INCORPORATION OF ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT) DATA IN GEOLOGICAL MODELLING AS METHOD TO INCREASE MODEL ACCURACY IN UNSERPENTINISED ULTRAMAFIC HOSTED NICKEL LATERITE DEPOSIT

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ABSTRACT
Nickel laterites develop as residual soils over ultramafic terrain through the processes of chemical weathering. The formation of this residual deposit is controlled by the nature of the bedrock, climatic factors, degree of tectonisation and morphology of ground surface. If geological modelling of nickel laterite deposit is carried out solely based on drillholes, no other data support are used to assist the geologist in correlating the drillholes. Therefore, capability of a model to resemble the actual laterite layers surfaces (i.e., limonite-saprolite & saprolite-bedrock contact) depends heavily on the spacing of the drillholes. The denser the drillholes, the closer a model to the actual geological layer surfaces. In addition to that issue, incomplete drilling is also a problem faced by PT Vale Indonesia, Tbk (PTVI). It is one factor contributing to ore gain in resources and reserve reconciliation, which means that the yielded ore tonnage from excavation is greater than the estimated tonnage from a geological block model. It occurs notably for type of ore hosted by unserpentinised ultramafics. In this type of ore, large ultramafic boulders (up to 15 m) may present in saprolite zone and trick the geologists to conclude that they have penetrated the barren underlying bedrock. So, they stopped the drilling at the saprolite boulders. Consequently, drillholes and the resulted geological models are not deep enough; the resulted top-bedrock (or saprolite-bottom) correlations are inaccurate as well. When deal with these issues, ERT (Electrical Resistivity Tomography) is proven as powerful method. The ERT approach has the ability to image the variation of the geological surfaces irregularity between drillholes, including the top of the bedrock. Result of ERT interpretation can be a guidance for drilling and help geologist in the drillholes correlation as well. Recent study at unserpentinised hosted laterite deposit in one of Sorowako West Block’s area found that involvement of ERT result to the geological modelling increased the accuracy of the geological model. The study was carried out by comparing the geological models that are generated solely based on drillholes, with geological models that involving ERT as additional data. The comparation revealed that limonite and saprolite bottom surfaces of previous model, that are generated solely based on drillholes, was observed much smoother than the ERT guided model. In fact, over-smoothing is clearly observed in the previous model, disregarding the local laterite surface irregularity between holes. In some areas, the interpreted saprolite-bottom from ERT are deeper than the saprolite bottom of the drillholes, suggesting indication of incomplete drilling. The study also resulted in that saprolite volume of ERT guided model in study area was by ratio 119.5 % bigger than the previous model’s. This result alligns with the resource and reserve reconciliation outcome that suggest an ore gain in the unserpentinised saprolitic ore.

I. INTRODUCTION
Currently, geological modelling of nickel laterite deposit at PTVI is carried out solely based on drillholes. Despite topography has been taken into account for consideration, correlation between drillholes is simply done by the sense of the geologists. No other data support are used to assist the geologist to correlate the drillholes. Therefore, capability of a model to resemble the actual laterite layers surfaces (i.e., limonite-saprolite & saprolite-bedrock contact) depend heavily on the spacing of the drillholes. The denser the drillholes, the closer a model to the actual geological layer surfaces. While laterite layers geometry are very irregular, drillholes spacing are mostly at 50 m for measured resources, and farther for indicated & inferred resources. In many cases, these drillhole spacing could not capture the variation of the layers depth and thickness between those
holes due to the irregularity of the layer surfaces.

In addition to that issues, incomplete drilling is also a problem faced by PT Vale Indonesia, Tbk (PTVI). It is one factor contributing to ore gain in resources and reserve reconciliation, which means that the yielded ore tonnage from excavation is greater than the estimated tonnage from a geological block model. It occurs notably for type of ore hosted by unserpentinised ultramafics. In this type of ore, large ultramafic boulders (up to 15 m) may present in saprolite zone and trick the geologists to conclude that they have penetrated the barren underlaying bedrock. So, they stopped the drilling at the saprolite boulders. Consequently, drillholes and the resulted geological models are not deep enough; the resulted top-bedrock (or saprolite-bottom) correlations will be inaccurate as well.

An effort was then made by PTVI Exploration section to overcome these issues. Geophysics is an option. PTVI started with Ultra-GPR survey. However, the Ultra-GPR have weakness when working in high dielectric soils and dense forest as in Sorowako laterite, where presence of surrounding trees may cause significant interference to the result. Furthermore, the radar is only capable of imaging the top of bedrock to maximum depth of 20 m. While, the bedrock depth at Sorowako may up to 65 m.

In 2012, PTVI started with ERT (Electrical Resistivity Tomography) trial, and the result was encouraging. Despite the ERT does not produce actual samples, ERT approach has the ability to image the variation of the irregularity of the geological surfaces between drillholes, including the top-bedrock. When used together with drillholes, primacy of each data can provide better information to produce a model that more resemble the actual geological surfaces without requiring very close space drilling. It becomes the answer for the incomplete drilling issue as well. When top-bedrock can be predicted before drilling, we can reduce the number of incomplete drillholes and make more accurate geological model.

To follow up the survey, a study was later performed to review the current geological model of the area. Current models that are generated solely based on drillholes are compared with model that guided by ERT outcome & drillholes. Comparation include the shape of geological surfaces and saprolite volume to observe the differences between them.

II. LATERITE DEVELOPMENT

Nickel laterite develop as residual soils, typically over mafic and ultramafic terrain through the processes of chemical weathering (Ahmad, 2005). In general, the laterite consist of several zones, i.e, 1) bedrock zone; 2) saprolite zone; and 3) limonite zone (Figure 1, Figure 2 & Figure 3). The bedrock zone lies at the very bottom of the laterite profile. It marks the original ultramafic rock that has not yet been affected by the processes of tropical weathering. Saprolite zone lies above the unaltered bedrock. It consist of partially to completely decomposed boulders under the influence of tropical weathering. The process of weathering started along joint and fracture surface and have resulted in the formation of “boulders” within the saprolite zone. Original rock textures are still recognizable and the weathered profile has not collapsed yet. Limonite lies at the top of the laterite profile. The limonite zone represent the ultimate products of tropical weathering of ultramafic rocks and residual concentration of non-mobile elements (Ahmad, 2009).

III. RESISTIVITY SURVEY THEORY

As it is a form of resistivity survey, the purpose of ERT (Electrical Resistivity Tomography) is to determine the subsurface resistivity distribution by making measurement on the ground surface. The ERT is a combination of electrical sounding and profiling. Loke (2004)
described that the ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock.

To understand the resistivity survey concept, we can start from the simplest case with a homogeneous subsurface and single point current source on ground surface (Figure 4). In this case, the current flows radially away from the source, and the potential varies inversely with distance from the current source. The equipotential surface have a hemisphere shape, and the current flow is perpendicular to the equipotential surface (Loke, 2004).

In reality, the resistivity measurements are made by injecting current into the ground through two current electrodes (C1 and C2 in Figure 5), and measuring the resulting voltage difference at two potential electrodes (P1 and P2).

From the current (I) and potential (ΔΦ) values, an apparent resistivity (ρ_a) value is.

\[ \rho_a = k \frac{ΔΦ}{I} \]

\[ k = \frac{2\pi}{\left( \frac{1}{r_{C1P1}} - \frac{1}{r_{C1P2}} - \frac{1}{r_{C2P1}} + \frac{1}{r_{C2P2}} \right)} \]

k is geometric factor that depends on the arrangement of the four electrodes (Loke, 2004).

The calculated resistivity value is not the true resistivity of the surface, but an “apparent” value that is the resistivity of a homogeneous ground that will give the same resistance value for the same electrode arrangement. The relation between “apparent” and the “true” resistivity is a complex relationship. To determine the true subsurface resistivity from the “apparent” resistivity values is the “inversion” problem (Loke, 2004).

Two-dimensional electrical imaging tomography surveys are usually carried out using a large number of electrode, 25 or more, connected to a multi-core cable (Loke, 2004, after Griffiths & Barker, 1993). Normally, a constant spacing between adjacent electrode is attached. The electrical tomography method requires collection of data at several multiple of a to provide information at range of depth, termed n levels of data points to build a pseudosection (Figure 6).

IV. ERT SURVEY & LATERITE ELECTRICAL PROPERTIES

A serie of ERT survey trial have been carried out in Sorowako for types of ultramafics with varying degree of serpentinitisation. The survey uses the ABEM-Terrameter LS 8 channel and employ the gradient array configuration, instead of the conventional array such as Wenner, Schlumberger, Pole-Dipole or Dipole-Dipole. The main advantage of this gradient array is the quickness for greater number of points because it works on 8 channel. The gradient array is able to acquire a large set of data. Various couples of M-N (potential electrodes) are simultaneously measured for a same couple of A-B (current electrode) injection (Figure 7). Gradient array also offers the best resolution in the sub surface (Levieux & Savin, 2014; Dahlin & Zhou, 2004, 2005). Results obtained by gradient array are equivalent to the combination of a pole-dipole and dipole-dipole array, and combine the following advantages : good surface resolution, great depth of investigation and good resolution of vertical structures (Levieux & Savin, 2014). To reach the maximum of investigation 70 m, or top bedrock at 65 m, 7 m of electrode spacing is selected for survey in Sorowako laterite (Levieux & Savin, 2014). The measured individual ERT line length vary from 441 m, up to 2 km. For long lines with length more than 441 m, the survey uses the roll-along technique.

After 3 years of trials with totally 90 km of lines, we arrive to conclusion that ERT works on its best performance on laterites that hosted by unserpentinised ultramafics.
Nevertheless, it is also working for the laterites that hosted by moderately or highly serpentinised ultramafics as well. A case study in one of Sorowako West Block deposit which hosted by unserpentinised peridotite resulted in that the laterite is divided into four geoelectrical layers as shown on Figure 7 (Levieux & Savin, 2014), i.e :

1. **An upper conductive layer**, 100 to 250Ωm. This layer is matching with upper limonite substratum (red limonite) with high rate of Al (2.5<Al<10%) and quasi-null rate of silicate (SiO$_2$<5%).

2. **An upper resistive layer**, 250 - 100Ωm. This layer occurs for all lines but not continue all along each line. This layer is matching with lower limonite (yellow limonite) substratum which have lower Al rate (<2.5%) and higher silicate rate (5<SiO$_2$<20%).

3. **A lower conductive layer**, 30 to 250Ωm. This one is matching with saprolite layer. The presence of silicate or freshrock boulders will increase the resistivity value of saprolite layers and hide some likely conductive area.

4. **A lower resistive layer**, 300 to 3000Ωm. This layer is matching with the bedrock.

**V. DOMAINING WITH ERT DATA**

Sinclair & Blackwell (2004) pointed out that domains are important in mineral inventory estimation because characteristics of one domain can have different on estimation than do characteristic of another domain. Based on their physical properties and chemical variability, domaining in nickel laterite deposit usually divided into three main group, the limonite, saprolite and bedrock. Nickel ores are mostly in the saprolite, depend on the assigned cut-off grade (Figure 3). From drillholes, we can easily separate those domains by their physical and chemical properties. Problem arises when we have to correlate them and define domains in areas between the drillholes since laterite profile is very irregular. A nickel bearing saprolite can be 5 m thick in a drillhole. Just 10 meters apart, the saprolite thickness can be reduced to zero (Figure 3). That is the main problem in drillholes correlation in nickel laterite deposit. We never know what really happen between the drillholes until we mine it.

The ERT survey gave the answer for this problem. As limonite, saprolite and bedrock has a distinguish geoelectrical characteristics, we can trace surface irregularity between holes of each domain. Figure 9 and Figure 10 illustrate the interpretation of limonite-bottom (LIM-BOT) and saprolite bottom (SAP-BOT) from an ERT data. The picture shows clearly how the limonite bottom and saprolite bottom are very irregular. Bedrock pinnacles may appear in the saprolite bottom. While, Figure 11 and Figure 12 show the comparison between the domains of current model that generated solely based on drilling, with the new geological model that supported by ERT data. When no data between drillholes, geologists tend correlate by dragging an almost straight line between holes. Thus, the resulted correlation tend to be oversmoothing, disregarding the local domain variation between holes.

In Figure 11, we can also observe that the interpreted saprolite-bottom from ERT are lower than the drillholes. This phenomenon suggests the indication of incomplete drilling, or a situation where the are not deep enough. It suspected that drillholes stopped in the saprolite boulder, than supposed in the bedrock. The consequence if we create model with this kind of problem is that the potential ore zone beneath the boulder will not be modelled. Therefore, it will not be surprising if the reserve reconciliation resulted in an ore gain, or condition where the yielded ore tonnage from excavation is greater than the estimated tonnage from a geological model.

**VI. VOLUME COMPARISON**

To investigate further, a volume to volume comparison was carried out for saprolite in the ERT survey area. The study area in Sorowako
West Block which have dense ERT lines is selected. Here, the ERT lines are 441 – 553 m long with 50 meters space between lines. The saprolite volume of current geological model that made solely based on drillholes was compared with saprolite volume of model that also supported by ERT data aside to drillholes. The calculation was performed with Datamine Studio 3 software and resulted in that the saprolite volume of the ERT supported model is by ratio 119.50% bigger than current models. This result allign with the resources and reserves reconciliation result that suggest an ore gain in the mining progress. Furthermore, the ERT data support is expected to bring improvement in the domaining process for the resources estimate. Thus, risk of discrepancy between block model and actual mine due to domaining can be reduced.

VII. CONCLUSION
Conclusions that can be drawn from the study are as follow :

1. Result on ERT survey work in laterite that hosted by unserpentinised ultramafic showed that the profile consist of four geoelectrical properties, i.e, the upper conductive layer for red limonite, upper resistive layer for yellow limonite, lower conductive layer for saprolite and lower resistive layer for bedrock.

2. The distinguish electrical properties for each laterite layer can help geologist in correlating layers (limonite, saprolite and bedrock) between drillholes, and enable the correlation to include the lateral variation of layer surface between drillholes.

3. With better correlation, we can obtain the better domains for the geological modelling and better resources estimates for the nickel laterite deposit. Thus, the risk of discrepancy between block model and the actual mine due to domaining can be reduced.

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Fig 1. Simplified laterite profile on a hill (Ahmad, 2009)

Fig 2. Comparison of conventional laterite classification and equivalent soils horizons (Ahmad, 2009)
Fig 3. Irregularity of the laterite layers, the limonite, saprolite and bedrock.

Fig 4. The flow of current from a point current source and the resulting potential distribution (Loke, 2004)

Fig 5. A conventional array with four electrodes to measure the subsurface resistivity (Loke, 2004)
Fig 6. The arrangement of electrode for a 2D electrical survey and the sequence of measurement used to build a pseudo section (Loke, 2004)

Fig 7. The moving gradient array configuration (Loke, 2004)
Fig 8. Representation with iso-contour of resistivity and chargeability. Black lines and number are referring to rank of geoelectrical layer: 1) upper – conductive layer; 2) upper – resistive layer; 3) Lower – conductive layer; and 4) lower – resistive layer (Levieux & Savin, Geophysical, 2014)

Fig 9. 3D representation showing all ERT- 2D south – north profile. Black triangles is contouring an obvious vanish of the first conductive layer (Levieux & Savin, Geophysical, 2014)
Fig 10. Final geological characterization of the geo-electrical system for the unsepentinised ultramafic hosted laterite (Savin, 2015)

Fig 11. Interpreted laterite layers for the laterite layers, the upper limonite bottom (red), lower limonite bottom (orange) and saprolite bottom (green).

Fig 12. Comparison between current geological model (current BM) and ERT guided model of the limonite-bottom & saprolite-bottom surface at
Fig 13. Comparison between current geological model (current BM) and ERT guided model of the limonite-bottom & saprolite-bottom surface