UNDERGRADUATED THESIS

ANALYSIS OF RELATIONSHIP BETWEEN LOSS ON IGNITION AND ELEMENTAL CONTENT OF LATERITIC NICKEL ORE IN THE WOLO AREA, SOUTHEAST SULAWESI PROVINCE

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APPROVAL PAGE

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ANALYSIS OF RELATIONSHIP BETWEEN LOSS ON IGNITION AND ELEMENTAL CONTENT OF LATERITIC NICKEL ORE IN THE WOLO AREA, SOUTHEAST SULAWESI PROVINCE

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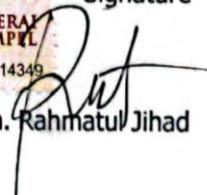
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ABSTRACT

The formation of laterite nickel deposits is controlled by several factors during the chemical weathering process, mainly by the chemical properties of the water that may be partially retained in the laterite nickel ore. Laterite deposits contain organic and inorganic materials which are cumulatively called loss on ignition (LOI) when it goes through the combustion process at high temperatures. The LOI content in lateritic nickel ore will affect the ore processing process so it needs to be analyzed. This study aims to analyze the relationship between LOI and the elemental content of lateritic nickel ore samples. The method used is X-Ray Diffraction analysis to determine the minerals in the sample, X-Ray Fluorescence analysis to determine the elements content in the samples, and LOI measurement using the high temperature combustion method in the furnace. The results of analysis exhibit limonite samples are dominated by goethite and gibbsite with minor quantity of magnetite and in saprolite samples are dominated by quartz and goethite. The LOI measurement reveal that the LOI value of limonite was higher than of saprolite. The results of the analysis on limonite samples, shows that LOI is positively correlated with Fe_2O_3, Na_2O, and Al_2O_3 while LOI is negatively correlated with CaO, MgO, SiO_2, MnO, Ni, Co, and Cr_2O_3. In the saprolite samples, the results of the analysis shows that LOI is positively correlated with Fe_2O_3, MnO, Ni, Cr_2O_3, Co and Al_2O_3 while LOI is negatively correlated with CaO, MgO, SiO_2, and Na_2O. The existence of this correlation can be identified the variations of elementals mobility at the weathering profile.

Keywords: Correlation, element, loss on ignition, nickel, mineral

ABSTRAK

Pembentukan endapan nikel laterit dikendalikan oleh beberapa faktor selama proses pelapukan kimia, utamanya oleh sifat kimia air yang mungkin sebagian tertinggal dalam bijih nikel laterit. Endapan laterit mengandung bahan organik dan non organik yang secara kumulatif disebut loss on ignition (LOI) apabila melalui proses pembakaran pada suhu tinggi. Kandungan LOI pada bijih nikel laterit akan mempengaruhi proses pengolahan bijih sehingga perlu dianalisa. Penelitian ini bertujuan untuk menganalisis hubungan antara LOI dengan kandungan unsur sampel bijih nikel laterit. Metode yang digunakan adalah analisis X-Ray Diffraction untuk mengetahui mineral pada sampel, analisis X-Ray Fluoresence untuk mengetahui unsur yang terkandung pada sampel, dan pengukuran LOI menggunakan metode pembakaran dengan suhu tinggi pada tungku. Hasil analisis menunjukkan pada sampel limonit didominasi oleh goetit dan gibbsit dengan sejumlah kecil magnetit dan pada sampel saprolit didominasi oleh kuarsa dan goetit. Pengukuran LOI menunjukkan bahwa nilai LOI pada limonit lebih tinggi daripada saprolit. Hasil analisis LOI yang dilakukan pada sampel limonit, menunjukkan LOI berkorelasi positif dengan Fe_2O_3, Na_2O, dan Al_2O_3 sedangkan LOI berkorelasi negatif dengan CaO, MgO, SiO_2, MnO, Ni, Co, dan Cr_2O_3. Pada sampel saprolit, hasil analisis menunjukkan LOI berkorelasi positif dengan Fe_2O_3, MnO, Ni, Cr_2O_3, Co dan Al_2O_3 sedangkan LOI berkorelasi negatif dengan CaO, MgO, SiO_2, dan Na_2O. Dengan adanya korelasi ini dapat diidentifikasi variasi dari mobilitas unsur pada di profil pelapukan.

Kata kunci: Korelasi, unsur, kadar hilang pijar, nikel, mineral

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Makassar, October   2022

Muh. Rahmatul Jihad

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX

CHAPTER I

INTRODUCTION

1.1   Background

Nickel laterite accounts for 60 to 70% of the world's Ni resources was although it has been mined for about 140 years. Until 2000 it was accounted for less than 40% of global Ni production and the remainder from sulfide ores. Lower grades, complicated maintenance processes, high energy requirements, and isolation from industrial demand centers and appropriate infrastructure contributed to its slow development of nickel laterit ore. Total production of Ni from laterite ores has increased to 46% of global supply in 2008, exceeding 50% in 2010 and is expected to reach 60% by 2014. Lateritic nickel ore also accounts for 20-30% of total Co supply (Wilburn 2012).

Nickel laterite is a deposit formed by prolonged and intense weathering of peridotite. The weathering process removes the main components of peridotite, MgO, and SiO_2, leaving 5 to 7 percent of the original rock residue enriched with other major components, such as Fe, Al, and Cr, as well as minor constituents, such as Ni, Mn, Cu, and Co. In general, sediments formed in situ in the host ultramafic rock consist of a more or less complete weathering profile, which may be complicated by the absence of multiple weathering zones in the profile due to mechanical erosion. Erosion and sedimentation cause the formation of transported sediments. Many of these sedimentary deposits have been buried, melted, and, in some cases, folded and metamorphosed (Golightly, 2010).

Some Ni laterites are being formed and are essentially in equilibrium with their current environment. Examples include Ni laterite developed on Miocene ophiolites in Sulawesi, where current rainforest conditions are thought to have existed since the

ophiolite exposure (Freyssinet et al, 2005). However, most deposits have grown and developed under changing climatic and/or tectonic conditions over time, thereby modifying the ore or producing new ore types (Golightly, 2010). The multi-phase development is typical for deep laterite regolith, especially in cratonic environments that have been exposed to subaerial conditions throughout much of the Phanerozoic (Butt and Zeegers, 1992).

In the formation of lateritic nickel deposits, there are several contributing factors that have been explained a little, such as from water weathering that may still remain in lateritic nickel ore. During its formation there are also several laterite deposits containing organic matter, so it is necessary to carry out an LOI analysis to determine the percentage of water content in the processing of the lateritic nickel ore. Loss on Ignition analysis was used to determine the loss of content in the sample. The loss on ignition method shows the content of material lost during the burning process by comparing the weight of the sample before and before burning, where before the burning process, the sample contains some water and volatile material, but after the burning process the only mineral part of the soil is left. This method determines the content of the sample at high temperature using a furnace (Zhang and Wang, 2014).

In addition to this, several large companies also usually use the fuse bead process in analyzing samples. The process of making fuse bead samples is carried out using very high temperatures so that some compounds was lost due to the oxidation process or combustion process so that there is a need for an analysis of Loss on Ignition in the fuse bead sample that has been made with the aim of knowing the total oxide contained in a sample. In the fuse bead process, it is necessary to have a controller in the process, so this research is here to compare the relationship between LOI and and elements that can later be used in several companies in the analysis process by paying attention to several element properties such as mobile, immobile and also semi-mobile.

1.2 Problem Statements

Based on the background, the research problems in this study are as follows:

1. What is the mineral composition of limonite and saprolite samples of lateritic nickel ore?

2. How is the results of variations loss on ignition value of lateritic nickel ore samples?

3. What is the relationship between loss on ignition and elemental content in lateritic nickel ore samples?

1.3 The Objectives

Based on problems of research above, the aims of this research are as follows:

1. to analyze the mineral composition of limonite and saprolite samples of lateritic nickel ore.

2. to find out the variations of the loss on ignition value of lateritic nickel ore samples;

3. to analyze the relationship between loss on ignition and elemental content of lateritic nickel ore samples.

1.4 Research Benefits

This research can be used for information about the relationship between loss on ignition and elemental content of lateritic nickel ore. In addition, this research can also be used as a reference for companies that use the fuse bead method in the analysis process of lateritic nickel ore samples to find out whether there are errors in the process, by looking at the readings between loss on ignition and elemental content, if there is a very large difference in value.

1.5   Research Methods

The research methods that was carried out in this research are preparation, study literature, field activities, data processing and analysis, preparation and seminar thesis. This research process is also supported by several literatures in the form of books and journals related to research, as well as information from lecturers and supervisors.

1. Formulation of the problems

   This method is carried out at the beginning of the study to find out the main problems that was discussed in the study. With this method, it was easier to determine the research formulation and objectives.

2. Literature Studies

   This method is a literature review and collection of references or literature related to the problems to be studied in order to support the research to be carried out. This activity was carried out from the beginning to the end of the study.

3. Field Work

   Field work are direct data collection in this study by conducting a sample preparation process of 39 samples in this activity and also continuing the analysis process in the laboratory. In the analysis process in the laboratory, a sample fuse bead was carried out which was then be analyzed using WDXRF with the Bruker S8 Tiger. In addition, an analysis using XRD was also carried out to determine the mineral composition of lateritic nickel ore in the Wolo Area, Southeast Sulawesi Province. The information obtained was recorded in a notebook and documentation using a camera.

4. Processing and Analysis Data

   Data processing and analysis was carried out after conducting several analyzes in the laboratory. The results of the analysis using XRD was then be processed

to determine the mineral composition of the sample. The activity carried out in this method is to compare the loss on ignition and elemental content of lateritic nickel ore, where in this activity there are 39 samples. The results of the calculation loss on ignition are obtained from the ignition process using an analytical furnace and generates the ignition loss in percent. Analysis of the elemental content of lateritic nickel ore using Bruker S8 Tiger and produces nickel laterite ore content in the form of percent of Ni, Co, Na_2O, MgO, Al_2O_3, SiO_2, CaO, Cr_2O_3, MnO, and Fe_2O_3.

5. Preparation and seminar thesis

In the preparation of the thesis, all data and information that has been obtained during the research was accumulated in a report that is compiled systematically according to the rules for writing that has been set by the Mining Engineering Department, Engineering Faculty, Hasanuddin University. After that, it was continued in a seminar which is the final stage of this research.

1.6   Sampling Location

This study uses samples of lateritic nickel ore located in the Wolo District, Kolaka Regency, Southeast Sulawesi Province, Indonesia. The sampling location can be reached using air transportation, from Makassar via Sultan Hasanuddin Airport to Pomalaa, Kolaka Regency, Southeast Sulawesi to arrive at Sangia Nibandera Airport with a travel time of 50 minutes. Furthermore, the journey from Pomalaa to the PT Ceria Nugraha Indotama site is taken using a four-wheeled vehicle with a travel time of ±1 hour. The map of the sampling location is in appendix A.

CHAPTER II

NICKEL LATERITE AND LOSS ON IGNITION

2.1   Characteristics of Ni Laterite Deposit

Laterite regolith generally consists of much or all of the following (from below) saprolite, plasma zone, mottled zone, thorny crust or gravel containing iron and/or alumina, and clay (Eggleton, 2001). Saprolite can make up more than 80% of the total profile thickness. They grow in winter to temperate conditions, according to current and/or past climate regimes. Laterite regoliths composed of ultramafic rocks can contain economically important concentrations of Ni in one or more horizons, and these units are known commercially as "Ni laterites". There are three types of deposits, based on the predominant Ni-carrying minerals: oxides, hydrated Mg silicates, and clay silicates. This section has important implications for remediation and whether the deposition can provide an economically viable natural resource. Generally, Ni laterite samples have two types of ore, namely the oxide phase and the hydrosilicate phase or clay silicate. Due to different mineral processing requirements, mines generally tend to use only one type of mineral processing (Brand et al, 1998).

The oxide deposit (limonite ore) is dominated by Fe oxyhydroxide, especially goethite, in the middle to upper saprolite and up to the plasmic zone. Nickel is hosted mainly in goethite, by Fe substitution and/or by adsorption. Edible oxides (eg asbolane, lithiophorite) are generally abundant and rich in Co and Ni. Decreasing, transitioning from iron-containing saprolite ores such as Ni to lower saprolite and saprock is characterized by an increase in MgO content, from less than 2% to more than 20% (Mg discontinuity) and increasing. Silicates, such as secondary modified serpentine and other hydro silicates, smectite and primary mineral residues. Silization is a typical weathering

product of ultramafic rocks, especially dunes and serpentinized dunes, where low Al content has limited clay formation. Removing silica by crushing and screening is an important and useful step, increasing the effective material and available resources (Elias, 2002).

Precipitatation of hydrated Mg silicates are formed in lower to middle saprolites, with Ni concentrated in serpentine varieties of nickel, talc, chlorite and sepiolite. Some of which are undefined and are informally known as garnierites. This is the highest grade deposit (locally 2% to more than 5% Ni) and, historically, the majority of laterite Ni of this type. They represent about 32% of the total Ni laterite resources. Most hydrate Mg silicate deposits are developed in serpentinized ophiolitic harzburgite peridotite and are best known from the high relief of tectonic active regions in the Circum-Pacific and Caribbean. Similar mineral accumulations in some deposits in the Urals and Greece were formed by serpentinite weathering in karst limestone environments, but it can be debated whether they are actually Ni laterites (Glazkovsky et al, 1977).

Lateritic deposits of Ni silicate clays have only recently been recognized and exploited as a type of ore, although the presence of thick Ni-containing clays in regolite formed in serpentinized peridotite bedrock has long been recognized. The major ore minerals are saponite and Ni-like smectite in saprolite and pedolite medium to top. Silicate clay deposits appear only at sites with relatively low relief, particularly in shield regions in Western Australia (Murrin Murrin; Bulong), southern Urals (Buruktal, Russia), Burundi and Brazil, but San Felipe (Cuba), also of this type. The lower gubal and saprolite woods consist of primary and weathered serpentine, chlorite and saponite, locally with abundant secondary silica and magnesite. It passes up into the saprolite smectiterich and the plasmic zone which, together, form the ore (Gaudin et al, 2005).

2.2 Mineralogical Characteristics of the Nickel Laterite Deposit in Sulawesi

Indonesia is the world's largest supplier of nickel ore, the nickel laterite resources are mainly distributed in the Moluccas and Sulawesi regions. Therefore, the investigation on the mineralogical characteristics of Indonesian nickel laterite ores has attracted more and more attention (Zhang, 2019). Farrokhpay reported the mineralogical characteristics of Weda Bay nickel laterite ore from Indonesia. They found that the nickel-rich saprolites were mainly composed of serpentines, quartz, clays, and small amount of iron oxide. The nickel grade of representative nickel laterite ore sample is 2 to 3%. Exceptionally, the nickel grade of Fe-(Ni)-rich serpentine was about 5 to 10%. In addition, when serpentine and silicate (such as Fe-Mg-(Ni) smectites) coexist precisely, it is difficult to achieve mineral separation (Farrokhpay, 2019).

Fu reported the mineralogical characteristics of nickel laterite ore from the East Sulawesi, Indonesia. They found that the nickel laterite deposits mainly consist of red soil layer, limonite layer, saprolite layer, and bedrock layer. The silicate mineral is mainly composed of serpentine, and the Fe-oxyhydroxide is mainly composed of goethite along the laterite profile. In addition, from the bedrock layer to the surface red soil layer, the concentration of silicon and magnesium gradually decreased, while the concentration of iron, aluminum, and chromium gradually increased, and the highest nickel concentrations (11.53% NiO) were observed in saprolite layer (Fu, 2014).

In addition, Kadarusman also reported the geochemistry of the East Sulawesi, Indonesia. They found that the ophiolite is widely distributed in the East-Central Sulawesi Island. From the bedrock layer to the top of the deposit, the peridotite and magnesite silicate gradually differentiate into isotropic gabbro, and then into sheeted dolerites and basalt volcanic rocks. Residual peridotite is dominantly spinel lherzolite intercalated with

harzburgite and dunite. There are significant differences in mineral composition of magnesium ferric silicate in different areas (Kadarusman, 2004).

The nickel laterite deposit is located in Sulawesi Island Indonesia. The ore body length, width, thickness, and di angle are 4000 to 4400 m, 1700 to 3000 m, 6 to 50 m, and to 30°, respectively. It is a very large nickel deposit with nickel resource of 4 million tons. Figure 2 is the geological features of the nickel laterite deposits in the Southeast Ophiolite Belt, Sulawesi Island Indonesia. It can be seen that the weathering crust of the nickel laterite deposits can be divided into three distinct weathering zones, which are residual laterite zone, rotten rock zone, and bedrock zone. Among them, the rotten rock zone is the main nickel deposit layer, especially that the middle–lower part of the rotten rock zone has the highest nickel concentration, and the average concentration of nickel is more than 1.6 wt%. In addition, the nickel concentration of some sections is above 1.8%, and the highest concentration of a single sample can reach 5.84 wt%. The mineral composition of the middle-lower part of the rotten rock zone is very complicated, including serpentine, olivine, chlorite, clay, hematite, and limonite (Zhang, 2019).
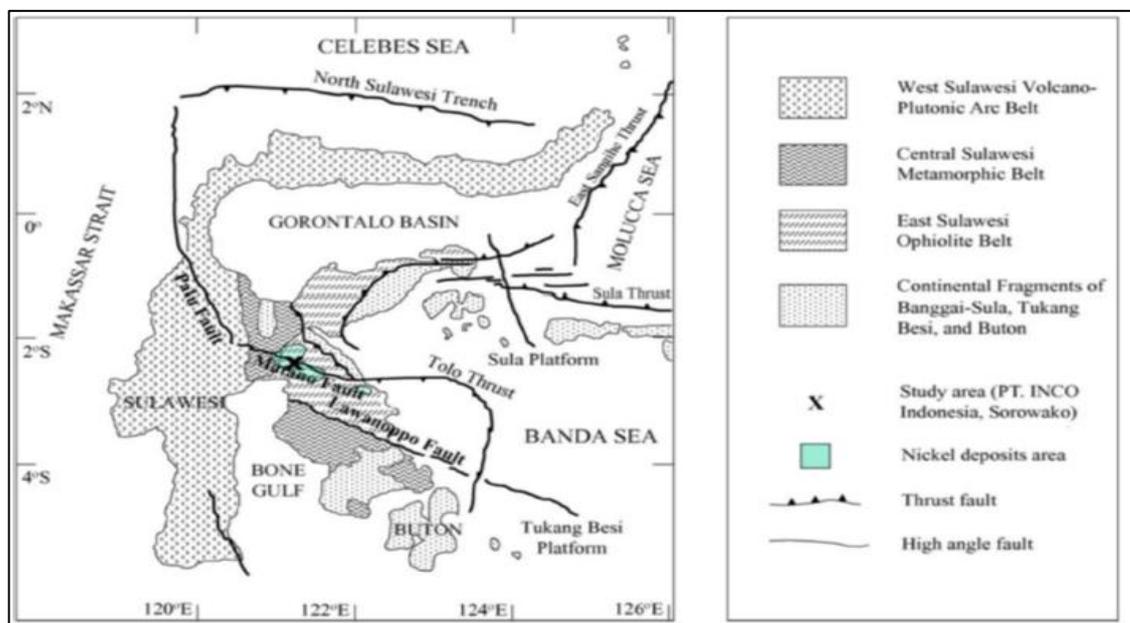

Figure 2.1 The geological features of the nickel laterite deposits in the Southeast Ophiolite Belt, Sulawesi Island, Indonesia (Zhang, 2019).

Zhang was used the nickel laterite ore from the Southeast Ophiolite Belt, Sulawesi Island, Indonesia, in these experiments and produce The chemical compositions of the nickel laterite are listed in Table 1. It can be seen that the concentrations of Ni, Fe_2O_3, SiO_2, MgO, and loss on ignition (LOI) in nickel laterite ore are relatively high. In addition, the laterite nickel ore also contains higher contents of Cr_2O_3 and Mn, which are 1.13 wt% and 0.35 wt%, respectively (Zhang, 2019).

Table 2.1 Chemical compositions of the nickel laterite ore samples (Zhang, 2019).

Ni (%)	Fe_2O_3 (%)	FeO (%)	SiO_2 (%)	MgO (%)	CaO (%)	Al_2O_3 (%)	Cr_2O_3 (%)	Mn (%)	Co (%)	S (%)	P (%)	LOI (%)
1,99	17,55	25,07	0,22	35,39	17,93	0,28	3,21	1,13	0,004	0,01	0,005	14,37

The serpentine (lizardite and nepouite) is mainly a Ni-bearing mineral phase, the Fe mainly exists in the green rust, and the lizardite and gonyerite also contain a small amount of Fe. The olivine, magnetite, and chromite are not observed, this is mainly due to their concentration being below the detection limit.

2.3 Factors Affecting the Distribution and Formation of Nickel Laterites

2.3.1 Bedrock geology

Laterite nickel lithology forms almost exclusively in olivine-rich ultramafic rocks and is similar to serpentinization. Several minor deposits in Greece were formed by weathering of sediments containing lateritic debris derived from serpentinized peridotite (Valeton et al. 1987). This type of deposit is partly influenced by the lithology of ultramafic rocks. Peridotite can form oxides and can hydrate Mg or clay silicates, whereas dunite mainly forms oxide deposits, many of which have free silica that can dilute the ore. The degree of serpentinization of peridotite affects the nature and abundance of

hydrate Mg silicates formed in profiles developed in non-arid environments (Pelletier 1996). In non-serpentinized rocks, the deposits tend to be rich in oxides, with little silicate mineralization (eg, West Soroako, Indonesia). In weak to moderate serpentine rocks, the silicate zone is thicker and consists mostly of newly formed "garnierite" as vein, filler and fracture layer, and Fe-Mg smectite formed from olivine. However, Ni is also guided by a modified primary rhythm, in which Ni is exchanged for Mg at octahedral sites. In highly serpentinized rocks, rich in Ni replaces cadalites as the main ore mineral (Manceau and Calas, 1985).

Structural fractures, faults and shear zones in bedrock and regolite can greatly affect the thickness, grade and, in some cases, the type of laterite Ni deposit. In general, this effect is passive, with pre-existing structures influencing the characteristics of the waterway by creating a barrier to water flow or, more generally, by increasing permeability and promoting deeper weathering and preferential Ni concentration along the fracture zone. In addition, concomitant bedrock weathering movements occurring in the bedrock and new low-angle shear in the regolith formed by slope failure may be the focus of Ni concentration. Several different mineral strains and behaviors and collections indicate that tectonic activity and supergene mineralization are synchronous and occur under changing weather conditions (Cluzel and Vigier, 2008).

2.3.2   Groundwater and Organic Matter

Water chemistry that interacts with the laterite Ni profile is quite typical. At the bottom of the profile, they are characterized by high concentrations of dissolved Mg and Si and relatively high pH, as shown for waters from the Cerro Matoso mine in Colombia. Analysis of waters from New Caledonia and Colombia showed that bicarbonate, rather than sulfate and chloride, was the predominant anion. These observations suggest that the biogenic activity and organic compounds in these tropical soils may have played a role in the development of at least the upper part of this profile. The role of termites in

disturbing the laterite profile by bringing saprolytic material to the surface has been discussed (Truckenbrodt et al, 1991). However, there are few specific studies on the role of biogenic processes in the formation of Ni laterite. Currently, many experimental and field-based studies in geomicrobiology are focused on identifying the role of biogenic processes in mediating the phase change between amorphous Fe phases, Fe oxyhydroxides, and hydroxides. There is a small number of recent studies on the role of bacteria in the mobilization of Ni from Fe oxides (Zachara et al, 2001).

2.3.3 Climate

Most of the lateritic Ni deposits occur in the humid tropics at this time. Many deposits in Indonesia (such as Soroako, Veda Bay) and parts of West Africa (Sipolou, Conakry) and South America (Onça, Puma, Vermelho, Cerro Matoso) have a rainforest climate characterized by rainfall >1800 mm per year and dry season. less than 2 months. However, most of the deposits, including those in New Caledonia, the Philippines, northeastern Australia, the Caribbean, Burundi, and much of Brazil, are located in humid seasonal savannas (900–1800 mm of summer rainfall and 2–5 mm of dry season) month). Thorne calculated that Ni laterite develops where rainfall exceeds 1000 mm/year and the average monthly temperature is between 22–31°C (summer) and 15–27°C (winter) (Thorne et al, 2012).

There are also sizeable deposits in the hot, semi-arid to dry climates of central and southwestern Australia and in the more humid Mediterranean to temperate regions of the US (Oregon and California), the Balkans, Turkey and the Urals. However, each of these regions is considered to have a warmer and more humid climate, when deposits form, even at high latitudes (such as southwestern Australia). Subsequent climatic modifications of deposits are generally minor, as is the deposition of magnesite and silica under semi-arid to dry conditions in Australia. There is no clear relationship between the current climate and ore type, grade or size. Although hydrate Mg silicates are most

abundant in the tropics and clay silicates are found in semi-arid areas, this distribution is generally due to tectonic, structural and geomorphological settings, which affect drainage status and susceptibility to erosion (Anand and Paine, 2002).

2.2.4 Weathering age

Since most laterite Ni deposits, and the landscapes in which they occur, formed and evolved over time in different weathering regimes, we can only estimate the most intense weathering period, rather than assuming a specific weathering period. set. Direct dating regoliths have only been performed in some areas and rarely in Ni laterite itself. The oldest sediments occur in cratons, which may have undergone subaerial weathering for much of the Phanerozoic. At the Yilgarn Craton in Western Australia, paleomagnetic dating at Murrin Murrin and sites near Cawse and Bulong give some Palaeozoic ages, indicating a very early weather onset. However, most of the dates in this semi-arid region now show the main phases of humid tropical weather in the Middle to Late Cretaceous, Paleocene, and Late Eocene-Oligocene. In addition, episodic weather is expected in northern Australia and in central South America and West Africa, but where humid tropical conditions generally persisted throughout the Cenozoic (Anand and Paine, 2002).

Many of the deposits are in younger accretionary terrariums, with best date limits for deposits buried by later sediments. In the Urals, weathering of Upper Devonian serpentinites began in the late Triassic, with some Ni laterites buried in the middle Cretaceous. Nickel laterites developed in Lower Jurassic-Cretaceous ophiolites, and sediments from ophiolites in Greece were buried by Middle to Upper Cretaceous sediments (Valeton et al, 1987), while aldag sediments in Turkey probably formed in the Paleocene to mid-Miocene (Tavlan, 2011). Weather on the new islands of the Caribbean and western Pacific (New Caledonia, Philippines, Indonesia) also comes from the Eocene–Oligocene. Some precipitates form very quickly, for example, the ophiolite in Sulawesi is Miocene in age (Sevin et al, 2012).

2.2.5 Geomorphology

Nickel laterites occur in regions with a deep, strongly weathered regolith. This implies (1) formation in terrains with suffi cient tectonic stability and low relief that the rate of weathering exceeds that of erosion, and (2) preservation due to low relief and protection from erosion by either burial or armouring by ferruginous or siliceous duricrusts. These conditions prevail in cratons but less so in accretionary terranes. In the latter, most deposits occur in dissected plateaux, where uplifted remnants of a previously more extensive regolith cover are being actively eroded and are well preserved only beneath duricrust on crests, upper slopes and terraces. The topography of these different settings affects drainage and, in turn, the nature and grade of Ni laterite, especially on peridotite (Butt and Cluzel, 2013).

On cratons and locally elsewhere, low relief and high water-tables result in impeded drainage, which reduces the rate of removal of weathering solutions and the intensity of leaching. Resultant Ni concentrations are largely residual, with little absolute accumulation. In areas of high relief in accretionary terrains or on hills in cratons, the regolith is generally free-draining with a deep water-table. This maximizes the rate of leaching and movement of groundwater, giving an absolute enrichment deep in the saprolite in addition to a residual concentration, generally expressed by high-grade hydrous Mg silicates in saprolite and a well-developed oxide zone (Butt and Cluzel, 2013).

2.4 Ore Chemistry and Implication for Mineral Processing

There are currently three commercial methods of processing lateritic nickel ore. Due to the mineralogical variations in these deposits, different processing techniques are generally more suitable for certain sections of the profile. However, this variability also allows some of the ore's benefits prior to processing. In silicate ores, for example,

weathered parent rock residues can be removed mechanically. In mixed silica-oxide deposits, where the ore is associated with Fe and Mn oxides, the barren silica can be removed by filtration after crushing (Simons, 1988).

Most Ni laterite producers mine mostly hydrosilicate ores for energy-intensive pyrometallurgical processes (partial reduction and dry ore smelting). The main products are ferronickel and nickel matte grains, which are used in the production of stainless steel. High recovery of Ni is achieved by this operation, but Co cannot recover it as a by-product. Many deposits have their own power plant (eg, Cerro Matoso) due to their high energy requirements which can be considered the most important factor in determining the economic viability of laterite hydrate silicate deposits. Access to low-cost hydroelectric power is a distinct advantage (eg, Soroako, Indonesia). The Caron process is less commonly used to treat oxide ores. The process involves drying and roasting the ore in a reduced atmosphere, then washing it with low pressure ammonia. Ni and Co were recovered by solvent extraction and then further purified. Again, such as smelting, drying ore, and reducing roasting use a lot of energy. Consequently, this technology may not be selected in the future for new nickel laterite projects (Gleeson, 2003).

There has been a recent resurgence in the processing of oxide deposits with high pressure acid leaching (HPAL) technology. Sulfuric acid at a temperature of 250 °C or more and a pressure of 4,500 kPa dissolves Ni and Co from the dominant oxide ore (Krause et al., 1998). The metal is extracted from the leach solution by precipitation as a sulfide (with the addition of H_2S) or as a hydroxide (with the addition of lime), or by solvent extraction and electrowinning. This process also applies to clay silicate ores but the relatively high levels of Si in these deposits can cause problems at the autoclave stage and the process becomes more expensive. The dominant components of HPAL's operational costs are related to the supply of large quantities of sulfur and the production of sulfuric acid. For many years, the only producer of HPAL was Moa Bay in Cuba

(operating at relatively low pressures and temperatures). The low cost of sulfur and improvements in solvent extraction and autoclave technology have increased interest in this processing technology. Three new plants in Western Australia at Bulong and Murrin Murrin (smectite silicate ore) and Cawse (oxide ore) started operations in 1999, but all had serious capital and operating costs, as well as engineering and construction material problems. A new HPAL plant is also planned for Goro in New Caledonia to treat the hydrous oxide and silicate portions of this profile (Mihaylov et al, 2000). Despite the difficulties faced by this new generation HPAL plant, this technology favors Caron's washing technology and smelting technology and it is likely that more HPAL plants was built in the future to meet the increasing demand for nickel as sulphide. resources are becoming scarce (Elias, 2002).

2.5   Loss on Ignition

Sequential loss on ignition (LOI) is a common and widely used method for estimating the organic and carbonate content of sediments. The weight loss during the reaction is easily measured by weighing the sample before and after heating and is closely related to the organic matter and carbonate content of the sediment (Bengtsson and Enell, 1986). Dean evaluated the method and concluded that the LOI provides a fast and inexpensive method for determining the carbonate and organic content of weak clay sediments and calcareous rocks with accuracy and precision comparable to other more sophisticated geochemical methods (Dean, 1974). Bengtsson and Enell, in their instructions on the technique, mention that this method provides a rough indication of the organic matter and carbonate content of sediments (Bengtsson and Enell, 1986).

Depending on the ignition temperature, various losses of volatile salts, structural water and inorganic carbon can occur (Sutherland, 1998). LOI can be highly dependent on exposure time. The fact that some authors did not mention the exposure time at all

(Belis et al, 1999) suggests that the general assumption is that at 550 °C organic matter burns rapidly and thereafter no further weight loss occurs. The analyst should be aware that reactions other than the combustion of organic matter may occur at 550 °C, i.e. dehydration of clay minerals or metal oxides, loss of volatile salts, or loss of inorganic carbon in minerals such as siderite, magnesite or rhodochrosite (Lamoureux, 1999).

Loss on ignition and thermal decomposition methods are more widely used due to their ability to analyze samples in a more time efficient manner. Some laboratories have opted to use loss on ignition (LOI) in place of dichromate wet chemistry methods. While LOI does eliminate the disposal costs, this method still requires venting of the muffle furnace and introduces technician safety issues unless the muffle furnace is allowed to significantly cool before removal of the samples. Furthermore, LOI can significantly overestimate organic carbon due to loss of hydration water around ions in soil with significant salt, salts with thermal decomposition temperatures less than the LOI furnace temperature, and hydration water in the interlayers of smectic clays (Crouse, et al, 2014).

Measurement of Loss on Ignition (LOI) as an estimate of rock water content by classical analysts is generally unsuccessful. Due to the presence of volatile components other than water, Fe can also be oxidized in most rocks. This LOI measurement may also be useful in certain geological studies as an actual estimate of the amount of volatiles, or for example as an indicator of changes in volcanic rock as a result of hydration or calcification of mafic minerals. The determination of the LOI is often included in the overall rock analysis scheme when a brief analysis that includes, perhaps, only nine or ten major oxides, and does not require full details of the concentrations of various volatile components, is sufficient for a particular geological/geochemical condition study (Lechler and Desilets, 1987).

Regardless of the analyst's estimate of which oxide may be dominant in a given sample, when the ratio is not measured, the amount of Fe should always be reported as iron oxide. In this way, the error generated by calculating some ferrous iron as ferrous iron is almost the same magnitude, but the opposite sign, as applied to the analytical volume by summing the observed LOI, and sums up the exact results. If iron and iron concentrations are determined and reported, the observed LOI must be corrected for weight gain due to iron oxide oxidation to obtain an accurate estimate of the volatile volume and analytical volume (Costa et al, 1983).

No standard protocol exists for LOI analysis, but it is well documented that LOI is affected by ignition temperature, duration of ignition and ignited sample mass (Abella & Zimmer, 2007). Determination of weight percent organic matter and carbonate content in sediments by means of LOI is based on sequential heating of the samples in a muffle furnace (see Dean, 1974; Bengtsson & Enell, 1986 for more details on the method, but note that in the equations for calculation of LOI in the latter publication the weight loss is related to the wet weight of the sediment instead of the dry weight). After oven-drying of the sediment to constant weight organic matter is combusted in a first step to ash and carbon dioxide at high temperature. The LOI is then calculated using the following equation:

$$LOI = \left(\left(\left| \frac{M2-M3}{M2-M1} \right| \right) X \ 100 \right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(2.1)$$

where,

M1 = mass of empty crucible (g)

M2 = mass of the crucible + sample (g)

M3 = mass of the crucible + test sample after being heated (g)