Integration of Geological Mapping and Remote Sensed Studies for the Discovery of Iron – Ore Mineralization in Mutomo – Ikutha Area, SE Kenya

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Abstract This research integrates geology with remote sensing techniques to establish characteristic features that can be used to discover iron ore mineralization within the Neoproterozoic rocks of Mutomo – Ikutha area in south eastern Kenya. The association of hornblende gneiss and shearing as well as alteration processes near the mineralized regions appear to play an important role in the distribution and localization of the iron mineralization. The methods used in this research include Image processing techniques applied on the digital subset ETM+ data that cover Mutomo – Ikutha area and geological field mapping. These techniques generated several products of enhanced satellite imagery, such as colour composite images, ratio images and principal component images. These techniques have been successfully used in the lithological discrimination of iron ore bearing sheared hornblende gneisses. The capabilities of remote sensing data to characterize the iron ore bearing gneisses, in addition to characterization and mapping the hydrothermal alteration zones helped in identification of iron mineralization regions. Extensive field geologic and geochemical investigations to the pronounced zones delineated by the image processing technique, led to discovery of four locations of high iron anomalies with some iron mineralization, mainly connected to the studied Neoproterozoic hornblende gneisses. Chemical studies were carried out using atomic absorption spectrophotometer (AAS) and X-Ray fluorescence, for some selected mineralized samples. Petrographic analysis and physical properties of the iron minerals were carried out as well. These investigations confirm the present iron mineral to be magnetite ore enriched with phosphates. The magnetite is found in close association with apatite, chalcopyrite, quartz, and chlorite. Relics of corroded magnetite grains occur along the Tiva river bed as well as along the road sides.

Keywords Remote Sensing, Iron Ore, Neoproterozoic

1. Introduction

The study area is located between longitudes 38° 4'E to 38° 20'E and latitudes 1° 48'S to 2° 8'S in South Kitui within the Kitui County occupying about 100 Km² (Figure. 1). In this paper, we show how we have used remote sensing and field based investigation to come up with a structural and a mineral resource map. New geological structures discovered include shear zones and faults that control iron ore mineralization. Orientation analysis has revealed two shear zones associated with iron ore mineralization. The Tiva shear and Mutito shear trending in the NW-SE direction. Another important discovery is the location of Mineral deposits associated with alteration within the gneisses. Although previous researchers had done geological mapping and produced maps for Ikutha area, the structures, lithology and mineral resources discovered were missing. This research attempts to answer some of the questions for the gaps left by the previous researchers.

Image Processing techniques were applied in this work to define the main characteristic features of the gneisses rock-bearing iron mineralization. The enhanced thematic mapper plus (ETM+) digital data of Landsat 7 satellite was used to recognize and map the investigated area. The constructed colour composite images and application of principal component analyses of ETM+ data led to identify and characterize the iron ore -bearing gneisses in the investigated area.

Figure 1. The map showing the area of the project. Major towns within the area include Mutomo and Ikutha.

2. Geology of the Study Area

The Mozambique Belt is a major N-S trending metamorphic and lithotectonic domain that extends along the Eastern Coast of Africa, as well as in Saudi Arabia, Madagascar, India and Sri Lanka. It was first defined by Holmes [1], mostly on metamorphic and structural criteria. The Mozambique is a Neoproterozoic Belt (900 to 550) which was affected by the Pan African tectonothermal event about 650 Ma, as suggested by (Kennedy [2] ; Kazmin [3]; Kröner [4] ; Cartier [5]) who considered it as a major phase of division of the African continent linked to the development of mobile belts. The Pan African event encompasses a wide time span from 650 to 500 Million years. Mozambique Belt is considered as an orogen resulting from the oblique collision between two Gondwana fragments, [Muhongo [6] Burke and Derwey [7]; Gass [8]; Key et al. [9]; Kröner [4]). Stern [10] proposed its name to be changed to East African Orogen. The fact that the collision was oblique resulted in the development of large shear zones parallel to the direction of the orogeny after the main collision phase, owing to tectonic escape phenomena. The geology, and structures, tectonic the history of the Mozambique Belt in Kenya has been reviewed, by (Mathu and Tole [11] 1984; Key et al. [9]; Mathu [12]; Mathu et al.[13]; Mathu et al.[14]; Gaciri et al.[15]; Biyajima et al.[16]; Suwa et al.[17] ; Opiyo – Aketch and Nyambok, 1984; [18] Hackman et al.[19];Mosley [20]; Nyamai [21], and [22-27].

An attempt has been made here to update the geology of Mutomo – Ikutha area. This is to fill the gap left by the previous geologists who missed out some of the geological details that have been noted during the current survey. The current survey has also managed to establish continuity of rock units from the area mapped by Saggerson [28] to the area mapped by Walsh [29]. The rocks of the Mozambique mobile belt are considered to be the metamorphosed equivalents of originally sedimentary rocks, the sedimentary pattern being retained. The repetition of certain beds, e.g. the meta-calcareous horizons in the area, the presence of originally carbonaceous limestone, and preserved current-bedding and stratiform succession are considered proof of sedimentary origin. Evidence of lateral variation is observed in this area. The pelitic gneisses grade into rocks which do not contain the higher-grade index mineral. An example of lateral variation is seen south of Mutomo area where the biotite gneisses grade imperceptibly into biotite-hornblende gneisses. Another lateral variation is noted in Ikutha area where biotite gneiss grades gradually into biotite hornblende gneiss.

An attempt has been made here to classify rock units of the area based on field relation, lithology and colour into groups and formation. These groups include; Ikutha and Mutomo groups. The formations and members of these groups have been subsequently discussed in the following sections.

Table 1. Lithostratigraphy of Mutomo – Ikutha area

SUPER GROUP	GROUPS	FORMATIONS	MEMBERS
UKAMBA SUPER GROUP	IKUTHA GROUP	● TIVA GNEISSES	<ul style="list-style-type: none"> ● Hornblende gneiss ● Quartzo-feldspathic gneiss ● Hornblende biotite gneiss ● Hornblende diopside gneisses ● Granitoid gneiss ● Amphibolites ● Migmatites
		● KASALA GNEISSES	<ul style="list-style-type: none"> ● Hornblende-biotite gneisses ● Hornblende-diopside gneisses ● Crystalline limestone
	MUTOMO GROUP	MBEBETWA GNEISSES	<ul style="list-style-type: none"> ● Biotite gneisses ● Migmatites
		KAPOPONI GNEISSES	<ul style="list-style-type: none"> ● Biotite-garnet gneisses ● Feldspar porphyroblast gneiss ● Calc-silicate granulite ● Migmatites ● Quartzo feldspathic gneiss

(a)

(b)

Figure 2: (a) Nzamba-Miusiani hill – A view taken from Ngotheni area in Ikutha area composed of high grade metamorphic rocks, (b) Mutomo hills, along Mutomo – Mutha road composed of high grade metamorphic rocks.

2.1. Iron Mineralization and Stratigraphic Setting of Mutomo – Ikutha Segment in Mozambique Mobile Belt of SE Kenya

Mineralization in the study area is mainly controlled by the stratigraphy and structures. Stratigraphy of Mutomo – Ikutha area is largely classified on the basis of the lithology of the rocks (Table 1). According to the regulation of the international Subcommission on Stratigraphic Classification [30] of the international Union of the Geological Sciences (IUGS), the stratigraphy of Mutomo – Ikutha area is considered to be composed of lithostratigraphic rock units. In designing nomenclature of the rocks in the study area, the North American Stratigraphic code prepared by the North American Commission on Stratigraphic Nomenclature, and the rules for naming geological units in Norway [31], have been used. It involves a general description of the unit, origin of its name and where possible to its earlier work, areal distribution, including the best exposed areas and stratotype; the contact relations and thickness estimates; the division of the unit into sub-units and origin of the unit based on the available evidence. The stratigraphic descriptions of the study area starts with Ukamba super group, which is referred to as Ukamba group by Mosley [20].

2.2. Lithostratigraphy of Mutomo – Ikutha Area

The rocks of the Mozambique mobile belt in this area are

classified lithostratigraphically as above.

3. Image Processing of Remotely Sensed Data

The remotely sensed raw data of the studied areas are included in Landsat-7 Enhanced Thematic Mapper Plus (ETM+) data scenes number 167/61 (Path/Row) covers Mutomo – Ikutha area. Subsets of the digital ETM+ imagery covering the studied areas were obtained. The image processing techniques were applied in this work using ENVI 4.8, ArcGIS 10 and PCI, GeoAnalyst software-package. Geometric correction has been done for the digital data of the ETM+ bands of the study areas. Raw digital satellite data usually includes geometric distortions due to sensor geometry, scanner, platform instabilities, earth rotation, earth curvature, etc. and it was necessary to correct and adapt them ([32], Lillesand et al [33], [34]). The georeferencing was carried out using ground control points selected from topographic sheets of scale 1:50,000 (175/1 of Ikutha, 164/3 of Mutomo, 164/4 of Mutha and 172/2 of Ithumba). The root mean square error (RMS) in the geometric processing was 0.54 [35]. The following parameters have been used in the registration procedures: UTM Projection, Zone 37S, and Arc 1960 Datum.

Image enhancement techniques were applied to the selected subset of the ETM+ data for the study area. The

achievement of the goal of the application of remote sensing techniques on the studied gneisses led to identify and characterize the studied iron ore bearing gneisses based on the different remote sensing processes of ETM+ data such as color composite image, principal component and band ratio images.

3.1. Colour Composite Images of ETM Data

Digital images are typically displayed as additive colour composites using the three primary colours, red, green and blue (RGB). Different spectral bands of ETM+ data have been selected and combined in RGB colour system to make colour composite images for the studied areas. These combinations were tried to select the best colour composite ETM image to be useful in extracting meaningful information about visual lithological discrimination of the studied hornblende gneiss rocks such as combination of ETM bands 7, 4 and 2 (Figure.5).

3.2. Principal Component Analysis of ETM+ Data

Different bands of multispectral data are often correlated and thus contain similar information i.e. have similar visual appearances. This correlation means that there is redundancy of information. The principal components (PC) transformation is used, to reduce this data redundancy, by

compressing multispectral data sets and calculating a new coordinate system [36]. The application of the PC on the present data is to compress all of the information contained in an original n-channel (band) data set, into fewer number of channels or components, that could be displayed separately as single stretched PC-images, or as component in color composite PC-image [37]. The colour composite image of principal components PC1, PC2 and PC3 for the studied areas successfully distinguish and characterize the studied gneisses (Fig. 3).

3.3. Band Ratios of ETM+ Data

Addition, subtraction, multiplication and division of the pixel brightness from two bands of image data to form a new image are particularly simple transformations to apply in image processing technique. Multiplication seems not to be as useful as the others, band differences and ratios being most common. Differences can be used to highlight regions of change between two images of the same area. Ratios of different spectral bands from the same image are found useful in reducing the effect of topography and for enhancing subtle differences in the spectral reflectance characteristics for rocks and soils [32]. The use of the band ratio technique was applied to the satellite ETM+ Landsat 7 digital data for this study area.

Figure 3. Landsat thematic mapper colour composite of Ikutha regional area. ETM+ bands 3,2,1 = RGB.

Figure 4. False colour composite image of principal components PC1, PC2, PC3 displayed in RGB for Mutomo – Ikutha area

The reflectance values in band 7 (2.08 to 2.35 μm) of TM data depend mainly on the hydroxyl content of the rocks. The ratio of band 5 to band 7 was used as a measure of the intensity of the hydroxyl absorption (2.2 to 2.4 μm region). This ratio was used because band 5 is not within the confines of the Fe –bearing aluminosilicate related or hydroxyl-related absorption features, whereas band 7 is within the hydroxyl absorption wave lengths [38]. The high value of band 5/7 ratio appears in light tone due to the high content of hydroxyl bearing minerals.

The spectral band ratio is one of the most common powerful techniques applied for mapping the minerals of alteration zones (clay, alunite and iron minerals) [36]. Recognition of hydrothermal altered rocks associated with mineral deposits was carried out using image processing techniques such as band ratio images in addition to colour ratio composite images. The spectral bands of ETM+ are well suited for recognizing assemblage of altered minerals. The hydrothermal minerals that were detected by the Landsat image processing of the data of selected areas could be classified into two groups: hydroxyl (clay minerals) and hydrated mineral (sericites) detected by band ratio 5/7 (Figure 4) on one hand, and minerals containing iron (magnetite) detected by band ratio 3/1 on the other hand (Figure 4). Applying these techniques led to the recognition of more than three zones of altered rocks within the studied gneisses along Tiva River.

3.4. Colour Composite ETM+ Band Ratio Images

Colour composite images have been constructed using combination of three ETM band ratios. Different ETM band ratio combinations were carried out to select the optimum colour composite image to use in the visual lithologic discrimination of the investigated area. Some of these combinations are illustrated in (Figure. 5). The best selected result was the colour composite image produced by the combination of bands 5/7, 4/5 and 5/1 (Figure. 5).

This selected image was prepared as shown in (Figure. 5) in which band 5/7 image was assigned by the red component, band 4/5 image by the green component and band 5/1 image by the blue component. The selected colour composite image (Figure. 5) diagnoses some aspects between the different rock units, which was not obviously identified in the FCC image in (Figure. 3). For example, it determines and delineates the black cotton soil (purple colour) from the gneisses. The silica rich rocks display red – purple colour in this image (Figure. 5) due to the high band 4/5 ratio. The migmatites appear on this image in blue colour due to the high band 5/1 ratio. The boundaries between the black cotton soil and the older gneisses could be delineated in the western part of the mapped area using the colour composite image of ratio bands (Figure. 5).

Figure 5. Landsat Enhanced Thematic Mapper colour composite of Mutomo - Ikutha area. The colour composite image produced by the combination of bands 5/7, 4/5 and 5/1

Figure 6. Landsat Enhanced Thematic Mapper colour composite of Ikutha regional area. TM bands 4,3,2 = RGB.

Figure 7. Lineated hornblende gneisses West of Tiva River. Lineation has been caused by shearing of the hornblende gneisses.

Figure 8. Structural lineaments extracted from the Mutomo – Ikutha image and their frequency rose diagram

3.5. Lineaments Extraction

The automatic lineaments extraction from Landsat ETM+ panchromatic band of the study areas was carried out under the default parameters of GeoAnalyst-PCI package. These lineaments have been visually edited to extract only the structural lineaments. The obtained total structural lineaments in Ikutha area were 56. The rose diagram of these lineaments shows that their predominant trend is NNW (Fig. 8). The zones of high lineament intensities concentrated at the central and eastern part of River Tiva (Figure 7). The intersected lineaments, on the other hand, are found to be restricted and concentrated only in the southern part of the Ikutha town (Fig. 6).

It could be concluded that the alteration zones and/or mineralized zones in the investigated areas, delineated by band ratio images of the studied gneisses coincide more or less with high lineaments intensity and/or lineaments intersection or both together.

3.6. Image Criteria of the Study Areas and the New Discovered Iron Mineralized Zones

From the previously studied remotely sensed data, it is worth mentioning that there are many criteria of the alteration zones that could be used as a guide for the exploration of Iron mineralization in the gneiss in the Mozambique mobile belt of Kenya. The most important criteria used as a tool to increase the potentiality of the iron mineralization was to distinguish high and low reflectance

portions in the study area. Moreover, construction of the alteration map of the studied interpreted from the image processing helped in the discovery of the new zones of mineralization (Figure 9 and 10) and could be used in the exploration for iron mineralization in the future.

The methods applied in this work for the exploration of hydrothermal iron ore mineralization using satellite image processing, are based on the surface spectral features characteristic of this type of hydrothermal iron mineralization, which, will allow favourable areas for exploration. The occurrence of hydrothermal altered rock (Figure 9) is one of the main features that can be utilized to determine the localization of iron mineralization. By comparing the intensity of the extracted structural lineaments, and their intersections to the altered zones, depicted from remote sensing processing technique, it could be recognized that the alteration zones, more or less coincide with the high frequency and intersected lineaments.

The distribution of hydrothermal alteration within the processed Landsat images become the key to locate the main outflows of a hydrothermal system, which led, after the field checking, to recognize high Fe_3O_4 (Table 2) anomalies and mineralized zones within the study area. Therefore, many locations are delineated in this work as altered zones, whether by clay minerals and sericite. Iron oxides are frequently observed in the outcrops of hydrothermally altered gneisses. Therefore their identification is a useful key to define areas related to deeply mineralized zones (Figure 10)

Figure 9. hornblende gneiss that has undergone hydrothermal alteration (sericitization) south of Ikutha town.

Figure 10. Hydrothermal alterations map of Ikutha area, interpreted from the Landsat ETM images and field works

Table 2. Chemical analysis of the samples collected from the locations labelled on figure 8.

Ref. No.	SiO ₂	Al ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	MnO	Fe ₃ O ₄	P ₂ O ₅	LOI	Total	Lithology-Mineral/rock type
1	2.91	0.60	8.40	0.24	0.17	0.030	0.05	0.400	81.30	5.70	NIL	99.80	Magnetite +Apt
2	3.83	0.76	3.77	0.20	0.14	0.030	0.30	0.400	86.10	4.10	NIL	99.63	Magnetite +Apt
3	6.97	1.47	0.99	0.19	0.17	0.030	0.18	0.400	88.30	1.00	NIL	99.70	Magnetite
4	5.05	0.33	0.25	0.30	0.12	0.030	20.70	0.600	71.00	ND	NIL	98.38	Magnetite +Sphene
5	4.78	0.11	0.60	0.47	0.11	0.03	21.70	0.60	70.70	0.50	NIL	99.60	Magnetite +Sphene(Ti)

4. Field Proving with Laboratory Investigations

Extensive geological, field proving and geochemical investigations were carried out for the alteration zones (Figure 10), delineated in the studied gneisses by the Landsat image processing. During the field works, the geochemical investigations revealed that the Fe_2O_3 is relatively high in the sheared gneisses as well as altered gneisses. The three locations discovered as high geochemical anomalies with some iron mineralization, are mainly connected to the hornblende gneisses and hornblende biotite gneiss of Tiva group.

These locations include Timboni, Kitambasye and Mutuluni in Ikutha area

The mineralized zones of Tiva gneisses are found to be mainly connected or hosted by the hornblende gneisses that follow the direction of the strong and nearly vertical shear zone striking N320°W-S140°E in the western part of Ikutha town.

The Fe_2O_3 anomaly at the northern part of Timboni, is mainly connected and hosted by highly altered and weathered gneisses and structurally controlled by NNW-SSE shear zone (Figure 10). One of the striking feature of this anomaly is its association with high content sericite unlike the anomalies of Timboni area which are associated with apatite.

5. Summary and Conclusions

This study aimed to use the capability of remote sensing techniques integrated with geological investigations to characterize the iron bearing gneisses and to detect hydrothermal alteration zones, and their associated structures suitable for iron mineralization. The study area including the most promising iron bearing gneisses was selected in Mutomo – Ikutha area, SE Kenya. The achievement of the goal of the application of remote sensing techniques on the studied gneisses led to identify and characterize the studied iron bearing gneisses based on different remote sensing processes of ETM+ data, such as colour composite image, principal component, and colour ratio composite images.

Recognition of hydrothermal altered rocks associated with mineral deposits, was carried out using image processing technique such as band ratio images, in addition to colour ratio composite images. The spectral bands of ETM+ are well suited for recognizing assemblage of altered minerals. The hydrothermal minerals that were detected by the Landsat image processing of the data of selected areas could be classified into two groups: Hydroxyl (sericite minerals) and hydrated mineral/ detected by band ratio 5/7 on one hand, and minerals containing iron (magnetite) detected by band ratio 3/1 on the other hand. Applying these techniques led to recognize more extended zone of altered rocks within the studied gneisses. The association of hornblende gneisses, shearing and faulting along river Tiva in Ikutha area appear

to play an important role in the distribution and localization of the mineralization.

Image processing techniques are applied to the digital subset ETM+ data of the studied areas. These techniques generated several products of enhanced satellite imagery such as colour composite images, ratio images and principal components. These techniques have been successfully used in the lithological discrimination of iron bearing gneisses.

The capabilities of remote sensing data to characterize the iron bearing gneisses in addition to characterization and mapping the hydrothermal alteration zones usually help in localization of iron mineralization.

Extensive field geologic and geochemical investigations to the zones delineated by the image processing technique led to the discovery of four locations of high Fe_2O_3 anomalies (Table 2) with some Iron mineralization, mainly connected to the studied gneisses. These location include Timboni, Muangeni, Kitambasye and Mutulini (East of Timboni). This work showed the important criteria that can be considered as tools to increase the potentiality of the iron discovery in Mutomo – Ikutha area. Moreover, construction of the alteration map of the different studied gneisses, interpreted from the image processing can be applied in the discovery of new zones of mineralization. This technique can be used in exploration for iron mineralization in the future elsewhere in the Mozambique mobile belt having similar conditions.

REFERENCES

- [1] Holmes A., The sequence of Precambrian orogenic belts in Southern and Central Africa. XVIII International Geological Congress, 14, pp. 254-269, 1951.
- [2] Kennedy W., *The structural differentiation of Africa in the Panafrikan tectonic episode. 8th Annual Report of the Research Institute for African Geology.* University of Leeds, pp. 48-49, 1964.
- [3] Kazmin V., Some aspects of Precambrian development in East Africa. *Nature*, 237, pp. 158-160.
- [4] Kröner A., 1991. African linkage of Precambrian Sri Lanka. *Geologische Rundschau* 80(2), pp. 429-440, 1972.
- [5] Cartier L.E., Livelihoods and production cycles in the Malagasy artisanal ruby sapphire trade: a critical examination. *Resources Policy*, 34, 80 - 86, 2009
- [6] Muhongo S. Late Proterozoic collision tectonics in the Mozambique belt of East Africa: Evidence from ulunguru mountains (Tanzania). *Journal of African Earth Sciences* 19, pp 103 – 108, 1994.
- [7] Burke K., and Derwey, J., *Orogeny in Africa*. 3rd ed. Ibadan University Press, pp. 583-608, 1972.
- [8] Gass I., The evolution of the Pan African crystalline basement in NE Africa and Arabia. *Journal of the Geological Society of London*, 134, pp. 129-138, 1977.

- [9] Key R., Charsley, T.J, Hackman, B.D, Wilkinson, A.F., Rundle, C.C., *Superimposed Upper Proterozoic Collision controlled Orogenies in the Mozambique Belt of Kenya*. Precambrian Research 44, pp. 197-225, 1989.
- [10] Stern J.R., Arc assembly and continental collision in the Neoproterozoic East African Orogeny: Implication for the consolidation of Gondwanaland. Annual Rev. Earth Planet. Sciences, 22, pp. 319 – 351, 1994.
- [11] Mathu E.M. and Tole M.P. Geology of the Ithanga Hills area. Journal of African Earth Sciences, 2, pp. 1-16, 1984.
- [12] Mathu E.M., The Mutito and Ikoo faults in the Pan – African Mozambique belt, Eastern Kenya. In: Mason, R. (Ed.), *Basement Tectonics*, Kluwer Academic publishers, Netherlands. pp 61 – 69, 1992.
- [13] Mathu E.M., Ngecu, W.M., Nyamai C.M. and Davies T.C., Proterozoic island tectonism in the Kenyan Mozambique belt east of Nairobi. In: Muhongo, S. (Ed.) *Proceedings of the International Geological Field Conference on the Mozambique belt in East Africa, Tanzania*. 8, pp.59 UNESCO, Nairobi, Kenya, 1991.
- [14] Mathu E.M., Ichang'i D., and Dindi E.W., The geology, structures and tectonics of the Mozambique belt in Kajiado district, S.W. Kenya. In: Muhongo, S. (Ed.) *Proceedings of the International Geological Field Conference on the Mozambique belt in East Africa, IGCP 348 Field meeting in Arusha, Tanzania and Voi, Kenya*, pp. 24-25. UNESCO, Nairobi, Kenya, 1994.
- [15] Gaciri S.J., Altherr R., Nyamai C.M. and Mathu E.M., Distribution of elements in mineral pairs from Mozambique belt rocks of Matuu area, central Kenya. In: Opiyo-Akech, N., 1984 edition, *Proceedings of the 5th Conference on the Geology of Kenya - Geology for Sustainable Development*, pp. 57-62. UNEP/ UNESCO, Nairobi, 1993.
- [16] Biyajima K., Suswa, K., and Miyakawa K., Mantled gneiss dome in the Mozambique belt around Machakos area, Kenya. Preliminary Report. African Studies, Nagoya University, pp. 6 – 13, 1975.
- [17] Suwa K., Suzuki, K., Miyakawa, K. and Agata, T., Vanadium and vanadium grossulars from the Mozambique metamorphic rocks, Mgama Ridge, Kenya. 4th Preliminary Report of African Studies, Nagoya University, pp. 87-96, 1979.
- [18] Opiyo-Akech N. and Nyambok I.O., Precambrian geology of the Ishiara area, Kenya. Journal of African Earth Sciences , 2, pp. 61-65, 1984.
- [19] Hackman B.D., Charsley, T.J., Kagasi J., Key R.M., Siambi W.S. and Wilkinson A.F., Geology of the Isiolo Area Report. Geological Survey of Kenya, No.103, 88 pp, 1989.
- [20] Mosley P., Geological evolution of the late Proterozoic "Mozambique Belt "of Kenya. Journal of Tectonophysics , 221, pp. 223-250, 1993.
- [21] Nyamai C.M., Petrography and Geochemical of Mozambique belt rocks of the Matuu area, Central Kenya. In: UNESCO, *Geology for Sustainable Development, Newsletter/Bulletin* 10, pp 154 – 155, 1995.
- [22] Nyamai C.M., Mathu E.M, Ngecu W.M. A review of the geology of the Mozambique Belt in Kenya. In: *Proceedings of the 9th International Geological Conference of the Geological Society of Africa – Regional Trends in African Geology*, Accra, Ghana. pp 334 – 347, 1993.
- [23] Nyamai C.M., Opiyo-Akech N., Gaciri, S.J. and Fujimaki H., Geochemistry and Tectonomagmatic affinities of the Mozambique belt intrusive rocks in Matuu-Masinga area, central Kenya. Gondwana Research, 2, pp. 387-399, 1999
- [24] Nyamai C.M., Opiyo-Akech N., Gaciri, S.J., and Fujimaki H., Structures, Metamorphism and Geochronology of the Mozambique belt metamorphic and intrusive rocks from Matuu-Masinga area, central Kenya. Journal of African Science Technology and Engineering Series 1, pp. 47-55, 2000a
- [25] Nyamai C.M., Opiyo-Akech N., Gaciri S.J., Johansson B., and Sato Y., Petrography, mineral chemistry and thermobarometry of the Neoproterozoic Mozambique belt rocks of Matuu-Masinga area, central Kenya. In: Mukhopadhyaya, D., Ghosh, S.S., Chakrabarti, B.K., Sanyal, S. and Gupta, S.D. (Eds.) *Proceedings of the International seminar on Precambrian crust in Eastern and Central India, UNESCO-IUGS-IGCP-368, Journal of Geological Survey of India Special Publication*, 57, pp. 296-316, 2000b.
- [26] Nyamai C.M., Gaciri, S.J., Opiyo-Akech N., Johansson B., and Sato Y., Conditions of pyroxene crystallization and thermobarometry of the Neoproterozoic Mozambique belt intrusive rocks of Matuu-Masinga area, central Kenya. In: Nyamai, C.M. and Maimba, M. (Eds.) *Proceedings of the 8th and 9th Regional Conference of the Geology of Kenya*, Geological Society of Kenya, pp. 116 -122, 2002.
- [27] Nyamai C.M., Mathu E.M., Opiyo-Akech N., Wallbrecher E., A reappraisal of the geology, geochemistry, structures and tectonics of the Mozambique belt in Kenya, east of the rift system. African Journal of Science and Technology Science and Engineering Series, 4, pp. 51-71, 2003.
- [28] Saggerson, Geology of the South Kitui area, report 37. Geological survey of Kenya, 49pp, 1957.
- [29] Walsh J., Geology of Ikutha Area, Report 56. Geological Survey of Kenya, 78pp, 1963.
- [30] International Subcommission on stratigraphic classification, (ISSC), – International stratigraphic guide, H.D. (Ed), John Wiley and Sons, N.Y., 200P, 1976
- [31] Nystuen Rules and recommendations for naming Geological Units in Norway. Norwegian committee on stratigraphy (Norsk Geologisk Tidsskrift 69, Suppl. 1, 1-111), 1989.
- [32] Mather, P.M. Computer processing of remotely sensed images, and introduction, John Wiley and sons, ISMN: 0-471-9064-4, 1987
- [33] Lillesand, T.M. Kiefer, R.W. and Chipman, J.W. Remote sensing and image interpretation. 5th ed., John Wiley and sons Inc. New York, ISBN 0-471-25515-7, 763P, 2004.
- [34] Richards, J.A. Remote sensing, Digital Image Processing, and Introduction, Sec. Ed., Springer Verlag, P.340, 1995.
- [35] Bernstein, R. Digital Image Processing for Remote sensing, Wiley, New York, 1978.
- [36] Sabins, F.F. Remote sensing for mineral exploration, Ore Geology Reviews, 14: 157-183, 1999.
- [37] Vincent, R.K. Fundamentals of Geological and Environmental Remote Sensing, Prentice-Hall, Inc, U.S.A.,

366p, 1997.

[38] Sultani, M., Arvidson, R.E., and Sturchio, N. Lithologic

mapping in arid regions with Landsat thematic mapper data: Meatiq dome., Egypt, Geological Society of America Bulletin, 99: 748-762, 1987.