

DISTRIBUSI SPASIAL SUSEPTIBILITAS MAGNETIK DAN KOMPOSISI UNSUR PASIR BESI MUARA SUNGAI MAMBERAMO, PAPUA

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Abstrak

Endapan pasir besi pada lingkungan muara dapat menunjukkan variasi spasial yang kuat akibat transportasi sedimen, pemilahan hidrodinamik, dan perbedaan kelimpahan partikel pembawa Fe. Penelitian ini mengkaji distribusi spasial suseptibilitas magnetik spesifik massa dan komposisi unsur pasir besi dari Muara Sungai Mamberamo, Papua, Indonesia. Sampel dikumpulkan dari 40 titik, kemudian suseptibilitas magnetik diukur menggunakan Bartington *susceptibility meter* dan dipetakan dengan QGIS. Lima sampel representatif dianalisis menggunakan *X-ray fluorescence* (XRF). Nilai suseptibilitas berkisar antara $44,43 \times 10^{-8}$ hingga $2841,62 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, dengan nilai tertinggi pada titik 21 di dekat muara sungai. Analisis XRF menunjukkan Si dan Fe sebagai unsur dominan. Sampel 21 juga memiliki kandungan Fe tertinggi (42,56 wt%). Hasil penelitian menunjukkan endapan pasir besi yang heterogen secara spasial dan adanya pengayaan lokal partikel pembawa Fe yang responsif secara magnetik.

Kata Kunci: Pasir Besi, Suseptibilitas Magnetik, X-Ray Fluorescence, Komposisi Unsur, Sungai Mamberamo.

SPATIAL DISTRIBUTION OF MAGNETIC SUSCEPTIBILITY AND ELEMENTAL COMPOSITION OF IRON SAND FROM MAMBERAMO RIVER ESTUARY, PAPUA

Abstract

Iron-sand deposits in estuarine environments can show strong spatial variability due to sediment transport, hydrodynamic sorting, and differences in Fe-bearing particles. This study investigated the spatial distribution of mass-specific magnetic susceptibility and elemental composition of iron sands from the Mamberamo River estuary, Papua, Indonesia. Samples were collected from 40 locations, and magnetic susceptibility was measured using a Bartington susceptibility meter and mapped with QGIS. Five representative samples were analyzed by X-ray fluorescence (XRF). Susceptibility ranged from 44.43×10^{-8} to $2841.62 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, with the highest value at sampling point 21 near the river mouth. XRF showed Si and Fe as the dominant elements. Sample 21 also had the highest Fe content (42.56 wt%). The results indicate spatially heterogeneous iron-sand deposits and localized enrichment of magnetically responsive Fe-bearing particles.

Keywords: Iron Sand, Magnetic Susceptibility, X-Ray Fluorescence, Elemental Composition, Mamberamo River.

INTRODUCTION

Iron-rich sands are naturally occurring sedimentary deposits that contain varying proportions of magnetically responsive Fe-bearing particles together with non-magnetic silicate and other mineral components. Their magnetic and compositional characteristics are influenced by the nature of the source rocks as well as by weathering, erosion, sediment transport, grain-size sorting, and depositional processes. Consequently, magnetic measurements are widely used to investigate the distribution and concentration of magnetic particles in natural sedimentary environments [1].

Among the magnetic parameters commonly used in sediment studies, magnetic susceptibility provides a rapid and non-destructive measure of the bulk magnetic response of a material to an applied magnetic field. Variations in magnetic susceptibility may reflect differences in the concentration, mineral type, and grain-size distribution of magnetic particles. Therefore, spatial variations in magnetic susceptibility can provide useful information on sediment distribution and provenance when interpreted together with complementary compositional data [2,3].

Natural iron-sand deposits commonly contain Fe-bearing minerals such as magnetite, maghemite, hematite, ilmenite, and related phases, although their relative abundance varies considerably depending on geological setting and sedimentary processes. Magnetite generally exhibits a stronger magnetic response than hematite and many silicate components, causing variations in the abundance of Fe-bearing phases to influence the bulk magnetic susceptibility of iron-sand deposits. However, magnetic susceptibility alone cannot uniquely identify the mineral phases responsible for the measured magnetic response, because bulk magnetic properties are influenced by mineral concentration, magnetic mineralogy, grain size, and magnetic domain state. Integration with complementary compositional or component-specific measurements is therefore important for constraining magnetic mineral assemblages [1,4].

Figure 1 shows the typical physical appearance of the iron-sand material investigated in this study. The original field material consists of dark-colored sandy

sediment characteristic of the deposits observed along the Mamberamo estuarine coast.



Figure 1. Physical appearance of iron sand collected from the Mamberamo River estuary.

Estuarine environments are particularly important for investigating spatial variations in magnetic sediment because they represent transition zones where river-derived particles are redistributed under interacting fluvial and marine processes. Previous studies have demonstrated that magnetic properties of estuarine sediments may vary substantially across relatively short spatial distances as a consequence of changes in sediment provenance, hydrodynamic sorting, transport pathways, and depositional conditions. For example, magnetic measurements have been successfully used to examine sediment provenance and transport in tropical fluvial-marine systems [2] and estuarine environments [5-7].

Iron-sand deposits in Indonesia also exhibit pronounced spatial variability in their magnetic and chemical characteristics. Previous studies have demonstrated that magnetic susceptibility, grain-size distribution, and Fe concentration can be integrated to investigate selective enrichment and provenance of iron-sand deposits in Aceh, Indonesia [3]. These findings indicate that magnetic susceptibility provides more meaningful information when interpreted together with compositional and grain-size characteristics rather than as an isolated parameter.

Northern Papua represents another important region for natural iron-sand studies. Previous investigations along the northern coast of Papua have identified Fe-rich sedimentary deposits with distinctive magnetic and elemental characteristics. River iron sand from Jayapura has been characterized using magnetic and compositional analyses, demonstrating

substantial Fe-bearing mineral content and measurable magnetic properties [8]. Iron sand from the Tor River estuary in Sarmi has also been characterized using magnetic, elemental, and mineralogical analyses, demonstrating enrichment of Fe-bearing magnetic phases following magnetic separation [9]. A subsequent spatial investigation along the Sarmi coast reported mass-specific magnetic susceptibility values of approximately $3000\text{--}4000 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, indicating substantial spatial variation and localized accumulation of magnetically responsive particles [10]. These studies provide an important regional reference for the present investigation because the Tor River estuary represents one of the closest previously characterized iron-sand depositional systems along the northern coast of Papua.

The Mamberamo River represents a particularly interesting setting for investigating such deposits. It is one of the major river systems of northern Papua and transports large quantities of sediment from the interior of the island toward the Pacific margin. Along its course, the Mamberamo River traverses extensive floodplain environments, where its turbid, silt-rich flow particularly during periods of heavy rainfall promotes bank erosion, sediment transport, and the continuous deposition of new sediment across the river system [11]. Previous geological studies indicate that the Mamberamo region forms part of the North Papua Basin and contains thick clastic sedimentary successions associated with the geological evolution of northern Papua [12]. These active erosion, transport, and depositional processes, together with the broad coastal and estuarine setting, provide favorable conditions for hydrodynamic sorting and localized accumulation of dense sediment fractions.

Despite the occurrence of dark iron-rich sands along the Mamberamo estuarine coast, systematic information regarding their magnetic properties and elemental composition remains limited. Previous iron-sand studies in northern Papua have mainly focused on the Sarmi and Jayapura regions, whereas spatially resolved magnetic data from the Mamberamo River estuary have not been reported. The original survey therefore aimed to characterize the spatial distribution of magnetic susceptibility and the elemental composition of iron-sand deposits across this estuarine environment.

In the present study, magnetic susceptibility was measured at 40 sampling locations distributed across the eastern and western sectors of the Mamberamo River estuary. The resulting susceptibility values were spatially mapped, while X-ray fluorescence (XRF) spectroscopy was used to determine the elemental composition of selected representative samples. Because XRF provides elemental rather than crystalline-phase information, the compositional analysis was interpreted primarily in terms of Fe enrichment and associated major elements.

Accordingly, this study aimed to (1) determine the spatial distribution of mass-specific magnetic susceptibility across iron-sand deposits of the Mamberamo River estuary, (2) characterize the elemental composition of representative samples using XRF spectroscopy, and (3) examine the correspondence between magnetic susceptibility and Fe enrichment in the selected representative samples. The results provide baseline information on the spatial magnetic and elemental characteristics of iron-sand deposits in one of the major river-coastal systems of northern Papua.

MATERIALS AND METHODS

Study Area and Sampling Design

The study was conducted in the coastal zone of the Mamberamo River estuary, Mamberamo Raya Regency, Papua, Indonesia. The Mamberamo River flows northward toward the Pacific Ocean and forms an extensive lowland, deltaic, and estuarine environment. The study area included the coastal sectors located to the east and west of the river mouth.

The original field survey was designed using geographic coordinates recorded with a Global Positioning System (GPS) GARMIN ETREX 10. Sampling points were distributed along the estuarine coastline to represent the spatial variability of the iron-sand deposits. A total of 40 sampling locations were established, consisting of 20 points in the eastern sector and 20 points in the western sector of the study area. The geographical setting and distribution of the sampling area are shown in Figure 2.

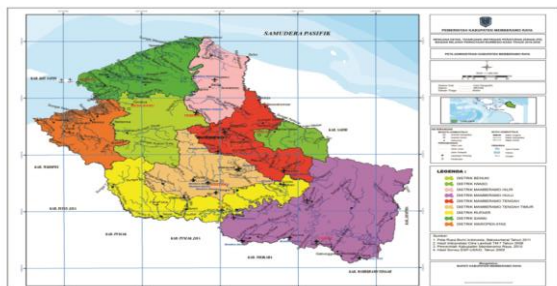


Figure 2. Location of the study area at the Mamberamo River estuary

Sample Collection and Preparation

In the laboratory, the samples were washed with distilled water and dried. The dried samples were subsequently sieved using a 50-mesh sieve to remove coarse particles and other materials that could interfere with subsequent measurements. The prepared sediment was then transferred into sample holders for magnetic susceptibility measurements.

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Magnetic Susceptibility Measurement

Magnetic susceptibility was measured for samples obtained from all 40 sampling locations using a Bartington MS2B magnetic susceptibility system (Bartington Instruments Ltd., Witney, UK) equipped with a dual-frequency sensor. Each sample was measured three times, and the mean of the three measurements was used as the representative magnetic susceptibility value for the corresponding sampling location.

The results were reported as mass-specific magnetic susceptibility (χ) in units of $\text{m}^3 \text{kg}^{-1}$. The susceptibility values were used to compare the bulk magnetic response of iron-sand sediments among different sampling locations.

Because magnetic susceptibility represents the collective response of magnetically responsive components within the bulk sediment, the measured values were used primarily as an indicator of spatial variation in magnetic properties rather than for direct identification of individual magnetic mineral phases.

The geographic coordinates of the 40 sampling locations were combined with their corresponding magnetic susceptibility values and processed using Quantum Geographic Information System (QGIS) software. The spatial distribution of magnetic susceptibility was then mapped to visualize sectors exhibiting relatively high and low magnetic responses across the Mamberamo River estuary.

The susceptibility distribution map was subsequently used to evaluate spatial patterns of magnetically responsive sediments within the study area.

X-Ray Fluorescence Analysis

Five representative samples: samples 7, 18, 21, 24, and 39, were selected for XRF analysis. These samples were chosen to represent contrasting spatial sectors within the study area rather than on the basis of numerical ranking of the final laboratory magnetic susceptibility values. Importantly, the exact magnetic susceptibility values were not yet known when the representative samples were selected for compositional characterization. Based on the spatial characteristics and relative magnetic responses identified during the sampling stage, samples 7, 18, 21, and 24 were selected from sectors expected to exhibit relatively stronger magnetic characteristics, whereas sample 39 represented a comparatively lower-response sector. Thus, the five XRF samples were intended to provide spatially representative compositional information across contrasting sectors of the estuary, rather than to represent the mathematically highest and lowest susceptibility values within the complete 40-sample dataset.

The elemental composition of the five representative iron-sand samples was determined using X-ray fluorescence (XRF) spectroscopy. The analysis was conducted to quantify the relative abundance of major and minor elements contained in the bulk iron-sand sediments. The measured elemental components included Fe, Si, Al, Ca, K, Ti, Rh, Cr, Mn, Ni, Zr, Sr, Rb, Zn, V, Cu, Y, and Cl. Their abundances were reported as weight percentages (wt%). The original XRF dataset shows that Fe, Si, Al, Ca, K, and Ti were the major elemental components within the analyzed samples.

Because XRF determines elemental composition rather than crystalline mineral phases, the XRF data were interpreted primarily

in terms of elemental enrichment, particularly Fe content. Specific Fe-bearing phases such as magnetite (Fe_3O_4), hematite ($\alpha\text{-Fe}_2\text{O}_3$), maghemite ($\gamma\text{-Fe}_2\text{O}_3$), or ilmenite (FeTiO_3) were therefore not assigned solely on the basis of the XRF measurements.

Data Analysis

Magnetic susceptibility values obtained from the 40 sampling locations were analyzed descriptively to determine their spatial variability and range across the study area. The susceptibility data were integrated with geographic coordinates and visualized using QGIS to identify spatial patterns of relatively high and low magnetic response. Elemental compositions obtained from the five XRF-analyzed samples were compared descriptively with their corresponding magnetic susceptibility values. Particular attention was given to Fe because variations in the abundance of Fe-bearing components were expected to contribute substantially to the measured magnetic response. Because elemental composition was available for only five purposively selected samples, the relationship between Fe content and magnetic susceptibility was interpreted descriptively rather than through inferential statistical correlation.

RESULTS AND DISCUSSION

Spatial Distribution of Magnetic Susceptibility

The mass-specific magnetic susceptibility of iron-sand samples collected from the 40 sampling points showed pronounced spatial variability across the Mamberamo River estuary. The measured values ranged from $44.43 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ to $2841.62 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, with an overall mean of $450.49 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ and a median of $215.78 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. The substantially higher mean than median reflects the influence of several locations with markedly elevated magnetic susceptibility. The highest value was recorded at sampling point 21 ($2841.62 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$), whereas the lowest value occurred at sampling point 36 ($44.43 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$).

The spatial distribution shown in Figure 3 demonstrates that the magnetic response was not uniformly distributed along the estuarine coastline. Several localized zones of relatively high susceptibility were identified, particularly around sampling points 7, 17, 18, 19, 21, and

24, where χ exceeded $1000 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. In contrast, a substantial number of sampling locations, particularly toward the western part of the surveyed coastline, exhibited considerably lower susceptibility values.

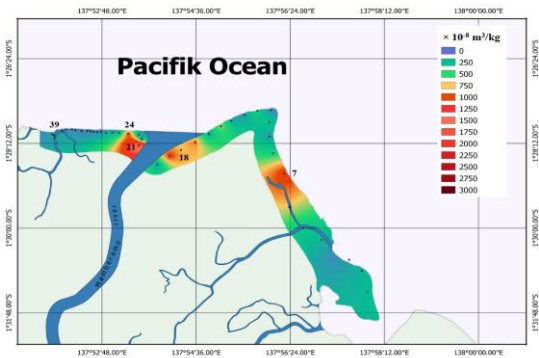


Figure 3. Spatial distribution of mass-specific magnetic susceptibility of iron-sand samples across the Mamberamo River estuary

The most prominent magnetic anomaly occurred at point 21, located close to the river-mouth sector. This localized enrichment may reflect hydrodynamic sorting at the estuarine outlet, where the interaction of river discharge, tidal currents, and coastal processes can preferentially concentrate denser, magnetically responsive Fe-bearing particles while finer and lighter sediment fractions remain suspended or are transported farther offshore. Similar density-selective accumulation of magnetic minerals has been reported in estuarine environments under spatially variable hydrodynamic conditions [13]. The susceptibility map accordingly shows a concentration of higher magnetic-response zones around the estuarine outlet rather than a continuous high-susceptibility distribution along the entire coastline.

This heterogeneous distribution is consistent with the behavior expected for iron-rich sediments in fluvial-coastal environments. Magnetic susceptibility in natural sediments is influenced by the concentration, type, and grain size of magnetically responsive minerals, while sediment source, particle size, and hydrodynamic sorting can further modify the bulk magnetic signal [14]. Magnetic properties have therefore been widely applied as sedimentary fingerprints for evaluating spatial changes in sediment provenance and transport pathways.

Table 1. Geographic coordinates and mass-specific magnetic susceptibility of iron-sand samples collected from the Mamberamo River estuary

Sampling point	Sampling coordinates		Susceptibility (χ) ($10^{-8} \text{ m}^3 \text{ kg}^{-1}$)
	La	Lo	
1	1°31'21.33"S	137°57'52.68"E	236.20
2	1°30'54.59"S	137°57'46.31"E	376.34
3	1°30'35.12"S	137°57'25.61"E	119.08
4	1°30'14.75"S	137°56'59.89"E	214.49
5	1°30'0.02"S	137°56'38.59"E	399.10
6	1°29'33.16"S	137°56'22.93"E	703.01
7	1°28'50.33"S	137°56'16.86"E	1466.12
8	1°28'24.36"S	137°56'4.60"E	754.72
9	1°28'3.13"S	137°56'0.09"E	295.32
10	1°27'45.19"S	137°56'0.12"E	548.09
11	1°27'29.60"S	137°56'1.67"E	66.64
12	1°27'30.45"S	137°55'46.37"E	620.35
13	1°27'35.74"S	137°55'31.50"E	401.05
14	1°27'43.19"S	137°55'16.23"E	327.95
15	1°27'50.29"S	137°55'4.48"E	558.74
16	1°28'0.11"S	137°54'50.93"E	163.54
17	1°28'10.45"S	137°54'34.89"E	1715.96
18	1°28'20.42"S	137°54'18.53"E	1493.44
19	1°28'28.30"S	137°54'5.85"E	1214.79
20	1°28'38.74"S	137°53'51.20"E	178.05
21	1°28'14.33"S	137°53'30.17"E	2841.62
22	1°28'6.46"S	137°53'33.51"E	217.07
23	1°28'1.15"S	137°53'29.84"E	71.25
24	1°27'59.63"S	137°53'18.16"E	1269.61
25	1°27'58.47"S	137°53'7.60"E	264.40
26	1°27'58.31"S	137°52'59.83"E	95.32
27	1°27'58.31"S	137°52'52.32"E	77.45
28	1°27'57.39"S	137°52'47.07"E	76.40
29	1°27'57.85"S	137°52'42.67"E	65.58
30	1°27'57.19"S	137°52'38.39"E	53.36
31	1°27'56.58"S	137°52'34.87"E	166.43
32	1°27'56.58"S	137°52'31.12"E	78.07
33	1°27'56.21"S	137°52'24.58"E	75.88
34	1°27'55.16"S	137°52'17.41"E	112.61
35	1°27'54.08"S	137°52'13.67"E	49.03
36	1°27'54.26"S	137°52'6.46"E	44.43
37	1°27'56.37"S	137°52'2.21"E	56.29
38	1°28'4.44"S	137°51'53.52"E	68.39
39	1°28'1.46"S	137°51'53.01"E	347.83
40	1°28'0.41"S	137°51'51.08"E	135.66

The occurrence of discrete high-susceptibility zones in the Mamberamo estuary may indicate preferential accumulation of magnetically responsive Fe-bearing particles at particular depositional sites. Such localized enrichment is plausible in estuarine environments, where variations in river discharge, coastal currents, sediment grain size,

and hydrodynamic energy can produce spatial sorting of mineral particles. Studies of the Pearl River Estuary, for example, have shown that magnetic mineral concentration and particle characteristics vary spatially within an estuary and can reflect both sediment sources and transport pathways [6].

However, the present susceptibility data alone cannot determine the specific mineral phases responsible for the spatial variations. A high bulk susceptibility may result from a greater concentration of strongly magnetic Fe-bearing phases, differences in magnetic grain size, or a combination of these factors. This limitation is particularly important because the samples analyzed in the present study represent bulk sediments without prior magnetic separation. Therefore, the spatial susceptibility pattern is interpreted as variation in the overall contribution of magnetically responsive components rather than direct evidence for variations in a particular mineral such as magnetite, maghemite, or hematite.

A regional comparison can be made with iron sands from the Tor River estuary in Sarmi, also located along the northern coast of Papua. Mass-specific magnetic susceptibility values of approximately $3000\text{--}4000 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ have been reported for iron sands from the Sarmi coastal area [10], exceeding the maximum value observed in the present Mamberamo dataset. Earlier characterization of Tor River iron sand reported an average susceptibility of $3.083 \times 10^{-5} \text{ m}^3 \text{ kg}^{-1}$ for the raw material and showed a substantial increase in susceptibility following magnetic extraction [9].

The difference between the Mamberamo and Tor River deposits should not be interpreted solely in terms of absolute Fe abundance, because magnetic susceptibility is also influenced by mineralogical composition and particle characteristics. Previous studies of Indonesian iron sands have shown that susceptibility may vary with grain-size fraction and Fe content, with finer fractions in some deposits exhibiting both higher magnetic susceptibility and greater Fe enrichment [3]. Therefore, the pronounced spatial variation observed in the Mamberamo estuary likely reflects the combined effects of Fe-bearing particle abundance, mineralogical differences, and sedimentary sorting rather than a single controlling factor.

An important feature of the present dataset is the highest susceptibility recorded at sampling point 21 near the river-mouth sector.

XRF analysis also identified sample 21 as having the highest Fe content among the five representative samples. This correspondence suggests localized enrichment of magnetically responsive Fe-bearing particles and supports the combined interpretation of magnetic susceptibility and elemental composition.

Elemental Composition by X-Ray Fluorescence Analysis

X-ray fluorescence analysis revealed substantial compositional differences among the five representative iron-sand samples. The elemental composition was dominated by Si and Fe, followed by Al, Ca, K, and Ti, whereas the remaining elements occurred at considerably lower concentrations (Table 2). Fe content varied from 21.66 to 42.56 wt%, while Si ranged from 19.82 to 54.64 wt%. These variations indicate considerable spatial heterogeneity in the relative abundance of Fe-bearing and silicate-rich components within the Mamberamo River estuary.

Among the analyzed samples, sample 21 exhibited the highest Fe concentration (42.56 wt%) and simultaneously the lowest Si concentration (19.82 wt%). This compositional signature distinguishes sample 21 from the other four samples, in which Si remained the dominant element. Sample 21 also corresponds to the location with the highest measured mass-specific magnetic susceptibility, $2841.62 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. The co-occurrence of the highest Fe concentration and strongest magnetic response suggests a localized enrichment of Fe-bearing magnetically responsive particles near this part of the river-mouth sector.

A comparable association between Fe enrichment and elevated magnetic susceptibility has also been reported. In iron sands from Aceh, Fe concentration and magnetic susceptibility varied systematically across different grain-size fractions, with Fe-rich fractions generally showing stronger magnetic responses [3]. These findings indicate that magnetic susceptibility is influenced not only by total Fe content but also by the abundance, grain-size distribution, and characteristics of the magnetic mineral fraction.

Table 2. Elemental composition of representative iron-sand samples determined by XRF analysis.

Element	Composition (wt%)				
	Sample-7	Sample-18	Sample-21	Sample-24	Sample-39
Fe	21.6638	26.3185	42.5602	29.1533	31.3133
Si	54.6393	49.0345	19.8191	40.7069	37.6101
Al	9.2366	8.5333	17.0811	10.8689	11.7882
Ca	6.2378	5.9449	8.6977	10.3002	8.6069
K	4.0763	5.6591	5.2580	3.0823	5.2613
Ti	2.1565	2.1430	2.3583	2.6316	2.1085
Rh	0.4930	0.6779	1.5127	0.4863	0.9056
Cr	0.4827	0.3643	0.6581	1.2675	0.7455
Mn	0.3451	0.4061	0.5470	0.5513	0.4985
Ni	0.1583	0.1827	0.4228	0.2615	0.2351
Zr	0.2411	0.2560	0.3724	0.2292	0.2406
Sr	0.1008	0.1459	0.3189	0.1344	0.2095
Rb	0.0304	0.0495	0.1055	0.0325	0.0643
Zn	0.0424	0.0780	0.1026	0.0769	0.1108
V	0.0652	0.0709	0.0936	0.0911	0.0722
Cu	0.0177	0.0262	0.0527	0.0208	0.0285
Y	0.0131	0.0168	0.0204	0.0310	0.0193
Cl	0.0000	0.0923	0.0191	0.0742	0.1819

However, the Mamberamo data also demonstrate that bulk Fe concentration alone does not fully explain the magnetic susceptibility variations. Sample 39, for example, contained 31.31 wt% Fe, which is higher than the Fe contents of samples 7 (21.66 wt%), 18 (26.32 wt%), and 24 (29.15 wt%). Nevertheless, its magnetic susceptibility was only $347.83 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, substantially lower than those of samples 7, 18, and 24.

This observation is important because XRF measures total elemental Fe, irrespective of the mineral phase in which the Fe occurs. Iron may be incorporated into strongly ferrimagnetic phases, weakly magnetic or antiferromagnetic iron oxides, paramagnetic silicates, or other Fe-bearing minerals. Consequently, sediments containing similar amounts of total Fe can exhibit markedly different magnetic susceptibilities depending on mineralogy, grain size, magnetic domain state, and the relative proportions of magnetic and non-magnetic components [15]. Magnetic susceptibility is therefore most appropriately interpreted as a response to the magnetic mineral assemblage rather than as a direct measure of total Fe concentration.

The relatively high Si concentrations measured in samples 7, 18, 24, and 39, ranging from 37.61 to 54.64 wt%, indicate that a substantial fraction of the bulk sediment consists of Si-bearing components. Sample 7

showed the highest Si concentration (54.64 wt%) together with the lowest Fe content (21.66 wt%) among the five analyzed samples. In contrast, the pronounced decrease in Si and increase in Fe observed in sample 21 indicate a substantially greater relative contribution of Fe-bearing material at this location.

The presence of Al, Ca, K, and Ti further reflects the compositional complexity of the bulk estuarine sediment. Al varied from 8.53 to 17.08 wt%, Ca from 5.94 to 10.30 wt%, K from 3.08 to 5.66 wt%, and Ti from 2.11 to 2.63 wt%. The relatively narrow range of Ti compared with the much larger variation in Fe and Si suggests that the major compositional differentiation among the five samples is primarily associated with changing proportions of Fe-rich and Si-rich sediment fractions rather than large variations in total Ti concentration. For comparison, previous work on magnetically extracted iron sand from the Tor River estuary, Sarmi, Papua, reported an XRF composition dominated by Fe_2O_3 (54.4 wt%), with lower amounts of SiO_2 (21.6 wt%), Al_2O_3 (6.34 wt%), CaO (6.10 wt%), TiO_2 (4.27 wt%), and MgO (2.79 wt%) [9].

Direct quantitative comparison with the present Mamberamo samples should nevertheless be made cautiously because the Tor River material had undergone mechanical magnetic extraction, whereas the present XRF measurements were performed on bulk

sediment without magnetic separation [9]. Magnetic separation preferentially concentrates magnetically responsive Fe-bearing phases while reducing the contribution of non-magnetic components, thereby altering the relative composition of the analyzed material [16]. Consequently, differences in sample preparation must be considered when comparing the elemental compositions of the two deposits.

The XRF results should be interpreted cautiously because XRF provides elemental composition rather than direct crystalline-phase identification. Although Fe and Ti were detected in all five samples, their simultaneous occurrence does not by itself confirm the presence of ilmenite (FeTiO_3). Similarly, a high Fe concentration cannot distinguish among magnetite, maghemite, hematite, or other Fe-bearing phases because XRF primarily provides elemental composition rather than direct crystalline-phase identification. Identification of specific crystalline mineral phases requires a structure-sensitive technique such as X-ray diffraction [17,18]. Therefore, the present XRF results are interpreted as evidence of elemental Fe enrichment and spatial compositional variability rather than direct identification of specific iron-bearing mineral phases.

Overall, the XRF data reveal a heterogeneous elemental distribution across the Mamberamo River estuary. The most distinctive composition occurred at sample 21, where high Fe content, low Si content, and the highest magnetic susceptibility coincide. Nevertheless, the comparatively high Fe content but low magnetic susceptibility of sample 39 demonstrates that the magnetic response cannot be explained solely by total Fe abundance. Together, these observations indicate that both Fe enrichment and the mineralogical form of Fe-bearing components are likely to control the spatial magnetic characteristics of the Mamberamo iron-sand deposits.

CONCLUSION AND RECOMMENDATIONS

Conclusion

Iron-sand deposits from the Mamberamo River estuary exhibited pronounced spatial variation in mass-specific magnetic susceptibility, ranging from 44.43×10^{-8} to $2841.62 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. The highest

magnetic susceptibility was recorded at sampling point 21, located near the river-mouth sector, indicating localized enrichment of magnetically responsive sediment within the estuarine environment. The spatial susceptibility map further showed that high magnetic responses were concentrated in several discrete zones rather than being uniformly distributed along the surveyed coastline.

XRF analysis of five representative samples revealed substantial variation in elemental composition. Si and Fe were the dominant elements, accompanied by Al, Ca, K, Ti, and several minor elements. Most of the analyzed samples contained relatively high Si concentrations, whereas sample 21 was distinguished by the highest Fe content (42.56 wt%) and the lowest Si content (19.82 wt%) among the five samples. The coincidence of the highest Fe concentration and the highest magnetic susceptibility at this location suggests localized enrichment of Fe-bearing magnetically responsive particles near the Mamberamo River mouth.

Nevertheless, the elemental results also showed that total Fe concentration alone does not fully determine the magnetic susceptibility of the bulk sediment. The variation among sampling locations therefore reflects differences in the abundance and characteristics of magnetically responsive components within the iron-sand deposits. Because the present XRF analysis provides elemental rather than crystalline-phase information, the results are interpreted primarily in terms of Fe enrichment and spatial compositional variability rather than identification of specific Fe-bearing mineral phases.

Overall, the combined magnetic susceptibility mapping and elemental characterization demonstrate that the Mamberamo River estuary contains spatially heterogeneous iron-sand deposits, with the strongest magnetic response and highest Fe enrichment occurring in the river-mouth sector. These findings provide baseline information on the magnetic and elemental characteristics of iron sands from this relatively unexplored region of northern Papua.

Recommendations

Further investigations should examine the influence of grain-size fraction on the magnetic susceptibility and elemental

composition of the Mamberamo iron sands. Separating the bulk sediments into different particle-size fractions may provide a clearer understanding of the distribution of magnetically responsive Fe-bearing particles. In addition, magnetic separation or magnetic extraction is recommended to concentrate the magnetic fraction prior to further characterization. X-ray diffraction (XRD) analysis should also be conducted to identify the crystalline mineral phases present in the Fe-rich fraction and to distinguish among possible Fe-bearing phases such as magnetite, maghemite, hematite, and ilmenite. Combining grain-size fractionation, magnetic separation, XRF, and XRD would provide a more comprehensive characterization of the magnetic and mineralogical properties of the Mamberamo iron sands.

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