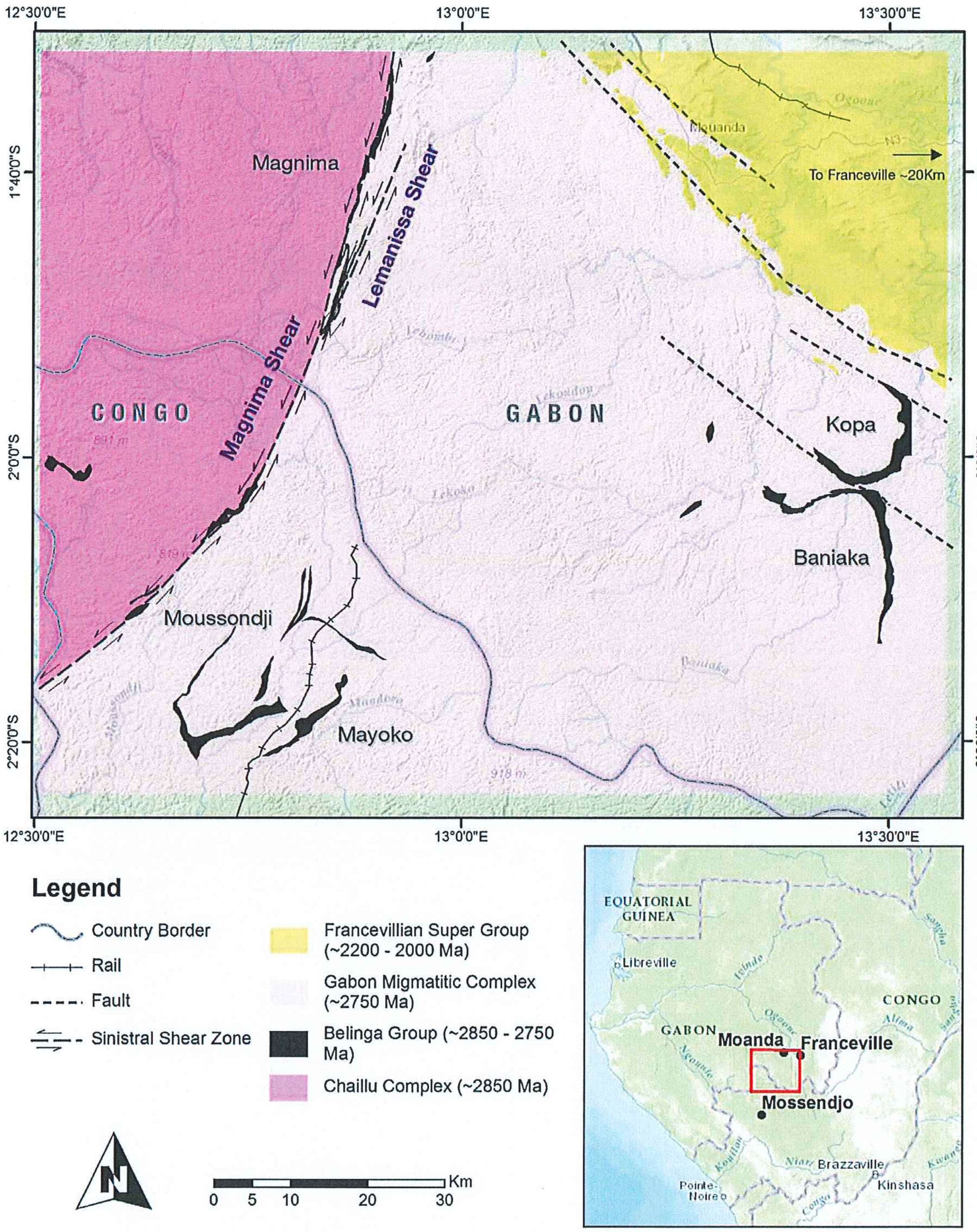

FIG 2 – Overview of greenstone belts in the study area.

Foliation data indicate a slight west-vergent geometry, suggesting some tectonic transport of the greenstones onto the Chaillu Complex along the Magnima shear during compression. The BIF units define a clear S-fold in the southern half of the belt, which together with stretching lineation data in sheared amphibolites and gneisses, suggests a late sinistral shear component to the Magnima shear.

In contrast, the Baniaka and Kopa greenstone belts form two arcuate belts, which wrap around basement domes of the Gabon Migmatitic Complex. Both belts are characterised by micro- to mesoscale tight to isoclinal folding within the BIF envelopes. Limited fold-axial planar lineation data in the southern part of the Baniaka belt indicate shallow northerly plunges of these folds. Several steep WNW trending brittle faults occur at Baniaka and displace the BIF. These faults are possibly related to the formation of the Lower Palaeoproterozoic Francevillian basins to the north. All margins of the greenstone belts show sheared contacts with the surrounding gneisses/granitoids.

Banded iron formation regolith

Based on auger and diamond drilling in the Baniaka and Kopa greenstone belts, weathering of BIF units extends from 30 m to 60 m below the present land surface. The uppermost

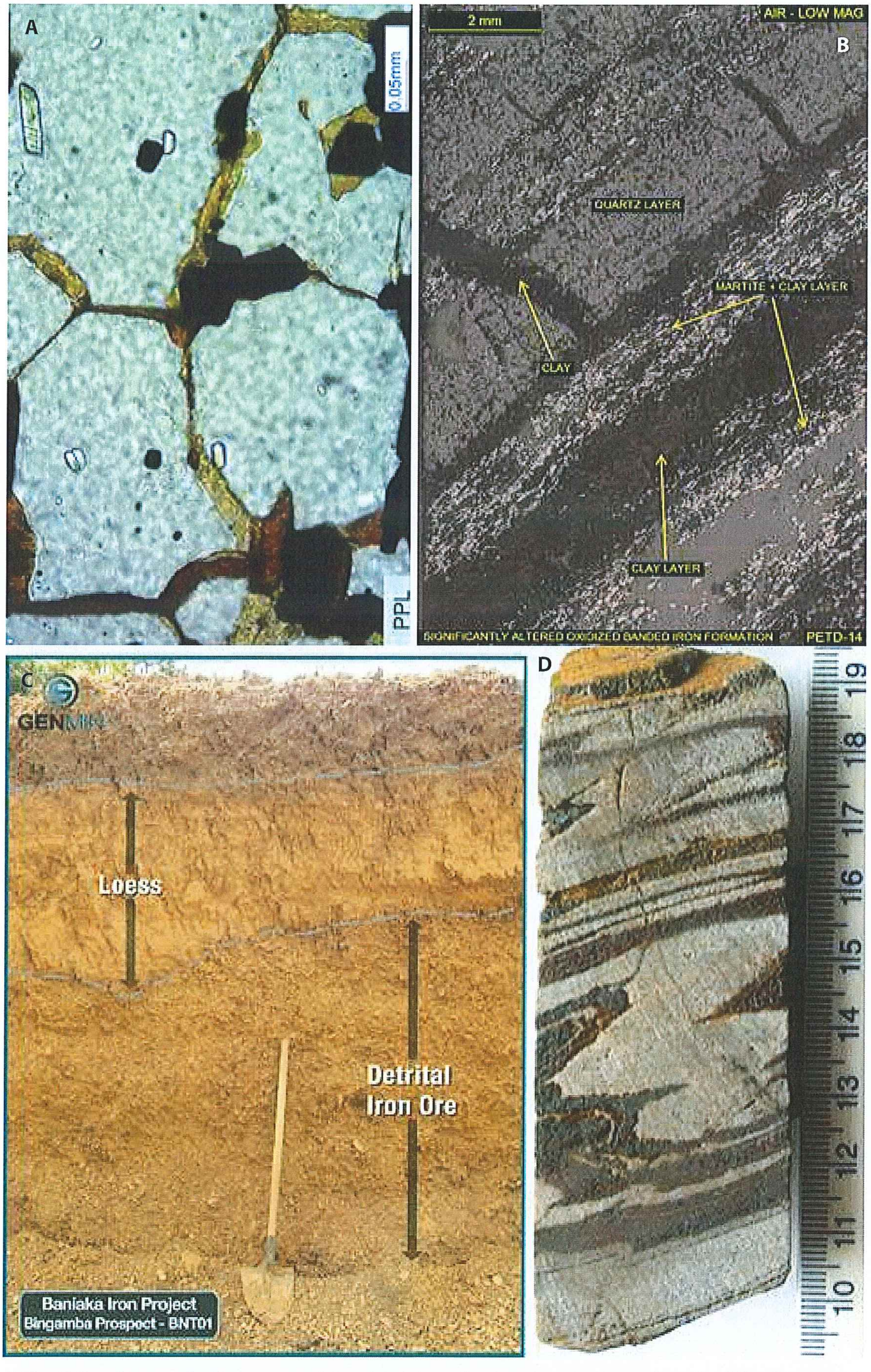

FIG 3 – (A) Films of Fe-oxy-hydroxides on quartz grain boundaries in banded iron formation at Baniaka sample number PETD28; (B) transitional green banded iron formation showing cracked quartz layers, magnetite bands now martite and clay bands after amphibole, sample number PETD14; (C) exposure of loess overlying detrital iron deposits at Baniaka, trench BNT01; (D) hard hematite core, sample PETD44 from hole BNDD012.

units of the regolith comprise a regionally extensive cover of loess underlain by a residuum of colluvium, eluvial lag and duricrust.

In the weathered zone, beneath the residuum and above the BIF protore, there is progressive hydration and oxidation of magnetite and amphibole, and depletion of silica moving upwards. Magnetite alters to hematite (martite) and Fe-oxy-hydroxides and the amphiboles are altered to clays and progressively replaced by hematite and Fe-oxy-hydroxides. The Fe-oxy-hydroxides also develop along grain boundaries of quartz (Figure 3) and, with the oxidation and alteration of the magnetite and amphibole, result in disaggregation of the BIF to form a fissile to powdery rock, composed largely of liberated quartz grains and hematite-martite.

The regolith profile from top (total oxidation) to bottom (partial oxidation to fresh) is summarised below. From base to surface there is a gradual increase in iron (iron grades below are from diamond core sample assays, minimum and maximum ranges of total Fe) and silica contents and a rapid decrease in amphibole content due to the supergene processes described above:

- loess
- residuum including detrital iron ore and duricrust (caprock and canga (CAN)) (46–57 per cent Fe)
- strongly oxidised plasmic-saprolite zone including disaggregated sandy to discoidal friable units (powder ore) (39–53 per cent Fe)
- partially oxidised saprock (hard hematite ore) (30–45 per cent Fe)
- transitional weakly altered BIF (green BIF) (32–39 per cent Fe)
- unaltered BIF (magnetite +/- amphibole BIF) (28–38 per cent Fe).

Geological model

A geological model was formulated for Baniaka based on exploration, which included geological mapping, geochemistry, petrology, trenching, pitting, auger and diamond drilling work (Figure 4).

Across the study area, a thin cover of yellow to light brown fine clay with minor silt occurs from 0.5–10 m thick. This is interpreted to represent a windblown blanket of loess (Thiéblemont *et al*, 2009b, p 268).

Beneath the loess a residuum is preserved on both the BIF and non-BIF lithologies, dominated by iron oxide and oxy-hydroxide and quartz particles and clays. The thickness of the residuum varies from 1 m to 16 m. The composition of the residuum varies depending on the substrate on which it is developed. On the country rocks, typically comprised of felsic schists, gneisses and amphibolites, often cut by recrystallised quartz veins, the residuum is comprised of nodules, quartz fragments, clays and occasional weathered bedrock fragments. The upper part forms an unconsolidated gravel and is referred to as lateritic colluvium (LCOL). This is typically underlain by a duricrust referred to as a lateritic duricrust (LAT). The duricrust comprises resistate materials from the substrate cemented by Fe-oxy-hydroxides. The gravel largely derives from weathering of the duricrust and often has a lag of the most resistant materials at its upper surface, referred to as the 'stone line'.

The residuum developed on top of the BIF and adjacent slopes comprises an upper unit of unconsolidated pebble- to boulder-sized gravels and a lower layer of duricrust. The gravels are referred to as DID and the duricrust as CAN or caprock. Preservation of the duricrust is variable and is most common on the flatter plateau areas.

The proximal CAN and DID are akin to eluvial lag deposits, often preserving a weak fabric from the substrate that has been subject to slope creep. Up profile and downslope, the DID is slightly more sorted with higher matrix content of fines material and is essentially a colluvium. Both the DID and CAN accumulations contain fragments of enriched BIF (eBIF) within a fine matrix comprised of fine-grained hematitic, goethitic-limonitic, silty material±quartz and loess. The eBIF fragments are often coarse-grained and clast-supported at the base, becoming matrix-supported towards the top as the proportion of in-mixed loess and clay increases.

In situ BIF is subdivided into four broad categories based on increasing depth, mineralogy, geochemistry and rock strength:

1. eBIF1 comprises of soft hematite ore logged as red powder ore (POR), grey powder ore (POG) and fissile hematite ore (FIO) and extends 5–30 m below the base of residuum; more than 80 per cent of original magnetite is replaced by hematite/martite or Fe-oxy-hydroxides, and the development of Fe-oxy-hydroxides along quartz grain boundaries and from alteration of amphiboles has resulted in complete or partial disaggregation of the original BIF.
2. eBIF2 comprises hard hematite ore logged as intact hematite ore and consists of hematite-dominant BIF with quartz beds clearly visible, extending 10 to 20 m further in-depth; although most magnetite (20–80 per cent) is replaced by hematite/martite, and Fe-oxy-hydroxides occur along quartz grain boundaries, the original fabric of the BIF is still present, and the rock has not entirely lost its integrity.
3. eBIF3, also described as transitional or green BIF (GBIF), is typically green/grey in colour from alteration of amphiboles and moderately magnetic. Here, oxidation of the BIF has resulted in partial (<20 per cent) replacement of magnetite by hematite and martite and amphiboles by clays and iron oxides; the original fabric of the BIF is evident, and the rock has not lost integrity.
4. Fresh BIF, being unweathered BIF, has magnetite as the dominant iron-bearing mineral. Three facies are defined being siliceous BIF (sBIF) comprising <20 per cent iron oxides, magnetite BIF (MBIF) comprised of alternating quartz and magnetite bands with limited or no amphibole, and amphibole-rich BIF (ABIF) with a significant proportion of amphibole in mafic bands.

Detrital iron deposits

The detrital iron deposits are classified into DID where >60 per cent of the clasts are BIF-derived (corresponding to a theoretical grade of >48 per cent Fe), hybrid (HYB) with between 30 per cent and 60 per cent of the particles being BIF-derived (theoretical grade between 37 to 48 per cent Fe), and LCOL, where <30 per cent of the fragments are derived from BIF (theoretical grade <37 per cent Fe).

Clasts in proximal BIF-derived eluvial deposits are angular, and many have high aspect ratios and occur as rods, interpreted to be preserved hinge zones of microfolds in the source BIF units. Other fragments have a platy aspect, representing fragments of limbs of original microfolds. The clasts are composed of hematite, goethite and kenomagnetite, and many are moderately magnetic.

Below the DIDs, strongly oxidised CAN caprock locally occurs at the interface between residuum and *in situ* rock. It contains small to large angular fragments of eBIF and varies

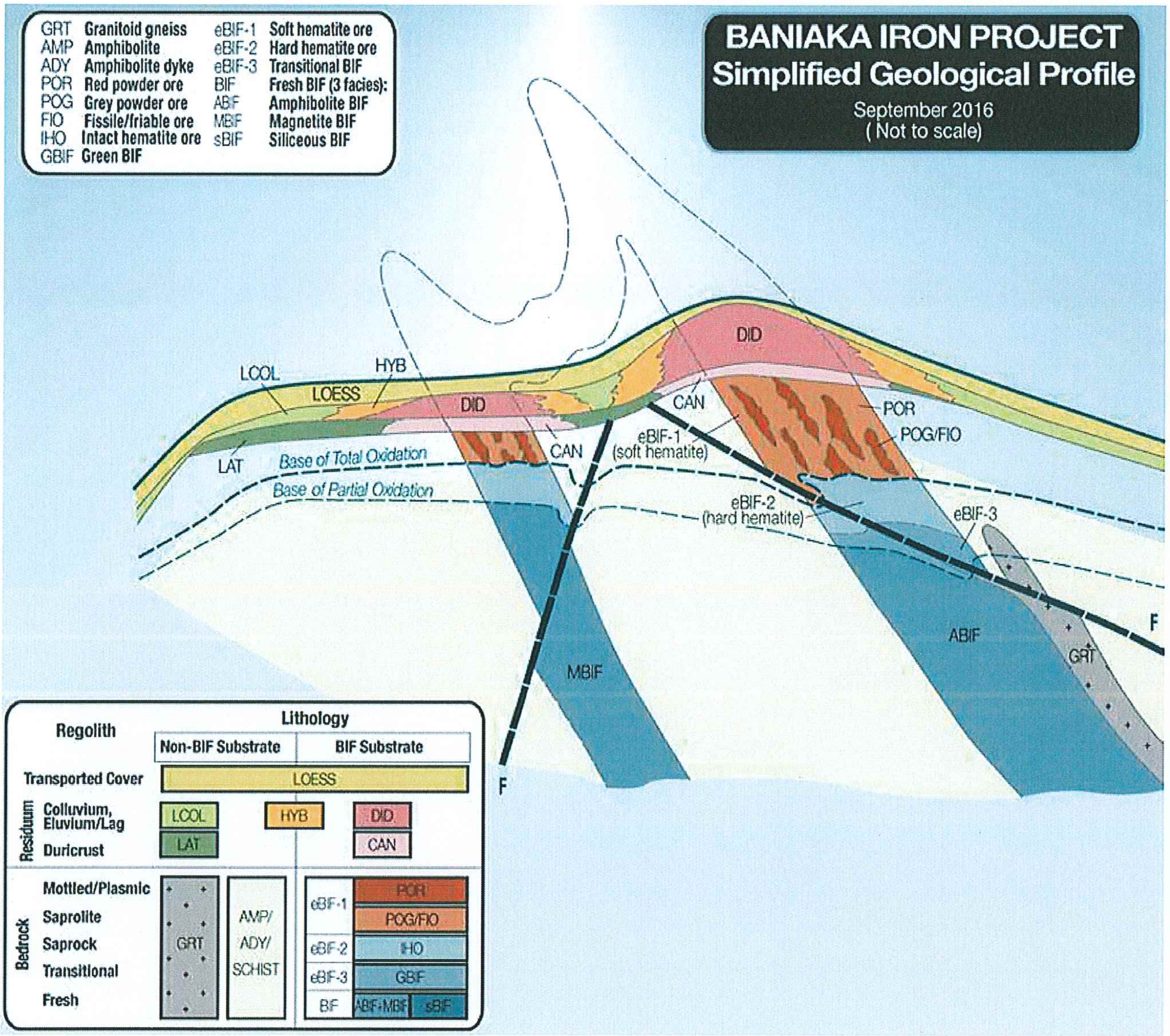

FIG 4 – Schematic geological profile of regolith at Baniaka.

from strongly to weakly cemented. The cement results from chemical deposition of iron oxides and oxy-hydroxides.

Below the caprock, strongly oxidised BIF occurs as plasmic (no original fabric) and saprolite (some original fabric preserved), materials where supergene processes have almost completely broken down and altered the BIF protore and removed a large component of the non-ore minerals. With increasing depth, these friable ores grade into semi-consolidated and then intact massive hematite BIF above the primary magnetite BIF.

METALLURGICAL TEST WORK

Ore types

Geological, geochemical, metallurgical and mining characterisation studies to date have focused on two ore types detrital (HYB and DID) and CAN ores (referred to henceforth as DID ores, see Figure 4), and soft hematite ore (referred to henceforth as powder ores). Work on the Baniaka DID is the most advanced, with introductory and bulk test work completed. Work on the hard hematite, transitional and magnetite BIF materials is at an early stage.

The detrital iron ores at Baniaka comprise a surface blanket covering kms of strike, 25-250 m wide and 1-16 m thick. The caprock component is minor and has a very similar composition to the gravel component. The distribution of the DID is reasonably continuous over the bedrock BIF units. Laterally, DID units shows a reduction in the eBIF clast content over tens of metres. The DID can be easily mined using surface strip-panel methods with a low stripping ratio.

The powder ore directly underlies the central thicker zones of detrital iron mineralisation and could be extracted in tandem with, or following the strip-mining of the DID.

Test work has shown both the detrital iron mineralisation and powder ore have very similar physical processing characteristics due to the clastic nature of the DID and the disaggregated particulate nature of the powder ore.

Sampling and test work programs

Metallurgical test work has utilised numerous representative samples collected from trenches (200 kg/sample), prospecting pits (10–50 kg/sample), small and large diameter auger holes (5–20 kg/sample) and diamond drill core composites (2–50 kg). Work on the Baniaka DID initially focused on determining the broad metallurgical attributes and developing a process flow sheet. Subsequent work has focused on assessing variability and better defining attributes such as bulk density and lump to fines ratios. Work on the powder ore is in the initial stages after which larger bulk samples will be tested.

The main DID metallurgical test work at Baniaka is based on seven large trench channel bulk samples and a further 54 samples taken from 28 pits. Two samples were taken from different depths in each pit to check for significant change in grade, granulometry and metallurgical response. Work on drill core composites of powder and hard hematite ores recently commenced.

Metallurgical sampling to date of DID on the Magnima belt is based on a total of 37 bulk samples from pits and a channel sample from a road trench. Work has commenced on a larger mass of bulk samples collected late in 2016.

The results of the work to date are reported in internal company reports (refer Loveday, 2014, 2015a, 2015b, 2015c, 2016a, 2016b, 2016c).

To assess any bias in particle size and grade distributions, comparative work to compare trench and pit samples with auger sampling has also been undertaken.

Results

The +1 mm fraction of the detrital iron ore type at Baniaka can be upgraded to lump (-31.5+6.3 mm) and fines (-6.3+1 mm) products, with grades >60 per cent Fe using a simple scrubbing and wet screening process. Oversize material (+31.5 mm) is crushed and returned through this circuit. Based on the pit samples with an average head grade of 51.6 per cent Fe, the average lump:fines ratio was 52:48. The mass yield of the lump and fines fraction averages 75–85 per cent.

Approximately 20 per cent of the feed reports to the -1.0 mm fraction. Test work on this by magnetic and gravity concentration showed this fraction to be amenable to upgrade, adding ~7 per cent of additional yield with either method, with product grades >60 per cent Fe. No significant changes were recognised with increasing depth. The grades of the individual products obtained were governed largely by the grade of the feed. The average grade of all of the detrital iron lump fractions was over 60 per cent Fe, while the average grade of all of the DID fines >1 mm fractions was 58.8 per cent Fe.

The detrital iron samples from the Magnima area recorded a higher proportion of lump versus fines >1 mm than in Baniaka, with mass yields of 70–80 per cent of the sample feed mass, similar to the yields reported at Baniaka. The lump iron content is consistently in the range 50–60 per cent Fe, with fines >1 mm grading between 45 and 55 per cent Fe. It is expected that DID mineralisation in the Magnima belt will be amenable to upgrade via a flow sheet similar to the one developed for Baniaka.

Sighter test work on two powder ore samples from Baniaka diamond drill core with head grades of 48.4 per cent Fe and 50.3 per cent Fe, showed that 31–38 per cent of all size fractions >0.5 mm graded from 51–65 per cent Fe (average 58 per cent Fe), indicating that initial concentration via wet screening through the detrital iron circuit would provide good results. Scanning Electron Microscopy (QEMSCAN, see: https://www.fei.com/qemscan/) analysis shows that the -1 mm fraction in both samples is mostly comprised of well liberated hematite and quartz particles. This suggests that good yields can be obtained using gravity separation methods such as spirals. Heavy Liquid Separation tests on the +45 micron -1 mm fractions (48 and 52 per cent of feed mass) indicated that approximately half this fraction could be recovered at >60 per cent Fe. In addition, the finer fraction <45 µm (approximately 18 per cent of the sample) is comprised of more than 80 per cent of iron hydroxides/oxides. A Davis Tube recovery test showed that 18 per cent of that fraction could be recovered and upgraded to 69 per cent Fe (Loveday, 2016b).

Metallurgical bias due to sampling method

Samples from three small diameter (90 mm) and 13 large diameter (150 mm) auger holes and adjacent pits were subjected to identical metallurgical test work to allow comparison between the sampling methods (Loveday, 2015c, 2016c, Table 2). In all tests, the head grade of the auger samples is reported as a few per cent lower, suggesting either loss of high-grade material or introduction of low-grade material in the auger sampling process. The size distribution analysis obtained from auger samples versus pit samples indicates an increase in mass for all fractions below 3 mm when sampling with auger. Moreover, there is a slight grade increase with diminishing size in auger samples, in comparison with the pit samples. The studies show that auger sampling alters the size distribution in the samples dramatically as compared to hand-dug pit samples. Yields of lump are greatly reduced (-20.5 and -26.0 per cent change for 90 and 150 mm auger respectively, Table 2), while the yield of fines >1 mm is modestly altered (-3.9 and -5.1 per cent yield for 90 and 150 mm auger respectively, Table 2).

DISCUSSION

Mayoko and Mayoko-Moussondji detrital mineralisation

The Mayoko and Moussondji belts are located south of the Magnima, Baniaka and Kopa belts discussed in this paper, and host the Mayoko-Moussondji and Mayoko projects respectively (Figure 2). At Mayoko, two types of detrital iron ore were described – transported ore, described as colluvium or detrital ore composed of mainly hematite in a clayey matrix; and capping ore, formed by supergene *in situ* enrichment and consisting of an agglomeration of variable-sized particles of hematite and goethite (Exxaro, 2014). The transported ore was shown to grade at 46.1 per cent Fe (Table 1), and mainly occurs on slopes alongside the BIF, while capping ore occurs on top of BIF (Exxaro, 2014). At Mayoko-Moussondji, BIF is reported to be overlain by *in situ* friable hematite, in turn overlain by colluvial hematite, which also extends onto slopes adjacent to BIF (Equatorial Resources Ltd, 2014). The overall grade of friable hematite and colluvial hematite was reported to be 44.4 per cent Fe. Based on these descriptions, DID similar to

TABLE 2

Summary of comparison test work on (90 and 150 mm) auger versus pit samples.

Sample	Per cent change compared to pit sample	
	150 mm auger	90 mm auger
Head	-1.8	-3.4
Lump mass yield	-26.0	-20.5
Lump grade (Fe%)	0.9	-0.9
Fines >1 mm mass yield	-3.9	-5.1
Fines >1 mm grade (Fe%)	2.2	0.1

those found in the Magnima, Baniaka and Kopa belts occur in the Mayoko and Moussondji belts, and have similar head grades at 45.55 and 51.60 per cent Fe respectively.

Supergene enrichment model

Based on mapping, pitting and drilling data, the DID described for the Magnima, Baniaka, Kopa, Moussondji and Mayoko belts are the result of cycles of deep weathering, erosion and 'hard-stand' periods. Although the mineralisation extends to depths well beyond the present-day water table, drill data shows only very localised evidence of hypogene alteration along later faults. Depth of oxidation is instead related to increased permeability of steeply-dipping BIF units along metamorphic layering, or to zones of increased fracturing (along fold hinges and adjacent to margin-parallel or cross-cutting faults). In this model, supergene (meteoric) fluids alter minerals in place (martitisation and cracking) and mobilise both iron and silica, with deposition of iron as oxy-hydroxides *in situ* and higher in the profile, and the gradual removal of silica from the system. Alteration of amphiboles to clays and replacement with re-mobilised iron up the regolith profile is an additional important process resulting in iron enrichment.

According to Burke and Gunnel (2008), the central African region has experienced tropical and subtropical conditions since at least sometime in the Early Cretaceous, providing a suitable time frame for the supergene processes that underpin the formation of detrital iron and powder ore deposits in the region.

Preservation of residuum

The detrital and duricrust deposits described in this paper correspond to residual materials, preserved on top of, or immediately adjacent to, bedrock BIF units. The occurrence of residuum appears to be controlled by the prevalence of low-relief topography, which promotes development of the residuum and allows its preservation. Given the fact that BIFs, composed of quartz and magnetite, are more resistant to chemical weathering than the surrounding country rocks, which contain feldspars and micas, BIFs often form elevated landforms including high ridges, low ridges and plateaus. In the Magnima and Mayoko belts, relief is more pronounced with higher elevations (700–750 masl and 800–840 masl respectively). The BIFs form steep ridges with narrow plateaus, while in the Baniaka and Kopa belts, the BIF units tend to form wide plateaus and rounded ridges at lower elevations (540–575 masl). As a result, there is extensive development of *in situ* residuum in the Baniaka and Kopa belts, while in parts of the Magnima and Mayoko belts, residuum appears to be more restricted. On tops of ridges underlain by BIF, ferruginous caprock developed with limited or no gravels, with any DID transported and diluted along the steep hillsides.

Thickness of the banded iron formation units

Work to date has shown that detrital iron mineralisation is most extensive, both in width and thickness, in the Baniaka and Mayoko belts, where the thickness of BIF has been locally estimated at 150 m at the Bingamba prospect, and 300 m at Mount Lekoumou respectively. In contrast, development of DIDs in the Moussondji belt and along the Magnima belt appears less extensive, both in thickness and width of mineralisation, while the BIF units in these belts are interpreted to have widths of <100 m. This seems to suggest that thicker BIF units provide a higher surface area available for weathering and Fe remobilisation, resulting in the development of more extensive DID.

Structural control

The BIFs studied here all have steep geometries, occurring in steep, upright, and sometimes overturned folds with dominantly shallow to gently-plunging fold axes. The folding resulted in structural thinning of BIF units along the limbs, and thickening in the fold hinges. In the Magnima, Baniaka and Kopa belts, this results in outcrop patterns showing narrow separate BIF units, merging into wider BIF units, interpreted to reflect exposure of hinge zones. The most extensive DIDs are located along those structurally thickened zones. Not only do hinge zones provide a structurally thickened BIF profile, but closely spaced subvertical cleavage along the hinge zones also potentially enhances rock permeability, which would promote deeper chemical weathering and oxidation.

In the Moussondji belt, the most significant mineralisation occurs at Makengui Hill, which was interpreted to be the locus of a boudin neck developed during the main folding event, and cross-cutting late fault (De Waele, Buckley and Jupp, 2012). In the Baniaka belt, the thickness of detrital iron mineralisation at the Bingamba prospect, in places seems to be linked to areas of demagnetisation on ground magnetic data, interpreted to relate to fault or fracture zones. We propose that late brittle faulting, in some cases reactivating earlier structures (boudin neck in Makengui Hill), resulted in increased permeability of BIF units, which promoted deeper levels of chemical weathering and oxidation.

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