Implicit Modelling of the Las Bambas Deposits, Peru.

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SUMMARY

3D implicit geological models are employed to better visualise, understand, and utilise all available data. They foster environments of robust dynamic analysis and interpretations, theoretical extrapolation and quantification of rock properties and mineral abundance. Through their use they encourage rigorous scientific discussion by allowing hypotheses to be explored virtually; maximising discovery and expansion.

The development of an implicit model for MMG's flagship project, Las Bambas in southern Peru, has advanced the understanding of the mineralising systems along with resource expansion and exploration opportunities. This model not only effectively demonstrates the major features of the system, but also provides a versatile experimental environment in which geological theories and generation of predictive geometries can, and are, frequently queried.

Las Bambas is a world class cluster of Cu deposits in the high Andes containing 12.8 Mt of contained copper. Eocene stocks, sills and dike swarms intruded Lower Cretaceous limestones of the Ferrobamba Formation, resulting in the generation of garnet-pyroxene-epidote-magnetite skarns, which were mineralised via magmatic-hydrothermal fluids flowing through permeable zones in the skarns and filling voids with bornite, chalcopyrite, chalcocite, and molybdenite mineralisation.

In this presentation, the value of implicit modelling is demonstrated by visualising the complex porphyry and skarn systems at Las Bambas, highlighting how it serves as an effective medium for illustrating deposit geometries and mineralisation relationships.

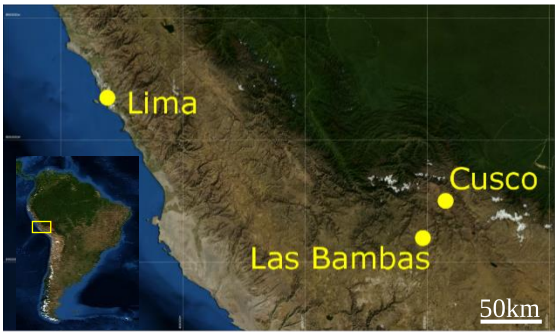
Key words: Las Bambas, Peru, Porphyry-Skarns, Implicit Modelling, Leapfrog Geo.

INTRODUCTION

Geological Overview of the Las Bambas Project

Las Bambas is located in a belt of Cu (Mo) deposits associated with porphyry/skarn systems situated in the Cotabambas Province, Apurimac Region, south-eastern Peru. This metallogenic belt is controlled by the Andahuaylas – Yauri Batholith of Eocene - Oligocene age (e.g., Perelló et al, 2003), consisting of multiple intrusions of calc-alkaline composition emplaced into Mesozoic sedimentary units, including the limestones of the Ferrobamba Formation. The intrusive rocks of the batholith, where in contact with the limestones in certain locations, focused skarn bodies with Cu (Mo) mineralisation.

This project consists of three proven porphyry-skarn deposits (Figure 1). The interaction with fluids from the intrusive rocks have resulted in the metasomatic growth of garnet-pyroxene-epidote-magnetite skarn causing volume loss in the host rocks which creates pore space. These skarns have then undergone mineralisation through the infilling of inter-crystalline spaces and veins with Cu – Mo sulphides from late stage magmatic – hydrothermal fluids (Cannell et al., 2017)



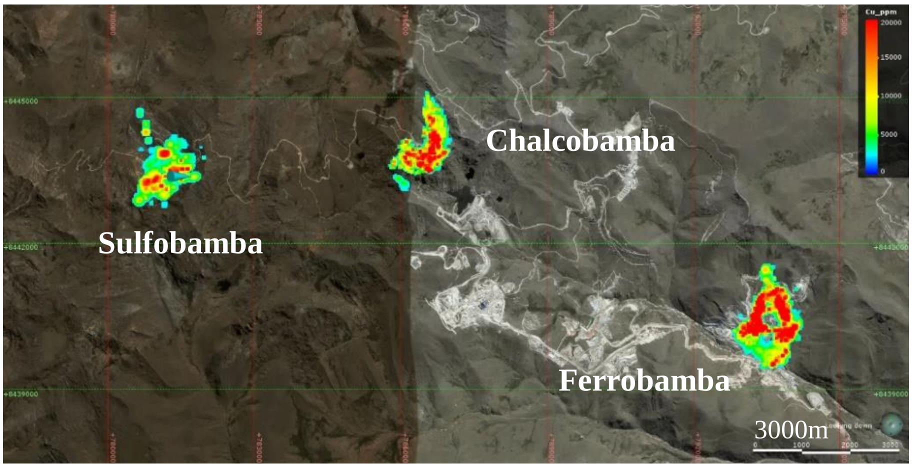


Figure 1. General Location (above), and (below) Las Bambas porphyry skarn deposits. Coloured by maximum vertical Cu grade from drilling (Blue: 0% to Red: >= 2%).

Both porphyry hosted and exo-skarn mineralisation styles are present, showing a proximal relationship to particular limestone monzodiorite contacts, possibly highlighting the syn-mineral intrusive phase. Most of the high-grade copper is hosted in the exo-skarn zones (Figure 2). Frequently observed is a progression of replacement from chalcopyrite to bornite to chalcocite, however, zones rich in magnetite remain chalcopyrite rich rather than progressing to bornite. Lower grade porphyry-style mineralisation is dominated by quartz, sulphide (chalcocpyrite, bornite) ± magnetite, biotite veins with calc-potassic halos (biotite, actinolite, K-feldspar, clinopyroxene). Endo-skarn mineralisation can also occur formed by pervasive pyroxene, garnet, epidote and sulphide mineralisation near the intrusive contacts. Three deposits have been defined to date at Las Bambas (Figure 1):

- Ferrobamba (1453Mt @ 0.62% Cu measured [M] + indicated [I] + inferred [In]) is characterised as a steeply dipping cylindrical skarn orebody of chalcopyrite with widespread upgrading to bornite ± chalcocite surrounding a pre/syn-mineral intrusive body, with further mineralisation along nearby limestone-monzodiorite contacts and some zones within the monzodiorites.

- Chalcobamba (338Mt @0.55% Cu M+I+I) is comprised of a roof pendant of limestone protolith which has been garnet-magnetite-chalcopyrite altered over monzodiorite and adjacent stockwork mineralisation

- Sulfobamba (304Mt @0.5% Cu I+I) is a southward shallowly dipping mineralised diorite contact, with a secondary north-east trend caused by a later dike generation.

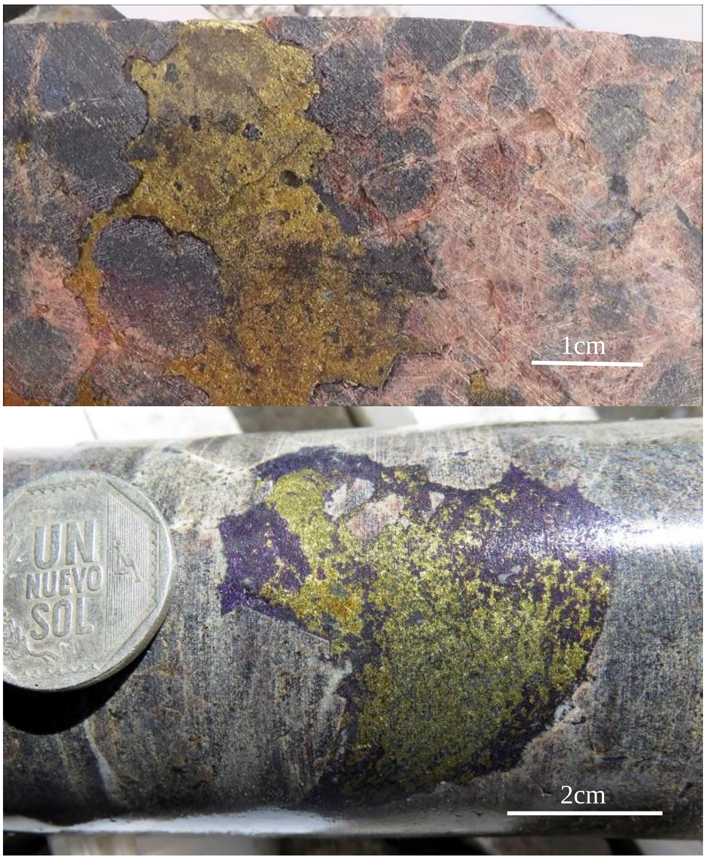


Figure 2: Above: Coarse magnetite altered garnet skarn with late stage chalcopyrite infilling, and partly replacing the garnet. Below: At Ferrobamba the chalcopyrite is commonly upgrade to bornite

The Role of Implicit Modelling at Las Bambas

The development of the Las Bambas implicit model has provided a geoscientific toolkit for geologists across project departments, which was not possible using previous systems. Historically, explicit methods were employed, using detailed 2D sectional interpretation which had absolute control over the final geometry of the orebodies and mine critical geology.

Implicit modelling was undertaken to move towards a data rich 3D environment where the visualisation of geological data was not only made available to every geologist, but where the interpretation of such a complex system could be done directly in 3D. A key requirement of the model was the ability to extrapolate surfaces into zones with sparse data as an aid to resource expansion and exploration targeting. In addition, the model needed to be a tool for quantification of mineral and rock properties, as well as to encourage the testing of competing geological hypotheses.

Implicit modelling relies on user defined rules that are applied to a selected dataset to automatically generate 3D surfaces and volumes. This allows geological interpretation to be updated quickly, or for multiple scenarios to be run simultaneously by simply altering the rules or data. This reduces the considerable time taken to formulate manual 2D re-interpretations and removes some occurrences of bias and error by geologists. The objects generated by an implicit model are predictive both between and beyond data points, allowing application of a rigorous scientific approach to test theories regarding relationships between units, extrapolated geometry, or zones of high grade without proximal data. The implicit model created within the Leapfrog Geo software has been highly effective in not only understanding the deposits at Las Bambas but communicating geological knowledge to stakeholders.

METHOD AND RESULTS

The Development of the Implicit Model Using the Leapfrog Geo Software

The process of generating an implicit model of protolith volumes can be categorised into 4 main phases:

- an initial inspection of natural trends,
- reclassification of geological logging and other data into model appropriate categories,
- object construction,
- chronological experimentation.

Iterative trend analysis involves the use of spheroidal radial basis functions (RBFs) to model each rock unit using downhole geological logging. From the initial observations of these objects, an anisotropic bias can be introduced to add a trend to the RBF interpolants, increasing connectivity along the geologist's preferred direction. The result of this first stage is a rapid understanding of the primary geometry of a deposit and a framework to build more geologically feasible volumes. In the case of Las Bambas, the geological database was found to contain considerable logging inconsistencies, largely due to the presence of numerous intrusive phases, similar in appearance. This first pass modelling was an effective way to highlight areas where data needed to be verified.

Initially, using only lithology classifications from the historical logging, thin intrusive units were often discontinuous when modelled due to misclassification in the logging of intrusive generation, or assumption of an incorrect geometry. This spurred a campaign of relogging and ore body knowledge studies which involved the relogging of 14drillholes on a type section detailing the lithologies, alteration and vein paragenesis, and then a further 100+ drillhole intervals throughout the deposit to extend the geological confidence in three dimensions. These studies identified 3 additional chronologically constrained sets of dikes, 1 set of sills, and 3 new intrusive stocks in addition to the 6 previously defined intrusive units, which were re-classified in a separate lithology column and propagated throughout the rest of the database (~300km of core) using the interval select technique (Figure 3). The end product is approximately 200 separate dikes with 11 intrusive generations. The geological volumes were then constructed using various implementations of the RBF algorithm to generate dike networks, intrusive stocks, and tectonic or formational boundaries.

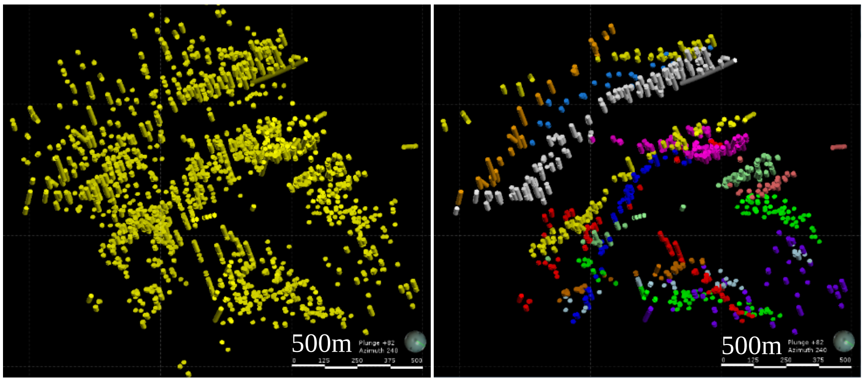


Figure 3: Left: Logging of the MZQ monzodiorite unit at Ferrobamba showing the initial state of the geological database. Right: Digitally re-logged MZQ where individual dikes have been classified as separate objects in order to model them as implicit interacting units.

Finally, geologically consistent volumes are created using Leapfrog Geo's automated workflow by assigning chronology to each object and simulating relationships akin to geological overprinting. Lithological classification is either included in the object (target lithology), excluded (older formations), or ignored (in the case of younger units, missing or irrelevant data). In a robust geological model, every volume affects every 'older' volume, thus if the chronology or classification is incorrect, the resulting volumes will be geologically unreasonable. At Las Bambas competing chronological theories and lithological groupings were tested extensively before geochronological analyses were available. An example of this are the breccia occurrences at Chalcobamba and Ferrobamba, initially logged as an amorphous body of tectonic and hydrothermal breccia. By modelling and discarding multiple scenarios, these were resolved into separate zones of tectonic breccia, bedding parallel breccia within the Ferrobamba limestone, and a shallowly plunging breccia pipe at Chalcobamba.

The final protolith model is represented by a consistent volume for each rock-type (Figure 4) and is then able to be used for analysis of numeric properties, i.e Cu Grade.

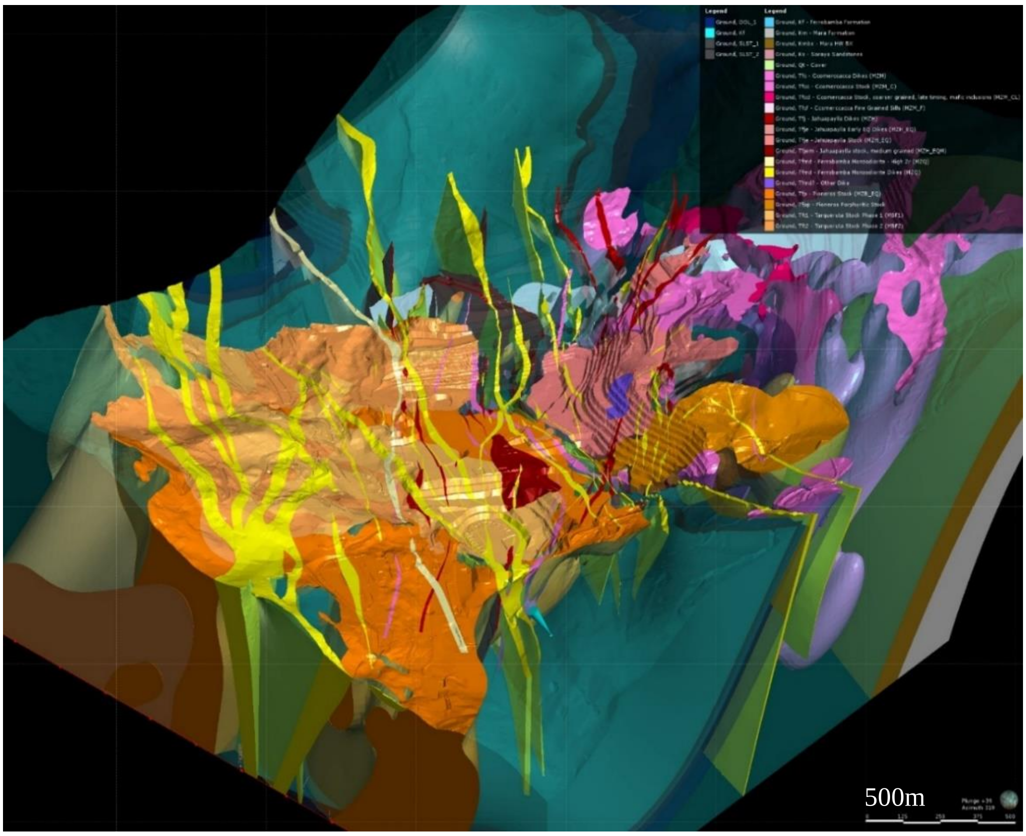


Figure 4: Final protolith model cut away to 2016 mining surface

Observations from the Interpolation of Rock Properties and Mineral Abundance

The protolith model serves to geologically domain numeric data from downhole assays, petrophysics and visual abundance or alteration logs so that the effect of multiple rock types is removed during interpolation. At Las Bambas assay data and visually logged estimates of minerals, and alteration were modelled using numeric RBF interpolants as an analogue for broad zones of propagation. The observations made using these methods include:

- Garnet interpolation within the limestone protolith at Ferrobamba shows a clear pattern surrounding the complex series of intrusions with higher abundances closer to the pre/syn-mineral Jahuapaylla monzodiorite stock (red, Figure 5) and to a lesser extent the earlier monzodiorite intrusions. Magnetite follows a similar pattern with a more restrictive extent surrounding the Jahuapaylla stock. Epidote is most abundant in endo-skarn with abundance mirroring the garnet pattern but located within the intrusive rock volumes.

- Cu grade within the exo-skarn matches the pattern of garnet abundance, with the same contacts favouring high grade mineralisation where a good precursor garnet skarn was formed. Again, nearby contacts are mineralised and show a reducing grade with proximity to the central Jahuapaylla stock (deep red, Figure 5). Mineralisation within the central Jahuapaylla stock is concentrated around its edges, and geological investigation of this zone indicates this mineralisation to be hosted in high grade quartz-chalcopyrite-bornite veins that are focussed around the stock margins, but do not continue into the centre of the stock. Modelling shows that the highest Bn:Cpy ratios are slightly removed from the contact. Spatial co-incidence of the stockwork hosted mineralisation and the exo-skarn mineralisation suggested that the two mineralisation styles are temporally and genetically related, which has been confirmed with geochronological dating (Cannell et al., 2017). Logging studies also established that endo-skarn mineralisation occurs in some of the other intrusive units (e.g. purple northern unit in Fig. 5), with the Cu grades matching the epidote contents.

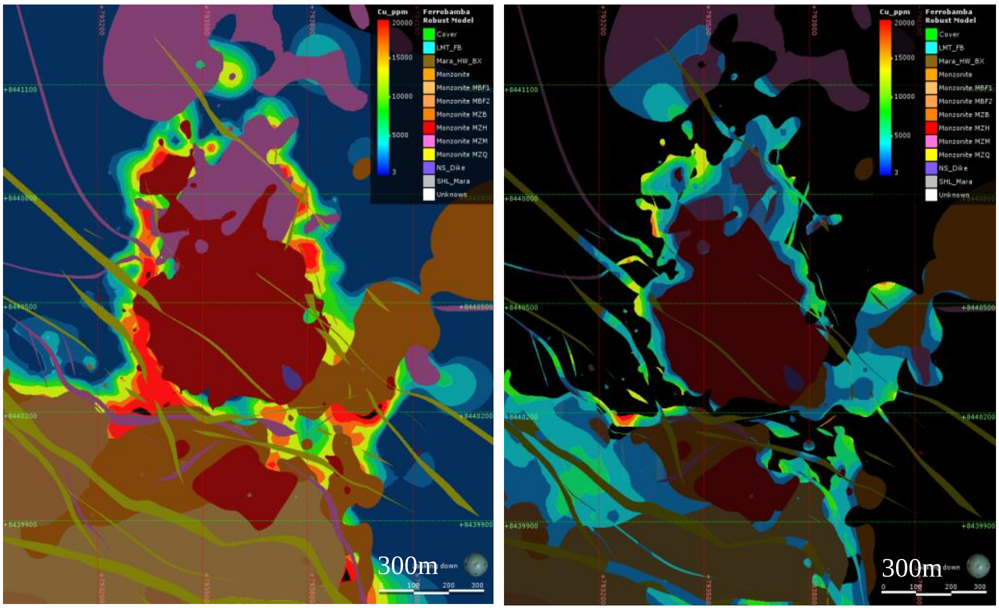


Figure 5: Interpolated Cu Grades within geological volumes. Left: Exo-skarn grade within limestone protolith volume which shows a strong relationship to the central Jahuapaylla Stock. Right: cu distribution inside the porphyries, due to porphyry stockwork and endo-skarn mineralisation. Both show a strong affinity to the - limestone contacts.

- After classification and modelling of the primary intrusive units, there remained numerous and disparate thin dike intervals that could not be modelled using the pre-existing codes. Subsequent geological studies found that although having some textural and compositional variability, they could all be grouped into the same family, and were denoted as Jahauapaylla porphyritic dikes as they appear to be overlapping in age with the Jahauapaylla stock, and have a similar relationship to mineralisation with vein stockworks and skarns forming at their contacts. Once grouped together, these dikes have been modelled to occur in several sets with different orientations, and which exert a secondary control on mineralisation.

- Large tonnage, low grade porphyry mineralisation in the south of Ferrobamba (Fig. 5) can be observed to pass through the boundaries of three intrusive stocks with no major change in grade on a north-west trend. This mineralisation is broadly zoned around the Jahuapaylla southern stock (deep red, smaller stock, Fig. 5), which forms a barren core composed of strongly developed but barren quartz veins with potassic halos. Sulphide percentages in these veins increase outwards, forming a halo of mineralisation in the early stocks, and local high-grade zones at the stock – limestone margins. In addition, north-west striking Jahuapaylla porphyritic dikes have local stockworks formed at their contacts and may have been partly responsible for this mineralisation.

- At Chalcobamba, most of the limestone protolith has been altered to magnetite-garnet skarn. Magnetite is inversely proportional and subsequent to garnet and is associated with the highest-grade chalcopyrite.

- A previous understanding of mineralisation at Sulfobamba denoted latite dikes as the responsible intrusive phase for the mineralisation due to broad ore trends being parallel to their north-east strike. Treating the dikes as a late unrelated object demonstrated that the grade in the limestone fills interstitial space and that the dikes are post mineral features. The contact with a shallowly dipping diorite is observed to be a more likely fluid pathway for further mineralisation, with a quartz-feldspar porphyry exerting a secondary control on mineralisation. This was confirmed by logging to be syn-mineralisation (Santos, 2017)

These observations were used in conjunction with other detailed studies to increase orebody knowledge and provide an understanding of resource extension potential.

Implicit Exploration Targeting

Appropriate targeting criteria may be used to automatically generate volumes representing mineral potential within the geological model. At each of the deposits at Las Bambas, the primary skarn hosting contacts were modelled as a thin layer inside the limestone volume and extrapolated at depth. Removing areas that were proximal to existing drilling or planned mining left a volume representing resource extension and exploration targeting potential. The result at Ferrobamba was a significant target zone plunging downward from known mineralisation (Figure 6). As new drilling information is loaded into the protolith model, the target zones shift to accommodate the additional information, allowing subsequent drilling plans to be modified with a very short turnaround.

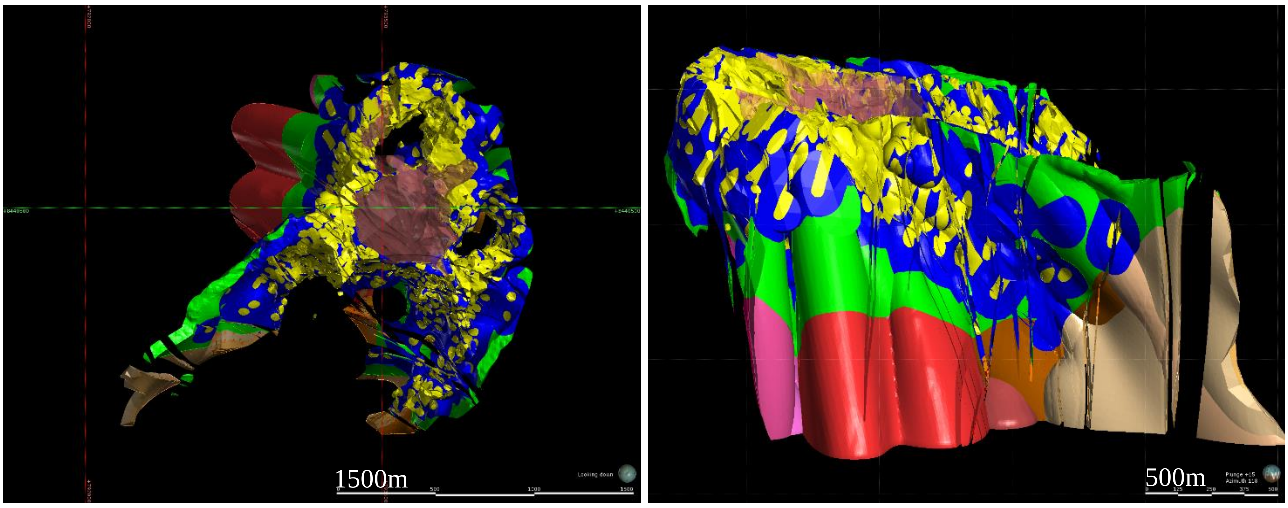


Figure 6: Plan (left) and oblique (right) view of extrapolated of target zone 'skins' proximal to likely mineralising fluid pathways split by a ranking classification. Yellow: 25m buffer around assay data. Blue: 100m buffer around assay data. Green: long term resource expansion. Red/pink/browns: exploration volumes where colour denotes proximal intrusive.

CONCLUSIONS

The generation of a 3D implicit model at Las Bambas has proven valuable for multiple reasons:

- The ability to perform scenario based modelling has led to a more robust interpretation of the configuration of the intrusive units, and breccia bodies at Las Bambas.
- Numeric interpolation has provided an effective way to visualise and understand the broad controlling factors on mineralisation including the identification of likely fluid pathways related spatially to certain intrusive phases.
- Automated generation of target volumes using extrapolated fluid pathways can give additional confidence to an exploration drilling program.

Implicit modelling is greatly enhanced by having geological understanding of the ore deposit and an established geochronological and structural framework, and in turn can feedback valuable information to the visualisation, modelling and interpretation of the ore deposit, and in the targeting of extensions to mineralisation.

ACKNOWLEDGMENTS

MMG Las Bambas	-	Alex Santos, Jim Wise, Steve Brown, Tyler Caswell, Quinn Smith,
MMG	-	Marcus Tomkinson, David Kelly, Helen Williams.

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