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Geological interpretation of Eastern Cuba Laterites from an airborne magnetic and radioactive isotope survey

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Resumen

Se han utilizado varias técnicas geofísicas en la región oriental de Cuba para distinguir las principales características geológicas de las lateritas, que poseen importancia económica para la extracción de hierro, níquel y cobalto. Las mediciones geofísicas incluyen un estudio aeromagnético y mediciones de isótopos de torio (eTh), potasio (K) y uranio (eU). Los resultados de las mediciones espectrométricas establecen diferencias entre los yacimientos de lateritas. De la aplicación del método magnético e isotópico se determinó la distribución y desarrollo de las cortezas lateríticas, así como la ubicación de alteraciones hidrotermales que afectan a las lateritas, lo cual es muy útil durante la exploración y explotación minera. Esas alteraciones indican la presencia de silicatos, que tienen un efecto negativo en el proceso metalúrgico. Se conoce que las cortezas lateríticas tienen altos contenidos de eU y eTh. De los contenidos de eU y eTh se infiere que las lateritas de la región de Moa se formaron antes que las de Mayarí. De estas mediciones fue posible inferir el origen, espesor y edad de las cortezas lateríticas.

Palabras clave: Cortezas lateríticas, exploración de torio y uranio, Cuba.

Abstract

In eastern Cuba area several geophysical techniques have been applied to distinguish the main geological characteristics of the laterites which are of economical importance for the extraction of iron, nickel and chrome. The geophysical measurements include an aeromagnetic survey and thorium (eTh), potassium (K) and uranium (eU) isotope measurements. The results of gamma spectrometer measurements make a distinction between laterite reservoirs. The application of the magnetic and isotope methods allowed the determination of the distribution and development of the laterite crust, as well as the determination of hydrothermal alterations affecting the laterites, which is very useful for mining exploration and exploitation. Such alterations indicate the presence of silicates, which have negative effects on the metallurgic process. It is known that laterite crust has a high content of eU and eTh. From the content of the isotope abundance (eU and eTh) it was possible to infer that Moa laterites were formed before the Mayari Region. From the measurements it was also possible to infer the origin, thickness and age of the lateritic crust.

Key words: Lateritic crust, thorium and uranium exploration, Cuba.

Introduction

In Cuba, one of the largest reserves of exploitable laterites with high content of iron (Fe), nickel (Ni) and cobalt (Co) is located in the eastern region (Fig. 1). The research done in these deposits hase been useful to solve problems such as: horizontal limit determination of the laterite crust, genesis, kind of crust (*in situ* or redeposit) and differentiation of the lateritic column (complete or incomplete; Lavaut, 1998).

Earlier laterite exploration was not very successful because of the lack of resolution of previous geophysical methods and the instruments used.

The purpose of this work is to show that the present magnetic and radioactive airborne exploration can locate and characterize in Cuba several laterite deposits with high content of Fe, Ni, Co.

Geological setting

In the region, outcrops are mainly ophiolitic rocks (Fig. 1) belonging to the Mayari-Baracoa belt (Iturralde-Vinent, 1996). Main outcrops are Mayari-Cristal and Moa-Baracoa massifs (Proenza *et al.*, 1999a). These ophiolites are a mixture of serpentinized ultrabasic rocks, constituted mainly by harzburgites, dunites, lherzolites and pyroxenites, overlain by a thick weathered crust that generates lateritic deposits rich in Fe, Ni and Co. Basic rocks are represented by gabbro-olivines, gabbro-norites, anorthosites and plain gabbros (Ríos and Cobiella, 1984). Volcanic arc sequences from Cretaceous and Paleogene as well as sedimentary rocks are less abundant (Cobiella, 2000; Iturralde-Vinent, 1996; Proenza *et al.*, 1999b).

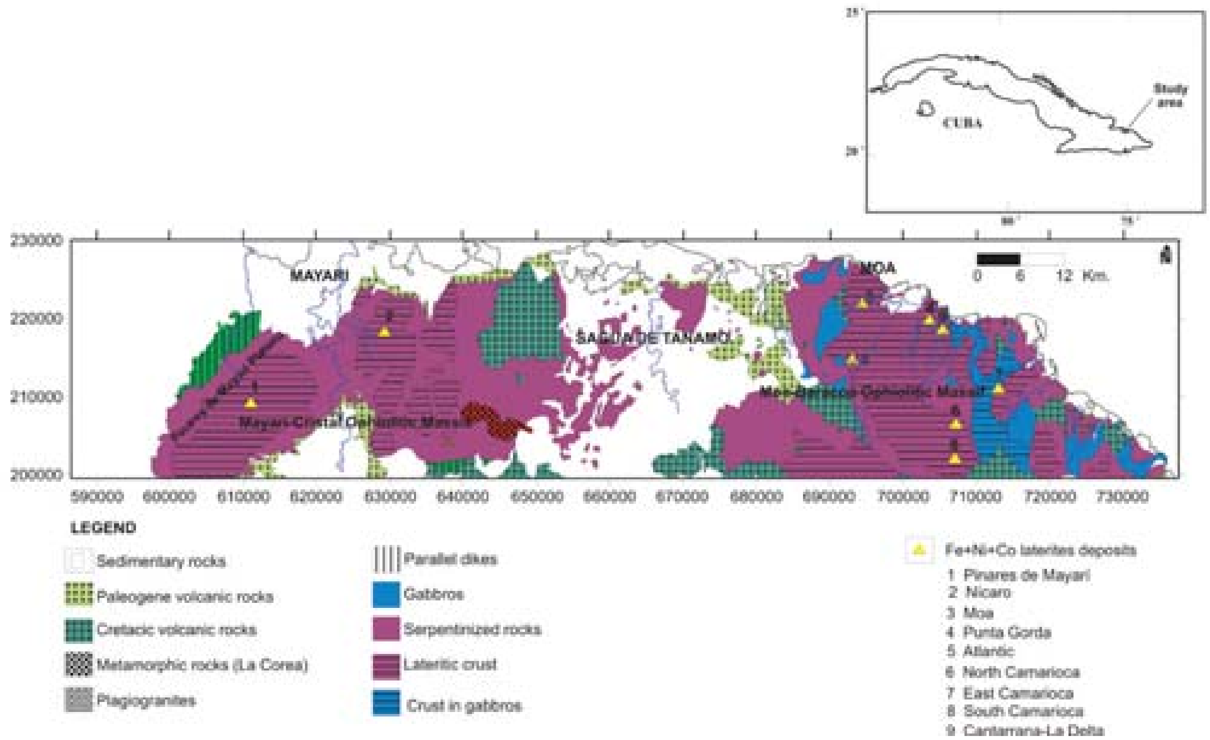

Fig. 1. Geologic scheme of the north-eastern region of Cuba (modified from Albear *et al*., 1988).

The lithology of the weathered lateritic crust in eastern Cuba is well defined by their vertical zonation. The lithology along a profile over the weathered area is constituted by six lithotypes (Table 1): two are non-structural and shallow and four are inner structural that form the central and lower part of the weathered crust. Below these layers is the non-weathered rock (Lavaut, 1998).

Airborne data

Aerogamma spectrometric and aeromagnetic data were collected by Chang *et al*. (1991), with N-S flight lines, with 500 m of spacing with an average flight altitude of 70 m over the topographic surface. The aerogamma spectrometric measured total radioactivity intensity (Iγ), and narrow window frequencies for K, eU and eTh isotope decay, while the aeromagnetometer measured the rotational invariant amplitude of the zero frequency magnetic field (ΔT).

Method description

In earth sciences we deal with many variables or sets of data. Most of the time the geological information contained in a single set of data is redundant and a linear relation between the data may exist (Alfonso-Roche, 1989). Thanks to multivariable statistics it is possible to transform one set of original data to another set where variables will be independent or orthogonal between them. The new variables will not be redundant and may be reduced from p (original variables) to q (new variables), where q≤p. The transformation has the following form:

$$Y_i = \sum_{j=1}^{p} a_{ij}\, x_j;\ i = 1; 2; \ldots q \qquad (1)$$

where
Yi: new variables
$\{a_{ij}\}$: coefficient matrix to get the new variables
x_j: original data or variables.

Correlation matrices were used in this study in order to measure the linear dependence between the original data sets. It was considered linear when the correlation coefficient was around α<0.05. The relationships between them and the kind of distribution of the measured parameters, were verified by means of the Kolmogorov-Smirnov test, with a α<0.01 (Marrison, 1967; Alfonso-Roche, 1989; Bluman, 1992; Hamed, 1995).

Factor analysis (FA) which comes from multivariate statistics (MS) was also used; its purpose is to find the

Table 1

Weathering crust Lithology of the ultramafic rock in eastern Cuba (taken from Lavaut, 1998).

Genetic lithologic zone	Cuban lithologic types	French lexicon	Types of weathering profiles
Dehydration zone of hydroxides iron	In-structurals ochres with ferruginous concretions	Ferricrete	Goethitic-hematitic-gibbsitic in-structurals
Complete ochretization zone	In-structurals ochres without ferruginous concretions	Limonite = Red earth	Goethitic-gibbsitic in-structural
Complete ochretization zone	End structurals ochres	Fine Limonite=Saprolite	Structural incomplete goethitic-gibbsitic
Partial ochretization zone	Initial structural ochres	Half saprolite	Structural complete goethitic-serpentinític
Lixiviation zone and initial ochretization	Leached host rock and lightly with ochres	Thick saprolite	Structural incomplete serpentinític-clay
Cracking zone	Cracking host rock with hipergenic philoniane and massive mineralization zone	Host rock	Structural incomplete serpentinític--querolític

principal components. The goal is to transform the original data to a new domain where variables are independent. This transformation is done by linear combination of the original (Alfonso-Roche, 1989).

New variables are not correlated but also can be sorted with decreasing variance. This method is used to decrease the number of observed variables without losing information contained in the data. In FA it is assumed that in the original variables only q common factors work. The p-q factors are named non-common or singular and it is assumed that these do not influence the new variables. This can be expressed as:

$$x_i' = \sum_{j=1}^{q} a_{ij} f_j + b_i e_i \qquad (2)$$

where

$\sum_{j=1}^{q} a_{ij} f_{ji}$ represents the influence of the q common factors over the new variable.

$b_i e_i$: is the random influence of the p-q singular factors over x_i'. b_i is constant and e_i a random variable with zero average and non-correlated with the q common factors.

Such factors can be used to reveal non evident features within the observed data. They are also used to decrease the number of variables and to characterize those that are similar. This is useful for geologic mapping (Marrison, 1967; Alfonso-Roche, 1989; Reimann *et al*., 2002). FA method was used over all the sets of data (I, eU, eTh, K and ΔT) and the ratios (eU/K and eTh/K).

The correlation matrix between the original sets of data reveals a high correspondence, indicating that they carry similar information. The factor analysis shows a good applicability because it shows non evident geological features. In this study we refer to K factors as those obtained from the original K data and the ratios (eU/K and eTh/K); the same procedure is true for the other isotopes.

Factors eU and eTh are very sensitive to changes in the clay content of the rocks, considering that those chemical elements are common in clays (Galbraith and Saunders, 1983). Same factors can also be used to limit lateritic crusts and determine their lateral variation thickness (Batista *et al*., 2002a).

Factors eTh and eTh/K are very sensitive to rock weathering (Galbraith and Saunders, 1983; Portnov, 1987; Braun *et al*., 1993) and clay content (Portnov, 1987). Factors K, eU/K and eTh/K are susceptible to hydrothermal alterations (Portnov, 1987).

Results

The northeast area of the study region is of particular interest because of the development of lateritic crust. Batista and Rodríguez-Infante (2000) and Batista *et al*. (2002b) performed a qualitative interpretation of the aeromagnetic data, correlating the anomalies with the presence of serpentinized ultrabasic rocks on surface and making suggestions about their depths. They also suggested some faults and correlated the negative magnetic anomalies with hydrothermal alterations as seen in Fig. 2 and 3.

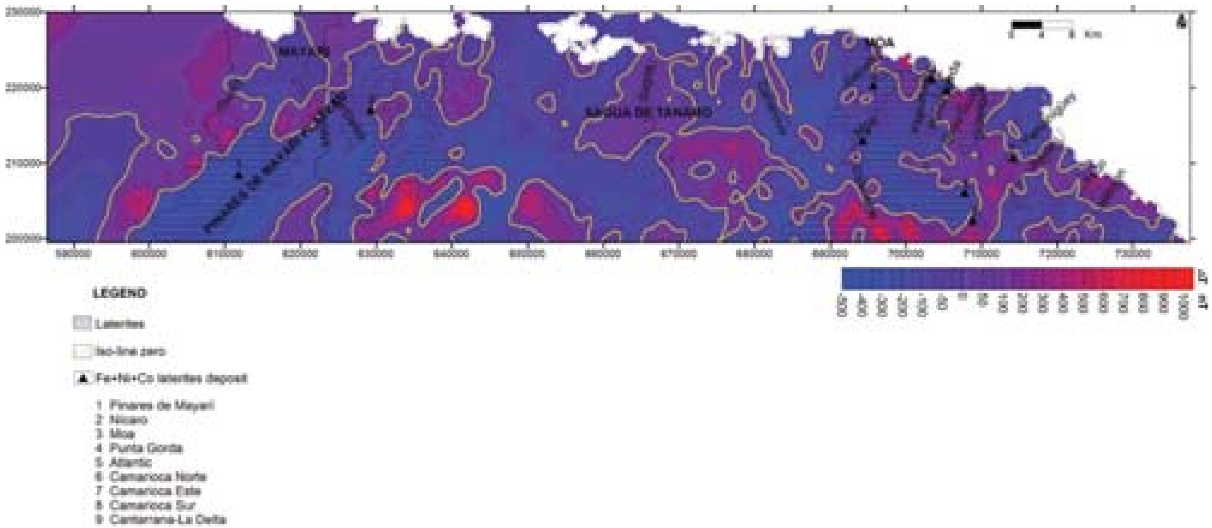

Fig. 2. Map of ΔT reduced to the pole of the Mayarí-Sagua-Moa region (modified from Batista *et al*., 2002).

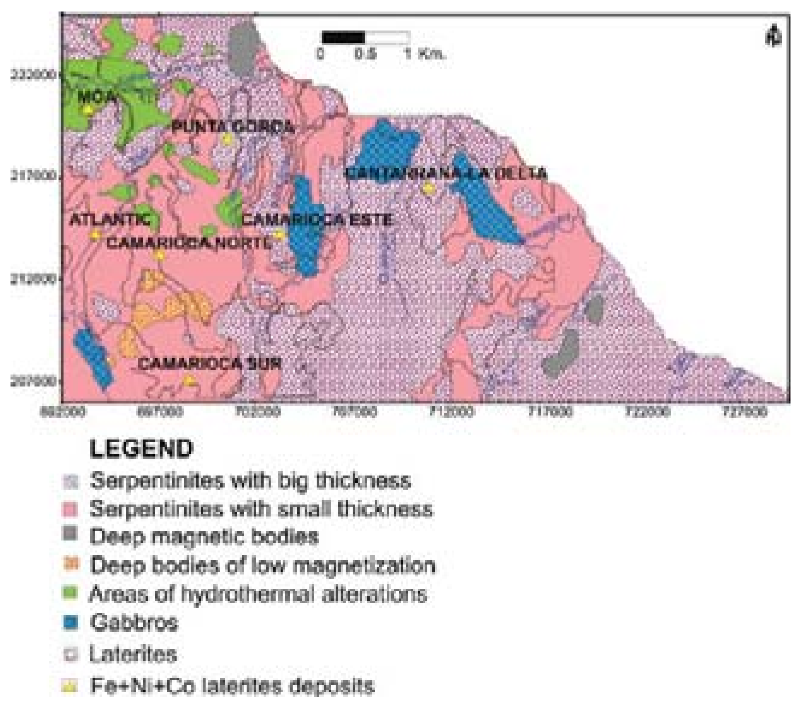

Fig. 3. Geology inferred from aeromagnetic interpretation of the Moa region (modified from Batista and Rodríguez, 2000).

These negative magnetic anomalies are also associated with lateritic deposits, perhaps because of hydrothermal alteration at the same place. This is of economic importance for the extraction of Ni and Co sulfurs (Rojas and Beyris, 1994). Some negative anomalies can also be associated with the presence of sedimentary rocks or a thinning of the serpentinized ultrabasic bodies (Karlsen and Olesen, 1996).

Batista *et al*. (2002a) observed that in NE region of Cuba, the mafic and ultramafic rocks with poor development of a lateritic crust are characterized by low radioactivity values (Fig. 4, 5 and 6; Table 2). Galbraith and Saunders (1983) have observed a similar behavior in other regions. However, areas with considerable development of lateritic crust (rich in Fe-Ni-Co) register high contents in eU and eTh.

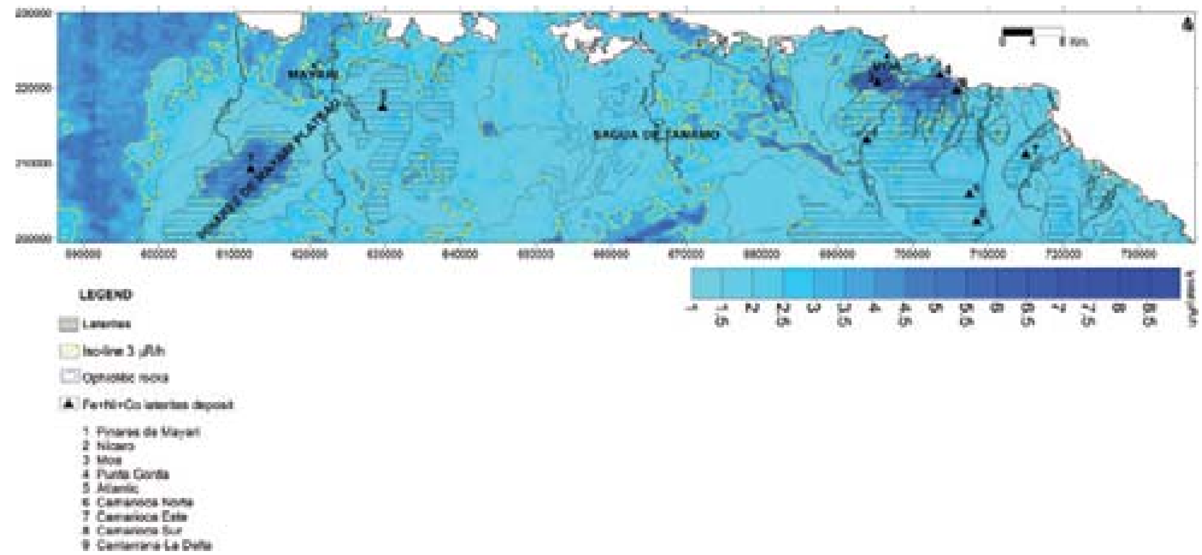

Fig. 4. Map of airborne radiometric (Iγtotal) of the Mayarí-Sagua-Moa region (modified from Batista *et al*., 2002).

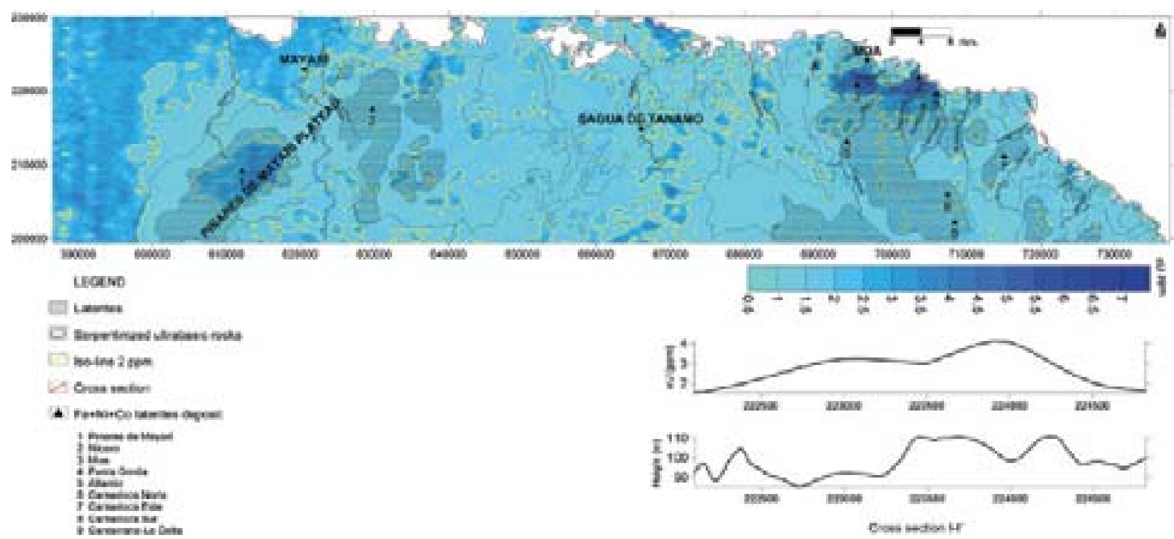

Fig. 5. Map of eU content of the Mayarí-Sagua-Moa region (modified from Batista *et al*., 2002).

Table 2

Radiometric medium value of the rocks type main of the north-eastern region of Cuba.

Rocks type	eU (ppm)	eTh (ppm)	K (%)	It (μR/h)
Sedimentary rocks	2.04	2.69	0.5	2.86
Volcanic rocks	1.77	1.63	0.6	2.53
Gabbros	1.43	1.7	0.35	1.97
Serpentinized ultrabasic rocks	1.66	2.34	0.35	2.29
Laterites crust	1.87	3.39	0.35	2.72

The higher contents in eU and eTh are located over the Moa, Punta Gorda and Pinares de Mayarí laterite deposits. However a considerable difference in eU and eTh is registered between Moa and Mayari. In other regions of the world, Galbraith and Saunders, 1983; Kögler *et al*., 1987; Portnov, 1987; Braun *et al*., 1993; Casas *et al*., 1998; Vogel *et al*., 1999, gave some idea about the genesis, formation time and the maturity grade of the lateritic crust, according to contents of eU and eTh. A thorough explanation of the high values over those weathered crusts is in Batista et al. (2002a). According to those ideas we indicate that the larger eTh contents in the laterític Moa crust suggests that formation time is longer than the laterític Mayari crust, because eTh content increases with weathering and rock aging.

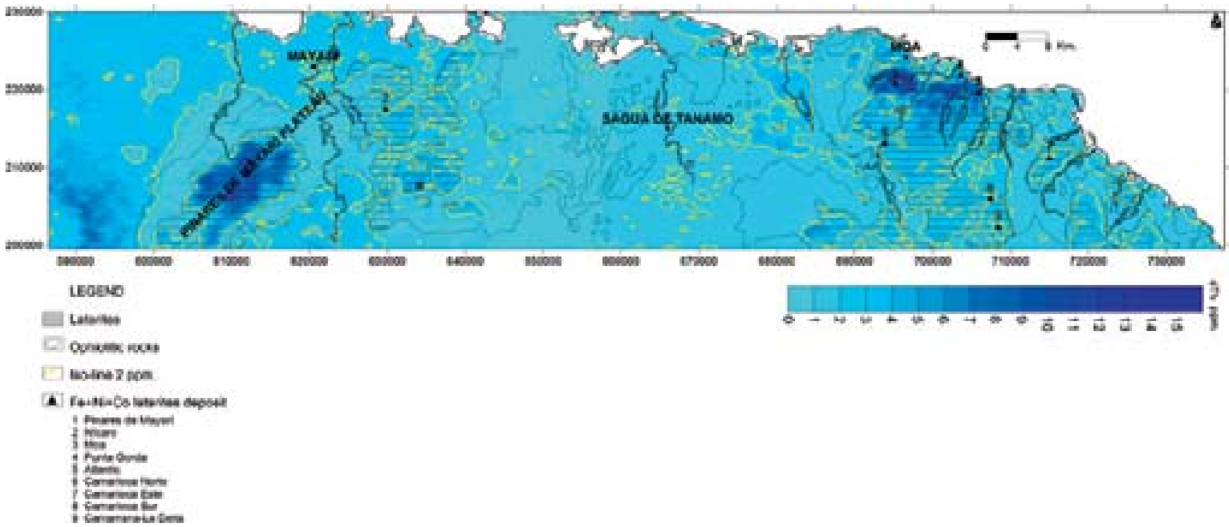

Fig. 6. Map of eTh content of the Mayarí-Sagua-Moa region (modified from Batista *et al*., 2002).

We have observed that most of these laterite deposits register values that range from 3 μR/h in total gamma ray (Fig. 4), 2 ppm in eU and eTh (Fig. 5 and 6), $1x10^{-3}$ in the ratio eTh/K (Fig. 7) and $5x10^{-4}$ in eU/K ratio (Fig. 8). With these values it was possible to find laterite zones not previously reported.

There is a direct correlation between eU and eTh content due to the long decay of uranium and thorium isotopes, suggesting thicker and redeposited laterites (Galbraith and Saunders, 1983; Kögler *et al*., 1987; Casas *et al*., 1998; Vogel *et al*., 1999). Therefore, we consider that such identified laterites are well developed and have a long formation time. The correlation between eU-eTh and laterites is more evident in serpentinized rocks. In sedimentary formations this correlation indicates the presence of redeposited laterites. Similar correlation has been observed in other world sites (Eliopoulos and Economou-Eliopoulos, 2000).

The inverse correlation between eTh and K in weathered serpentinized ultrabasic rocks, indicate the presence of laterites rich in Fe+Ni. This is because K isotope is lost during the weathering process of the igneous rocks while thorium was accumulated at the ferruginous material (Portnov, 1987).

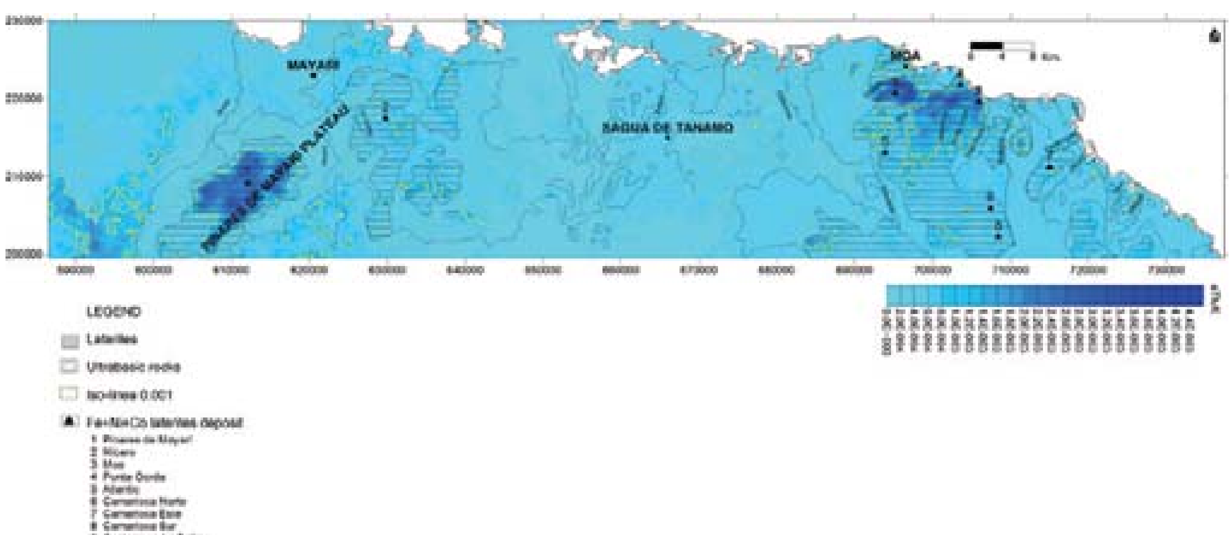

Fig. 7. Map of eTh/K of the Mayarí-Sagua-Moa region (modified from Batista *et al*., 2002).

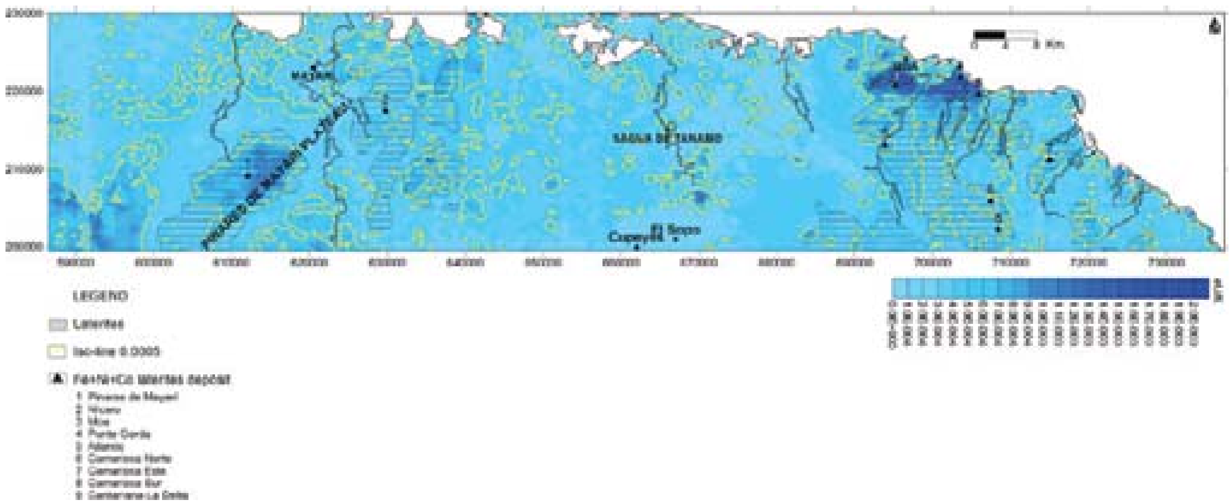

Fig. 8. Map of eU/K of the Mayarí-Sagua-Moa region (modified from Batista *et al*., 2002).

With the application of the correlation matrices and the factor analysis method it was possible to observe lateral variations of some geological features, as follows. In serpentinized ultrabasic rocks, with the eU and eTh factor it was possible to find several things as; 1) To locate lateritic crust areas with larger thickness and correlated with the location of the most important Fe+Ni+Co laterites deposits in the region (Table 3 and Fig. 9a). 2) To propose new laterite areas not previously mapped (Fig. 9a). This was demostrated by the redeposited laterites reported over sedimentary and volcanosedimentary formations in the region, showing a good agreement (Chang *et al*., 1991). 3) To propose a qualitative idea of the thickness variation of laterites crusts (Fig. 9a and 10). On Fig. 9b a comparison

Table 3

Factorial matrix and test of kindness of adjustment of the north-eastern region of Cuba. F1, F2 y F3: factors. The boldfaces indicate the variables that more contributes in the factors (> 0.70). Alone the factors are shown that contribute information and whose variables possess a normal distribution. D: Maximum discrepancy between the accumulative distribution of empiric and the theoretical probability one. Dα: Critical value of D; α<.01: Significance nivel; n: Number of samples.

Rocks type	Factorial matrix (Kolmogorov-Smirnov)					Test of adjustment kindness		
	Variables	**F 1**			**Rotation**	**D**	**n**	**D_α**
Serpentinized ultrabasic rocks (Sagua-Moa)	eU	.87				.002		
	eTh	.97				.002		
	K	-.17				.004		
	Iγ	.94				.002		
	ΔT	.07			Not rotated factors	.004	13393	.01
	F	-.42				.001		
	eTh/K	.98				.002		
	eU/K	.89				.002		
	eU/eTh	-.49				.003		
	Variables			**F3**	**Rotation**	**D**		
Serpentinized ultrabasic rocks (Mayarí)	F			-.05		.01		
	Iγ			-.17		.01		
	K			-.94		.01		
	eTh			-.06	Not rotated factors	.01	4920	.021
	eTh/K			.03		.02		
	eU			.06		.02		
	eU/K			.37		.01		
	eU/eTh			.16		.01		
	Variables	**F 1**	**F2**	**F3**	**Rotation**	.01	**n**	**D_α**
Lateritic crust (Moa)	eU	.88	-.02	-.03		.01		
	eTh	.98	.02	-.97		.01		
	K	-.02	.82	.07		.01		
	Iγ	.97	0	-.71		.02	3755	.02
	ΔT	.01	.58	.33	Not rotated factors	.02		
	F	-.49	-.02	.03		.01		
	eTh/K	.98	0	-.97		.01		
	eU/K	.88	-.05	.03		.007		
	eU/eTh	-.49	-.07	.83				

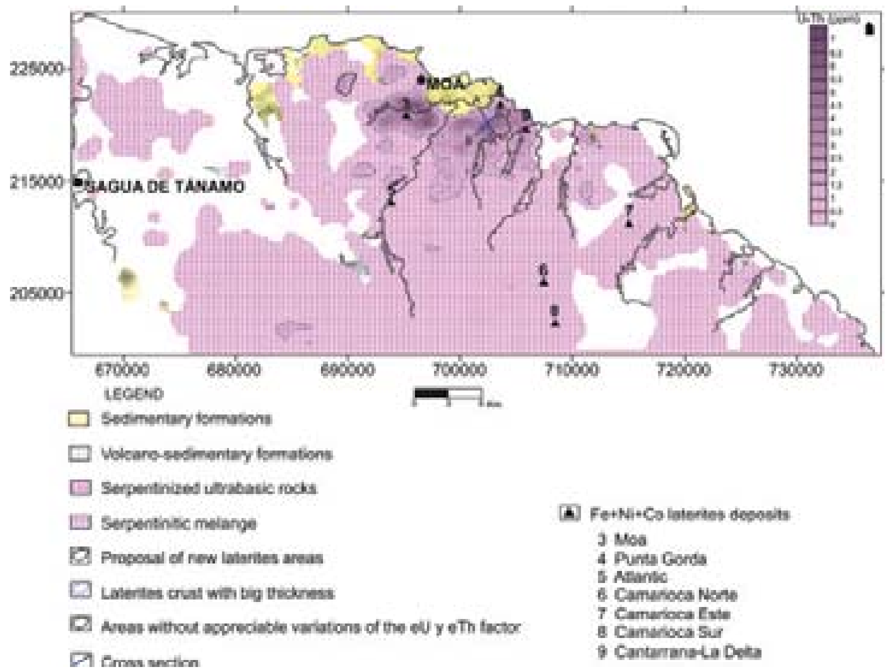

Fig. 9a. Variations of the eU-eTh factor in the Sagua-Moa sector. The increase of the gray color tonalities points out the qualitative valuation of the increase of thickness of the laterites crust in the serpentinized ultrabasic rocks and the increase in the clay grade of the sedimentary and volcano-sedimentary rocks.

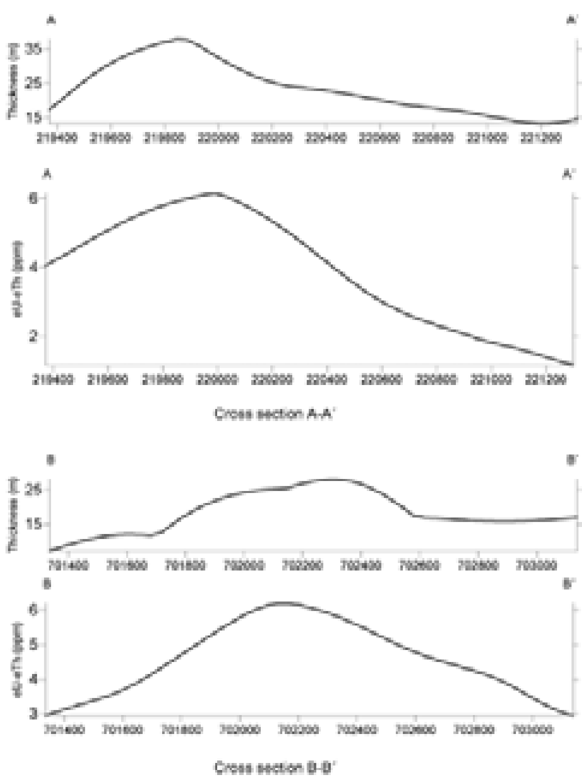

Fig. 9b.

of the thickness with the eU-eTh factor in the lateritic crust of the Punta Gorda deposit is presented, through two cross sections, traced in Fig. 9a. The high correspondence between both parameters justifies the idea of inferring the variations of the thickness of the lateritic crust according to eU and eTh concentrations.

The K factor shows the presence of hydrothermal manifestations on serpentinized ultrabasic rocks (Table 3, Fig. 11) previously reported by Navarrete and Rodríguez (1991). These areas are also shown as negative magnetic anomalies (lower than -25 nT) and alignments related with faults.

The Gyarmati and Leyé O'Conor (1990) map was used as reference for the analysis of laterites in situ and redeposited over serpentinized ultrabasic rocks and gabbros of the Moa region (Fig. 12). From the statistical data analysis we found that redeposited laterites have higher content of eU and eTh than those in situ. Thicker laterite deposits over serpentinized ultrabasic rocks also have higher eU and eTh content (Table 4).

The correlation of matrices in different laterites areas shows a significant relation in eU and eTh contents, related to chemical-mineralogical characteristic and their genesis.

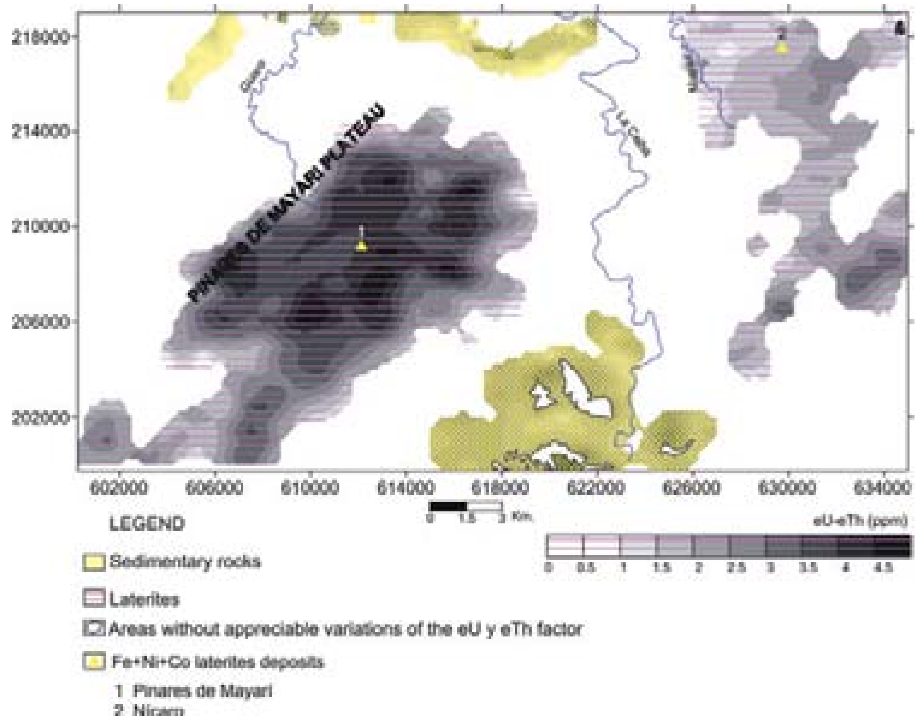

Fig. 10. Variations of the eU-eTh factor in the Mayari sector. The increase of the gray color tonalities points out the qualitative valuation of the increase of thickness of the laterites crust and the increase in the clay grade of the sedimentary rocks.

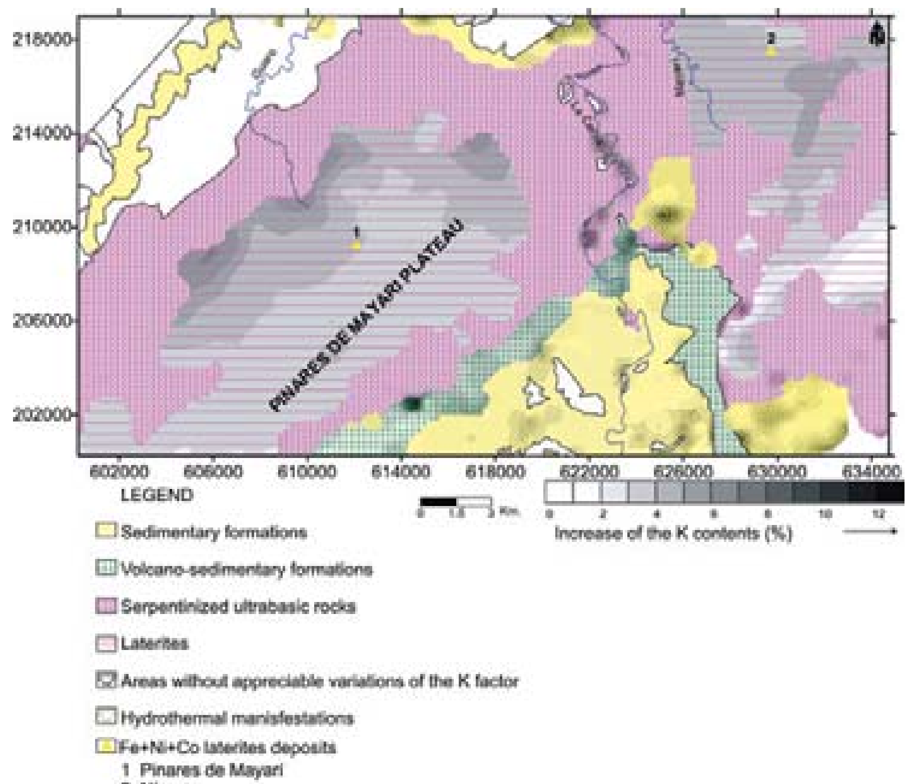

Fig. 11. Variations in the potassium (K) content of rocks of the Mayarí sector, according to K factor.

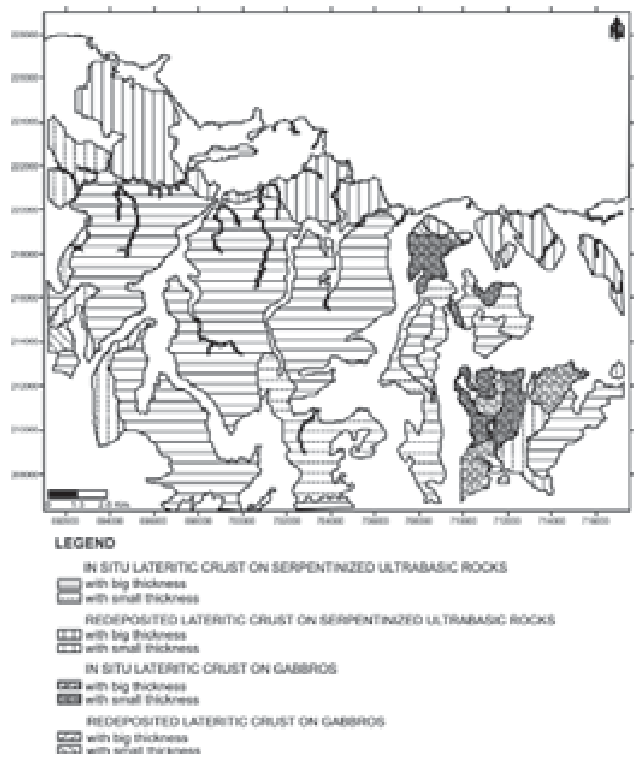

Fig. 12. Map of lateritic crusts of the Moa (taken from Gyarmati and Leyé O'Conor, 1990).

Table 4

Radiometric medium value of the laterítica crust type of the Moa region.

Lateritic crust type	eU (ppm)	eTh (ppm)	K (%)
In situ with big thickness	2.18	4.4	0.35
Redeposited with big thickness	3.12	4.86	0.35
In situ with small thickness	1.61	2.39	0.35
Redeposited with small thickness	1.93	2.58	0.35

High positive correlations between eU and eTh are observed in thicker laterite areas or redeposited (Table 5). There is also a positive correlation between eU, eTh and ΔT in areas of serpentinized ultrabasic rocks (Table 6), suggesting a larger thickness of the lateritic crust over the serpentinized ultrabasic rocks, considering results in other investigations (Batista and Rodríguez-Infante, 2000; Zaigham and Mallick, 2000).

Laterites with variable thickness over serpentinized ultrabasic rocks show a positive correlation between eTh and ΔT (Table 7). Considering that eTh content increases with weathering and rock aging (Galbraith and Saunders, 1983; Portnov, 1987; Braun *et al.*, 1993) and that ΔT increases as magnetic rock thickness increases (Karlsen and Olesen, 1996; Batista and Rodríguez-Infante, 2000), a relation is suggested between the formation time, crust development and magnetization. Therefore, larger laterites crust and larger thickness show a larger magnetic anomaly. This behavior was also present in larger thickness of serpentinized ultrabasic rocks.

Table 5

Correlation of matrix in redeposited laterites of the Moa region.

	eU	eTh	K	Iγ	ΔT	F	eTh/K	eU/K	eU/eTh
eU	1								
eTh	.94	1							
K	.49	.63	1						
Iγ	.97	.99	.59	1					
ΔT	.00	-.19	-.08	-.12	1				
F	-.79	-.90	-.40	-.07	.51	1			
eTh/K	.95	1.00	.56	.99	-.19	-.90	1		
eU/K	.99	.91	.36	.95	.01	.77	.92	1	
eU/eTh	-.80	-.91	-.53	-.88	.50	1.00	-.91	-.77	1

The factor analysis for the Moa laterites shows lateral variations at the eU-eTh factor (Table 3, Fig. 13), indicating variations in laterite thickness, according to Table 8 and cross sections of the Fig. 9b. These variations are influenced by geomorphology, pH, Eh (oxidation potential), the water table, organic material content and modal per cent of mineral phases with high absortion capacity (ferrihydrite, goethite and amorphous percent; Jubeli *et al*., 1998; Luo *et al*., 2000). The production of uranium and thorium absortion by iron oxides and hydroxides in laterites requires a longer period of time and thicker laterite crusts (Jubeli *et al*., 1998; Von Gunten *et al*., 1999; Luo *et al*., 2000).

Table 6

Correlation of matrix in serpentinized ultrabasic rocks of the Moa region.

	eU	eTh	K	Iγ	ΔT	F	eTh/K	eU/K	eU/eTh
eU	1								
eTh	.85	1							
K	.48	.26	1						
Iγ	1.00	.88	.46	1					
ΔT	.56	.22	.27	.53	1				
F	.99	.76	.53	.97	.64	1			
eTh/K	.85	1.00	.25	.88	.22	.75	1		
eU/K	1.00	.85	.48	1.00	.56	.99	.85	1	
eU/eTh	.99	.76	.53	.98	.64	1.00	.76	.99	1

Table 7

Correlation of matrix in laterites with small thickness of the Moa region.

	eU	eTh	K	Iγ	ΔT	F	eTh/K	eU/K	eU/eTh
eU	1								
eTh	.89	1							
K	.62	.54	1						
Iγ	.97	.98	.60	1					
ΔT	.46	.61	.44	.56	1				
F	-.82	-.88	-.41	-.78	-.85	1			
eTh/K	.89	1.00	.54	.97	.61	-.89	1		
eU/K	1.00	.89	.60	.97	.46	.62	.89	1	
eU/eTh	-.64	-.90	-.47	-.80	-.67	1.00	-.90	-.64	1

Table 8

Correlation of matrix in laterites of the Punta Gorda deposit of the Moa region.

	Thickness	eU	eTh
Thickness	1		
eU	.60	1	
eTh	.60	.89	1

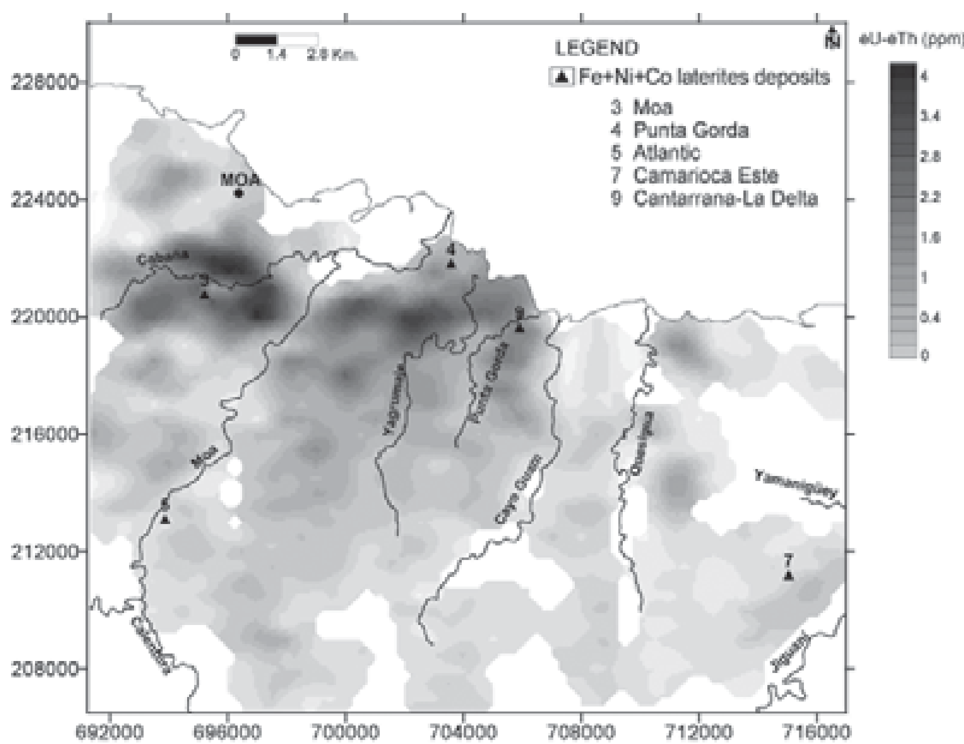

Fig. 13. Variations thickness of laterites of Moa, according to eU- eTh factor. The increase of the gray color tonalities points out the qualitative valuation of the increase of thickness of the laterites crust.

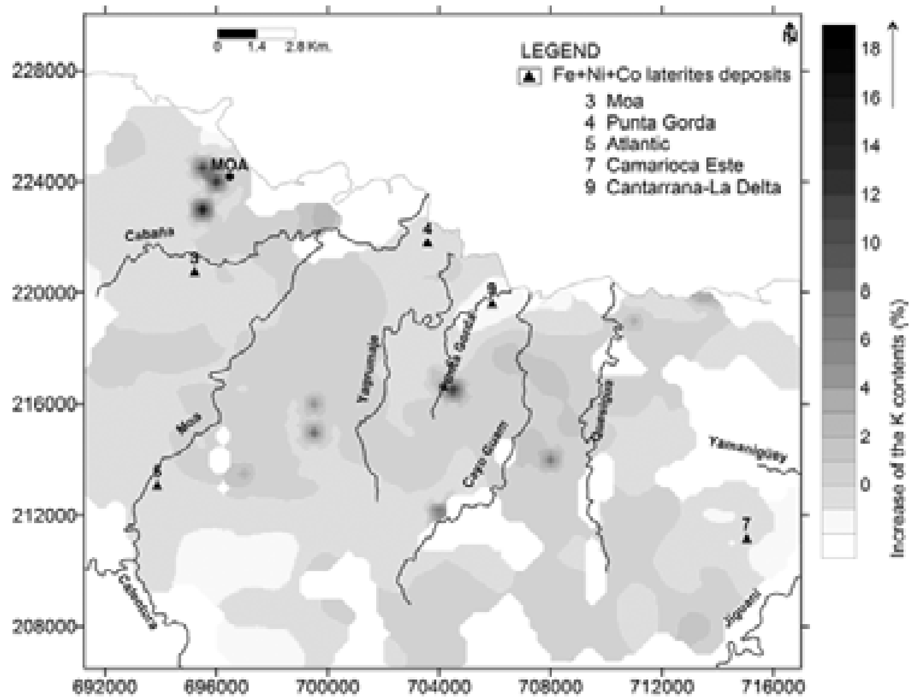

Fig. 14. Variations in the K concentrations of the Moa laterites, according to K factor.

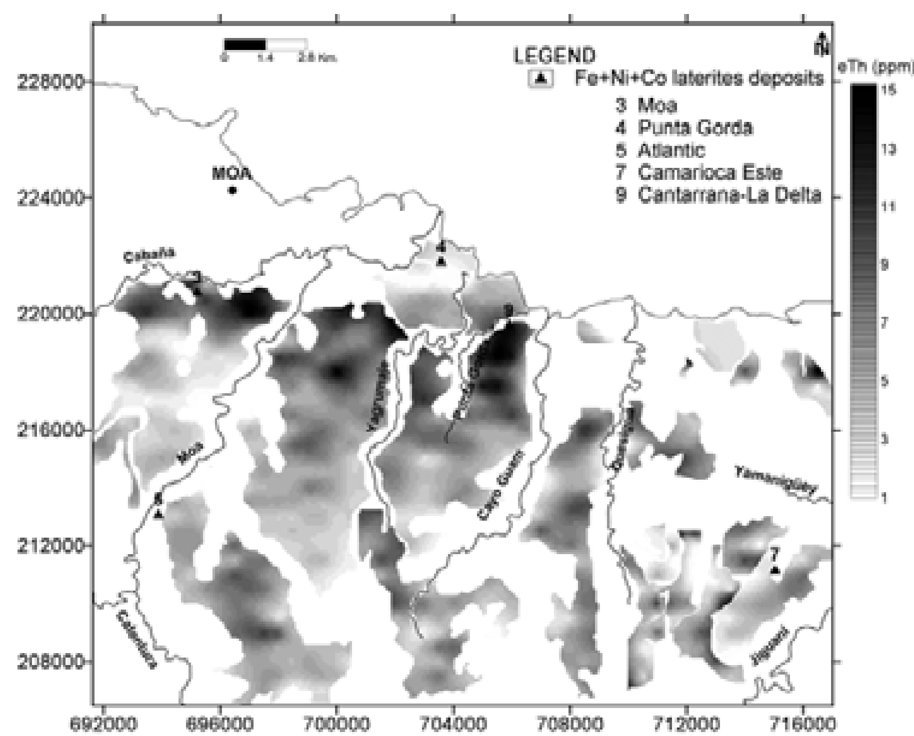

Figure 15. Variations in the time of formation and development of the lateritic crust of Moa according to the eTh factor. The increase of the gray color tonalities points out the qualitative valuation of the increase of bigger time of formation and development of laterites.

The factor analysis shows lateral variations in K content (Table 3, Fig. 14). Maximums are located at the central part of the region and at the SW part of the city, correlating some of them with hydrothermal alterations reported by Batista and Ramayo (2000). This could also be related with volcanic rocks or gabbros (sills and dikes) intruding the peridotites.

Hydrothermal alteration of Fe-Ni-Co enriched laterite deposits is useful for mining exploration and exploitation, because such alterations indicates the presence of silicates, which have negative effects on the metallurgic process (Rojas and Beyris, 1994). This kind of weathered crust presents gold mineralization associated whit quartz-veins (Batista and Ramayo, 2000), as has been observed in the Cabañas sector (SW Moa) with 30 and 52 ppb of gold.

We have also observed that higher eU concentrations are present in laterite areas with topographical depressions, where more organic material is present, as shown in Fig. 5 at A and cross section I-I´, to the SW of Moa. This kind of correlation has been observed in other world sites, where the eU concentration increases during the leaching of the weathered rocks only when appropriate topographical conditions exists (Jubeli *et al*., 1998).

The eTh factor shows lateral variations (Table 3, Fig. 15) related with formation time, developments and laterite thickness as seen in other world sites (Galbraith and Saunders, 1983; Portnov, 1987; Braun *et al*., 1993). The inverse correlation of this parameter with ΔT, suggest a large development of lateritic crust, in serpentinized ultrabasic rocks but with lower thickness, as shown in Fig. 6 with capital letter B.

Conclusions

The applications of airborne radioactivity and magnetic data have been useful to find the horizontal boundaries for known laterite crust, to propose new areas and to detect hydrothermal alteration over such laterites. High content in eU and eTh is common in laterites, but redeposited laterites shows even higher content. High values in those elements are also present in thicker, developed or redeposited laterites over serpentinized ultrabasic rocks. From the eU, eTh, K and ΔT relations, the laterite formation time, thickness, morphological features and possible hydrothermal alterations can be estimated. We found that Moa laterites have longer formation time and thickness than Mayari. Factors characterized the different kind of laterites, genesis differences and thickness variation. Lateral variation in eU- eTh factor is related with thickness variation in laterites. eTh factor is related with the formation time, development and thickness of laterites. K factor shows the presence of hydrothermal alterations. This last is an important indicator of the presence of silicates that may affect the metallurgical processes and also is an indicator of the possible presence of precious metals on those alterations. Lateral variation of the total magnetic field and eU or eTh or K content is related with the laterite thickness and underlayered rocks.

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