RENDICONTI Società Italiana di Mineralogia e Petrologia, 37 (1), 1981: pp. 387-406

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AN APPLICATION OF MOVING AVERAGE ANALYSIS AND R-MODE FACTOR ANALYSIS TO A REGIONAL GEOCHEMICAL RECONNAISSANCE ON RESIDUAL SOILS OF SOUTHERN SUDAN

ABSTRACT. — In Southern Sudan a geochemical reconnaissance survey has been carried out on the residual soils of the area between the Amadi-Bor-Kapoeta alignement and the borders of Sudan with Uganda, Zaire, Kenya and the Central African Republic.

Climatically this area falls in the Tropical Savannah Belt. Physiographycally three sectors can be distinguished: the Southern Mountains, east of the White Nile, with soils of the Humid Montane Catenae; the Ironstone Plateau with soils of the Latosols Catenae and the Southern Clay Plain of the Upper Nile Basin with alkaline-clay soils.

Lithologically the crystalline basement is made up of medium to high grade metamorphites, extensively migmatized and granitized. Within this basement, mylonitic to pseudotachilitic bands are found along the Nimule-Rumbek trend. East of this belt, Palaeozoic basic dykes and Cretaceous alkaline magmatites cut the basement. In the eastern end of the studied area, there are volcanics representing an extension of the Ethiopian Trap Series. The area is covered by continental clastics (Umm Ruwaba Formation) Tertiary-Pleistocene in age and residual soils.

The B horizon, at an average depth of 20 cm, has been sampled, with a density of one sample per 300-350 km^2. The minus 80 mesh fraction has been analyzed by means of X-ray fluorescence for Al, Fe, Mn, Ti, Cu, Mo, Pb, Zn, Nb and Sn.

The log-transformed data have been treated statistically by means of a moving average analysis and R-mode factor analysis.

The elemental distribution of the regional trends has been determined and maps relative to the most interesting distribution are reported.

Using the R-mode factor analysis four metal associations (Sn-Mo-Fe; Ti-Nb-Zn-Al; Cu-Zn-Al; Pb-Mn-Zn-Fe) have been recognized. This factor model accounting for 74.45 % of the data variability, has been chosen as the most meaningful solution in terms of the geological features and secondary environment characterizing the studied area.

On the basis of the relationships between recognized metal association and geological features, bedrock and/or surficial, three target areas have been identified representing alkali-granites, nepheline-syenites and mafic rocks (dykes, greenstones). One of them, the area in which nepheline-syenites and alkali-granites occur, has been identified for immediate follow-up evaluation.

RIASSUNTO. — È stata condotta, nel Sudan Meridionale, una prospezione geochimica riconoscitiva sui suoli residuali dell'area compresa tra l'allineamento Amadi-Bor-Kapoeta ed i confini internazionali del Sudan con Kenya, Uganda, Zaire e Repubblica Centrafricana.

Da un punto di vista climatico l'area ricade nel « Tropical Savannah Belt », caratterizzato

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dall'alternanza di una stagione secca e di una piovosa. Sia le piogge che la durata della stagione umida aumentano regolarmente da nord-est verso sud-ovest.

Per quel che riguarda morfologia e pedologia possono essere distinti tre settori principali: le « Southern Mountains », ad est del Nilo Bianco, con suoli della « Humid Montane Catenae »; l'« Ironstone Plateau », ad ovest del Nilo Bianco, con suoli della Latosols Catenae e la « Southern Clay Plain » del Bacino dell'Upper Nile con suoli alcalino-argillosi.

Da un punto di vista litologico è presente un Basamento Cristallino con metamorfiti di medio-alto grado, estesamente migmatizzate e granitizzate, d'età Precambriano-Paleozoico inferiore. In questo basamento lungo l'allineamento Nimule-Rumbek si rinvengono bande da milonitiche a pseudotachilitiche. Ad est di questa fascia il basamento è tagliato da dicchi basici di età paleozoica e da magmatiti alcaline cretaciche. All'estremità orientale dell'area studiata si ritrovano vulcaniti riferibili alle Trap Series dell'Etiopia. L'area, infine, è coperta da depositi clastici continentali (Umm Ruwaba Formation) la cui età va dal Terziario al Pleistocene e da suoli residuali.

È stato campionato l'orizzonte B dei suoli, ad una profondità media di 20 cm e con una densità di un campione ogni 300-350 km^2. La frazione inferiore ad 80 mesh è stata analizzata a mezzo di fluorescenza a raggi X per Al, Fe, Mn, Ti, Cu, Mo, Pb, Zn, Nb e Sn.

I dati ottenuti sono stati log-trasformati e trattati statisticamente per mezzo dell'analisi delle medie mobili e dell'analisi fattoriale; è stata così determinata la distribuzione degli elementi e si sono costruite carte dei trends regionali, delle quali vengono qui riportate le più interessanti.

Per mezzo dell'analisi fattoriale sono state riconosciute quattro associazioni di metalli (Sn-Mo-Fe; Ti-Nb-Zn-Al; Cu-Zn-Al; Pb-Mn-Zn-Fe). Il modello fattoriale 4, entro cui ricadono queste quattro associazioni, responsabile del 74,45 % della variabilità dei dati, è stato scelto come il più significativo in relazione alle caratteristiche geologiche ed all'ambiente superficiale della zona in studio.

Sulla base delle relazioni esistenti tra l'associazione di metalli riconosciuta, le strutture geologiche, la litologia e l'ambiente superficiale, sono state identificate tre aree caratterizzate da graniti alcalini, sieniti a nefelina e rocce basiche, su cui orientare una futura prospezione geochimica a carattere strategico.

Introduction

A reconnaissance geochemical survey of the Southern Provinces of Sudan (Bahr el Ghazal, el Buheyrat and Equatoria), where no mineralization is known, was carried out. The area is bordered in the south and west by Kenya, Uganda, Zaire, and Central African Republic; in the east by the Kapoeta meridian; and in the north by the Bor-Amadi alignment (figs. 1 and 2).

The study was divided into three stages: 1) photogeological mapping; 2) field work to check the photogeological map and to collect samples for petrographic and radiometric analyses; 3) preliminary geochemical prospecting on soils, alluvium and stream sediments. The principal results of the geochemical survey on the residual soils are reported in this paper.

Sampling was carried out at nominal density of one sample per 300-350 sq./km. The samples were analyzed by X-ray fluorescence for Al, Fe, Mn, Ti, Nb, Cu, Pb, Zn, Sn, and Mo.

The data were processed by means of the moving average and R-mode factor analyses. The geochemical dispersion patterns have been interpreted with respect to the known geology of the area.

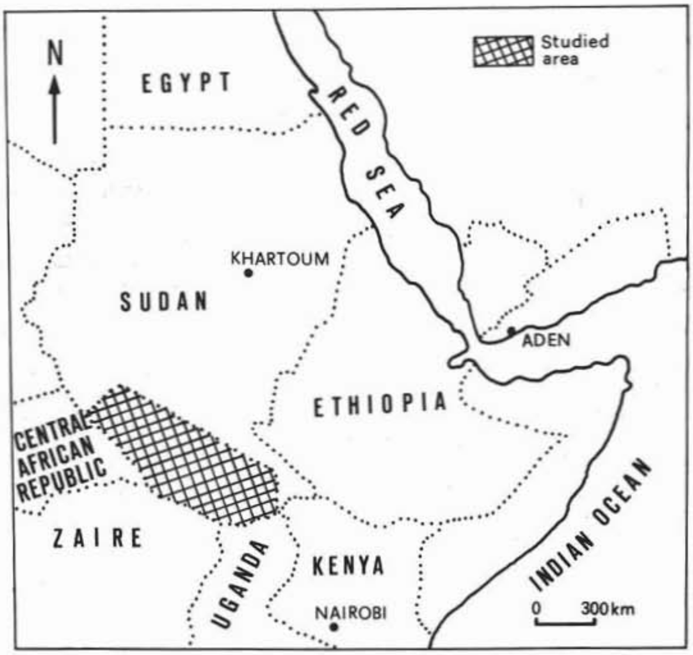

Fig. 1. — General location map of field area.

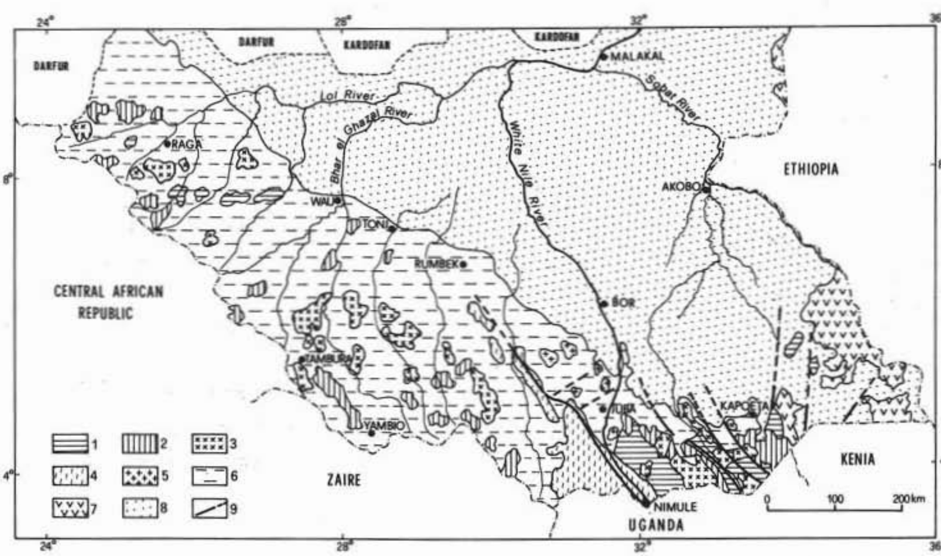

Fig. 2. — Lithological sketch map of the Southern Sudan. 1 - Biotite-garnet and sillimanite gneiss; horneblende gneiss; charnockite gneiss; amphibolites; garnet and pyroxene amphibolites. 2 - Various types of migmatite gneiss, augengneiss, granitoid gneiss. 3 - Migmatite granites, frequently with K-feldspar mega-crystals, micro-granodiorites and microgranites concordant with the wall rocks. 4 - Various typer of high grade metamorphites, migmatite gneiss and migmatite granites with frequent mylonites and blastomylonites bands. 5 - Alkali-granites, nepheline-syenites etc. 6 - Lateritic cover on indifferenziate basement. 7 - Volcanics. 8 - Umm Ruwaba Formation. 9 - Faults.

Geology

a) Bedrock

Geological studies on the Southern Sudan are very scarse (WHITEMAN, 1971; Southern Sudan Geological Map, 1976; CIVETTA et al., 1979). Our work was carried out by means of a photogeological survey, followed in the field by geological-structural and geochemical regional surveies. The lithological map shown in figure 2 has been prepared from the photogeological survey results, supplemented by limited field evaluations.

The following terrains, stratigraphically, from youngest to oldest, have been distinguished (WHITEMAN, 1971; CIVETTA et al., 1979):

— Umm Ruwaba Formation (Tertiary-Pleistocene);
— Volcanics (Tertiary);
— Laterites (Mesozoic?-Tertiary);
— Alkali-granites and nepheline-syenites (Cretaceous);
— Crystalline Basement (Precambrian and Precambrian-Early Palaeozoic).

The crystalline Basement is made up of medium-high grade metamorphic rocks, extensively migmatized and intruded by granitic bodies. In this lithological complex the following can be found: biotite-garnet gneiss, charnockite gneiss, garnet-sillimanite gneiss, amphibolite gneiss, amphibolites and garnet amphibolites. Due to a very intensive isoclinal folding, it is impossible to reconstruct the stratigraphy of this complex, which underwent migmatization until concordant granitic bodies were formed.

In Eastern Equatoria, discordant basic dykes cut through the Basement rocks. An intensive post-crystalline deformation phase with the formation of bands ranging from mylonites to pseudotachylites, with northwest-southeast trends, occurs from Nimule almost reaching Rumbek.

In the same area and particularly near Juba, structures connected with an alkaline magmatism have been found. The rock types are alkali-granites and nepheline-syenites, Cretaceous in age, and discordant with the Basement. Around Naghishot, on the Sudan-Uganda international boundary, analogous phenomena have been reported (VAIL, 1976).

Large areas underlain by volcanics, representing an extension of the Ethiopian Trap Series, occur on the Basement complex in the eastern part of the studied area. Clastic (Umm Ruwaba Formation) and residual (laterites) continental deposits have been found as well. The latter, Mesozoic-Tertiary in age, outcrops especially west of the White Nile. Their thickness is variable and never exceeds 15 m.

The Umm Ruwaba Formation, Tertiary-Quaternary in age, is made up mostly of sandy-argillaceous fluvio-lacustrine deposits with minor conglomerates. It outcrops north of the Kapoeta-Wau alignment; the thickness of this formation increases toward the north, pinching out toward the south where eluvial deposits overlie the Basement.

b) Economic

From the mining point of view the Southern Sudan is completely unexplored. In fact except for the Hofrat en Nahas mines, which are anyway situated in the Darfur, at the western extremity of the studied area, along the border with the Central African Republic, explored and studied by various companies, other evidence of mineralizations is fruit of sporadic and occasional informations.

The Hofrat en Nahas deposits are a polymetallic sulphide ones related to pegmatitic-pneumatolitic and hydrothermal processes associated with igneous and metamorphic rocks of the Basement complex. The mineralizations consist mostly of copper sulphides with uraninite, gold and molybdenum (AFIA and WIDATALLA, 1961). According to U.N.M.S.P. (1971) these deposits could be attributed to a « Porphyry copper system ». The ore reserves amount to 8,741,000 tons with an average copper content of 4.01 %. The mines are not exploited because of lack of transport and energy in the area. Other indications of mineralizations concern placers of gold around Kapoeta and Juba, and of cassiterite in the Ibba-Sue basin at the border with Zaire (ANDREW, 1943), while columbite is reported in the area between Juba and Nimule (ANDREW, 1946).

It has to be stressed anyway the high mineral potential of the nepheline-syenites, because it is well known that in East Africa with such a type of magmatic rocks, singenetic and residual ore deposits of Nb, Mo, P, U+Th, base metal sulphides and aluminium are associated (DEANS, 1966; BLOOMFIELD et al., 1971; REEDMAN, 1974).

High potential for uranium epigenetic deposits, finally, has the Umm Ruwaba Formation, because its belt, bordering the oxidizing environment of the lateritic cover, could host uranium roll-type deposits (CIVETTA et al., 1980).

Physiography

Physiographycally three areas can be distinguished in the Southern Provinces of the Sudan (fig. 3).

1) *The Southern Clay Plain*, corresponding to the alluvial plain of the Upper Nile Basin, is characterized by negligible relief, resulting in the formation of extensive swamp areas during the rainy season. The surficial terrains of this area are essentially clayey, with sandy gravelly lenses.

2) *The Ironstone Plateau*, which extends northwards from the Nile-Congo watershed, is characterized by groups of subdues hills. In this area a very extensive and usually thick lateritic cover occurs.

3) *The Southern Mountains*, which fall to the East of the White Nile, are characterized by high relief (Mount Kinyeti, 3,168 m).

Climatically the study area falls in the « Tropical Savannah Belt » (LEBON, 1965). Only in a narrow belt along the Zaîre boundary, owing to rainfalls exceeding 1,500 mm/years, does a tropical rain forest grow. Rainfall regularly increases south-west-wards from 800 mm/year to more than 1,600 mm/year (fig. 3). To the east of the White Nile, in the Southern Mountains area, it exceeds 2,000 mm/year.

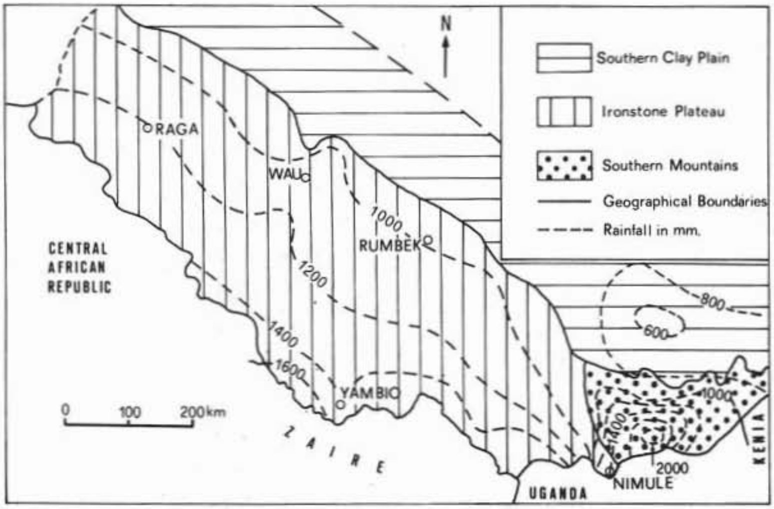

Fig. 3. — Climatic geographic map.

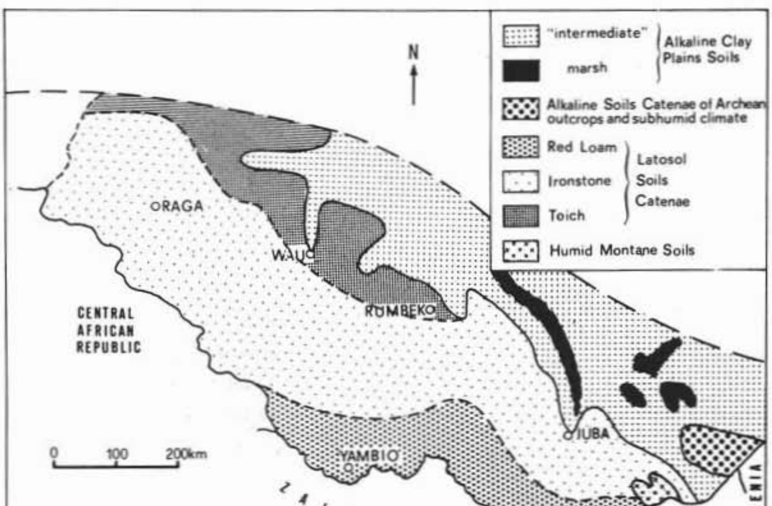

Fig. 4. — Soils map.

In thes tudied area the pedology is largely influenced by the climate and morphology (LEBON, 1965; fig. 4). Alkaline Clay Plain Soils are present in the Southern Clay Plain. LEBON (1965) notes that in this region extensive areas « are annually inundated, and include the great extension of "intermediate land", as well as the lower lands nearer the perennial marshes, which is fooded or moistened for much of each year. The soils are cracking montmorillonitic clays, alkaline and calcareous, but without gypsum. Locally, there is evidence of impeded drainage.

The top soil can be acid, but further down is alkaline ».

Soils which can be attributed to the Alkaline Soils Catenae have also been identified in the Southern Mountains, east of the White Nile. These areas are characterized by outcrops of felsic rocks and subhumid climate. In the Southern Mountains, covered by montane forest the presence of soil of the Humid Montane Catenae is very probable, although no account of this has so far been given.

In the Ironstone Plateau, finally, soils of the Latosol Catenae are present. These soils are weakly acid, becoming more acid after cultivation. The clay fraction is mainly kaolinite and the silica ratio and content of exchangeable bases are low. Three belts (Red Loam, Ironstone and Toich) essentially related to the rainfalls have been distinguished among the terms of this Catenae.

Sampling, analytical techniques and data processing

a) *Field sampling*

The Southern Sudan has a very extensive and, in places, thick residual soil cover. The generally flat topography of this area lends itself to the formation of a thick residual cover since the flowing surface waters remain long enough to leach the soluble compounds of the soil, leaving in situ the insoluble ones.

X-ray analyses of samples from the lateritic cover have shown the presence of quartz, goethite and kaolinite in some areas, and quartz, kaolinite, hematite and gibbsite in others.

The presence of quartz and gibbsite in the soils and their pisolitic texture suggest that the material sampled from the residual soils in this study would be classified as B horizon, according to Bayliss (1972).

A reconnaissance sampling of the residual soils was carried out in the above described area (fig. 4). The samples were collected at an average depth of 20 cm.

About 200,000 sq./km were sampled at a nominal density of one sample per 300-350 sq./km. Because of the already mentioned physiographical aspects of the region under investigation, the sampling was carried out mostly along the motorable roads.

b) *Sample preparation and analysis*

The collected samples were dried, sieved to minus 80 mesh and then crushed, powdered and analyzed for Al, Fe, Mn, Ti, Cu, Mo, Pb, Zn, Nb and Sn by X-ray fluorescence following a regression method based on full matrix correction (Franzini and Leoni, 1972; Leoni and Saitta, 1976). The precision and the accuracy of the analyses for the different elements, at the 68 % confidence level, is as follow: Al_2O_3: 2.7 %; Fe_2O_3: 3.2 %; MnO: 5.0-%; TiO_2: 2,3 %; Cu: 3.5 %; Mo: 5.0 %; Pb: 3.6 %; Zn: 3.5 %; Nb: 4.0 %; Sn: 3.5 %.

c) *Data processing*

Statistical methods were utilized in the identification of anomalous and background population of the geochemical data for the residual soils. Generally

TABLE 1
Range and threshold values

Element	Range		$\bar{x} + 2\sigma$	
Al	2 - 16	%	16	%
Fe	1 - 35	"	50	"
Mn	77 - 8239	p.p.m.	4365	p.p.m.
Ti	700 - 53200	"	10000	"
Nb	7 - 321	"	50	"
Sn	1 - 9	"	15	"
Mo	1 - 23	"	17	"
Zn	4 - 279	"	87	"
Pb	2 - 254	"	114	"
Cu	2 - 122	"	117	"

the raw data distributions obtained in this survey are markedly positively skewed, whereas when log-transformed their distribution more closely approximate normality (AHRENS, 1954 a; 1954 b; 1957). For this reason all data have been log-transformed prior to subsequent statistical work.

For all elements the threshold values (Tab. 1) were selected at the mean plus two standard deviations of the log-transformed data (LEPELTIER, 1969; ROSE, 1972).

Histograms showing the distribution of the log-transformed data are indicated on their respective geochemical maps (figs. 5 to 11).

To determine the regional trends of the elements a moving average analysis

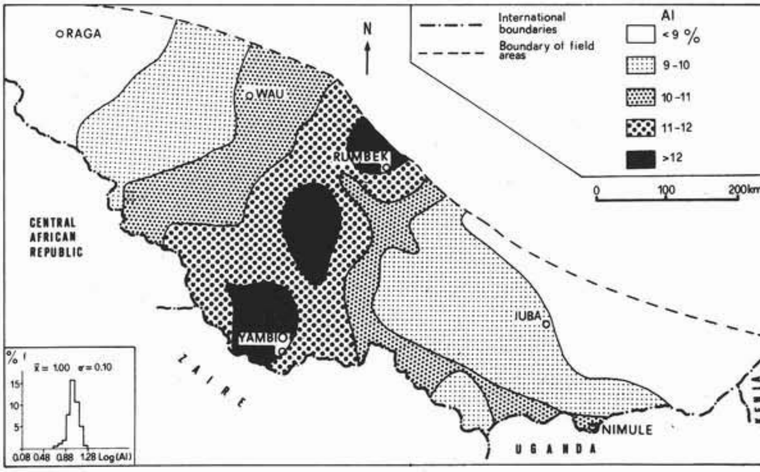

Fig. 5. — Aluminium regional distribution (%) map of residual soils.

was employed in this study. This technique has been used by different authors in similar studies in Africa (GARRET and NICHOL et al., 1969; ARMOUR-BROWN and NICHOL, 1970). « The moving averages are computed by moving a search area across the data. The mean contents of a variable are computed for samples contained within the search area at various point as the search area moves progressively over the entire region of the survey » (HARBAUGH and MERRIAM, 1968).

In the area under investigation the sample density was not always constant;

TABLE 2

Factor models derived from the R-mode factor analysis

FACTOR MODEL	EIGEN VALUES %	1 +	1 −	2 +	2 −	3 +	3 −	4 +	4 −	5 +	5 −	6 +	6 −	7 +	7 −	8 +	8 −	9 +	9 −	10 +	10 −
1	32.67																				
2	51.39	Fe Mn Zn Pb Cu Al Mo Sn			Nb Mo Ti Sn Al Zn Fe																
3	63.60	Zn Mn Pb Fe Al Cu		Nb Ti Zn Al Mo	Cu		Sn Mo Fe Al														
4	74.45	Cu Zn Al Fe Mn Sn	Nb Mo	Ti Nb Zn Al			Sn Mo Fe Al		Pb Mn Zn Fe Al Mo												
5	81.62	Cu Al Zn	Mo Nb	Ti Nb Al Zn			Sn Mo Fe Al		Pb Al Zn Fe	Mn Zn Fe Mo Cu											
6	87.62	Al Zn Fe Sn Ti		Nb Ti Mo Zn			Mo Sn Fe Al		Pb Fe	Mn Zn Fe		Cu									
7	91.93	Al Zn Fe		Nb Mo Ti			Sn Fe Mo Al	Sn	Pb Fe	Mn Zn Fe Mo		Cu		Ti Nb							
8	95.45	Al Sn Fe		Nb Ti Mo Al	Fe		Mo Fe Sn	Sn	Pb Fe Al	Mn Fe Zn		Cu Fe		Ti Nb		Zn Al Fe Mn					
9	98.35	Al Fe Zn		Nb Mo Ti	Fe		Mo Fe Sn		Pb Fe	Mo Fe Zn		Cu Fe		Ti Nb		Zn Al Mn Fe		Sn Fe Mo			
10	100	Al Zn Fe		Nb Ti Mo			Sn Fe				Pb	Mn Fe Zn		Cu		Ti Nb		Zn Al Mn Fe		Fe	

KEY

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however, the average density was 1 sample per 300-350 sq./km. A search area of 10,000 sq./km (100 × 100 km) was employed with an overlap of 50 %. This resulted in an average of 20-25 samples per search area and each sample was computed four times for the calculation of the average value to be fixed in the centre of the search area. For every search area the mean, the variance and the standard deviation of the log-transformed data were computed.

Computer program used for the moving average analysis was written by De Vivo, Lima and Marigliano (1980).

To portray the distinctive metal associations occurring in the area a R-mode factor analysis has been carried out. This technique is extensively described in published texts (Rummel, 1970; Davis, 1973) and it has been throughly used by different authors in geochemical surveies (Armour-Brown and Nichol, 1970; Closs and Nichol, 1975; Nichol et al., 1969; Häkli, 1970; Saager and Sinclair, 1974; Tripathi, 1979). It can be seen that most of the works with factor analysis has been carried out on stream sediments, whereas little use, up to now, has been made on soil geochemical data.

Table 3

Communalities and eigenvalues for the R-mode factor analysis

Factor model	Elements										Eigen-values %
	Al	Nb	Pb	Sn	Mo	Cu	Zn	Ti	Mn	Fe	
1											32.67
2	56.4	65.5	35.0	40.0	45.7	33.2	54.0	60.2	48.9	75.2	51.39
3	58.5	75.3	49.3	82.0	57.8	35.1	71.3	68.4	52.8	85.5	63.60
4	64.4	76.9	74.4	83.4	83.2	70.3	75.9	75.4	54.0	86.7	74.45
5	84.4	77.3	86.5	84.7	85.4	71.4	76.1	75.8	87.7	86.9	81.62
6	87.2	87.2	91.7	85.9	90.1	99.8	79.3	75.9	91.6	87.4	87.62
7	88.1	92.8	96.8	86.6	91.1	99.8	86.0	97.5	92.7	87.9	91.93
8	92.1	97.0	97.1	89.4	94.3	99.9	94.8	99.8	99.8	90.2	95.45
9	99.0	97.4	99.9	99.8	96.5	99.9	99.8	100.0	99.9	91.5	98.35
10	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.00

Metal associations have been obtained using varimax criterion (Kaiser, 1958).

Computer programs used in this investigation were from the Gas package by Willington (1973).

The factor analysis (Armour-Brown and Nichol, 1970) is a sophisticated method by means of which the interrelations existing between different variables can be established on the basis of their correlation coefficients, that allow to express the interrelations in terms of characteristics metal associations.

Among the different solution arising from this type of analysis (Tab. 2-3) the proper factor model, and therefore the metal associations portrayed in it, is selected in function of the geology and of the surficial environment characterizing the study area.

Plotting on maps the factor scores of each metal associations for each sample, it is possible, then, to determine the strenght of that association for each specific sample site. In this way the geochemical parameters related to the main geological processes characterizing the study area can be isolated with respect to the total variability of the data (Closs and Nichol, 1975).

Results and discussion of results

In the studied area no mineralizations have been reported. The anomalous values resulting from this study may therefore be related either to not yet known mineralizations, or to a variation of the geological features or to changes in the secondary environment.

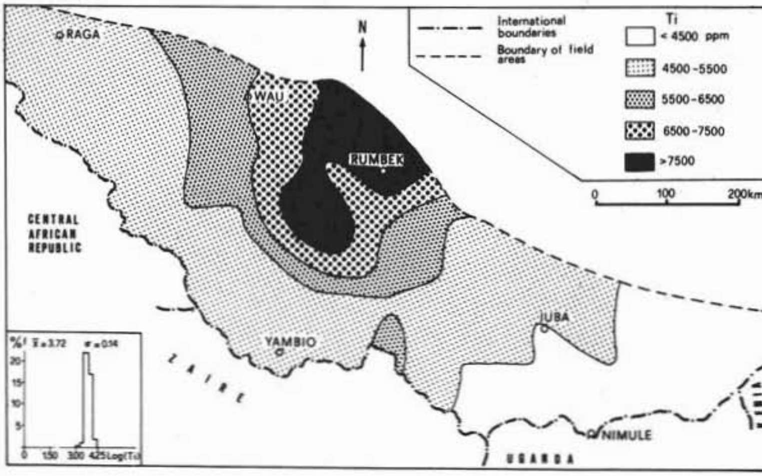

Fig. 6.—Titanium regional distribution (p.p.m.) map of residual soils.

The reason for the anomalies can be established with a fallow-up survey in the specific target areas resulting from this study.

The examination of the element distributions of the residual soils shows the presence of significant variations in the background concentrations. In certain cases different elements show the same variation and distribution in the background concentration, indicating the existence of metal associations. Differences in the distribution of the elements are indicated in the other cases. Noteworthy are the anomalies shown by: the Nb (> 50 p.p.m.) north of Juba and around Rumbek; the Mo (> 17 p.p.m.) around Juba; the Ti (> 10,000 p.p.m.) around Rumbek, Juba and particularly at the border with Uganda; the Pb (> 114 p.p.m.) in the western sector and particularly between Amadi and Rumbek; the Zn (> 87 p.p.m.) east of the white Nile.

Moving Average Analysis

The most distinctive elemental distribution of the regional trends resulting from the moving average analysis are here discussed and illustrated. The istograms showing the approximate normal distribution of the log-transformed data are given below the maps (figs. 5-11).

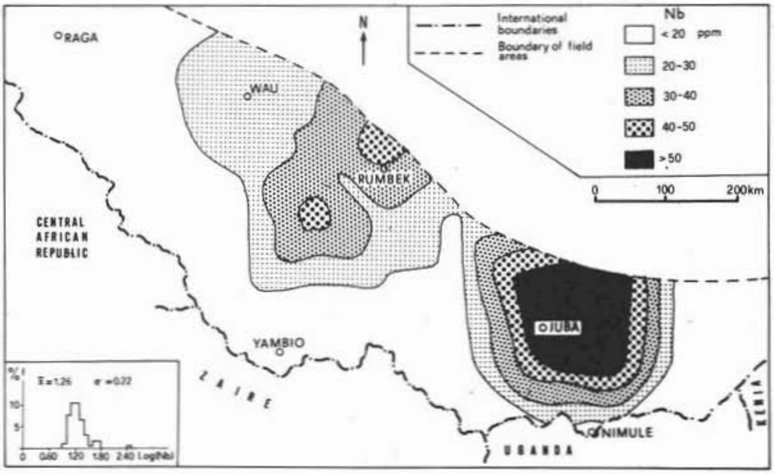

Fig. 7. — Niobium regional distribution (p.p.m.) map of residual soils.

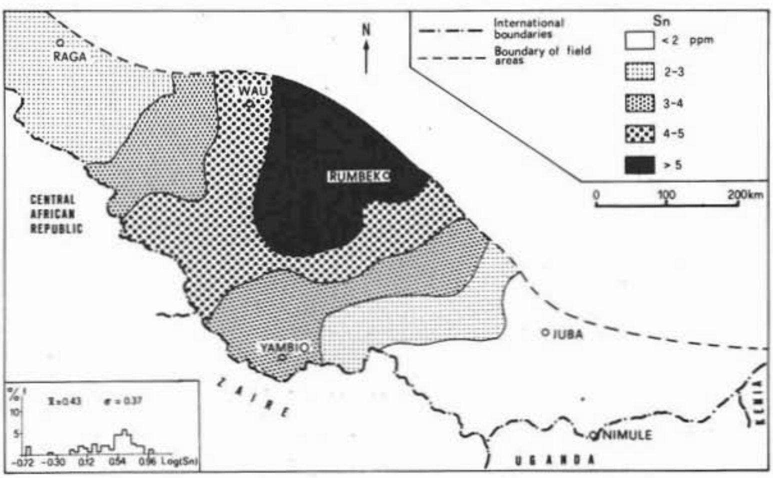

Fig. 8. — Tin regional distribution (p.p.m.) map of residual soils.

The location of each high-low pattern and its relationships to known geological features, bedrock and/or surficial environment, when possible, is discussed.

The principal results may be summarized as follows:

Aluminium (fig. 5) shows three regional highs, northeast-southwest oriented on the Yambio-Tonj-Rumbek alignment. These highs correspond to areas where the lateritic cover is thicker and more extensive.

The titanium regional distribution (fig. 6) shows one high around Rumbek. This high coincides with two highs of the aluminium.

The niobium regional distribution (fig. 7) shows one distinct high in the area around Juba and a relative one in the Rumbek area coinciding with the titanium regional high. The high niobium concentrations may be related to the nepheline-syenite bodies outcropping in this area.

The tin distribution (fig. 8) give one high in the Rumbek area as for titanium and aluminium.

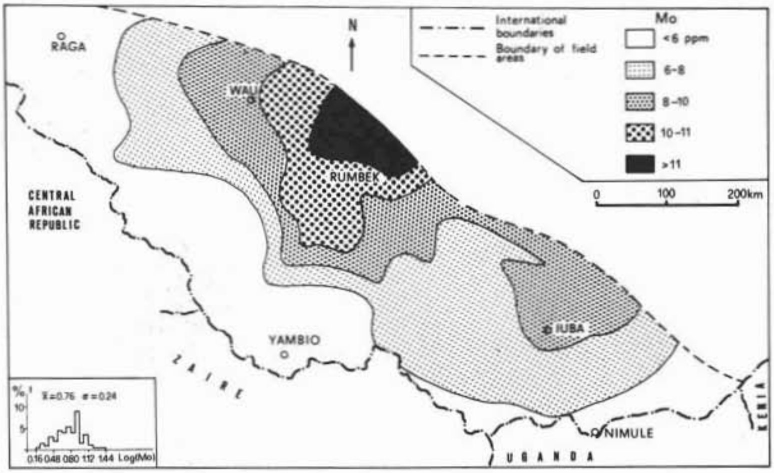

Fig. 9. — Molybdenum regional distribution (p.p.m.) map of residual soils.

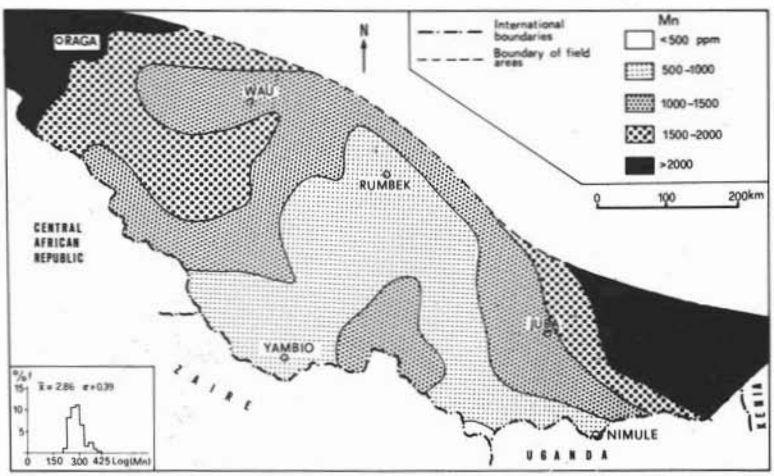

Fig. 10. — Manganese regional distribution (p.p.m.) map of residual soils.

The molybdenum regional distribution (fig. 9) shows an high on the Tonj-Rumbek area and a relative high in the Juba area coinciding with the niobium highest concentrations. As for niobium these highs may be related either to the nepheline-syenites or to alkali-granites outcropping in the area.

The manganese (fig. 10) and the zinc (fig. 11) regional distributions show high concentrations in the eastern sector, whereas a different distribution is shown in the western sector. In fact the manganese indicates high values in the Raga area and the zinc in the Wau area. The high concentrations in the eastern sector should be related either to the basic dykes (dolerite, gabbro) or to the volcanics there extensively occurring. The high concentrations in the western sector as well as the high values for copper, lead, and iron are related to the lateritic cover.

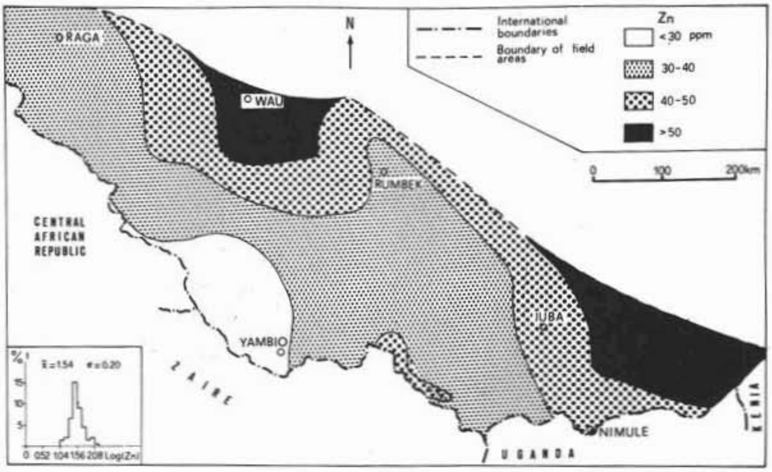

Fig. 11. — Zinc regional distribution (p.p.m.) map of residual soils.

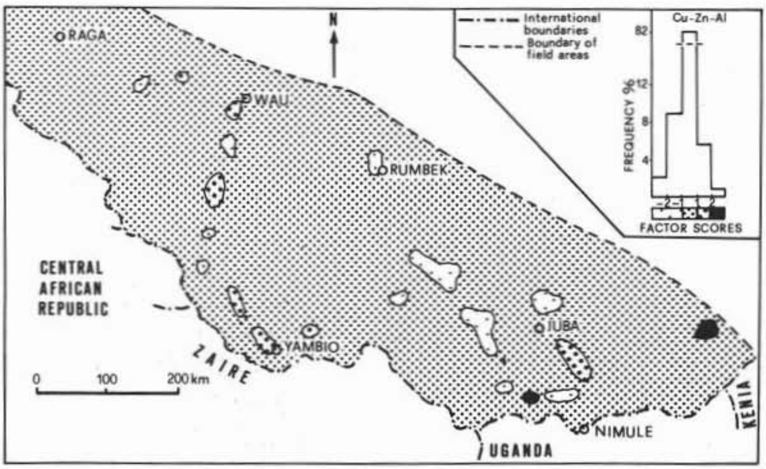

Fig. 12. — Distribution of Cu-Zn-Al association factor scores.

R-Mode Factor Analysis

The metal associations already qualitatively established by means of single element distribution can be defined through the determination of interelement correlation coefficients (Tab. 4). In fact it can be seen that correlations exist for example between niobium and titanium; aluminium, zinc and iron; tin, molybdenum and iron, whereas poor correlations exist between other elements as for niobium with tin, molybdenum with zinc and titanium. Negative poor correlations are also evidenced as for niobium with iron, copper and lead, for copper with molybdenum and titanium.

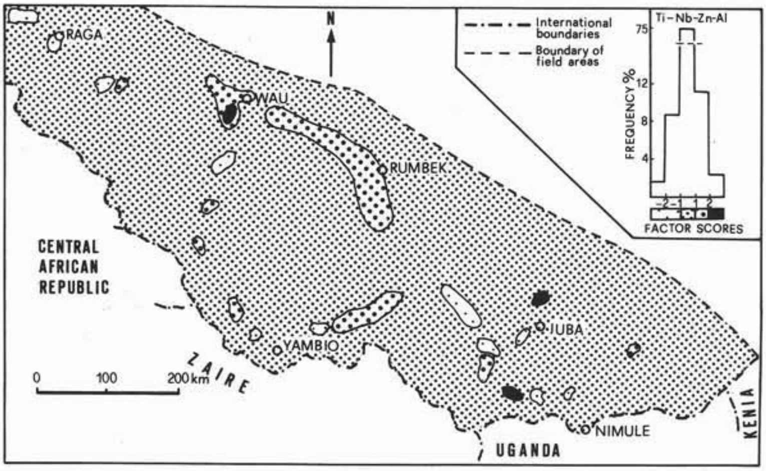

Fig. 13. — Distribution of Ti-Nb-Zn-Al association factor scores.

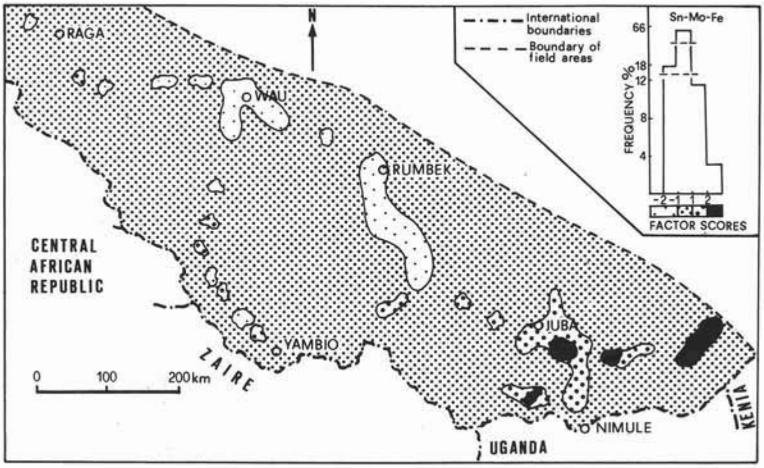

Fig. 14. — Distribution of Sn-Mo-Fe association factor scores.

The series of models generated by means of R-mode factor analysis are shown in tab. 2.

The similar distribution of titanium and niobium, of copper and zinc and of molybdenum and tin resulting from the moving average analyses indicate the existence of metal associations related to the geological and/or surficial processes.

Elements with loading in the range 0.4-1.0 are considered significant members of a particular association. The four factors model accounting for 74.45 % of the data variability was chosen as the most meaningful solution. In fact the element association appearing in this model can be considered related either to the geological phenomena (e.g. Cu-Zn-Al related to mafic dykes; Ti-Nb-Zn-Al related to nepheline-syenites) or to the secondary environment of the studied area (e.g. Pb-Mn-Zn-Fe to lateritization processes). The element associations distributions resulting from the four factors model are shown on the relative maps (figs. 12-15). On these maps is also drawn a frequency histogram of the factor scores characterizing each association.

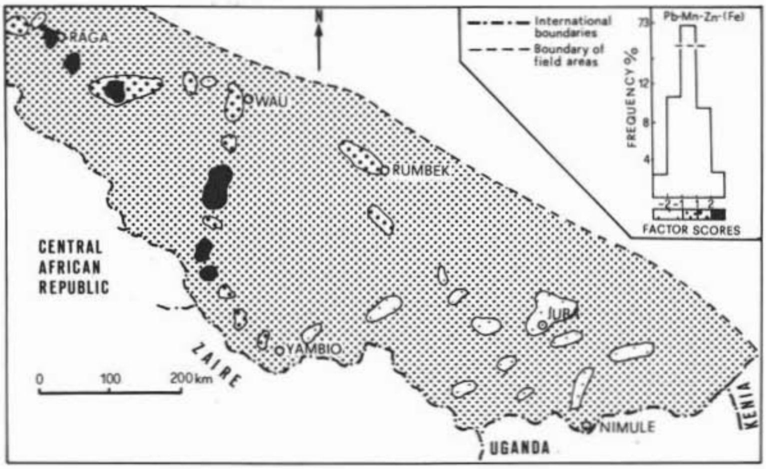

Fig. 15. — Distribution of Pb-Mn-Zn-Fe association factor scores.

Copper-Zinc-Aluminium

The Cu-Zn-Al association (fig. 12) accounts for 43.89 % of the data variability (tab. 5) with loadings of 0.8, 0.4 and 0.4 for Cu, Zn and Al respectively.

The distribution of high factor scores of this association is concentrated in the eastern part of the area where basic dykes and volcanics outcrop.

Titanium-Niobium-Zinc-Aluminium

This association (fig. 13) accounts for 25.13 % of the data variability (tab. 5) with strong loadings of 0.8 for Ti and Nb and weaker loadings of 0.5 for Zn and Al. This trace element suite is thought to be related to nepheline-syenite bodies outcropping in the eastern area and particularly north of Juba.

The high values present in the Rumbek and Wau area cannot be, at this stage, related to any known geological features because of the thick lateritic cover. Considering the extensive outcrops of alkaline rocks in Southern Sudan, they may indicate in these areas the presence of such rock types under the lateritic cover.

Tin-Molybdenum-Iron

This assemblage (fig. 14), representing 16.41 % of the data variability (tab. 5), is a strong association with loadings of 0.8 for Sn and Mo and 0.7 for Fe. Also the high values of this association must be related to the extensive alkali-granite and nepheline-syenite bodies. Noteworthy is the fact that this association in some areas (i.e. Wau and Rumbek) has an anthipathetic behaviour compared to the Ti-Nb-Zn-Al association.

TABLE 4

Correlation matrix

	Al	Nb	Pb	Sn	Mo	Cu	Zn	Ti	Mn	Fe
Al										
Nb	⊙									
Pb	⊙	–								
Sn	⊙	○	–							
Mo	⊙	◉	○	◉						
Cu	○	–	○	○	–					
Zn	●	⊙	⊙	○	○	⊙				
Ti	⊙	●	–	⊙	○	–	⊙			
Mn	⊙	○	⊙	○	⊙	⊙	◉	○		
Fe	●	–	⊙	◉	●	⊙	◉	○	●	

● >0.5
◉ 0.4-0.5
⊙ 0.2-0.4
○ 0.0-0.2
— Negatively correlated

TABLE 5

Positive eigenvalues for the ten and four factor models

Factor number	Percent Eigenvalues			
	factor model 10		factor model 4	
1	32.67	32.67	43.89	43.89
2	51.39	18.71	69.02	25.13
3	63.60	12.21	85.43	16.41
4	74.45	10.85	100.00	14.57
5	81.62	7.18		
6	87.62	6.00		
7	91.93	4.31		
8	95.43	3.50		
9	98.35	2.93		
10	100.00	1.65		

Lead-Manganese-Zinc-Iron

This association (fig. 15), with loadings of 0.8, 0.6, 0.5 and 0.4 for Pb, Zn and Fe respectively, accounts for 14.57 % of the data variability.

High levels of this association occur only on the western sector of the investigated area, where a thick and widespread lateritic cover outcrops. In particular the scavenging effect of Mn and subordinately of Fe oxides should have played a decisive role in the determination of this association (CHAO and THEOBALD, 1976). In fact in the samples the concentrations of the other elements, and particularly that one of the Pb, increase with increasing concentrations of Mn and Fe oxides. This is also confirmed by the fact that the high levels of this associations are similar to the features portrayed by the single elements distribution noted in the moving average analysis of Pb, Zn, Mn, Fe and Cu.

Conclusions

The minor elements distribution and their associations, resulting from a geochemical reconnaissance survey on the residual soils of the Southern Sudan, have been interpreted in the light either of the geological features or of the secondary surface phenomena related to lateritization processes.

The distribution of the minor elements resulting from the moving average analysis and particularly the use of the R-mode factor analysis has led to a notable simplification of the data because it has been possible to identify the metal associations of the dominant features contributing to the residual soils composition. Consequently it has been possible to describe the distribution of 10 minor elements in terms of four metal associations representative of different bedrocks and secondary environment.

In addition, because different rock-types are characterized by distinctive geochemical associations, the use of factor analysis can give a notable support in interpreting the geology of areas where outcrops are scarse, as it the case of most of the surveyed area.

The principal results can be summarized as follow:

a) the metal association Sn-Mo-Fe is related to the alkali-granites or to the nepheline-syenite bodies extensively outcropping in the eastern sector;

b) the metal association Ti-Nb-Zn-Al showing similarity with the distribution of the regional trends of Ti, Nb and Al, is clearly related to the nepheline-syenites outcropping north-northwest of Juba. In the areas of Rumbek and Wau. similar rock types can be hypotized to exist under the thick lateritic cover, according to the metal associations there portrayed;

c) the metal association Cu-Zn-Al, showing some similarities with the Zn and Mn distribution, is very probable related to the basic rocks (dykes, greenstones) and/or to the volcanics outcropping east of the Nimule Belt;

d) the metal association Pb-Mn-Zn-Fe shows high levels only in the north-western part of the studied area. They are to be related to the thick and extensive lateritic cover there occurring.

On the basis of the above stated relationships between metal associations and geological features, bedrocks and/or surficial, *a*), *b*) and *c*) have been identified as target areas for their mineral potential.

It is well known that all over Africa tin deposits are associated with rocks (« younger granites »; OLADE, 1980) comparable to the ones occurring in the target area *a*). Particularly special attention has been paied to the search of primary source of tin, as lode mineralizations and low grade disseminated ore bodies in this type of rocks? (TAYLOR, 1969; SAINSBURY and HAMILTON, 1967). In other parts of Sudan itself tin, molybdenum and wolfram mineralizations connected with alkali-granites are reported (WHITEMAN, 1971).

The target area *b*) is characterized by the presence of nepheline-syenites as a product of an alkaline magnetism.

It is well known that with such a type of magmatism syngenetic and residual ore deposits of Nb, Mo, P, Rare Earths, U + Th, base metal sulphides and aluminium are associated (DEANS, 1966).

This is consistent with the anomalies found in this area.

In East Africa such a metal association has been found in connection with carbonatite complexes to which undersaturated alkaline igneous rocks are associated (Deans, 1966; Bloomfield et al., 1971; Reedman, 1974).

The metal association similarity and the presence of an alkaline magmatism both in the surveyed area and in East Africa could suggest that the Southern Sudanese nepheline-syenites belong to a carbonatite complex. In addition, the data of a radiometric survey, carried out in Southern Sudan by the same authors, show the existence of a radiometric anomaly in the areas where nepheline-syenites outcrop (Civetta et al., 1980).

The target area *c*), characterized by mafic rocks and volcanics, is interesting because the Cu-Zn-Al association identified could be related to the existence of sulphide mineralizations. In fact sulphide ore deposits have now been found on most of the continents in connection with mafic intrusions (Sudbury, Canada; Great dyke, Zimbabwe; etc.).

The area *d*) has not been considered as a target because the metal associations identified, clearly related to the widespread lateritic cover are too sparse and cannot be, at this stage, related to any definite geological feature or bedrock.

Among the three target areas individuated, following the above stated considerations, a priority for a follow-up survey has been suggested for the areas in which nepheline-syenites and alkali-granites occur, because its mineral potential seems to be very high. This in consideration of the fact that its mineral association and its geological features show close similarities with well known mineralized adjacent areas in East Africa (Uganda, Tanzania, Kenya and Zambia).

Acknowledgements. — The authors thank the Ministry of Industry, the Geological Survey of Southern Sudan, Dr. P. Eyobo and his staff for the useful and friendly collaboration given during the field work.

The authors also wish to thank deeply Dr. L. G. Closs (Colorado School of Mines) for critically reading the manuscript and for his helpful suggestions; and Mrs. Krystyna Urbaniak for the English review of the manuscript.

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