SAYAM Vol-II, Issue-I (June, 2024), Page No-13-24

Journal Homepage: https://sayamjournal.com/

Article

Magnetic Susceptibility proxy for the study of mechanism and climatic evolution of the top soil section at Precambrian Iron Manganese Mines area, Joda West, Odisha.

Swagata Das[1], Ashis Kumar Das[2*], Sneha Roy[3]

[1]Research Scholar,Department of Geological Sciences, Jadavpur University, W.B., India.
Email: dasswagata33@gmail.com
[2*]Assistant Professor,Department of Geology, Asutosh College , W.B., India.
Corresponding author Email: ashishkumar.das@asutoshcollege.in
[3]Post Graduate Student, Department of Geology, Asutosh College, W.B. India.
Email: roysneha361@gmail.com

ARTICLE INFO

Keywords:
Magnetic Susceptibility, Precambrian, Iron Formation, pedogenetic, lateritic soil, selective leaching.

Received : 26/09/2023
Accepted : 06/01/2024
Date of Publication: 02/06/2024

ABSTRACT

Low and high frequency (K_{lf}, K_{hf}) magnetic susceptibility (MS) of top soil sectionsin the Joda-West Iron-Manganese mines area, Odisha, was measured by using the BartingtonSusceptibility Meter. The variation or uniformity of the soil susceptibility values and the statistical measurements of frequency dependent MS parameters(K_{fd}) were compared to identify grain sizes and causes of enhancement of soil magnetic susceptibility. High MS values at low and high frequencies (K_{lf} = 40521 to 41328 X 10^{-5} S.I. unit, K_{hf}= 38593.8 to 39601.8 X 10^{-5} S.I. unit), high K_{fd} values and the statistical parameter R^2=0.98 indicate pedogenetic formation of magnetic minerals in studied soil samples. A distinct positive correlation between the frequency dependent MS values appear to appreciate the mechanism of a continuous alteration and selective leaching process operative during a long geological history for the origin of the lateritic soil in a uniform tropical to subtropical climate in the studied Fe-Mn mine area of Precambrian Banded Iron Formation. A gradual decrease of MS values with increasing depth might be due to accumulation of clay and silica constituents towards the lower part of the soil sections.

Introduction

Magnetic susceptibility is not only a function of strength and concentration of magnetic particles but also their grain sizes, grain morphology, and mineralogy. It can be used as a proxy for soil pollution levels. Thus the magnetic properties of the soil may reflect the magnetic mineralogy, composition and grain sizes. The main sources of soil magnetism are the magnetically susceptible minerals generated due to various lithogenic, pedogenic and anthropogenic processes (Bouhsane and Bouhlassa, 2018). The nature of parent rock material, physio-chemical characteristics, organic activity, and finally the secondary alteration processes of the soil are all in combination affect the ultimate percent of iron oxides and, consequently, the variation of magnetic susceptibility in soils. Thus the magnetic susceptibility measurements is a simple nondestructive technique to understand the changes in soil and landscapes due to various contributions of iron mineral concentrations generated in soils and also the variation of environmental conditions.

Magnetite, titano-magnetite and maghemite occurring as stable primary ferrimagnetic minerals in soil can accumulate as they are resistant to weathering. Whilst iron oxide minerals like haematite and maghemite occur as secondary minerals and generated due to weathering, alteration and lateritization processes.The sum of primary and secondary or neomorphic iron oxide minerals concentration cause soil magnetic susceptibility. The number of ferrimagnetic minerals is inversely correlated with the susceptibility values, which is also affected by particle size or domain states of minerals. The source material and the mechanism of formation affect grain sizes. Weathering of basic and ultrabasic igneous rocks produce lithogenic coarse grained multidomain (MD) ferrimagnetic minerals which are primary in origin. While it is considered that the very fine grained iron oxide minerals are generated due to pedogenesis (Maher and Taylor, 1988). The fine grained magnetic fractions exhibit frequency dependence in magnetic susceptibility and are super paramagnetic (SP) in nature. The SP minerals show varied magnetic relaxation, which results in magnetic viscosity—a time-decaying form of magnetization (Néel, 1949). So, measuring this attribute could be able to serve as a proxy for how soil forms and how it weathers in particular situations.

As a result of geochemical or microbiological processes, iron oxide minerals i.e., ferrihydrite and magnetite are formed in varied concentrations due to variable weathering and alteration of rocks and minerals with subsequent dehydration and oxidation of solution rich with excess ferrous ions (Schwertmann, 1988; Dearing et al., 1996). Low temperature oxidation of magnetite may produce maghemite When the parent material sufficiently hydrlized and subsequently dissolved by Fe-reducing bacteria. Fe^{2+} will be oxidized if it reaches a critical concentration. Alternate wet and dry situations in soils matching with variations in Eh-pH conditions encourage these transitions. Another perspective suggests that pedogenic hematite formation occurs alongside increase in ferrimagnetic minerals within soils located in tropical and subtropical regions due to sufficient dehydration required to convert ferryhydrite to haematite (Schwertman, 1988; Torrent et al. 2006). According to the hypothesis, the transformation progresses through different stages, leading to the formation of ferrimagnetic minerals such as ferrihydrite, super paramagnetic maghemite and very fine pigments of hematite. Each stage of the process varies in difficulty depending Climatic condition and the degree of weathering control the stages of the above process. Thus in relatively moist soils, ferrihydrite and maghemite grow faster than those of hematite. The development of haematite is more rapid in tropical soils that experience seasonal drying.

According to Tardy and Roquin (1992), the pathways of transformation for hematite and ferrimagnetic minerals align with the overall conditions conducive to the formation of laterites. Laterites are characterized by selective enrichment of minerals, formed through a range of hydration and dehydration processes in typical environment of soil formation and evolution. Due to its quantitative measurement of the amount of ferrimagnets and ease of measurement, magnetic susceptibility has an advantage over other soil development indicators. Only a relatively small number of assessments are available for tropical soils, whereas numerous studies have been undertaken on soil magnetism from varied climatic regions. The semi-quantitative model proposed by Dearing (1999), soil samples are differentiated into four categories with respect to their magnetic characteristics:

1. Soil samples with K_{fd}% < 2% and SP concentration < 10% (low SP grains).
2. Soil samples with K_{fd}% between 2% and 10%, where there is a mixture of SP and a coarser non-SP fraction < 0.005μm.
3. Samples with K_{fd}% between 10% and 14% and SP concentration > 75%.
4. Samples with K_{fd}% > 14%, which may represent infrequent values due to incorrect measurements or

pollution.

According to general consensus, an increase in soil magnetic susceptibility is linked to older soils and warmer, wetter climates (Singer et al., 1996; Torrent et al., 2010a). This relationship between soil development and magnetic properties is particularly evident in deeply weathered laterite soils, especially in regions characterized by the Precambrian Iron Formation.

In the humid tropical regions of the world, laterites are one of the most prevalent soil types (ferralsols, plinthosols, or oxisols; FAO, 2006; NRCS, 2006). They are the outcome of prolonged and vigorous chemical weathering of soils with varying moisture contents in humid tropical environments. According to Tardy and Roquin (1992), the intense weathering of silicate minerals typically releases Fe and Al ions that lead to the formation of kaolinite, gibbsite, and Fe-oxide minerals, primarily goethite and haematite. Laterites can be produced from a variety of lithologies, such as silicate rocks and limestone, and the chemical makeup of the source parent rocks has a significant impact on both their composition and behaviour (Schellmann, 1981). Haematite is a highly prevalent mineral that makes up lateritic soils (Torrent, et.al.1983; Fontes and Carvalho, 2005). It gives them their distinctive red colour and indicates the level of weathering (Schwertmann, 1993). High soil temperatures and little water activity cause ferrihydrites to dry up, which leads to the development of haematite. While the development of goethite is preferred to that of haematite during soil weathering under permanently wet soil moisture regimes, Torrent et al. (2006, 2010a) verified the paragenesis of haematite and maghemite.Soil magnetic susceptibility measurements are frequently used to interpret the climate signals in palaeosols (Maher & Thompson, 1999; Maher et al., 2003) and to identify soil contamination (Petrovský & Ellwood, 1999; Lecoanet et al., 2001).

Study area and Sampling Location

Joda is situated in the northern part of Odisha, in the Eastern Ghats mountain range. The town lies approximately 240 kms north of the state capital, Bhubaneswar. The region is characterized by hilly terrain and dense forests. The topography of Joda is characterized by hills, plateaus, and valleys with elevations varying across the area. Soil samples were collected from different depth levels of each of two vertical sections of about 15ft and top soil samples from three sites at Joda-West Fe-Mn Mines area, Odisha (Fig.1).

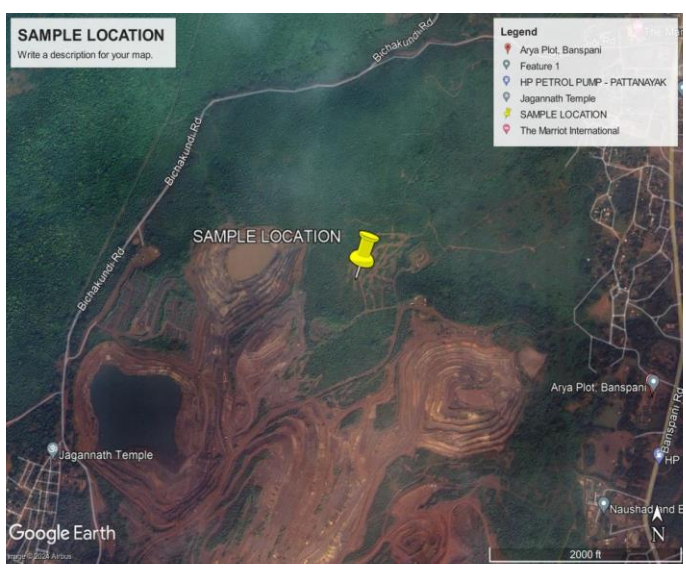

Figure 1 Generalized Location Map of Soil sampling site of the Studied Area

Physiography of the Area

The Joda region is physically a part of Odisha's Middle Mountainous Region, and the terrain is old and mature with a rough surface. The area's elevation ranges from 150 to 600 metres above mean sea level (MSL). The region is covered by toposheet No. 73F/8 from the Survey of India. The Jharkhand-Odisha iron ore belt, which extends along Odisha's northern border, includes this region (Jones, 1934). It extends westward from the Gorumahisani Hills in the Mayurbhanj district, via the Odisha districts of Keonjhar and Sundergarh, and up to the Jharkhand district of Singhbhum. The iron ore belt forms a horseshoe-shaped synclinorium and runs in a NNE-SSW direction (Jones, 1934; Dunn and Dey, 1942; Acharya, S, 2005).

Geology and Geomorphic Characteristics

A significant iron ore resource in India is located within the 1550 sq km region of the Singhbhum-Keonjhar-Bonai deposits. This area spans a range of prominent hills from the southwest of the Singhbhum district in Bihar into the Keonjhar and Sundergarh districts of Odisha. H.C. Jones identified over 135 ore bodies of varying sizes in this region. The range is predominantly capped with massive haematite, with only a few interruptions at three or four locations. Although not pronounced, there is evidence of the lateritization of capping. Due to folding and faulting, there are parallel ore bands in the northern portion of this range that may prevent repetition of the same zone. High-quality iron manganese ore deposits to the north and beyond Gua caps the parallel ranges, which form the crests of isoclinal folds. Palaeomagnetic study of the mother rocks, the Banded Haematite and Jasper of Odisha, shows an age of ~3000 Ma (Das et al.1996).

Climate and vegetation

Joda is a city in India's southeast that is a part of the Keonjhar district. Its extreme summer heat and high humidity levels set its climate apart. The maximum recorded temperatures in May typically reach 38 °C. The temperature in the district starts to rise swiftly in the spring. However, 43.3 °C is the highest temperature ever recorded. With the arrival of the monsoon in June, the weather improves gradually and continues to be pleasant through the end of October. December is the month with the lowest temperature, hovering around 11 °C. Even 7 °C has been recorded on occasion. Around 1910.1 mm of precipitation falls annually on average.The main vegetation of the area includes cash and food crops and forest cover. Although the primary occupation of civilians is in the mining industries, a considerable proportion of the population is also involved in agriculture and forestry. The main crops grown here for food and sale include maize, wheat, til, niger, and arhar. The forest covers a major part of the region, having thick as well as thin cover. Tropical dry deciduous and tropical moist deciduous are the main types of forest cover. The main species of trees found here are *Shorea robusto* (sal), *Anogeissus latifolia* (axlewood), *Terminalia crenulata* (saj), and *Madhuca latifolio* (mahua). The vegetation of the region *Diasporas melanoxylon* (tendu), *Lannea coromandelica* (gurjon), etc.

Objectives of the study

(i) Investigating the concentration and nature of magnetic fractions as indicators of soil formation and weathering in tropical environments.
(ii) Assessing whether magnetic susceptibility primarily reflects pedogenic processes or if there is a significant lithogenic influence.
(iii) Studying the correlation between soil reddening and variations in magnetic susceptibility along vertical soil profiles.

Methodology Sampling

Soil samples were collected from different depth levels of two vertical sections (SP-1, SP-2, SP-3 and SP-1b, SP-2b, SP-3b) and other three top soil sampling sites (Site-1, Site-2 and Site-3) at Joda West Fe-Mn mines area (Lat.21^{0}59′55.94″N, Long. 85^{0}24′35.33″E) using a plastic zip-lock pouch to minimize contamination (Fig.2).

Figure 2 Collection of samples from vertical soil section at Joda West Fe-Mn Mine area, Joda, Odisha.

Laboratory preparation of samples

For several days, the samples were air dried in the laboratory at a temperature of 30 degrees Celsius to avoid any chemical reactions. In the agate mortar, they were pulverized and sieved using an 80-mesh sieve before being kept in a plastic container for laboratory measurement. At laboratory temperature, susceptibility tests were then performed on sieved samples poured into a 10-ml plastic container.

Instrument for Measuring Magnetic Susceptibility

Figure 3 Bartington Magnetic Susceptibility Meter, Geophysical Laboratory, Asutosh College, Kolkata, West Bengal.

The magnetic susceptibility is measured using the MS2 device in the following ways:

The primary frequency-determining element of the sensor is a wound inductor, which is part of a high-temperature oscillator. When the inductor remains empty or air-filled, its value governs the oscillation frequency. The frequency of oscillation changes when the inductor is influenced by the specimen being measured. The variable of interest is minuscule, even if the value of 0 is constant. As a result, the period value must be used to address any thermally induced sensor drift. The magnetic susceptibility value is digitally displayed and output over a serial interface.

The volume susceptibility of all samples was measured in CGS units. The sensor's operational range specified a 10 cc sample container with interior dimensions of 24 mm in diameter by 23 mm in height, and a maximum base outside diameter of 26 mm. The sensor is compatible with cubic boxes measuring 1"(25.4 mm) and 7/8" (23 mm). In this case, 1-inch cubic boxes were employed to calculate the magnetic susceptibility (MS) values. Thus, the volume of each sample used for calculating MS values is 1 cubic inch. Typically, the sensor includes a movable platen with a 27.5-mm stem in most setups. After carefully placing the boxes atop the platen with each of the samples inside, measurements were taken.

A single frequency measurement was taken into account for calculating the magnetic susceptibility values. The Bartington Susceptibility Meter is the more popular name for this MS2 Magnetic Susceptibility System. Both the Low Frequency and High Frequency susceptibility values of each soil sample were measured in the Geophysical Laboratory, Department of Geology, Asutosh College, Kolkata, West Bengal (Fig.3).

Magnetic Susceptibility (MS) values:

TABLE-1

Site No.	Sample No.	Depth (in ft.)	Low frequency MS value in S.I. (10^-5)	High frequency MS values IN S.I. (10^-5)	Frequency difference in S.I. (10^-5)	Frequency difference percentage
SP1	SP1.1	0	40597.2	39601.8	995.4	2.45
	SP 1.2	0	40572	38593.8	1978.2	4.88
	SP 1.3	0	41126.4	38606.4	2520	6.13
	SP 1.4	0	40521.6	38707.2	1814.4	4.48
	SP 1.5	0	41328	39135.6	2192.4	5.3
	SP 1.6	0	40698	38770.2	1927.8	4.74
SP2	SP 2.1	5	16128	14288.4	1839.6	11.41

	SP 2.2	5	11491.2	10193.4	1297.8	11.29
	SP 2.3	5	14616	13078.8	1537.2	10.51
	SP 2.4	5	9828	8719.2	1108.8	11.28
	SP 2.5	5	3591	3276	315	8.77
	SP 2.6	5	5745.6	5216.4	529.2	9.21
SP3	SP 3.1	10	9676.8	8631	1045.8	10.81
	SP 3.2	10	8568	7572.6	995.4	11.62
	SP 3.3	10	9702	8555.4	1146.6	11.82
	SP 3.4	10	9588.6	8202.6	1386	14.45
	SP 3.5	10	5985	5191.2	793.8	13.26
	SP 3.6	10	3767.4	3301.2	466.2	12.37
SP1b	SP 1b.1	0	42411.6	39677.4	2734.2	6.45
	SP 1b.2	0	41554.8	39160.8	2394	5.76
	SP 1b.3	0	40080.6	37989	2091.6	5.22
	SP 1b.4	0	40950	38795.4	2154.6	5.26
	SP 1b.5	0	41101.2	39438	1663.2	4.05
	SP1b.6	0	41806.8	39967.2	1839.6	4.4
SP2b	SP 2b.1	5	7597.8	6627.6	970.2	12.77
	SP 2b.2	5	7257.6	6375.6	882	12.15
	SP 2b.3	5	9828	8542.8	1285.2	13.08
	SP 2b.4	5	9601.2	8290.8	1310.4	13.65
	SP 2b.5	5	11844	10193.4	1650.6	13.94
	SP 2b.6	5	11503.8	9840.6	1663.2	14.46

SP3b	SP 3b.1	10	11755.8	10130.4	1625.4	13.83
	SP 3b.2	10	10999.8	9450	1549.8	14.09
	SP 3b.3	10	11529	9689.4	1839.6	15.96
	SP 3b.4	10	11088	9626.4	1461.6	13.18
	SP 3b.5	10	11818.8	10292.4	1526.4	12.9
	SP 3b.6	10	11781	10306.8	1474.2	12.51
Site1	S1.1	0	22402.8	20588.4	1814.4	8.1
Site1	S1.2	0	30756.6	27895.4	2861.2	9.3
	S1.3	0	29358	27127.8	2230.2	7.6
	S1.4	0	27833.4	25477.72	2355.68	8.47
Site2	S2.1	0	23108.4	20878.2	2230.2	11.67
	S2.2	0	23108.4	20399.4	2709	11.72
	S2.3	0	10987.2	10231.2	756	6.88
	S2.4	0	17362.8	15687	1675.8	9.65
Site3	S3.1	0	48308.4	44982	3326.4	6.89
	S3.2	0	60278.4	57519	2759.4	4.58
	S3.3	0	66276	62722.8	3553.2	5.55
	S3.4	0	66175.2	63063	3112.2	4.6

Results and Discussions

Magnetic susceptibility (MS) at low and high frequencies (K_{lf}, K_{hf}) and the derived magnetic parameters, frequency difference (K_{fd}) and frequency difference percent (K_{fd}%), of the studied soil samples are shown in Table-1 . In the first location (SP-1), the top part of a vertical section shows the values of magnetic susceptibility at low frequency, ranging from 40521.6 to 41328 x 10^{-5} S.I. unit, with a mean value of 40806.36 x 10^{-5} S.I. unit. In the middle part of the section, about 2 m from the top, the MS values range from3591 to 16128x 10^{-5} S.I. units, with a mean MS value of 10232.46x 10^{-5} S.I. units. While in the lower part of the section about 3 to 4 m from the top, the MS values varied from 3767.4 to 9702 x 10^{-5} S.I. units, with a mean value of 7902.7x 10^{-5} S.I. units. The top soil samples collected from site-1 show the MS values ranging from 22402.8 to 30756.6 x 10^{-5} S.I. unit with a mean value of27587.7 x 10^{-5} S.I. unit, samples from site-2 show the MS values ranging from 20588.4 to 27896.4 x 10^{-5} S.I. unit with a mean value of 18774x

10^{-5} S.I. unit; and samples from site-3 have shown the MS values ranging from 48308.4 to 66276 x 10^{-5} S.I. unit with a mean value of 60259.5 x 10^{-5} S.I. unit.
The high frequency MS values of the top soil samples of site-SP-1 varied from 38593.8 to 39601.8 x 10^{-5} S.I. units, with a mean value of 38902.5 x 10^{-5} S.I. units. The top soil samples from site-1, site-2 and site-3 also show similar types of variation in high frequency MS values (Table-1) with mean H_f MS values of 25272.45, 16798.95, and 57071.7 x 10^{-5} S.I. units, respectively.
From the above data, it appears that in all five sites, i.e., SP-1, SP-b-1, S-1, S-2, and S-3, the topsoil samples show relatively high MS values, with a mean low frequency susceptibility value of 39087.342 x 10^{-5} S.I. unit and a mean high frequency susceptibility value of 35443.422 x 10^{-5} S.I. unit. While the soil samples taken from the middle and lower parts of the two vertical sections (SP-1 and SP-1b) show comparatively lower susceptibility values.

Frequency-Dependent Magnetic Susceptibility, κfd, Analysis:

The relative loss of susceptibility, K_{fd}, is expressed as the difference between K_{lf} and K_{hf} and is a useful measure to differentiate the mechanisms of soil formation and the occupational variability of soil magnetism (Bouhsane, N., and Bouhlassa, S., 2018). In the present study, the high K_{fd} values appear to indicate consistent pedogenetic formation of magnetic particles in soil.

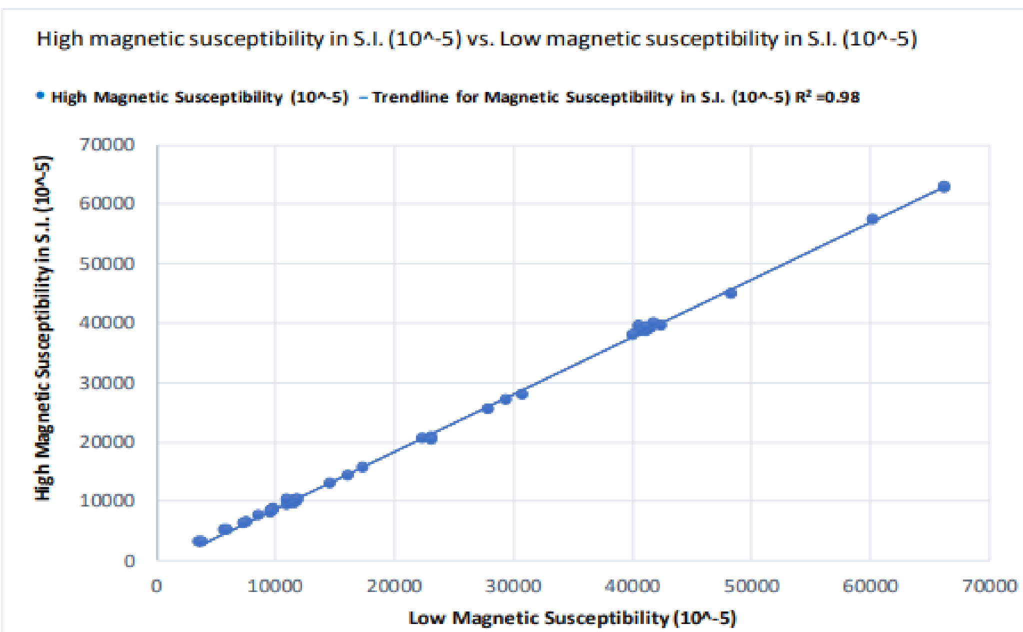

Figure 4 High field magnetic susceptibility(Khf) versus low magnetic susceptibility(Klf) showing positive correlation.

Comparing the K_{lf} versus K_{hf} values in different sections, it has been seen that the K_{if} values are higher than the K_{hf} values. This difference appears to indicate the presence of ultrafine or super paramagnetic grains (grain size <0.03 μm) (Dearing et al.,1996; Sangode et al.,2010). The frequency dependent susceptibility values, K_{lf} versus K_{hf}, indicate a high linear correlation with R^2=0.98 (Fig.4). This confirms that a continuous pedogenic alteration of magnetic particles took place over a long geological time period at the sampling sites in a more or less similar fashion.

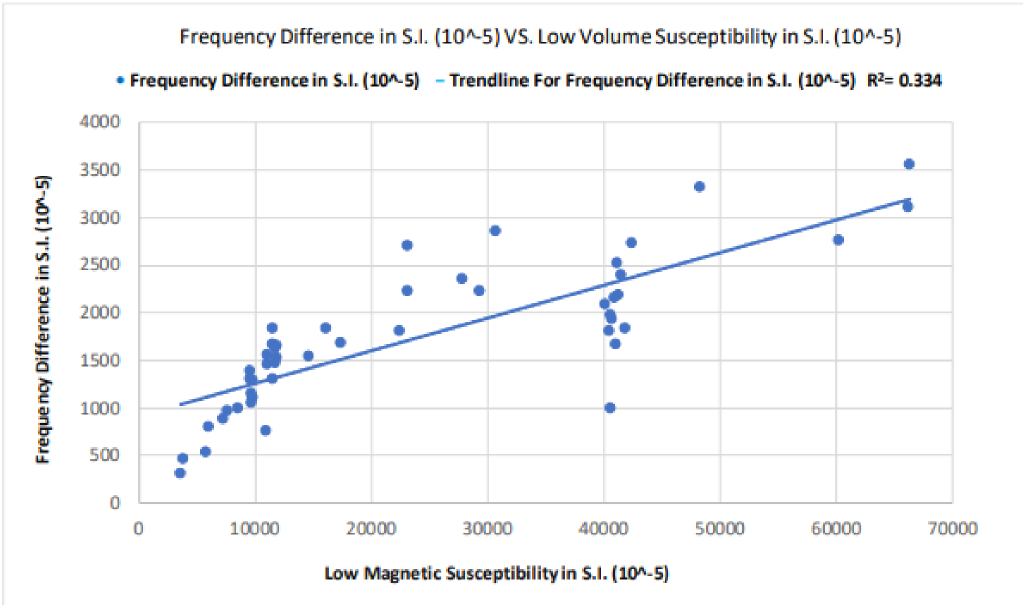

Figure 5 Frequency difference(K_{fd}) versus low volume susceptibility(K_{lf}) analysis showing distinct but low positive correlation.

The K_{lf} versus K_{fd} graph indicates a positive but low correlation between the low magnetic susceptibility and the frequency difference (Fig.5). Here the low regression value indicates that the independent (K_{fd}) variable is not effectively explaining the dependent variable(K_{lf}) in the regression model. This type of relationship may confirm that the increasing magnetic susceptibility in the studied soil samples is governed by the pedogenic contribution of magnetic minerals (Forster et al.,1994). A distinct positive correlation between K_{fd} and K_{lf} also indicates considerably a homogeneous magnetic mineralogy with uniform variation in the concentration of the magnetic particles in the soil samples. This also proves that a uniform chemical and physical alteration was the mechanism occurring cyclically both in the hot-dry and wet-rainy seasons in the studied areas of the Precambrian Banded Iron formation. In the present study, the percentage frequency-dependent susceptibility (K_{fd}%) values show a range from 2.45% to 15.96%, indicating a wide range of concentrations of SP grains, possibly according to the relative intensity of endogenetic and pedogenetic alteration in cyclical alternate wet and dry conditions occurring for a long geological time from Precambrian to the present. The soil samples are characterized by both SP (<1μm) and relatively coarser secondary magnetic particles, e.g., specularite (>10μm) which were significantly observed in the original BHJ rocks in these area (Das et.al., 1996). Considering the age of origin and a geologically long history of evolution of Archaean Banded Iron Formation of Odisha, it might be appreciated that a uniform weathering and physio-chemical alteration were experienced continuously by these rocks in a low latitude tropical to subtropical paleo climatic regions.

Conclusion

From the susceptibility measurements the following conclusions are derived:

i) Considerably high values of both the low and high frequency susceptibilities indicate that the studied soil samples of Joda West are enriched with high concentrations of iron oxide particles. Both the SP grains and the non-SP or coarser magnetic fractions have been identified from percentages of frequency-dependent susceptibility measurements.

ii) Soil samples were collected from the Iron Mines area of the Precambrian Iron Formation, and reasonably, the source of the soil susceptibility is the alteration of the mother rocks, i.e., the Precambrian Banded Haematite Jasper.

iii) A distinct linear positive correlation between the Low and High frequency magnetic susceptibilities indicates a uniform mechanism of chemical and physical alteration of BHJ rocks with successive wetting and drying of the material, which resulted in the palaeo-soil in the area. The variation in the leaching of silica might be the cause of the decreasing trend of the susceptibility values from the top soil to the bottom part of the soil sections.

Acknowledgement: The corresponding author would like to acknowledge the Asutosh College authority for the financial support of the research work. The authors acknowledge the geologists of Tata Steel Iron Mines for helping the collection of samples in the Joda West Fe-Mn mines area.The authors gratefully acknowledge the Geophysical Laboratory, Department of Geology, for using the Bartington Susceptibility Meter to measure all the soil samples. The authors also acknowledge the Department of Geology and Chemistry for allowing the measurement and the preparation of soil samples.

REFERENCES

1. Acharya, S. (2005). Genetic modeling of iron and manganese ore deposits of the Joda-Koira Iron Ore basin(F1-F3), India- Its application to explorations, *Proc. Vol. Int. Sem., Vision Mineral Development 2020 organized by SGAT*, pp.44-67.
2. Bouhsane, N. & Bouhlassa, S. (2018). Assessing Magnetic Susceptibility Profiles of Topsoils under Different Occupations.*Int. Jr. Geophys.V.2018*. Article ID 9481405, 8 pages.https://doi/10.1155/2018/9481405.
3. Das, A.K., Piper, J.D.A.,Basu Mallik, S. & Sherwood, G.J. (1996). Palaeomagnetic study of Archaean Banded Haematite Jasper Rocks from the Singhbhum-Orissa Craton, *India.Precamb. Res.Vol.80*, pp.193-204.
4. Dearing, J.A., Hay, K.L., Baban, S.M.J., Huddleston, A.S., Wellington, E.M.H.&Lovel,P.J.(1996). Magnetic susceptibility of soil: an evaluation of conflicting theories using anationaldataset. *Geophys. J. Int.*, 127:728-734.
5. Dearing, J. (1999). Environmental magnetic susceptibility: Using the Bartington MS2 system. *Chi Publishing, Keniloworth*.
6. Dunn, J.A. & Dey, A.K.(1942). "Geology and Petrology of Eastern Singhbhum and surrounding Areas". *Memoir Geological Survey of India, Vol. 69, No.2*, pp.281456.
7. FAO (Food and Agriculture Organization of the United Nations), (2006). World reference basefor soil resources 2006 - a framework for international classification, correlation and communication. *Worldsoilresourcesreports.103.Rome.* Available at *www.fao.org/ag/Agl/agll/wrb/doc/wrb2006final.pdf*
8. Fontes,M.P.F.&Carvalho,I.A.(2005).Colorattributesandmineralogicalcharacteristics,evaluatedbyradiometry,ofhighlyweatheredtropicalsoils.*SoilSci.Soc.Am.J.,69*:1162-1172.
9. Forster, T., Evans, M. E. & Heller, F. (1994). The frequency dependence of low field susceptibility in loess sediments. *Geophys. J. Int., 118*, 636-642.
10. Jones, H.C. (1934). The iron ore deposits of Bihar and Orissa. *Geol. Surv. India Memoiur, V-63*, pp.375.
11. Lecoanet, H., Leveque, F. & Ambrosi, J.P.(2001). Magnetic properties of salt-marsh soils contaminated by iron industry emissions (southeast France). *Journal of Applied Geophysics*, *48*(2), pp.67-81.
12. Maher, B.A., Alekseev, A. & Alekseeva, T. (2003). Magnetic mineralogy of soils across the Russian Steppe: climatic dependence of pedogenic magnetite formation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *201*(3-4), pp.321-341.
13. Maher, B.A. (1986). Characterization of soils by mineral magnetic measurements. *Phys. of the Earthand Plan.Int. 42*: 76-92.
14. Maher, B.A., Taylor, R.M. (1988). Formation of ultrafine-grained magnetite in soils. *Nature,336*: 368-370.
15. Maher, B.A. & Thompson, R. eds. (1999). Quaternary climates, environments and magnetism.*Cambridge University Press.*
16. Mullins, C.E. (1977). Magnetic susceptibility of the soil and its significance in soil science review.*J. Soil Sci. 28*: 223-246.
17. Néel, L. (1949). Théorie du traînage magnétique des ferromagnétiques en grains fins A vec applications aux terres cuites. *Annales de Géophysique, 5*:99-136.
18. NRCS (Natural Resources Conservation Service),(2006). *Keys to Soil Taxonomy,10th edn, NRCS, Washington,DC.*Available at:soils.usda.gov/technical/classification/taxonomy/
19. Petrovský, E.& Ellwood, B.B.(1999).Magnetic Monitoring of Air, Land and Water Pollution. *In Maher, B.A. and Thompson, R.,Eds., Quaternary climates, Environments and Magnetism, Cambridge University Press, Cambridge*,279-322.
20. Sangode, S. J., Vhatkar, K., Patil, S.K. & Meshram, D.C.(2010). Magnetic susceptibility distribution in the soils of Pune Metropolitan Region: implications to soil magnetometry of anthropogenic loading. *Current Sci. 98*(4)
21. Schellmann,W. (1981).Considerations on the definition and classification of laterites.*Lateritisation processes,proceedings of the international seminar on lateritisation processes,Trivandrum/India*: pp 1-10.

22. Schwertmann,U. (1988).Occurrence and formation of iron-oxides in various Pedo-environments. p. 267-308. *In: Stucki, J.W., B.A. Goodman, and U. Schwertmann.(eds.) Iron in soils and clay minerals. Reidel, Dordrecht.*
23. Schwertmann, U. (1993). Relations between iron oxides, soil color, and soil formation. In:Bigham, J.M. & Ciolkosz, E.J. (eds.) "Soil color". *Soil Sci. Soc. Am. Spec. Publ. 31*:51 69.
24. Singer, M.J., Verosub, K.L., Fine, P.& TenPas, J. (1996). A conceptual model for the enhancement of magnetic susceptibility in soils. *Quat.Int.,34-36*: 243-248.
25. Tardy, Y.&Roquin, C. (1992). Geochemistry and evolution of lateritic landscapes.- *In.Martini, I.P.&Chesworth,W.(eds.):Weathering,soilsandpaleosols–Developmentsinearthsurfaceprocesses 2:* 407-443. Elsevier.
26. Torrent,J.,Barrón,V.&Liu,Q. (2006). Magnetic enhancement is linked to and precedes hematite formation in aerobicsoil.*Geophys.Res.Lett.,33*:4pp,doi:10,1029/2005GL 024818.
27. Torrent, J., Schwertmann, U., Fetcher, H. & Alfarez, F. (1983). Quantitative relationships between soil colour and hematite content. *Soil Science, 136,* 354-358.
28. Torrent, J., Liu, Q. S.&Barrón, V. (2010a). Magnetic susceptibility changes in relation to pedogenesis in a Xeralf chronosequence in northwestern Spain. *European Journal of Soil Science,61*: 161-173.