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Investigation on Magnetic Susceptibility of Marine Core Sediment Belong to the Central Western Bay of Bengal

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ABSTRACT

4.12 cm marine core sediment was sub sampled to every 2cm interval with a total of 212 samples. Half part of each undisturbed whole length of the dried core sample(s) was used for studies of environmental magnetic properties such as magnetic susceptibility. The remaining part of the samples were dried at 60 ^{0}C, grinded and sieved through 230 mesh size and studied for organic carbon, calcium and magnesium carbonates by titration methods. Magnetic susceptibility measurements were carried out by using Kappa Bridge available in Germany. The obtained results have been interpreted based on the sediment core values of other physical parameters such as rate of sedimentation, age and organic carbon. Increased rate of sedimentation (0.006 to 0.013 cm/year) enhanced the magnetic susceptibility value reflecting its range 0.732×10^{-3} to 1.426×10^{-3}. Obtained positive correlations relating to rate of sedimentation with calcium and magnesium carbonates and magnetic susceptibility indicating about enrichment of the present sediments with carbonate shells in which biologically derived metals are more.

1. INTRODUCTION

Elements enter into environment and oceans by the two ways namely natural sources including erosion of ore-bearing rocks, wind-blown dust, volcanic activity, forest fires and processes derived from human activities by means of atmospheric deposition, through river runoff and direct discharges or dumping [1]. Sediment is any particulate matter that can be transported by fluid flow, which eventually deposited at the bottom of a water body. They are the important carriers of metals with major and minor quantities in the hydrological cycle. As metals are partitioned with the surrounding waters; they reflect the quality of an aquatic system. Coastal and estuarine regions are the important sinks for many persistent metal pollutants those accumulate with organisms by forming at the bottom of sediments. The hydrogenous fraction of deep-sea sediments consists of iron-manganese oxides chiefly and dispersed as micro nodules into the sediments and present as coatings on sedimentary particles. Iron-manganese oxides are precipitated directly from seawater; interstitial water during diagenesis; oxygenated hydrothermal fluids and concentrated trace elements greatly.

The accumulated elements belong to marine sediments like iron and such related metals of sediments cause to exhibit magnetic property namely magnetic susceptibility. The magnetic susceptibility of marine sediments is routinely measured in pale oceanographic studies because it can be used to correlate sedimentary sequences, to identify missing or disturbed sediment sections, and to help unravel past pale oceanographic and paleoclimatic variations both in marine and terrestrial sequences [2]. The magnetic record for a sediment sequence may reflect variations related to sediment source(s), and diagenetic (post-depositional) loss; transformation, and gain of magnetic minerals. The soils derived from sedimentary rocks usually contribute more magnetic susceptibility than its parent rock due to *in situ* conversion of iron oxides from anti ferromagnetic form such as hematite (α Fe_2O_3) to ferrimagnetic form like maghemite (γ Fe_2O_3). Wenjie Zhao et al. [3] mentioned that soil magnetism is affected by parent material and climate while parent material found to be constant, hence magnetism acts as proxy for annual precipitation reflecting lesser extent of annual temperature that related climatic parameters. The Bay of Bengal, being a major area influenced by the South Asian monsoon system, receives

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huge amounts of terrigenous sediments primarily through the Ganga–Brahmaputra River system along with inputs from peninsular rivers. Seasonal variations in rainfall and river discharge strongly regulate sediment supply, grain size distribution, and mineralogical composition, all of which directly influence magnetic susceptibility signals. Periods of intensified monsoon rainfall enhance delivery of ferromagnetic minerals, leading to higher susceptibility values, while weaker monsoon phases or enhanced marine productivity can dilute terrigenous input with biogenic components, reducing susceptibility. Thus, magnetic susceptibility variations at this site are expected to reflect the interplay between regional climate-driven monsoon dynamics and sediment supply processes.

Magnetic Susceptibility (MS) measurement was carried out by earlier investigators relating to variety of marine sediments. Deep-sea [4-6] and the assessment of sedimentary fabric [7] which is a sensitive indicator of temporal variations in the concentrations of terrigenous material supplied to the sea bed [8], a climate proxy in paleoclimatic and pale oceanography studies, often in association with the oxygen isotopic variations [9] were performed. Selection of suitable sediment cores for paleomagnetic studies [10] may be based on their MS values or measurement. The MS has been widely used in paleoclimatic proxies as supporting evidence [8, 11 – 16]. Information at required level on magnetic susceptibility of sediments related to central western Bay of Bengal is not available as the investigations are not abundantly available in the literature. Sedimentation and Organic carbon of marine sediment facilitates to understand magnetic behaviour of sediment. The present study location, Nizampatnam bay belongs to Guntur district in the AP state; south east coast of India. The provenance is associated primarily with marine ecosystem that having distribution of different metals in sediments due to pollution with anthropogenic activities, fishing and other industries, sand spits, modern beach dunes, alluvium etc [17]. The soil of the location is moisture; thus, the climate is humid, exhibiting hot in day times and cool in nights during October and November months. In this period, it receives tropical cyclones. The temperature starts falling from October onwards resulting to show around 10^0C in night times of certain days from December onwards. The winters are not too cold as the location is costal line reflecting to show around 15 to 25^0C. From bottom to top, the sedimentary sequences of Nizampatnam linked with Krishna River delta found to exhibit river channel, estuarine channel, mud flats, and flood plain. Therefore, accumulation of different minerals in sediments those contribute to magnetic property vary from time to time. Earlier investigators; relating to this location studied about aquatic ecosystem, heavy metals distribution, pollution of coastal sediments only [17] and no information about magnetic property of this coastal sediment is available. Earlier studies related to the Bay of Bengal have applied magnetic susceptibility as a proxy to reconstruct monsoon variability, terrigenous flux, and sedimentation patterns. Most of these works have been restricted to specific cores or localized regions, often focusing on either river-dominated input from the Ganga–Brahmaputra system or on distal sites that capture diluted marine signals. While these studies have highlighted the sensitivity of susceptibility to changing monsoon intensity, a comprehensive synthesis that integrates regional climate forcing with sediment supply dynamics across different depositional settings remains limited. Hence the aim of the present work is to investigate the Magnetic Susceptibility as a proxy study of organic carbon and sedimentation at Nizampatnam for understanding the paleoclimatic or paleoenvironment related marine sediment core belong to central western Bay of Bengal.

2. Sample Collection and Preparation

A 4.12 m long marine sediment gravity core was collected from the marginal coastal waters of central western Bay of Bengal having the location 15^0 25’ 226” N latitude and 81^0 09’ 735” E longitudes at a water depth 1589 m. After cleaning the surface of the sediment with a steel knife, the layering in the core was observed and the core was logged. Colour of the sediment was recorded with the help of a rock colour chart. Colour of the core is brownish oxidized layer up to 0 – 30 cm and from there till the end, it found to be in dark black. The upper sections are deposited in interglacial period where as lower portion deposited during last glacial period under anoxic conditions. The core was sub sampled with 2 cm interval to each specimen. These samples were put into self-sealing plastic bags, stored in plastic boxes and kept in the deep-freezer till onward transport to the Andhra University, Visakhapatnam.

Half part of each undisturbed specimen of the dried core sample(s) was used for studies of environmental magnetic properties such as magnetic susceptibility by using Kappa Bridge available in the University of Tuebingen of Germany. The remaining part of the samples was dried at 60 ^{0}C, grounded to fine powder on using agate mortar and sieved through 230 mesh sizes for analysis of major and minor elements by using PIXE at Institute of Physics (IOP), Bhubaneswar, these results have been published elsewhere [18]. Rate of sedimentation and age of the core was estimated with $^{10}Be/^{9}Be$ dating by using AMS facility at IUAC, New Delhi. Beryllium oxide is the preferred sample for AMS analysis of ^{10}Be. The obtained results were reported elsewhere by the present group [19].

3. Experimental Details

A few grams of sediment each specimen was filled into 2 to 3 cylindrical plastic boxes for magnetic measurement. The magnetic susceptibility (κ) measurements were performed with the MFK1-FA Kappa Bridge as shown in Fig. 1. The Kappa Bridge apparatus consists of the Pick-Up Unit, Control Unit and Computer. In principle the instrument represents a precision fully automatic inductivity bridge. It is equipped with automatic zeroing system and automatic compensation of the thermal drift of the bridge unbalance as well as automatic switching appropriate measuring range. The measuring coils at frequency F1 were designed as 6^{th} order compensated solenoids with remarkably high field homogeneity. Special diagnostics was embedded in MFK1 Kappa bridges, which monitors important processes during measurement with MFK1 and also with CS4 or CSL unit. The digital part of the instrument is based on micro-electronic components, with two microprocessors controlling all functions of the Kappa Bridge. The instrument has no control knobs, it is fully controlled by external computer via serial channel RS-232C. The main advantage of the new models MFK1-FA is the possibility to measure bulk susceptibility and AMS at three different operating frequencies F1: 976 Hz, F2:

3904 Hz, F3: 15616 Hz having sensitivity values of F1 SI; F2 SI and F3 SI units are 2 x 10^{-8}, 6 x 10^{-8}, 12 x 10^{-8} respectively. In the present studies measurements were performed with the frequency F1 that has sensitivity2 x 10^{-8}. The auto-ranging and auto-zeroing work over the entire measuring range can be performed. Automatic zeroing compensates real and imaginary components; the zeroing circuits are digitally controlled by firmware. The output signal from pick-up coils is amplified, filtered and digitalized, raw data transferred directly to the computer; which controls all the functions of instrument.

Fig. 1. Kappa Bridge MFK-1A

4. RESULTS AND DISCUSSION

4.1 Magnetic Susceptibility as a proxy for climatic variations

In the recent years magnetic susceptibility (MS) measurements have played very important role in understanding the earth climatic variations. The measurements are made on the sediments of the ocean core, lacustrine sediments and Loess. Magnetic measurements on the lacustrine sediments at Tibetan Plateau and ocean core studies at Indian ocean have confirmed that since 2.4 million years ago the tropical climate was strongly influenced by the northern hemisphere glaciations. After this study, whole core scanning for magnetic susceptibility has become a standard tool for investigation of deep-sea sediments with regard to climate change. The magnetic susceptibility of soils derived from sedimentary rocks is relatively higher than that of the parent rock. Le Borgne has suggested that this enhanced susceptibility of the soil is due to the *in-situ* conversion of the iron oxides from an ant ferromagnetic form such as hematite (α Fe_2O_3) or goethite (α FeOOH) to the ferrimagnetic form, maghemite (γ Fe_2O_3). The study performed by Boyle et al. [20] used a computer model based on known chemical reactions to simulate how climate affects the magnetic minerals. The results found that soil magnetism is affected primarily by parent material and climate while parent material reflected as constant. Thus, the magnetism acts as a proxy for annual precipitation and to a lesser extent of annual temperature, which are related to climatic parameters.

The low-field magnetic susceptibility of sediments (κ), which generally measured at fields < 1 mT, includes contributions from a number of mineral components as $\kappa t = \kappa f + \kappa a + \kappa p + \kappa d$, where κt is the total susceptibility, κf shows the susceptibility contributed by ferrimagnet minerals such as magnetite, κa reflect the susceptibility from imperfect anti ferromagnetism and ferromagnets, such as hematite and goethite, κp represent the susceptibility due to paramagnets such as Fe bearing silicates and κd related to the negative susceptibility arises by diamagnetic minerals namely calcium carbonate and quartz. In the present study, the authors compare the MS variations with organic carbon (OC) of the sediment core.

4.2 Magnetic Susceptibility

The obtained spectrum pertaining to low field magnetic susceptibility measured for entire core sample is shown in the Fig.2. The low field magnetic susceptibility measurements (κ) of the whole core show that the values vary in between 2.28x10^{-3} to 3.2 x10^{-4} and the obtained average is 1.05x10^{-3}. These values seem to be quite high and this infers that the magnetic mineral is responsible for the major contribution of susceptibility; which could be due to ferrimagnetic mineral (Magnetite) present in core source. Ferrimagnetic and paramagnetic elemental contribution to the magnetic susceptibility has been shown in the Figs 3 to 5. The rate of sedimentation is calculated from the ages obtained at various depths from the Be dating. It is found that the values of susceptibility have increased abruptly between the depths 10 to 80 cm, at these depths; it exhibited the increased rate of sedimentation. The susceptibility values seem to be more during the higher rates of deposition. These results may be authenticated with the earlier investigation [20] related to the sediment core recovered from the Yeongsan Estuary on the west coast of South Korea (3.2–to–19.8-m depth). It was mentioned about sediment cores influence by early diagenesis, down core variation reflecting significant decrease of magnetic susceptibility with increasing depth in the sub oxic zone (below the top shallow sediments (oxic zone) down to the sub oxic–sulfidic (anoxic) boundary) and relatively constant low-susceptibility values at depths below the sub oxic–sulfidic boundary, under anoxic zones (characterized by relatively low bulk magnetic susceptibility values ($\sim$19 – 245 $\times 10^{-6}$ SI). The correlation between the rate of sedimentation and susceptibility shows (r = 0.73) that the susceptibility signal is used as a precipitation indicator. The obtained susceptibility relation with other physical parameters namely rate of sedimentation, age and organic carbon is shown in Table 1.

Table 1. Rate of sedimentation, OC, age and magnetic susceptibility (κ)

Core depth (cm)	Rate of sedimentation (cm/year)	Organic carbon (OC)	Age (year)	Magnetic susceptibility (K) (H/m)
50	0.013	1.787	1300±169	0.001426
100	0.008	2.529	4902±637	0.001012
150	0.006	3.131	11120±1446	0.001171
200	0.004	3.216	19879±2584	0.001062
250	0.004	3.168	31212±4958	0.000955
300	0.003	3.968	45161±5871	0.000822
350	0.006	3.578	61786±8032	0.000732
	Correlation	0.91019		0.737989

From the whole core measurements of the susceptibility, the higher susceptibility values may indicate higher rate of precipitation and lower values may indicate relatively dry periods and the medium values during medium precipitation.

Total organic carbon along a core can be used as a promising parameter to study past climates and it is usually considered as a direct proxy for interpreting past climatic conditions. Significant negative correlations (r = -0.61) is observed between magnetic susceptibility and total organic carbon, which corroborates that the measured susceptibility has compliance with the past climate signal and seems to be reliable. Significant positive correlations are observed between rate of sedimentations with calcium and magnesium carbonate and magnetic susceptibility reflecting that these sediments enriched with carbonate shells in which biologically derived metals found to be more.

The authors have calculated the correlation coefficient between MS and TOC for a 20-sample sliding window (with 166 data points), the "depth" here is expressed in sample number (1 = top, 166 = bottom). The down core comparison of magnetic susceptibility (MS) and total organic carbon (TOC) reveals distinct intervals of coupling, decoupling, and transitional behaviour. These patterns reflect the interplay of terrigenous input, marine productivity, and post-depositional processes in the Bay of Bengal. Between depths ~60–85 and 120–135, MS and TOC show a strong positive correlation (r > 0.5). These intervals likely represent phases of enhanced terrigenous influx, where magnetite-bearing sediments were co-delivered with land-derived organic matter during periods of intensified monsoonal discharge and flooding. Such coupled peaks highlight the role of high-energy depositional events by facilitating both sediment and organic carbon burial. These intervals suggest that monsoon-driven fluxes significantly enhanced short-term carbon sequestration on the continental margin. In contrast, the interval between depths ~90–110 shows a pronounced negative correlation (r < –0.5), where TOC enrichment coincides with a decline in

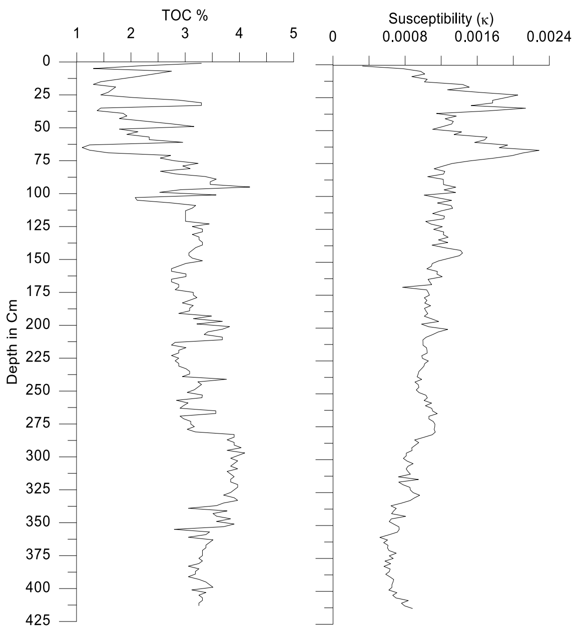

Fig. 2. Vertical variations of magnetic susceptibility (κ) and organic carbon (OC) in the core sediment of Nizampatnam Bay

MS. This decoupling is best explained by enhanced in situ marine productivity and/or improved preservation of organic matter under oxygen-poor bottom-water conditions, while the supply of terrigenous magnetic minerals was reduced or subjected to partial diagenetic dissolution. Such intervals may represent phases of stratified water columns, reduced ventilation, or weaker fluvial input, conditions that favour organic matter preservation. The uppermost ~1–40 samples and the deeper ~140–166 samples are characterized by weak or no correlation (r near zero), suggesting mixed control of depositional processes. These zones likely reflect transitional states where neither terrigenous flux nor productivity was the dominant factor, leading to variability without a clear relationship between MS and TOC. Overall, this record provides novel evidence for the Bay of Bengal that terrigenous sediment delivery and organic carbon burial are strongly coupled during monsoon-intensified flood events, but decoupled during intervals of enhanced productivity and preservation under oxygen-poor conditions. The alternation of correlated and anti-correlated intervals thus captures the dynamic interplay between climate-driven riverine input, marine biogeochemistry, and diagenetic processes.

4.2 Magnetic Susceptibility Vs Elemental concentration

In order to identify the relationship between the magnetic susceptibility and elemental concentrations, the correlation analysis has been carried out. Significant positive correlations are observed between the magnetic susceptibility with the concentrations of Mn (r=0.56), Sc (r= 0.49), Ca (r=0.48), V (r=0.39), Fe (r=0.21), Cu (0.19), Ni (r=0.17) and negative correlation with Cr (r= -0 02), Zn (r= -0.27) as shown in Figs 3 - 5. The significant positive correlations suggest that magnetic susceptibility values seem to be quite high and this infers that the magnetic minerals are responsible for the major contribution to susceptibility, which could be due to ferrimagnetic minerals present in core. The positive correlation between magnetic susceptibility with Mn (r=0.56) is significant due to the presence of Mn oxides [22] probable in the form of Manganese micro nodules. The larger contents of Fe, Ca, Ti,, Cr and Mn present in the core as shown in the plots 3 to 5 contribute to magnetic susceptibility while quantity of remaining elements found to be smaller, their contribution to susceptibility may be considered as insignificant. In this connection to understand impact of every individual element with all the other elements, Pearson's correlation coefficient analysis has been performed and obtained values are presented in Table 2 by which significance of some elements found to be high reflecting relationship among them contributing magnetic behaviour. Some of the observations are given below.

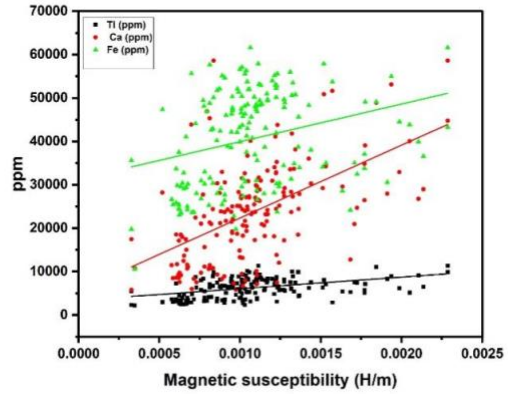

Fig. 3. Magnetic susceptibility (κ) with elemental concentrations (Ti, Ca, Fe) ppm

Iron and calcium are found to exhibit highest concentrations (60,000) showing stronger correlation with seven and six elements by Fe and Ca respectively. These reflecting their correlation with all the elements is at **significant of the 0.01 level (2-tailed). Hence these two elements play important role with regard to susceptibility of the core, their trend of susceptibility variation seem to be same with Mn while it is different relative to Ti and other elements as shown in Fig 4 and 3 respectively. Similarly, potassium is also showing higher correlation coefficient with five elements along with them is exhibiting significance at **significant of the 0.01 level (2-tailed) relating to all the elements. Remaining elements are seemed to indicate different type of association individually with all the other elements as shown in the Table 2 containing **significant of the 0.01 level (2-tailed), *. Correlation is significant at the 0.05 level (2-tailed) resulting varying correlations along with other elements. Fig 5 shows few elements having very low contents exhibiting different type of trend with regard to susceptibility variation. Among all the elements observed in the present studies; zinc found to show no significance with majority elements indicating its independent role/behaviour reflecting no impact on other elements.

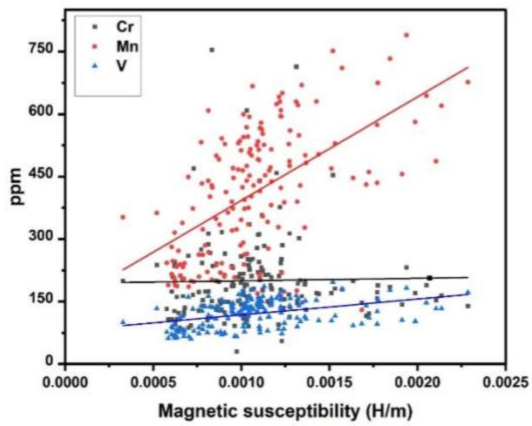

Fig. 4. Magnetic susceptibility (κ) with elemental concentrations (Cr, Mn, V) ppm

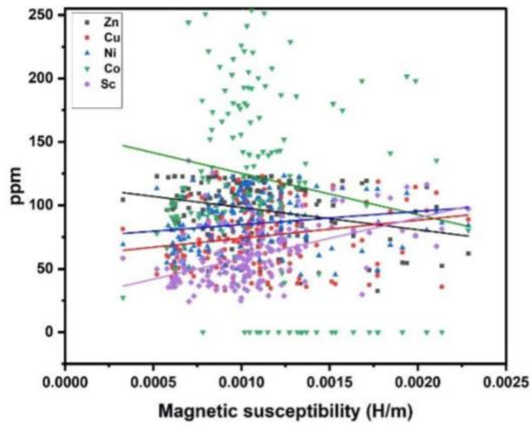

Fig. 5. Magnetic susceptibility (κ) with elemental concentrations (Cu, Ni, Zn, Co, Sc) ppm

5. CONCLUSIONS, LIMITATIONS AND FUTURE STUDY

1. Increased rate of sedimentation (0.006 to 0.013 cm/year) enhanced the magnetic susceptibility value reflecting its range 0.732x10-3 to 1.426x10-3 due to ferrimagnetic mineral (Magnetite) quantity presented or deposited in the core sediment along with its impact on the other elements as shown in the table 2

2. Results may be authenticated with the earlier studies [20] relating to the sediment core procured from the Yeongsan Estuary on the west coast of South Korea.

3. Some of the elements such as Fe, Ca, K etc found to show strong correlation with other elements reflecting their impact on the contribution to susceptibility with**. Correlation is significant at the0.01 level (2-tailed). In the case of elements like Cr, Sr, Co, Zn etc seem to be no much impact on other elements with regard to susceptibility as their correlation coefficient and significance is very low or absence

4. Relatively lower values of susceptibility have indicated during the dry or lower sedimentation periodhaving sediment cores influence by early diagenesis, down core variation reflecting significant decrease of magnetic susceptibility with increasing depth in the sub oxic zone.

5. Measurements of magnetic susceptibility related to sediment core can be considered as a precipitation indicator of the sediment that relating different parts of Indian Ocean including Andaman Sea and coastal lakes.

6. Measured susceptibility has the compliance with the past climatic signal and seems to be reliable with Paleoclimatic information concerned to Bay of Bengal and Indian ocean that reflecting monsoon variability, which caused due to complex interplay pertaining to regional climatic factors.

7. Limitation of the present investigation is that no textural study of the specimens has not been performed

8. Further, sediment cores from costal, inshore and offshore regions relating to the particular location/area need to be collected for study of them to get more authentic information regarding paleoclimatic studies.

Table 2. Pearson's Correlation coefficient along with the significance of elements present in the sediment core

	Fe	Ca	K	Ti	Mn	Cr	Sr	V	Zn	Rb	Ni	Cu	Co	Sc
Fe	1	.718**	.871**	.427**	.800**	.430**	.344**	.931**	.275**	.778**	.648**	.442**	.504**	.375**
Ca	.718**	1	.591**	.303**	.829**	.248**	.365**	.763**	.014**	.549**	.407**	.337**	.149**	.843**
K	.871**	.591**	1	.275**	.575**	.387**	.247**	.755**	.280**	.653**	.527**	.291**	.444**	.252**
Ti	.427**	.303**	.275**	1	.402**	.174* .025	.179* .021	.454**	-.006 .939	.445**	.326**	.292**	.271**	.117 .134
Mn	.800**	.829**	.575**	.402**	1	.292**	.400**	.814**	.034 .664	.582**	.441**	.316**	.213**	.654**
Cr	.430**	.248**	.387**	.174* .025	.292**	1	.126 .105	.395**	.054 .493	.191* .014	.237** .002	.089 .256	.306**	.109 .161
Sr	.344**	.365**	.247** .001	.179* .021	.400**	.126 105	1	.313	.002 .975	.181* .019	.215** .005	.982**	.981**	.338**
V	.931**	.763**	.755**	.454*	.814**	.395**	.313**	1	.158* .042	.794**	.634**	.511**	.473**	.438**
Zn	.275**	-.014** .856	.280**	-.006 .939	.034 .665	.054 .493	.002 .975	.158* .042	1	.169* .029	.260** .001	.200** .010	.143 .005	-.139 .075
Rb	.778**	.549**	.653**	.455**	.582**	.191* .014	.181* .019	.794**	.169* .029	1	.616**	.479**	.476**	.201** .009
Ni	.648**	.407**	.527**	.326**	.441**	.237** .002	.215** .005	.634**	.260** .001	.616**	1	.366**	.427**	.092 .236
Cu	.442**	.337**	.291**	.292**	.316	.089 .256	-.002 .982	.511	.200** .010	.479**	.366**	1	.433**	.153* .049
Co	.504**	.149 .055	.444**	.271**	.213** .006	.306**	.002 .981	.473**	.143 .065	.476**	.427**	.433**	1	-.187* .016
Sc	.375**	.843**	.252** .001	.117 .134	.654**	.109 .161	.338**	.438**	-.139 .075	.201** .009	.092 .236	.153 .049	-.187* .016	1

**. Correlation is significant at the 0.01 level (2-tailed), *. Correlation is significant at the 0.05 level (2-tailed).

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