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Ni grade distribution in laterite characterized from geostatistics, topography and the paleo-groundwater system in Sorowako, Indonesia

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ABSTRACT

Many nickel (Ni) resources and reserves originate from laterite-type deposits in which the grade distributions are generally controlled by the Ni content of the original strata, the degree of weathering, groundwater–rock interaction and the overall strata thickness and distribution. This study aims to clarify the three-dimensional (3D) Ni grade distribution and variation at a mine in the Sorowako area, central Sulawesi Island, Indonesia. Using geostatistics, the relationship between Ni and other chemical components is investigated, as well as topographic effects. Modeling of the grade distribution is achieved using ordinary kriging for single variables because the correlation of Ni with other components is weak. The modeling suggests that relatively high-grade zones are concentrated below a specific topographical type; that is a slight to moderate slope in the 5–19° range. The topography has likely controlled groundwater infiltration through rock fractures formed by the long-term tectonic processes affecting the area and the resultant groundwater interaction with the Ni-bearing strata. The initial Ni is carried as a dissolved phase and precipitated elsewhere, generating the Ni accumulation. By regarding the paleo-groundwater system as one controlling factor on the grade distribution, the thicknesses of limonite and saprolite layers formed by weathering are modeled around rock sampling points with flow being directed from the thinnest to the thickest points in each layer. This model is supported by the presence of Ni-bearing goethite in almost all the samples obtained from the limonite and saprolite layers. Notably, the 3D grade model indicates that the estimated paleo-groundwater flow direction corresponds with the transition from low to high Ni grades around the sampling sites. Weathering is therefore considered to have progressed along the paleo-groundwater flow direction, enhancing the thicknesses of limonite and saprolite layers, as well as the Ni grades, by prolonging the reaction between ferrous minerals and groundwater. The topographic control is considered to have enhanced recharge, infiltration, and reaction of groundwater.

1. Introduction

Ni deposits occur in two main types: laterite and magmatic sulfide deposits. Laterite deposits are more important in terms of the production volumes of Ni, with 70% of the global Ni demand originating from such (Dalvi et al., 2004). Although Ni laterite deposits are understood to have been generated by intense weathering of ultramafic igneous rocks, the Ni grade distribution is typically highly complicated by many interacting factors. These factors include the parent rock type, meteorological conditions, topography, tectonic setting, geological structure, groundwater, composition of organic material, and rates of weathering (Brand et al., 1998; Gleeson et al., 2003). One or more of these factors may be the predominant factor controlling the Ni grade distribution; however, they may vary between deposits and even within the same deposit. This causes the Ni grade distribution to be highly changeable and unpredictable.

Many studies have been devoted to understanding the enrichment processes of Ni in laterite deposits, taking the host rock and mineral composition and their influence on supergene Ni products into account (Colin et al., 1990; de Oliveira et al., 1992; Proenza et al., 2008; Talovina et al., 2008; Thorne et al., 2009; Gallardo et al., 2010; Alevizos and Repouskou, 2011; Sagapoa et al., 2011). Other important observations on Ni grade distribution have been made, such as enrichment from the weathering of serpentine minerals (Zeissink, 1969), Ni grade correlation with other metals (Co, Cr, Al, and Fe) concentrated in the residue of laterites (de Vletter, 1978) and the existence of mineralized veins causing high Ni grades (Dowd, 1992).

Rock fracture systems are also important in the enhancement of Ni grade in saprolite layers because they form preferential pathways for dissolved Ni transportation and ultimately precipitation (Pelletier, 1996). Meteorological conditions have also been identified as a key factor in Ni enrichment (de Oliveira et al., 1992; Lewis et al., 2006; Herrington et al., 2007; Thorne et al., 2012).

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Nevertheless, the distribution of Ni grade in a deposit, taking into account modeling of the controlling factors, requires more detailed investigation. The purpose of this study is to clarify these issues by spatial modeling of Ni grade using geostatistical techniques, and by considering the effects of topography and paleo-groundwater flow. Two software packages have been used to this end, ArcGIS®Geostatistical Analyst and S-GeMS (Stanford Geostatistical Modeling Software). In addition to borehole data, mineralogical and chemical analysis of soil and rock samples was undertaken using Energy Dispersive X-Ray Spectroscopy (EDX), X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), and petrographic studies achieved through optical microscopy.

2. Material and methods

2.1. Study area and geological setting

Sulawesi Island in central Indonesia contains one of the richest Ni laterite deposits in the world. Many of the individual deposits are concentrated in the Sorowako area of the South Sulawesi Province (Fig. 1). The international Ni mining company, PT. INCO Indonesia, developed this deposit and has been mining it since 1968. A total of 294 boreholes have been advanced in a lattice pattern along an E–W transect 1.6 km in length, and a N–S transect for 1.0 km across the deposit, to an average depth of 26.62 m below ground level. Within each borehole, metallogenic and chemical compositions were recorded at 1-m intervals (Table 1). The boreholes are spaced at 50-m intervals (Fig. 2), and given the density of geological data thus available, this deposit was selected as the test site for the Ni grade modeling presented here.

Sulawesi Island is situated at a triple junction of three tectonic plates; the Indo-Australian plate, the Pacific plate, and the Eurasian plate. The plate movements of these have been tracked as towards the north, west and south-southeast, respectively. The generation of the Ni laterite deposits is closely related to these convergent plate movements, given the development of active faulting, extensional basins and generally complex geological structures throughout the Cenozoic (Macpherson and Hall, 2002). The 'K'-shape of Sulawesi Island is attributed to four principal lithotectonic belts, which are bounded by large-scale tectonic dislocations and comprise the West Sulawesi Volcano-Plutonic Arc Belt, the Central Sulawesi Metamorphic Belt, the East Sulawesi Ophiolite Belt, and the continental fragments of Banggai-Sula, TukangBesi, and Buton (Fig. 1) (Mubroto et al., 1994; Kadarusman et al., 2004). The study area is located in the East Sulawesi Ophiolite Belt in which Cretaceous ultramafic rocks crop out because of subduction processes which occurred in the Miocene, approximately 10 Ma ago (Golightly, 1979; Suratman, 2000).

The Sorowako area is composed mainly of three rock units: Quaternary alluvial deposits and lacustrine deposits, Tertiary ultramafic rocks such as harzburgite in which the Ni laterite deposits are hosted, and Cretaceous sedimentary rocks (Golightly, 1979; Suratman, 2000). Most deposits are located in hill and low mountain topographic regions

Table 1
Borehole sample data indicating depth, Ni, Fe, SiO_2 and MgO content, layer and rock type, and mineralogy. The depth ranges of data at all sites were classified into three layers: limonite, saprolite, and bedrock.

Drillhole number	Depth range (m)	Ni (wt.%)	Fe (wt.%)	SiO_2 (wt.%)	MgO (wt.%)	Layer	Rock type	Primary mineral
A103966	0.20–1.00	1.04	45.20	7.80	1.50	lim		hmt
A103966	1.00–2.00	1.03	47.70	6.50	1.30	lim		hmt
A103966	2.00–3.00	1.09	48.80	5.70	1.20	lim		hmt
A103966	3.00–4.00	1.02	48.80	5.40	1.30	lim		hmt
A103966	4.00–5.00	1.18	46.90	6.40	1.60	sap		hmt
A103966	5.00–6.00	1.25	44.00	8.60	1.60	sap		hmt
A103966	6.00–7.00	0.29	7.30	34.70	41.20	sap		olv
A103966	7.00–7.90	0.29	7.20	26.70	30.60	bdr	hrz	olv
A103966	8.00–9.00	0.32	8.20	23.60	27.00	bdr	hrz	olv
A103966	9.00–10.00	0.29	7.10	27.30	31.50	bdr	hrz	olv
A103966	10.00–11.00	0.32	8.90	29.00	31.90	bdr	hrz	olv

lim: limonite, sap: saprolite, bdr: bedrock, hrz: harzburgite, hmt: hematite, olv: olivine.

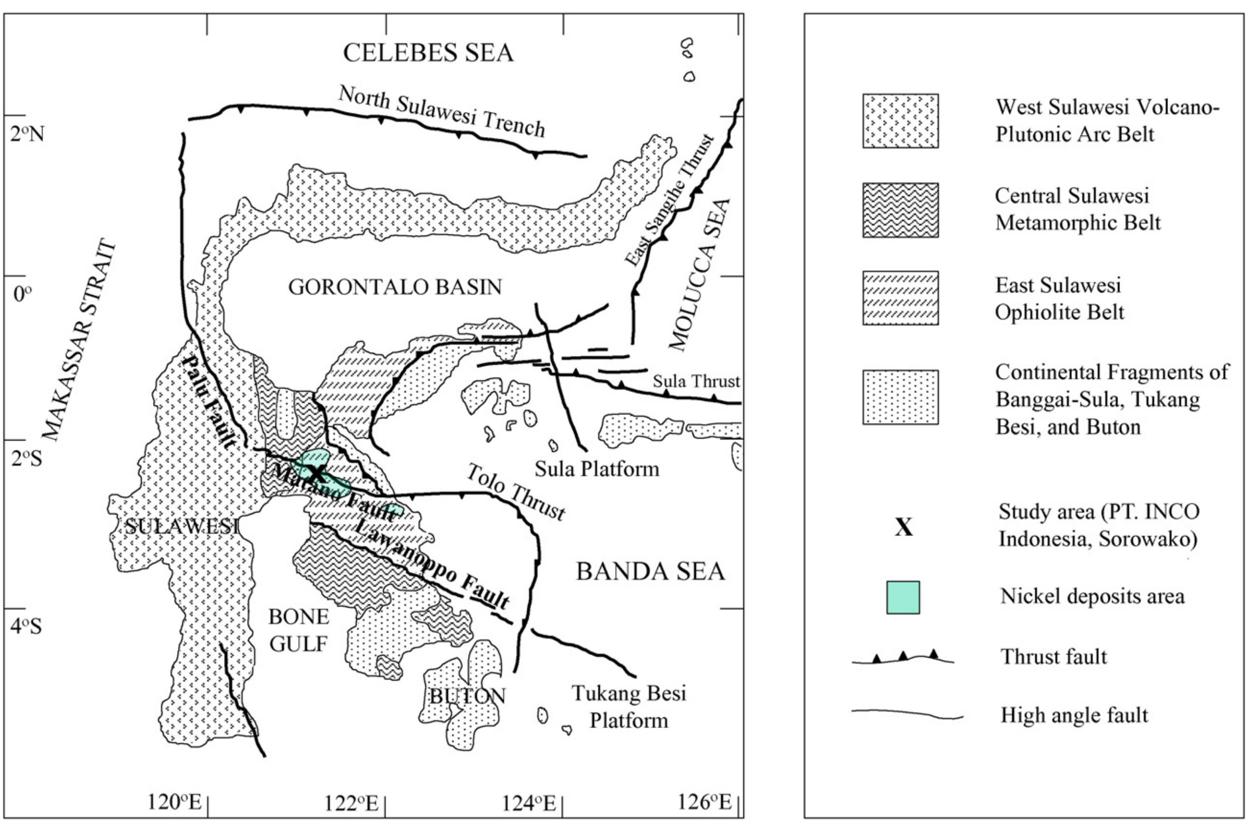

Fig. 1. Location of the study area (marked with an X) in South Sulawesi Province, Sulawesi Island, Indonesia, indicating the four principal tectonic belts and overall geological structure.