

GEOCHEMICAL CHARACTERISTICS OF HYDRATED IRON-ORE DEPOSIT IN DELA, SRI LANKA

D.T. JAYAWARDANA^{1,*}, N.W.B. BALASOORIYA² AND W.A.P. WEERAKOON³

¹Faculty of Applied Sciences, Department of Forestry and Environmental Science, University of Sri Jayewardenepura, Nugegoda, Sri Lanka

²Faculty of Applied Sciences, South Eastern University of Sri Lanka, Sammanthurai, Sri Lanka

³Uva Wellassa University, Passara Road, Badulla, Sri Lanka

*Corresponding author: e-mail-daham@sci.sjp.ac.lk

ABSTRACT

Sri Lanka is known for different kind of iron-ore deposits in the Precambrian basement. Among them, hydrated iron ores are predominant in the south-west region. This study describes geochemistry, weathering, alteration and provenance of hydrated iron-ore deposit and examine different chemical processes associated iron-ore generation. Field surveys were carried out at forty four (44) localities around Dela and X-ray Fluorescence Spectroscopy (XRF) was used to obtain concentrations of forty (40) major and trace elements from ore samples. Selected samples were also analyzed by Fourier Transform Infra Red Spectrometer (FTIR) aiming at identification of weathering and alteration effects. The average concentration of Fe₂O₃ in the deposit is 88 wt% indicating a high grade iron-ore. Conversely, all the other major oxides (MgO, Al₂O₃, SiO₂, P₂O₅, MnO, CaO and TiO₂) concentrations are not significant. Based on geochemical discrimination the deposit falls in to Phanerozoic iron stones indicating igneous intrusions to the Precambrian basement. The deposit can be conceded as detritus-free when originated since minute concentrations of trace elements are reflected in the samples. Major oxides of the study show residual enrichment of Fe₂O₃ due to effective leaching of mobile phase. Lower abundances of immobile trace elements may reveal lack of commonly known heavy minerals within the iron bearing formation. The FTIR spectrum of the iron-ore samples clearly demarcate chemical weathering processes as imposed by the deposit such as formation of secondary minerals (limonite), silicate oxidation and phosphorous decomposition.

Keywords: Geochemistry, Trace elements, Hydrated iron-ore, Weathering, provenance, Sri Lanka

INTRODUCTION

Iron is the most important among the metals which has been widely used in many industries worldwide. Total consumption of iron in the world is approximately 1500 million tonnes annually and it is gradually increased in the recent past (Basson, 2013). In general, most of the steel productions are associated with low-grade iron-ores located from China, Japan, Western Europe, Australia, South America, India and North America (Basson, 2013).

Iron-ores are hosted by deposits varying in sizes, grades and origins. Banded iron formations contain different iron-bearing minerals and minor amount of quartz, carbonates, silicates and sulfide minerals (Roy and Venkatesh,

2009). Rapitan-type deposits are marked with simple mineralogy and Precambrian iron formations are similar with respect to their average major element composition. The igneous iron-ores, including magnetite in mafic intrusions and large deposits of magmatic-hydrothermal affinity (Conliffe et al., 2012). High-grade ores are usually formed by hydrothermal processes. However, more than 95% of exploited deposits till today are of sedimentary in origin (Gutzmer and Beukes, 1998).

Geochemistry of iron deposits is significant. Iron-ores generally have more than 25 wt% of iron, usually in the form of hematite (Fe₂O₃), magnetite (Fe₃O₄), goethite [FeO(OH)], limonite [FeO(OH)*nH₂O] or siderite (FeCO₃) or combin-

ing more than one. Major element analysis reveals the presence of very little amounts of Al_2O_3 , TiO_2 , MgO , MnO_2 and CaO , especially in the banded iron formations (Roy and Venkatesh, 2009; Conliffe et al., 2012). In general, marked enrichment of iron in an ore is attributed to effective removal of SiO_2 , MgO and CaO during weathering and alteration (Gutzmer et al., 2008).

Iron-ores in Sri Lanka are known to present as three major categories such as primary deposit (magnetite), copper-magnetite type and secondary deposit (Hydrated iron oxide) (Cooray, 1984; Fernando, 1986; Hewathilake et al., 2013; Weerakoon et al., 2013). Magnetite in iron formations is discovered during early stage of geological mapping mainly from Wilagedera (1959) and Panirendawa (1962) in Chilaw district and Seruwila copper-magnetite type (1971) in Trincomalee district. Similar formation was also discovered recently in Kukurampola Wellawaya (Senaratne et al., 2001).

Hydrated iron-ores are extensively distributed and predominant in the south-western sector of the country (Cooray 1984; Fernando, 1986; Hapugoda et al., 1987; Dahanayake et al., 1987; Dahanayake, 1995). Several hydrated iron deposits are falling within the Rathnapura District of the Sabaragamuwa Province. Many such deposits are also scattered in Galle and Matara districts of the Southern province and Kalutara district of the Western province (Cooray, 1984; Fernando, 1986). Those deposits are usually available as low-grade surface reserves. Hence secondary mineral formation leading to leaching of elements during weathering can be expected.

Very limited studies have been carried out on the geochemistry of hydrated iron-ores in Sri Lanka (Fernando, 1986). Therefore, a study is necessary to investigate possible geochemical processes that can occur. The main objective of this research is to identify the chemical composition of hydrated iron-ore in Dela, Sri Lanka and to discuss its geochemical characteristics, provenance and weathering.

STUDY AREA AND PHYSICAL SETTINGS

GENERAL GEOLOGY

Dela deposit is located within the hinge of Rathnapura synform. The major rock types

present in the Highland Complex rocks are garnet-biotite-sillimanite gneiss (Khondalite) and charnockitic gneiss. In general, quartz, feldspar, sillimanite and biotite are the major mineral assemblages while minor amount of graphite and coarse grained garnet are also present (Cooray, 1984; Herath, 1995). Due to strong weathering, primary minerals in the Khondalite rocks are hard to observe at the surface. However, it has been recognized that hydrated iron-ore occurred as large blocks and boulders along with the crests of hills or slopes in Dela (Fernando, 1986). Those deposits generally formed parallel to the regional strike of the basement rock. Drilling in 1958 revealed that there is no continuity of the ore and one can only could recognize pockets and lenses of the deposit as a dominant iron-ore formation (Fernando, 1958; Cooray, 1984; Herath, 1995).

CLIMATE AND SOIL IN STUDY AREA

The present investigation was carried out in the area around Dela in the Rathnapura district which falls in the wet zone of Sri Lanka. The mean annual rainfall is > 1500 mm and the average annual temperature is $25^{\circ}C$ (Chandrapala and Wimalasuriya, 2003).

Wet zone is characterized by relatively higher weathering intensity (Chemical Index of Alteration (CIA) >60 ; Fernando et al., 2001) with gibbsite-kaolinite clays, laterite and limonite pebbles present in the soil (Herath, 1973). Residual soils in the zones have formed from a variety of rocks, mainly meta-igneous rocks and subordinately meta-sedimentary rocks. Non-agricultural soils are mainly immature, unconsolidated, fine-grained, sandy clay loams (Herath, 1984). No clear contrast exists among the soil horizons and they consist of rich organic matter layers at the upper parts. However, the underlying zones are moderately weathered sandy clay loams which contain some primary minerals and rock fragments.

METHODOLOGY

SAMPLING

A field survey was carried out to determine sampling locations in April 2013. Several locations, mainly in Dela and Noragolla and a few other locations in Rathnapura district were selected using a hand held Global Positioning System (GPS) with an accuracy of 1 m (Figure

1). The Dela limonite deposit was selected based on its level of weathering, physical extent and origin. Samples were collected mainly from fresh outcrops available at the surface.

SAMPLE PREPARATION AND ANALYSIS

Samples were analyzed for selected major and trace elements by means of Bruker handheld XRF at the Geological Survey and Mines Bureau, Sri Lanka. This instrument can be used for field and laboratory based geochemical analyses of earth materials (Higuera et al., 2012; Dahl et al., 2013; Gazley et al., 2014). Splits of each sample were oven-dried for 48 hours at 160 C. Powdered samples (<63 μm) were compressed into briquettes under a force of 200 KN for 60 seconds. The briquettes were then analyzed for forty (40) selected major oxides (MgO, Al₂O₃, SiO₂, P₂O₅, MnO, Fe₂O₃, CaO and TiO₂) and selected trace elements. XRF instrument was linearly calibrated by the manufacturer's calibration method, without standard samples, known as theoretical calculations. In addition, data quality can be significantly improved using least-squares regression techniques using standard samples for metal analyses. Average error for these elemental concentrations for XRF analyses is

around ± 10% (Kenna et al., 2011).

The selected samples were analyzed to study the level of weathering and alteration by Fourier Transform Infra Red (FTIR) spectrophotometer (Perkin Elmer 880) at the National Institute of Fundamental Studies, Kandy. The wavenumber of the FTIR spectra is ranging from 400 to 4000 cm⁻¹. Samples were analyzed using KBr pellet technique. The data were processed using Origin Pro 8 software (Origin Lab Corporation).

RESULTS AND DISCUSSION

PHYSICAL DESCRIPTION OF DELA IRON-ORE

In general, isolated hill forming outcrops are the major formations of Dela iron-ore. Boulders of the outcrops along the hilly slopes are also commonly present. During the field observations, the dark color mafic patches observed in the outcrops may be due to higher concentration of primary magnetite. Most of the outcrops are yellowish brown in color. This may indicate secondary mineral formation such as limonite due to hydration effect during chemical weathering. Very limited evidence has been recorded for the formation of hematite within

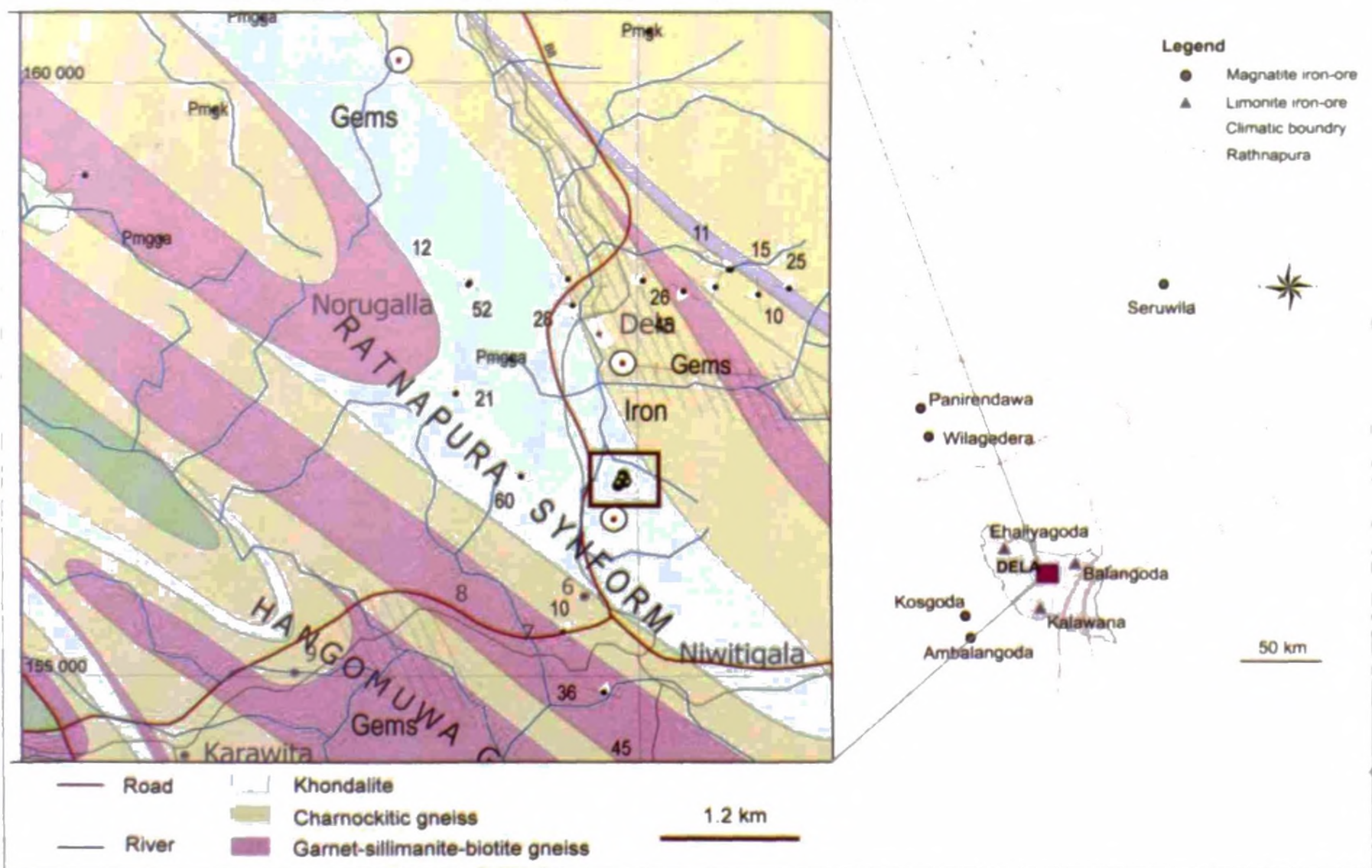


Fig. 1 Map showing the geology and location of sampling sites. In the location map, field circles denote magnetite iron-ores and field triangles denote limonite deposits.

the fresh outcrops. However, the soil surrounding Dela iron-ore is reddish brown in color due to oxidation of iron bearing minerals.

GEOCHEMICAL COMPOSITION OF IRON-ORE

Elemental concentration, their ranges and mean values for the limonite samples from Dela deposit are given in Table 1. The average concentration of iron in the samples is significantly high (Avg: 87.8 wt%). All the other analyzed elemental concentrations are significantly low (Table 1). Average levels of SiO₂, MgO and Al₂O₃ around 2.1 wt%, 1.8 wt% and 1.0 wt% respectively (ranges are 0.4-8.9, 0.7-8.3 and 0.8-3.7 wt%). However, all the samples show lower concentrations of SiO₂, MgO, Al₂O₃, K₂O and Na₂O. Further, trace elements such as Ni, As, Se, Zr, Nb, Mo, Rh, Cd, Sb, Hf, Ta, W, Pt, Au, Hg, Pb, Bi, Th and U are very low may be due to lower abundance with respect to major oxides and due to lower abundances in source rocks.

In Dela iron-ore, alumina content varies between 0.0 and 3.7 wt% with an average of 0.9 wt%. Kaolinite and gibbsite are the main alumina

bearing secondary minerals. Average alumina content in associated soils is somewhat high (Avg: 12.1 wt%; Table 1). Soil alumina shows an inverse relation with iron (Figure 5). Associated weathered soils in the ore samples are believed to be the main source of alumina bearing minerals. Element aluminum has the lowest residence time in water. Hence, alumina is relatively less mobile during chemical weathering than iron and much less than silica and therefore undergoes residual enrichment. Thus, in the iron ore in Dela relatively higher values of alumina are believed to be due to the residual enrichment process (Ramanaidou et al., 2008).

INTER-ELEMENT RELATIONSHIPS IN THE IRON-ORE

As shown in Figure 2, a positive linear correlation exists between Fe₂O₃ with Cr (R = 0.63). This further concludes that those elements may have been released due to weathering of iron oxides bearing mafic minerals (Evans and Landergren, 1978; Nriagu, 1998). Element Ti has mobility similar to Cr.

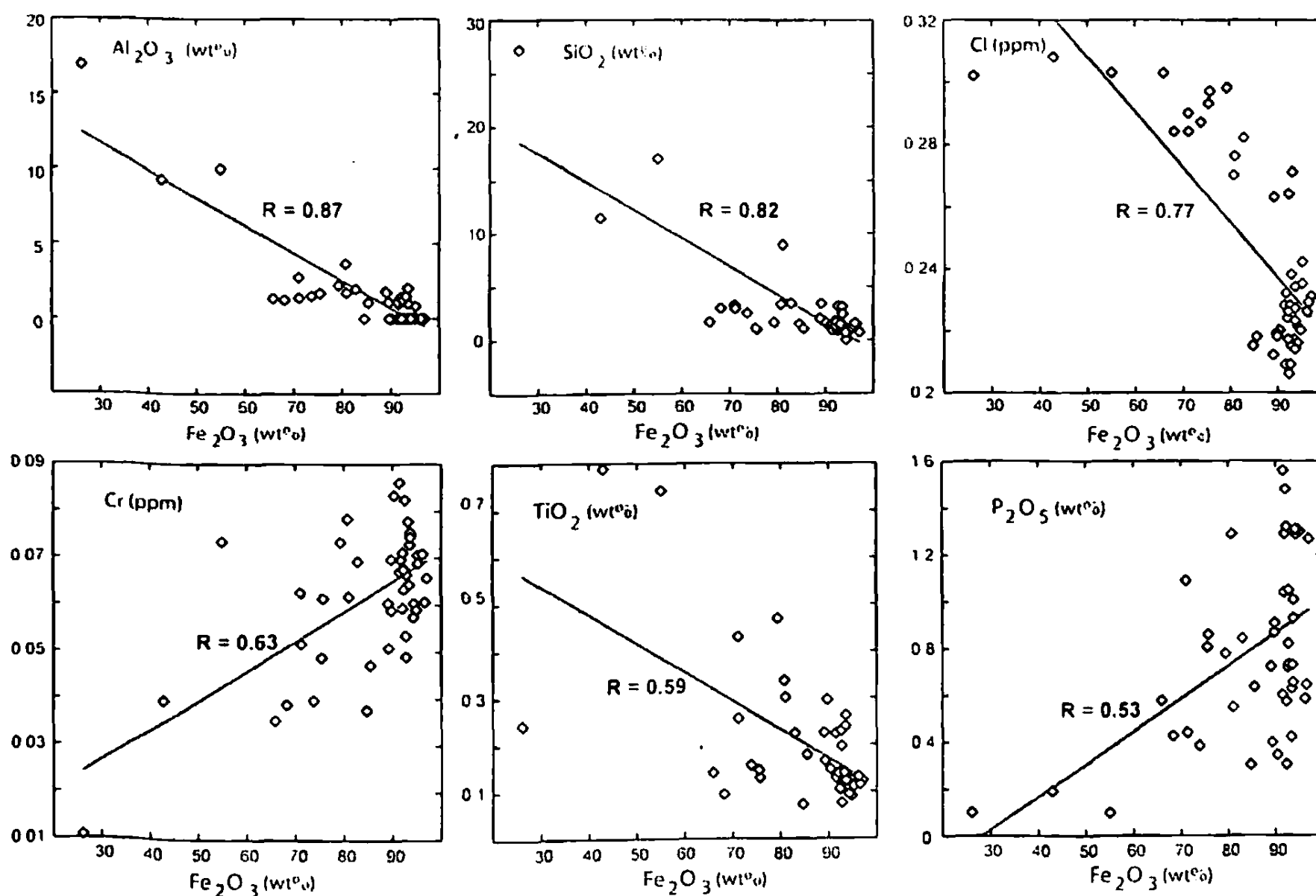


Fig. 2 Correlations of Fe₂O₃ with Al₂O₃, SiO₂, P₂O₅, TiO₂, Cl and Cr. Fitted regressions for iron-ore samples between the given elements.

Table 1a Geochemistry of Dela iron-ore sample (2013)

ID	(wt%)								(ppm)						
	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	TiO ₂	MnO	Fe ₂ O ₃	Cl	Ce	Cr	Co	V	Zn	Rb
DL1	ND	ND	1.5	0.3	0.02	0.15	0.70	90.3	0.22	0.32	0.08	0.45	ND	0.03	0.02
DL2	16.5	ND	1.5	0.3	ND	0.07	0.69	84.7	0.22	0.12	0.04	0.74	0.01	0.03	0.01
DL3	ND	1.0	1.1	1.0	0.03	0.13	0.45	91.8	0.23	0.27	0.07	0.51	0.01	0.02	0.02
DL4	ND	ND	1.0	1.1	0.02	0.13	0.44	92.9	0.24	0.28	0.07	0.50	ND	0.02	0.02
DL5	ND	ND	0.9	0.6	ND	0.22	1.80	91.4	0.23	0.32	0.09	0.50	0.02	0.03	ND
DL6	13.7	1.1	1.1	0.6	ND	0.18	1.90	85.5	0.22	0.16	0.05	0.63	0.02	0.02	0.02
DL7	ND	ND	0.9	0.7	ND	0.23	1.84	92.6	0.23	0.30	0.08	0.45	0.02	0.03	0.02
DL8	6.3	1.2	1.2	0.7	ND	0.08	0.46	92.8	0.22	0.14	0.05	0.58	0.01	0.03	0.02
DL9	4.4	ND	1.3	0.6	0.02	0.11	0.46	93.5	0.22	0.25	0.06	0.46	0.02	0.03	0.02
DL10	ND	ND	1.8	1.3	ND	0.13	0.44	92.0	0.22	0.19	0.06	0.26	0.02	0.03	0.02
DL11	ND	ND	1.7	1.3	0.03	0.11	0.44	92.4	0.21	0.18	0.06	ND	0.01	0.03	0.02
DL12	8.2	ND	ND	1.3	0.04	0.11	0.54	94.3	0.22	0.21	0.06	0.84	0.02	0.03	0.02
DL13	ND	ND	0.7	1.3	0.03	0.12	0.53	97.1	0.23	0.25	0.07	0.70	0.02	0.03	0.02
DL14	ND	ND	1.0	1.3	0.04	0.12	0.48	95.2	0.24	0.26	0.07	0.59	0.01	0.03	0.02
DL15	ND	0.8	1.0	1.3	0.04	0.11	0.48	95.2	0.24	0.26	0.07	0.61	0.02	0.03	0.02
DL16	ND	ND	1.7	0.3	ND	0.14	0.77	92.2	0.23	0.27	0.07	0.44	0.01	0.03	0.02
DL17	ND	ND	1.5	0.6	ND	0.12	0.48	96.6	0.23	0.22	0.06	0.53	0.01	0.03	0.02
DL18	3.2	ND	1.6	0.6	0.03	0.13	0.45	96.2	0.23	0.27	0.07	0.64	0.02	0.02	0.02
DL19	ND	1.1	1.8	0.9	0.02	0.30	2.56	89.7	0.22	0.22	0.06	0.43	0.03	0.03	0.01
DL20	ND	ND	1.8	0.9	0.02	0.30	2.60	89.8	0.22	0.21	0.07	0.40	0.03	0.03	ND
DL21	ND	ND	1.3	0.9	0.04	0.13	0.47	93.7	0.23	0.29	0.08	0.28	0.01	0.03	0.02
DL22	ND	1.0	1.4	1.0	0.03	0.12	0.46	93.7	0.23	0.25	0.08	ND	0.02	0.03	0.02
DL23	ND	ND	0.9	1.3	0.02	0.09	0.47	94.8	0.22	0.19	0.06	ND	0.01	0.03	0.02
DL24	ND	ND	0.7	1.3	0.02	0.09	0.47	94.2	0.22	0.16	0.06	ND	0.01	0.03	0.02
DL25	5.1	1.2	1.5	1.6	0.03	0.13	0.49	91.6	0.21	0.23	0.07	ND	0.02	0.02	0.02
DL26	3.8	1.4	1.3	1.5	0.05	0.14	0.51	92.1	0.22	0.27	0.07	ND	0.02	0.02	0.01
DL27	0.7	1.3	3.2	0.8	ND	0.20	0.39	92.7	0.21	0.17	0.05	ND	0.02	0.03	0.02
DL28	ND	2.0	3.1	0.7	0.02	0.24	0.39	93.6	0.21	0.27	0.07	ND	0.02	0.03	0.02
DL29	12.8	1.9	2.0	0.7	0.02	0.23	0.43	89.0	0.21	0.19	0.06	ND	0.03	0.02	0.01
DL30	ND	2.0	2.4	0.7	0.01	0.26	0.44	93.7	0.22	0.25	0.07	ND	0.02	0.02	0.01
DL31	ND	ND	1.7	0.6	0.02	0.11	0.49	92.4	0.26	0.28	0.07	0.66	0.01	0.04	0.02
DL32	ND	1.8	3.4	0.4	0.04	0.17	0.55	89.2	0.26	0.20	0.05	0.64	0.01	ND	0.02
DL33	4.0	1.7	8.9	0.5	0.03	0.30	1.10	81.0	0.28	0.25	0.06	0.65	0.02	0.02	0.01
DL34	ND	2.8	3.3	1.1	0.04	0.43	0.39	71.1	0.29	0.31	0.06	0.05	ND	0.01	0.01
DL35	ND	2.0	3.5	0.8	0.05	0.23	0.47	82.9	0.28	0.28	0.07	0.39	ND	0.04	0.01
DL36	ND	1.5	2.5	0.4	0.02	0.16	0.41	73.8	0.29	0.13	0.04	ND	ND	0.01	0.01
DL37	6.0	1.3	3.0	0.4	0.09	0.09	0.35	68.2	0.28	0.12	0.04	ND	ND	0.01	0.01
DL38	ND	3.7	3.4	1.3	0.04	0.34	1.48	80.8	0.27	0.33	0.08	0.46	0.01	0.01	0.01
DL39	ND	1.4	2.9	0.4	0.01	0.26	2.33	71.2	0.28	0.16	0.05	0.11	ND	0.01	0.01
DL40	6.3	1.7	1.0	0.9	0.03	0.13	0.35	75.7	0.30	0.24	0.06	0.19	ND	0.03	0.01
DL41	0.1	1.7	1.1	0.8	0.02	0.15	0.68	75.4	0.29	0.16	0.05	ND	ND	0.03	0.01
DL42	ND	1.5	1.5	0.4	0.05	0.14	0.50	93.2	0.27	0.26	0.08	0.65	0.01	0.05	0.02
DL43	2.5	2.2	1.6	0.8	0.04	0.47	0.36	79.3	0.30	0.29	0.07	0.21	ND	0.04	0.01
DL44	ND	1.4	1.7	0.6	0.03	0.14	0.38	65.9	0.30	0.15	0.04	ND	ND	0.02	0.01
Avg	2.1	0.9	1.9	0.8	0.02	0.18	0.75	88.1	0.24	0.23	0.06	0.33	0.01	0.03	0.01
Min	ND	ND	ND	0.3	ND	0.07	0.35	65.9	0.21	0.12	0.04	ND	ND	ND	ND
Max	16.5	3.7	8.9	1.6	0.09	0.47	2.60	97.1	0.30	0.33	0.09	0.84	0.03	0.05	0.02
SD	4.0	0.9	1.4	0.4	0.02	0.09	0.62	8.4	0.03	0.06	0.01	0.28	0.01	0.01	0.01

Table 1b Geochemistry of soil samples around Dela iron-ore deposit (2013)

ID	(wt%)								(ppm)						
	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	TiO ₂	MnO	Fe ₂ O ₃	Cl	Ce	Cr	Co	V	Zn	Rb
SOIL 1	1.7	16.9	27.2	0.1	0.03	0.24	0.15	26.1	0.30	0.24	0.01	ND	ND	0.01	0.01
SOIL 2	ND	9.3	11.5	0.2	0.02	0.79	0.26	42.9	0.31	0.15	0.04	ND	ND	0.02	ND
SOIL 3	ND	10.0	17.0	0.1	0.03	0.74	0.41	55.0	0.30	0.24	0.07	0.05	0.02	0.03	ND
Avg	0.6	12.1	18.6	0.1	0.03	0.59	0.27	41.3	0.30	0.21	0.04	0.02	0.01	0.02	ND
Min	ND	9.3	11.5	0.1	0.02	0.24	0.15	26.1	0.30	0.15	0.01	ND	ND	0.01	ND
Max	1.7	16.9	27.2	0.2	0.03	0.79	0.41	55.0	0.31	0.24	0.07	0.05	0.02	0.03	0.01
SD	1.0	4.2	8.0	0.1	0.01	0.30	0.13	14.5	ND	0.05	0.03	0.03	0.01	0.01	0.01

ND = Not Detected

However Ti show negative correlation with Fe_2O_3 ($R = 0.59$) may be due to lack of Ti rich mafic minerals in the deposit. Element P shows positive linear correlation with Fe_2O_3 ($R = 0.53$) reflecting the impact of chemical weathering in iron-ore deposit. Fe_2O_3 in the deposit show strong negative correlations with Al_2O_3 ($R = 0.87$) and SiO_2 ($R = 0.82$), this may be due to strong enrichment of immobile Fe_2O_3 due to dominant iron-bearing primary minerals in the deposit. In addition, leaching of mobile elements during chemical weathering is clearly shown in the strong negative correlations between Fe_2O_3 and Cl ($R = 0.77$; Figure 2).

COMPARISON WITH AVERAGE CONTINENTAL CRUST

Major oxides of the study samples show similar patterns with in situ soil and previous analyses of the deposit (Fernando, 1986; Figure 3). In general, SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , MnO, CaO and P_2O_5 show clear deviations from average values given to the upper continental crust (UCC; Rudnick and Gao, 2005). Results further reveal that iron-ore contains very little amounts of Al_2O_3 , TiO_2 , SiO_2 and CaO compared to UCC

and CaO during weathering (Gutzmer et al., 2008). However, MnO and P_2O_5 show significant enrichments of iron-ore samples than UCC indicating the presence of garnet in associated Khondalite formation (Cooray, 1984). Only MgO shows a similar composition with UCC which may reflect lower abundance of Mg-rich garnet in the deposit.

All the trace elements in the deposit are strongly depleted with respect to UCC. Most of those elements are incorporated with the heavy minerals (Bhatia and Crook, 1986; Taylor and McLennan, 1985). Therefore, the absence of immobile trace elements may indicate lower availability of ultra-stable and stable heavy minerals. Conversely, the depletion of mobile trace elements may be due to the lack of unstable minerals as well as due to elements leaching during weathering (Roser, 2000; Taylor and McLennan, 1985).

PROVENANCE AND ALTERATION IN DELA IRON-ORE

The major and trace element data provide information about genetic evolution of different

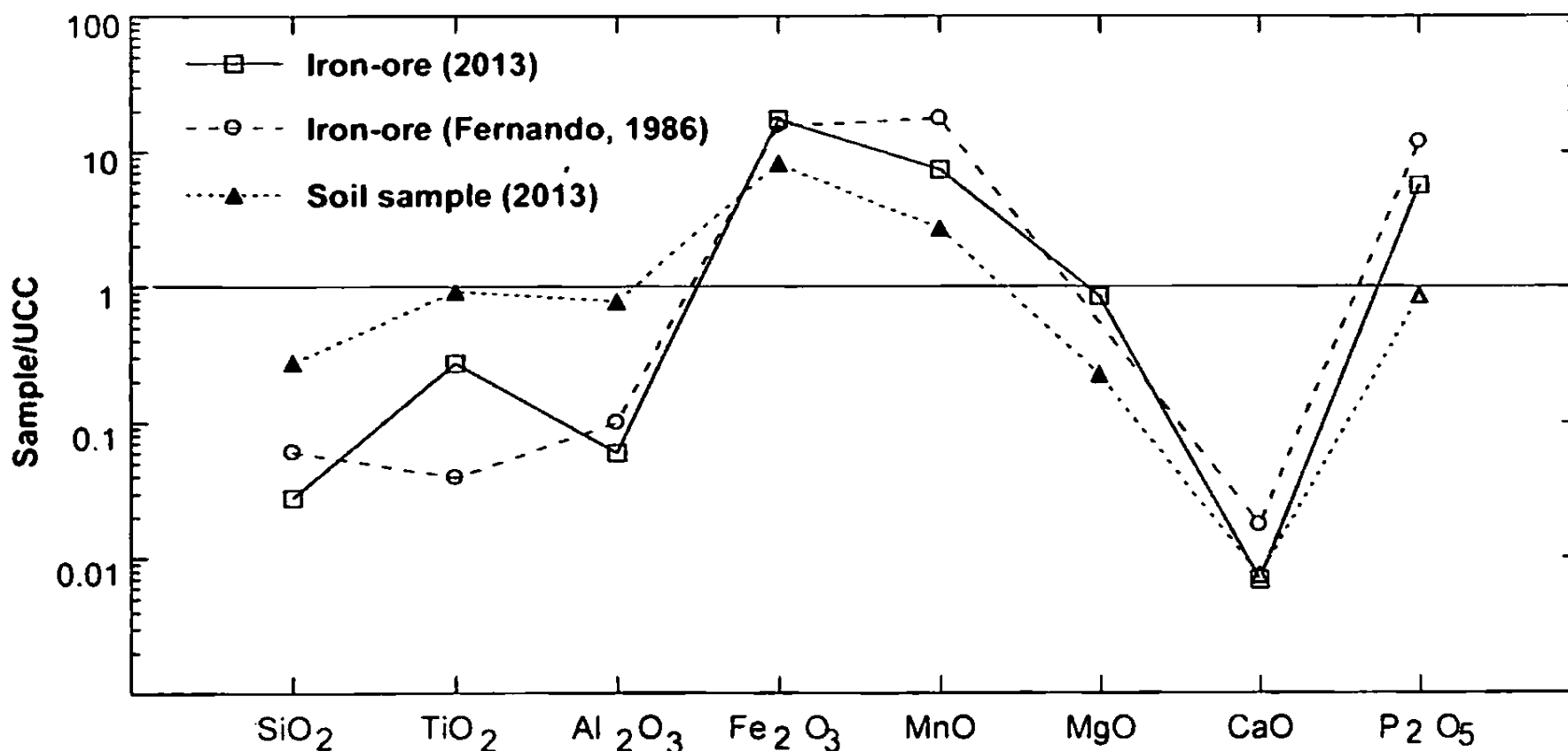


Fig. 3 Average major element compositions of the Dela-ore samples and soil samples normalized against average UCC (Rudnick and Gao, 2005).

(Figure 3). Strong depletion of CaO in iron-ore indicates the lack of carbonate minerals in the deposit. The marked enrichment of iron in all the ore samples is attributed to the iron-bearing minerals and effective removal of SiO_2 , TiO_2

types of ores and their possible components. Lepp and Goldsch (1964) estimated that the Precambrian iron formations contained smaller amounts of Al_2O_3 , TiO_2 , P_2O_5 , CaO and MgO than the post-Precambrian deposits.

Iron-ore samples and soil around the deposit lie in the Fe_2O_3 corner on a Al_2O_3 - SiO_2 - Fe_2O_3 plot (Figure 4) and in the Fe_2O_3 corner on a Fe - CaO/MgO - SiO_2 plot (Figure 5). These results conclude that Dela-iron formation is similar to other post-Precambrian types (Lepp and Goldich 1964; Govett, 1966). In contrast, soil samples around the deposit show a flat-lying trend in the Al_2O_3 - SiO_2 - Fe_2O_3 plot which reveals the partial removal of Fe_2O_3 during the soil formation.

The major element analyses of Dela-ore completed in the year 1986 is given in Table 2 (Fernando, 1986). Fe_2O_3 in the present study shows approximately 11% enrichment than the previous investigation (Avg 1986, 78.7 wt%; Avg 2013, 88.1 wt %). In addition, TiO_2 , MgO and CaO show slight enrichments. Conversely, other major elements such as Al_2O_3 , SiO_2 , P_2O_5 , MnO shows slight depletions (Table 1 and 2). All these changes are attributed to increase iron concentration of the deposit during the past due to alterations by chemical weathering reactions, residual enrichments and leaching of mobile elements from the system.

STRUCTURAL DESCRIPTION OF THE IRON-ORE DEPOSIT

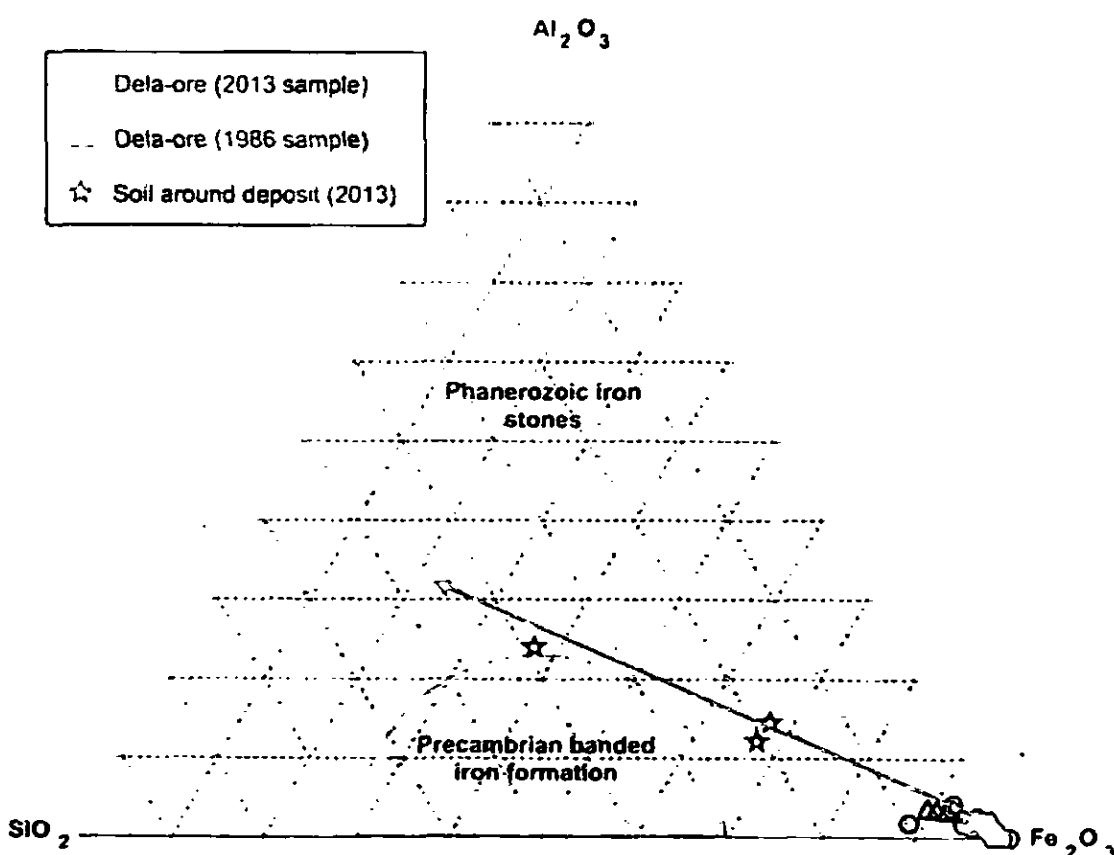


Fig. 4 Geochemical composition of Dela iron-ore and surrounded soil samples plotted within the Phanerozoic iron stone field (after Govett, 1966).

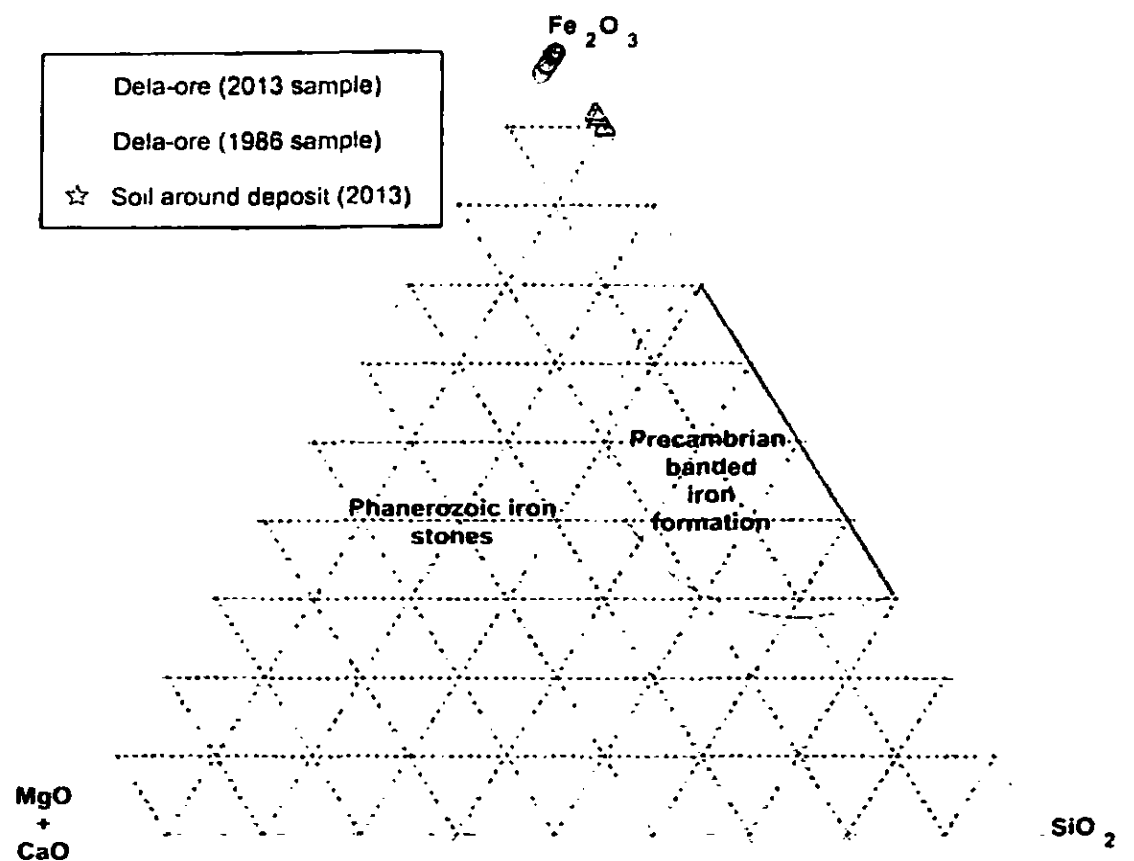


Fig. 5 Geochemical composition of Dela iron-ore and surrounded soil samples plotted within the Phanerozoic iron stone field (after Lepp and Goldich 1964).

Summary of the FTIR analysis is given in the Table 3. FTIR data can be used to investigate the structure and weathering pattern in the deposit (Figure 6). In the FTIR spectrums several major peaks were observed in wave numbers (cm^{-1}) of 3570, 3190, 2910, 2360, 1645, 1550, 1420, 1350, 1250, 1100, 1015, 890, 805, 600 and 500. However the level of absorbance usually did not exceed 0.02 except at wavenumbers of 2915 cm^{-1} (absorbance 0.025), 2360 cm^{-1} (absorbance 0.03), $1100\text{-}950 \text{ cm}^{-1}$ and 800 cm^{-1} (absorbance 0.04) and $700\text{-}450$ (absorbance 0.06). FTIR analysis was done for both weathered (DL 1) and non-weathered (DL 3 and DL 6) zones of the iron-ore (photographs; Figure 6). The analyses show similar spectrum patterns regardless of its physical weathering (spectrum; Figure 6).

This indicates that the chemical bonding of the deposit has not been changed drastically with weathering. Mineralogy of the deposit can be changed during weathering due to secondary mineral formation, thus the deposit shows different chemistry with unique chemical bondings.

Table 2 Geochemistry of Dela iron-ore sample (Fernando, 1986)

ID	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	TiO ₂	MnO	Fe ₂ O ₃
	(wt%)							
DC/1	ND	2.1	6.6	1.6	0.14	ND	1.14	76.4
DC/2	ND	2.2	4.3	1.8	0.11	ND	0.94	80.1
DC/3	ND	1.0	4.6	1.9	ND	0.10	0.58	80.4
DC/3	ND	0.8	0.8	1.8	ND	ND	4.39	77.8
Avg	ND	1.5	4.0	1.8	0.1	ND	1.8	78.7
Min	ND	0.8	0.8	1.6	ND	ND	0.6	76.4
Max	ND	2.2	6.6	1.9	0.1	0.1	4.4	80.4
SD	ND	0.7	2.4	0.1	0.1	0.1	1.8	1.9

Therefore, the different spectrums observed in this study show different absorption levels, which may reflect biological and chemical variations of the iron-ore. For instance, hydrated minerals contain water molecules bound in its molecular structure. However, due to weathering of iron-ore, water molecules can absorb/adsorb into the mineral phase which can impact on the overall chemistry of the system (Coates, 2000; Roy and Venkatesh, 2009).

indicate the oxidation of the silica in Dela-ore during weathering (Coates, 2000).

The Polysulfide (S-S) bond indicates sulfur bearing mineral such as pyrite. Organic sulfate bonds may represent weathering of those minerals in the iron-ore. In general, due to the biological leaching process S is converted in to sulfate ion and produce Fe²⁺ and Fe³⁺ irons. Major bonds of O-H bonded hydroxyl and H bonded OH reflect the water group. This may

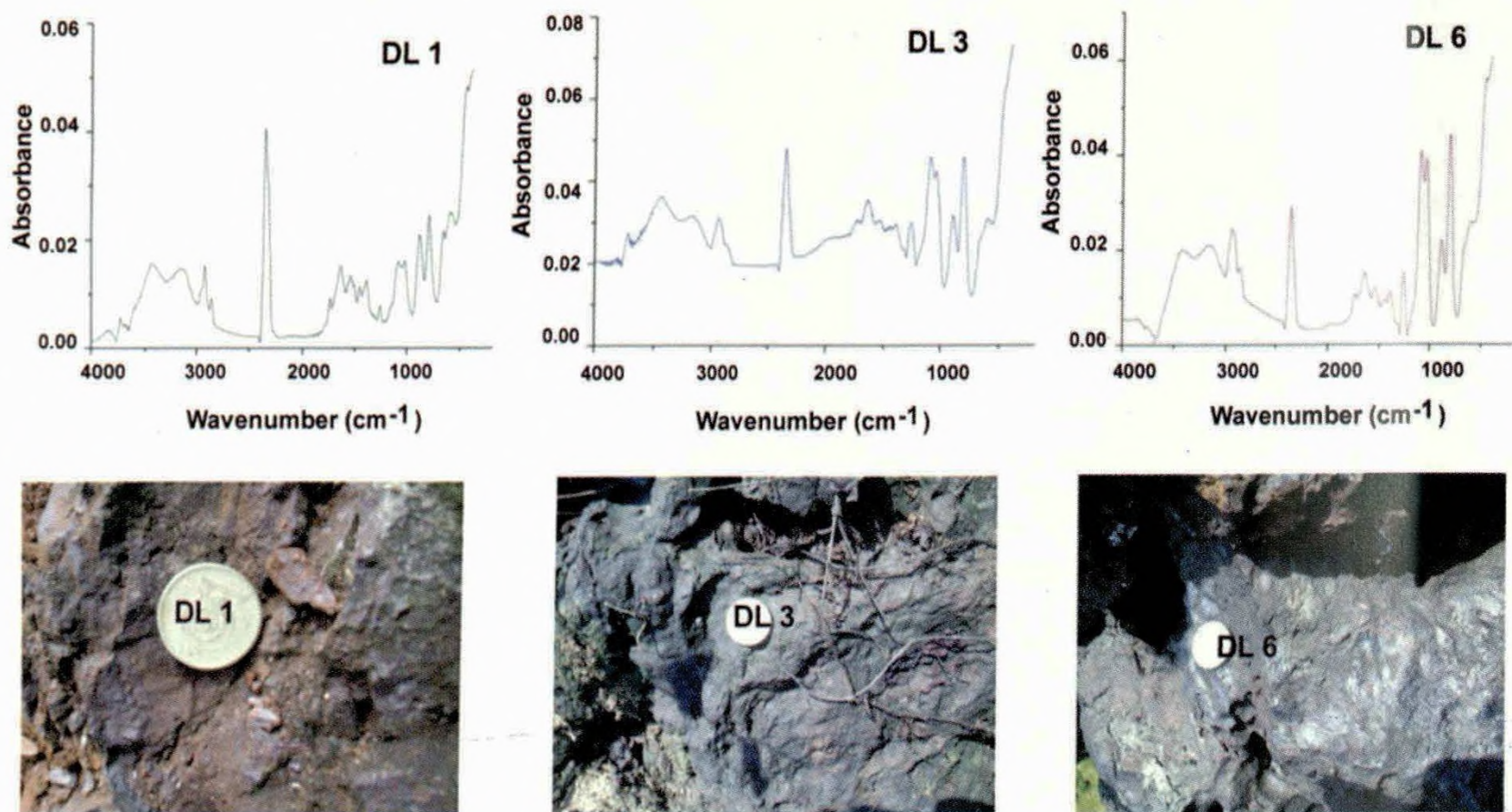


Fig. 6 FTIR spectrums for selected Dela iron-ore samples (DL 1, DL 3 and DL 6) with the field photographs.

According to FTIR summary given in Table 3, the P-H bond gives valuable information regarding the weathering grade of the deposit. P-H and P=O bonds were mainly formed due to decomposition of the P₂O₅ and which may release phosphoric acid (H₃PO₄), which further increased chemical weathering (Table 3; Figure 6). The Silicate ion bond may indicate the original structure of the silicate minerals present in the rock, however, organic Si-O-Si bond may

clearly indicate that iron-ore effectively absorbs water to convert primary minerals to limonite. Internally bonded OH is also identified in the samples which reflect chemically bonded OH group in hydrous minerals by origin. In addition, N-H bonds and long linear aliphatic chains may exist due to accumulation of organic matters and algae during weathering (Coates, 2000).

Table 3 FTIR spectrum of Dela-ore sample (Stringfellow et al., 1993; Coates, 2000)

Type of bond	Wavenumber (Cm ⁻¹)	Description
O-H broad hydroxyl ,H bonded OH	3570-3200	Water group
Internally bonded OH	3570-3540	Internally bonded OH
P-H	2320-2270	P ₂ O ₅ weathering
long linear aliphatic chain	2935-2860	Organic plants, algae
N-H bond	1650-1590	Organic plants, algae
Organic sulfate	1420-1370	Organic sulfur digestion
P=O	1350-1250	P ₂ O ₅ weathering
Phosphate ion and organic phosphates	1100-1000	P ₂ O ₅ weathering
Silicate ion	1100-900	Silicate weathering
Organic silicone Si-O-Si	1055-1020	Silicate weathering
Polysulfide(s-s)	500-470	Organic sulfur digestion

CONCLUSIONS

Geochemical discrimination using major element ratios of the deposit indicate Phanerozoic igneous iron formations in origin. Results of the study further indicate that it has a detritus-free source. Therefore, very low concentrations of trace elements are observed. Major oxides of the samples show residual enrichment of Fe₂O₃ due to effective leaching of mobile phase in the deposit. However, the final stage of the chemical weathering produces lateritic soils, which show considerably lower Fe₂O₃ content than the deposit due to impacts of later stage of weathering. Lower abundances of immobile trace elements in the iron-ore reveal a lack of other heavy minerals with respect to iron-bearing heavy minerals. Further, the FTIR spectrum of the iron-ore clearly attribute chemical weathering process to the deposit. Especially, O-H bonded hydroxyl and H bonded OH reflect the formation of limonite as a secondary mineral. In addition, during chemical weathering process of the deposit, evidences for silicate oxidation and phosphorous decomposition can also be identified from the FTIR data.

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