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A magnetic survey of mineral resources in northeastern Cuba

José Alberto Batista Rodríguez
Instituto Superior Minero Metalúrgico de Moa, Cuba

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RESUMEN

Se presentan los resultados de la interpretación del levantamiento aeromagnético escala 1:50 000 de la región nororiental de Cuba, en la cual afloran fundamentalmente rocas ofiolíticas caracterizadas por un alto grado de magnetización. Los datos aeromagnéticos fueron reducidos al polo y luego se realizaron los cálculos de gradientes horizontales y verticales y la continuación analítica ascendente. A partir de los resultados de estas transformaciones se delimitaron zonas donde predominan las rocas ultrabásicas serpentinizadas tanto en superficie como en profundidad, definiéndose la extensión lateral de estas rocas por debajo de las rocas que afloran en superficie. También se estimaron las variaciones de los espesores de las rocas ofiolíticas, el basamento de las rocas que afloran, la presencia de estructuras disyuntivas, y se proponen nuevas estructuras de este tipo. Por último se delimitan las zonas de alteración hidrotermal, lo cual posee gran importancia, ya que con las mismas se pueden vincular mineralizaciones de metales preciosos. Además, su delimitación en depósitos lateríticos permite orientar los trabajos de explotación minera, teniendo en cuenta el daño que causa al proceso metalúrgico la presencia de material silicio en las lateritas Fe+Ni.

PALABRAS CLAVE: Interpretación aeromagnética, ofiolitas, zonas de fallas, alteraciones hidrotermales, Cuba nororiental.

ABSTRACT

Interpretation of the aeromagnetic survey of northeastern Cuba at scale 1 50 000 is presented. Mainly ophiolitic rocks are characterized by a high magnetic response. The aeromagnetic data was reduced to the pole and the horizontal and vertical gradients, as well as the upward continuation were calculated. To define areas of serpentinized ultrabasic rocks at surface and depth, the magnetic field transformations were interpreted. We discuss lateral extension of outcrops, thickness variation of the ophiolitic rocks, basement extension and fault zones. Hydrothermal alterations indicate associated precious metal secondary mineralization. Operations are planned to limit damage to mining by siliceous material in Fe+Ni laterites.

KEY WORDS: Aeromagnetic interpretation, ophiolites, fault zones, hydrothermal alterations, north-eastern Cuba.

INTRODUCTION

The region studied is located on the northeastern sector of Cuba, where important Fe+Ni laterites and chromite deposits outcrop (Figure 1).

Air surveys have become an indispensable tool to geologic mapping and prospecting of mineral deposits in extensive or inaccessible regions, or in areas where geologic mapping is insufficient. It is also a helpful tool to know the distribution of rocks under the sedimentary cover and allocation of mineral bodies.

Aeromagnetic surveys are used in numerous investigations in Cuba as well as in other parts of the world. Examples are illustrated in Chang *et al.* (1990, 1991), Batista (1998), Batista and Rodríguez (2000), Batista *et al.* (2002), and elsewhere in Corner and Wilsher (1989), Charbonneau and Legault (1994), Miranda *et al.* (1994), Mickus and Durrani (1996), Shapiro *et al.* (1997), Chernicoff and Paterlini (1998), Chernicoff and Zapata (1998), Nash (1998), Nash and Chernicoff (1998), García (1999), Sintubin (1999) and Lagroix and Borradaile (2000). The interest in the geophysical data is illustrated also in the aeromagnetic map of North America (Finn *et al.*, 2001a,b).

In the study area, 70% of the rocks outcrop in the Mayarí-Baracoa ophiolitic belt and on the Cretaceous and Paleogene volcanic island arc (Figure 1), largely covered by a thick lateritic crust (Cobiella, 1988, 2000; Quintas, 1989; Iturralde-Vinent, 1995, 1996a,b,c, 1998; Proenza, 1997; Lavaut, 1998; Proenza *et al.*, 1999c; Batista, 1998; Batista and Rodríguez, 2000).

This geology affords efficient application of an aeromagnetic survey due to significant magnetization contrasts (Chang *et al.*, 1990, 1991; Batista, 2002; Batista *et al.*, 2002).

A 1:50,000 aeromagnetic survey of eastern Cuba was carried out to improve planning of mineral prospecting.

The aeromagnetic data were initially reduced to the pole. Horizontal gradients, vertical gradients and upward continuation were calculated and interpreted.

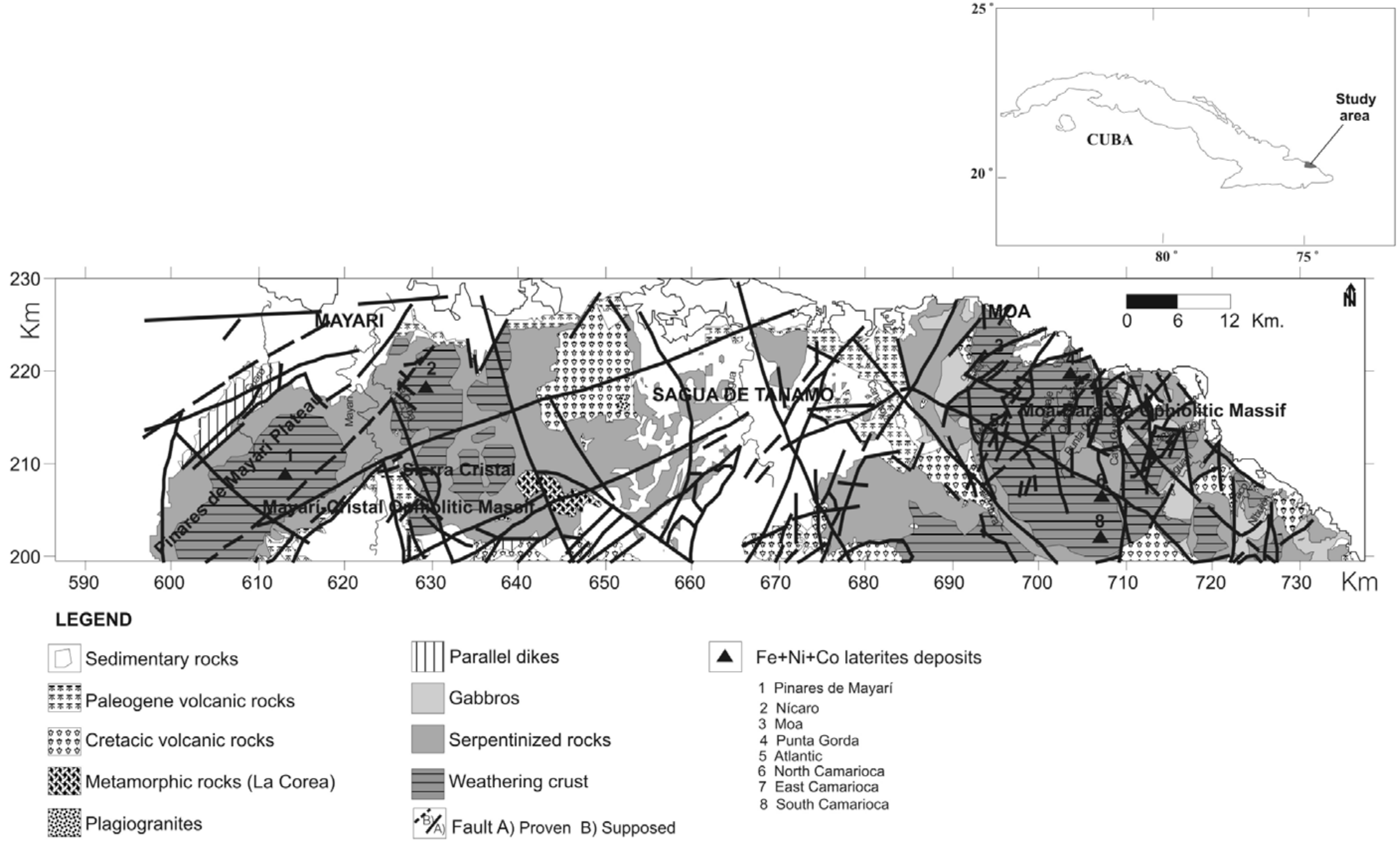


Fig. 1. Geologic scheme of the north-eastern region of Cuba (modified of Albear *et al.*, 1988).

MATERIALS AND METHODS USED

The aeromagnetic data of eastern Cuba were measured along flight lines with north-south direction, separated each 500 m and to an average height of 70 m, with an error of ±10 nT (Chang *et al.*, 1990, 1991).

A geological-geophysical interpretation was done by using all available geologic and tectonic information.

GEOLOGICAL FRAMEWORK

Eastern Cuba contains sequences of the Cuban folded belt and rocks of the "neoautochtonous" (Iturralde-Vinent, 1996a, b, c, 1998; Proenza, 1997; Proenza *et al.*, 1999a). In the Mayarí and Sagua-Moa-Baracoa massif (Figure 1) oceanic outcrops correspond to the northern ophiolites, and to the Cretaceous and Paleogene volcanic island arcs plus some sedimentary formations (Cobiella, 1988, 1997, 2000; Quintas, 1989; Iturralde-Vinent, 1995, 1996a, b, c, 1998; Proenza, 1997, Proenza *et al.*, 1999c).

The northern ophiolites are in the Mayarí-Baracoa ophiolitic belt (Iturralde-Vinent, 1994, 1996a, 1998). Their main outcrop is represented by the Mayarí-Cristal and Moa-Baracoa massifs (Proenza, 1997; Proenza *et al.*, 1999a). These ophiolites have been attributed to a backarc-marginal Sea system, located at the Cretaceous margin of the Bahamas Platform and the volcanic arc of the Greater Antilles Arc (Iturralde-Vinent, 1994, 1996a, 1998; Cobiella, 2000).

This ophiolitic belt constitutes an allochthonous pseudotabular body of ~170 km length. It exceeds 1000 m thickness (Iturralde-Vinent, 1996a, 1998). According to Fonseca *et al.* (1985, 1992), Iturralde-Vinent (1996a, 1998) and Proenza (1997), it contains different lithologies of a complete ophiolitic sequence, separated by tectonic contacts. The floor to roof sequence is composed of peridotites with tectonite textures, "ultramafic cumulate", mafic cumulate, diabase dikes and effusive-sedimentary rocks.

These ophiolites are structured in form of tectonic flakes, emplaced on volcano-sedimentary rocks of the Cretaceous island arc, which are covered transgressively by flyschoid sequences and olistostromes of Maastrichtian to Paleocene age (Mícara and La Picota formations). Occasional imbrications are observed between and under the ophiolites (Iturralde-Vinent, 1996a, b, 1998; Gyarmati *et al.*, 1997; Cobiella, 2000).

The ophiolitic rocks are mainly covered by volcano-sedimentary materials of the Paleogene island arc and by younger terrigenous carbonate sequences (Quintas, 1989; Iturralde-Vinent, 1996a, b, 1998; Proenza, 1997; Cobiella, 1997, 2000).

Mayarí-Cristal ophiolitic massif

Mayarí-Cristal ophiolitic massif is located in the western part of the Mayarí-Baracoa ophiolitic belt, covering an estimated area of 1200 km^2 (Figure 1), with a thickness from 1 to 1.5 km according to Fonseca *et al.* (1985). This massif contains mainly ultramafic complex and diabase dikes; the existence of the gabbro complex is debated and the volcano-sedimentary one has not been described (Iturralde-Vinent, 1996a, 1998; Proenza, 1997, Proenza *et al.*, 1999a; Cobiella, 2000).

The ultramafic rocks are predominantly constituted by harzburgites and dunites, and rarely by lherzolites and pyroxenites (Fonseca *et al.*, 1985; Nekrasov *et al.*, 1989; Navarrete and Rodríguez, 1991; Proenza *et al.*, 1999a). Pyroxenite dikes also exist in the massif, cutting the peridotite and the chromitite bodies (Iturralde-Vinent, 1996a, 1998; Proenza, 1997; Proenza *et al.*, 1999a; Cobiella, 2000).

The gabbro complex is not well exposed and its presence has been questioned. Knipper and Cabrera (1974) recognized an area composed by normal gabbros, amphibolite gabbros and diabases in the north-western end of the massif. Fonseca *et al.* (1985) and Nekrasov *et al.* (1989) do not recognize the existence of the gabbro complex. Navarrete and Rodríguez (1991) describe the presence of gabbros, microgabbros and gabbros-diabases and relate them to the mafic cumulative complex, although they stress that gabbro is not predominant. Iturralde-Vinent (1996a, 1998) recognizes a gabbro area together with diabase dikes.

The synthetic column of this massif (Figure 2) proposed by Proenza (1997) and Proenza *et al.* (1998b), contains from bottom to top: a) a harzburgite area with tectonite texture; b) an area of harzburgite alternation and dunite with abundant chromitite bodies and pyroxenite dikes (websterite); c) a possible area corresponding to the mafic cumulate (gabbro), which, if existing, should be extremely small; and d) the area of the diabase complex.

"La Corea melange" south of the massif (Figure 1), is an area of developing metamorphic rocks of about 25 km^2 (Adamovich and Chejovich, 1964; Millán, 1996). It is composed of blocks of metamorphic rocks separated by a serpentinitic matrix.

Moa-Baracoa ophiolitic massif

Moa-Baracoa ophiolitic massif is located at the end of the eastern Mayarí-Baracoa belt. It covers an approximate area of 1500 km^2 and it presents a considerable development of the ultramafic complex, of gabbro and volcano-

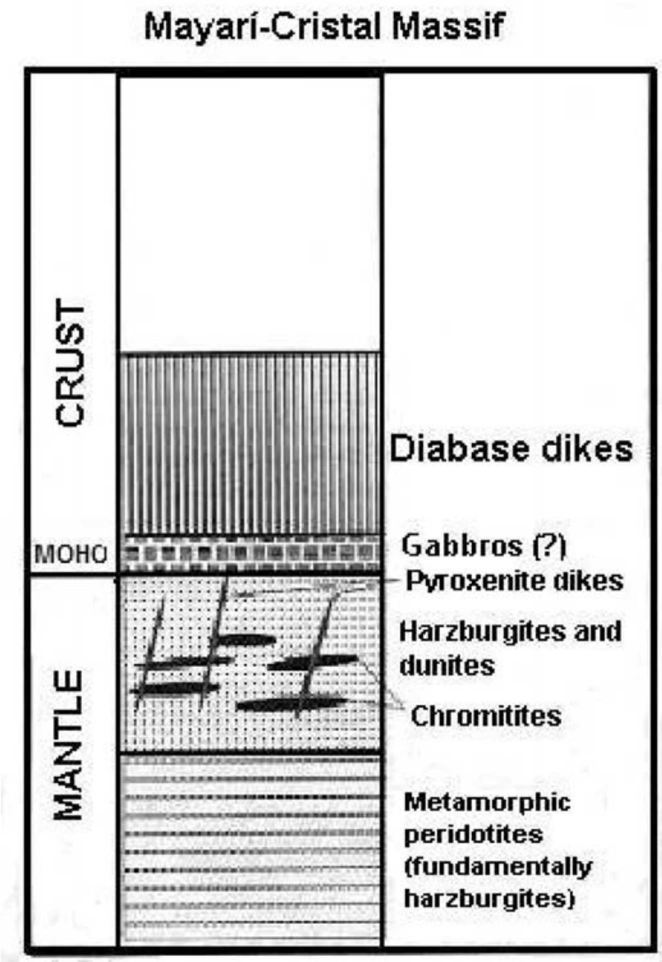


Fig. 2. Ideal synthetic column of the Mayarí-Cristal ophiolitic massif, proposed by Proenza (1997) and Proenza *et al.* (1998b), reconstructed from the authors' own and bibliographical data (Thayer, 1942; Iturralde-Vinent, 1989, 1994, 1996a; Fonseca *et al.,* 1985, 1992; Nekrasov *et al.,* 1989; Murashko and Lavandero, 1989; Navarrete and Rodríguez, 1991). The vertical axis is not to real scale.

sedimentary rocks (Proenza, 1997; Proenza *et al.*, 1999a, b, c) (Figure 1). According to Fonseca *et al.* (1985) the approximate thickness of the ultramafic complex is 1000 meters and that of gabbro is 500 meters. Quintas (1989) estimates a thickness of 1200 meters for the volcano-sedimentary complex.

The ultramafic complex is characterized by harzburgites and by dunites to a lesser extent. Plagioclase dunites, wehrlites, lherzolites, and pyroxenites have also been described (García and Fonseca, 1994; Proenza *et al.*, 1999a, b).

The gabbro cumulates form large bodies in the ultramafic complex. The dimensions of these bodies oscillate between 1 to 3 km wide, and 10 to 15 km long. The contact between the gabbro and the ultramafic complex is generally tectonic. Mainly the gabbro is covered by ultramafic rocks (Fonseca *et al.*, 1985), although Andó *et al.* (1989) suggest that in some sectors the contact is of transitional type. The main gabbro types described are: olivine gabbros, gabbronorites, gabbros, anorthosites and norites (Ríos and Cobiella, 1984; Fonseca *et al.*, 1985; Proenza, 1997; Proenza *et al.*, 1999a, b; Rodríguez, 2000).

The volcano-sedimentary complex is in tectonic contact with the other complexes of the ophiolitic sequence (Proenza, 1997; Proenza *et al.*, 1999a). It is conformed by amygdaloidal basalts and porphyry (sometimes with pillow structure), with hyaloclastite intercalations, tuffs, chert layers and limestones (Quintas, 1989).

In the synthetic column of this massif (Figure 3), proposed by Proenza (1997) and Proenza *et al.* (1998b, 1999c), we have from bottom to top levels: a) a harzburgite area with tectonite textures; b) a harzburgite area that contains bodies of dunites, plagioclase dunites, gabbro sills, gabbro dike and pegmatitic gabbro; c) the area of gabbros, which present at the base great development of crossed gabbros (olivine gabbros, gabbronorites), grading upward into isotropic gabbros; d) the area of the complex of diabase dikes?, and e) the effusive-sedimentary complex.

The sequence of Cretaceous volcanic island arc fundamentally contains basaltic andesites and basalts, mainly tuffs and andesitic lava-breccia, dacites, tuffs, argillites, shales (volcanomictic), basaltic lavas (Cobiella, 2000; Campos and Hernández, 1987; Millán, 1996; Proenza and Carralero, 1994; Iturralde-Vinent, 1996c, 1998; Gyarmati *et al.*, 1997).

According to Iturralde-Vinent (1994, 1996c), the basement of this volcanic arc is the oceanic crust of pre Aptian age, recognized in eastern Cuba as "Güira de Jauco" amphibolites.

In the contact of these Cretaceous rocks with the ophiolites, they are deformed and generally crushed to breccias. Sometimes the contacts coincide with cracked and foliated areas, or with chaotic masses that contain a mixture of ophiolite blocks and Cretaceous vulcanite (Iturralde-Vinent, 1996a, b, c, 1998; Cobiella, 2000).

The representative stratigraphic units of the Campanian Late-Danian are typically olistostromic sequences composed by fragments and blocks coming from the ophiolitic sequence and from the Cretaceous volcanic rocks (Cobiella, 1978a, b, 2000; Quintas, 1989, 1996). Brecciated limestones also appear, with volcanomictic conglomerate, breccia, marbles, tuffs, organo-detritic limestones, volcanomictic sandstones of calcareous cement, shales and tuffs (Iturralde-Vinent, 1976; Cobiella, 1978a, b; Quintas, 1989).

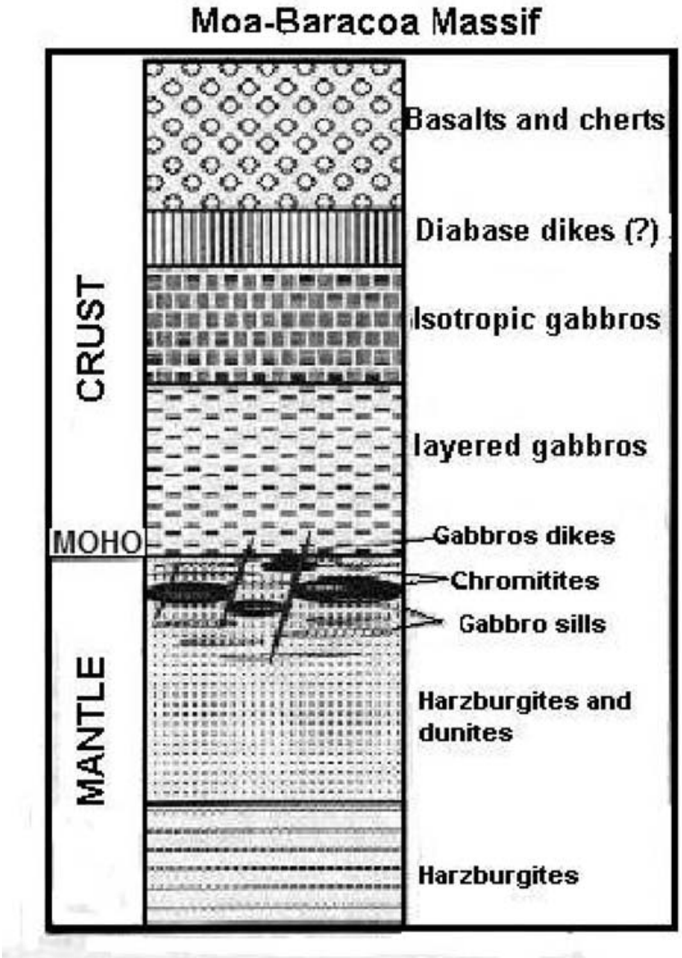


Fig. 3. Ideal synthetic column of the Moa-Baracoa ophiolitic massif, proposed by Proenza (1997) and Proenza *et al.* (1998b, 1999c), reconstructed from the authors' own and bibliographical data (Thayer, 1942; Guild, 1947; Ríos and Cobiella, 1984; Iturralde-Vinent, 1989, 1994, 1996a, Fonseca *et al.*, 1985, 1992). The vertical axis is not to real scale.

The sequences of the Paleogene volcanic islands arc are represented by vitroclastic-tuffs, litho-vitroclastic, vitroclastic-glass with intercalations of calcareous tuffs, tuffaceous sandstone, limestones, tuffaceous conglomerate, shales, marls, gravelites, volcanomictic conglomerate and some bodies of basalts, andesites, and andesites-basaltic, which attain 6000 m of thickness (Iturralde-Vinent, 1976, 1995, 1996b, 1998; Cobiella, 1988, 1997, 2000; Proenza and Carralero, 1994; Quintas *et al.*, 1995).

The rocks associated to the Paleogene volcanic island arc are located on deformed materials of the Cretaceous arc, ophiolites and the sedimentary basins of the Campanian Late-Danian period (Proenza and Melgarejo, 1998).

Tectonic setting

The tectonics of the Cuban eastern block is characterized by a high complexity, due to the occurrence of events of different nature that have been superimposed in time and that have generated structures of varied intensity and indications at the surface (Rodríguez, 1998a, b). This block is characterized by the development of thrust tectonics that affects the oldest sequences (Campos, 1983).

Locally this complexity in the study region shows fundamentally faulting with northeast and northwest direction (Figure 1) that intersects and displaces each other (Campos, 1983; Rodríguez, 1998a, b). Dislocations of complex folding are also observed, mainly in the proximity of the tectonic contacts (Campos, 1983).

PETROPHYSIC CHARACTERIZATION

The study of the physical properties of rocks and minerals is important during the development of geologic and geophysical investigations. It helps select the geophysical methods to use and provides elements for the processing and interpretation of the geophysical data and allow geological and structural characterization of the region being investigated.

Several petrophysical works, aimed fundamentally to study the magnetic properties of the rocks, have been carried out on this region. Among the most significant works are those of Zamashikov and Tobachkov (1971) in the Moa-Baracoa massif, Chang *et al.* (1990, 1991) in the Mayarí-Sagua-Moa region, Rodríguez (1982) in the ultrabasic rocks of oriental Cuba, and Batista (2002) in the Moa region.

In this investigation, the measurements of the natural remanent magnetization from previous studies were not considered, due to the few samples analyzed, their locations and the obtained values of magnetization (Rodríguez, 1982).

The physical properties of rocks vary according to lithological changes, and even within a lithological type, depending on the degree of mineralization and alteration (Logachev and Zajarov, 1986). The study region is largely occupied by ophiolitic rocks and in smaller proportion by volcano-sedimentary, sedimentary and metamorphic rocks (Quintas, 1989; Iturralde-Vinent, 1996a).

Previous investigations in this and other regions of the world report that inside the ophiolites, the ultrabasic rocks are characterized by the largest magnetic susceptibility (k) variations and can vary from weak until strongly magnetic, in correspondence with their serpentinization level, because during this process the transformation of the olivine or pyroxene to serpentine is produced, being free part of the iron that becomes magnetite. The largest k values are registered in the more serpentinized rocks. The later transformations of these rocks by carbonatization and listvenitization diminish the magnetic susceptibility again;

as do the hydrothermal alterations of seritization and quartzification because of alteration of the magnetite and enrichment in silica (Logachev and Zajarov, 1986; Ishihara, 1990, Alva-Valdivia *et al.*, 1997; Gunn *et al.*, 1998; García, 1999). The gabbros are weakly or strongly magnetic. Among them, the gabbro-norites and anortosites possess the lowest values in k, however, these values increase when they are enriched in magnetite or pyrrhotine.

The results of k measurements are noted in Table 1. Note that the igneous rocks possess the highest values in k, specifically the serpentinized ultrabasic rocks; thus the largest positive intensities in the magnetic field should be related to the geological and structural characteristics of such rocks, keeping in mind that they occupy most of the territory. In some small areas it can be caused by pyroxenites and diabases.

Table 1

Magnetic susceptibility (**K x $10^{-6}/4\pi$ SI**) of the main types of rocks of the Mayarí-Sagua-Moa region. According to authors' own and bibliographical data (Zamashikov and Tobachkov, 1971; Rodríguez, 1982; Chang *et al.*, 1990, 1991)

Types of rocks	Interval	Media
Sedimentary	0 – 600	50
Volcano-sedimentary	0 – 890	100
Diabases	4 – 5 025	2 400
Gabbro	10 - 900	107
Dunite	500 – 3 200	1 000
Serpentinized dunite	20 - 7200	1440
Harzburgites	500 – 3 900	1 179
Serpentinized harzburgites	10 – 9 150	1423
Piroxenites	390 – 4 630	2 410
Laterites	60 000 – 180 000	143 000

AEROMAGNETIC INTERPRETATION

Map of ΔT reduced to the pole (ΔTrp)

In the aeromagnetic survey of the region the intensities vary between -585 and 797 nT (Figure 4a). When reducing to the pole the map of ΔT (ΔTrp), the intensities oscillate from -456 to 1090 nT with means of 121 and -113 nT in the positive and negative values, respectively (Figure 4b).

In the map of ΔTrp the highest positive intensity value in the magnetic field are south of Sierra Cristal, while the negatives are located in the Pinares de Mayarí Plateau and its surroundings, and some locations between Sagua de Tánamo and Moa. Negative anomalies are related with areas of tectonic contact, suggesting that they may be caused by the decrease of magnetization in areas of tectonic weakness or by deeper rocks with smaller magnetization than the surrounding serpentinized rocks (Table 1). This has already been reported in some areas of this region (Campos, 1983; Murashko and Lavandero, 1989). Most of the outcrops of serpentinized peridotites are related to anomalies of high positive intensities and negatives, except to the south of the Pinares de Mayarí Plateau, where high negative intensities can be related to outcrops of Paleogene volcano-sedimentary rocks, at depths, or to other rocks of very low magnetization. We may dismiss serpentinized peridotites at depth, unlike the rest of the anomalies with high positive and negative intensities, where the serpentinized rocks prevail in surface and depth.

The high positive intensities of the magnetic field suggest large depths of highly magnetic rocks. In the case of the serpentinized peridotites these intensities increase proportionally to the increment of the serpentinization (Papayannopoulou-Econonomou and Kiskyras, 1981; Chang *et al.*, 1990, 1991; Batista, 1998; Batista and Rodríguez, 2000; Chernicoff and Paterlini, 1998; Gunn *et al.*, 1998; Zaigham and Mallick, 2000). In such areas, the serpentinized peridotites can be located at great depth and in some cases they can even show a very high serpentinization.

Where there is no presence of surface ophiolitic rocks, positive values of the magnetic field are registered, indicating the presence at depth, mainly of ultrabasic rocks (Zaigham and Mallick, 1994, 2000; Batista, 1998; Batista and Rodríguez, 2000; Chernicoff and Zapata, 1998).

High negative intensities of the magnetic field show near surface or outcropping rocks of very low magnetization and large thickness (Karlsen and Olesen, 1996; Batista, 1998; Batista and Rodríguez, 2000; Ghidella *et al.*, 1998). In ultrabasic rocks these are either thin or are underlain by not very magnetic, probably volcano-sedimentary, sedimentary rocks or acid rocks that have not been reported previously in the area (Campos, 1983; Chang *et al.*, 1990, 1991; Batista, 1998; Batista and Rodríguez, 2000). In a general way, if there are negative values where there is no outcrop of ultrabasic rocks, these do not extend laterally or don't possess a thickness able to be reflected in this magnetic field, or there are thick volcano-sedimentary and sedimentary rocks in the area, or carbonated rocks of the Bahamas paleomargin in depth, as reported in other regions of Cuba by Iturralde-Vinent (1994, 1996b) and Proenza and Melgarejo (1998).

These results suggest that it is possible to infer variations in thickness, as well as serpentinization levels of peridotites, from the behavior of the magnetic field. In the

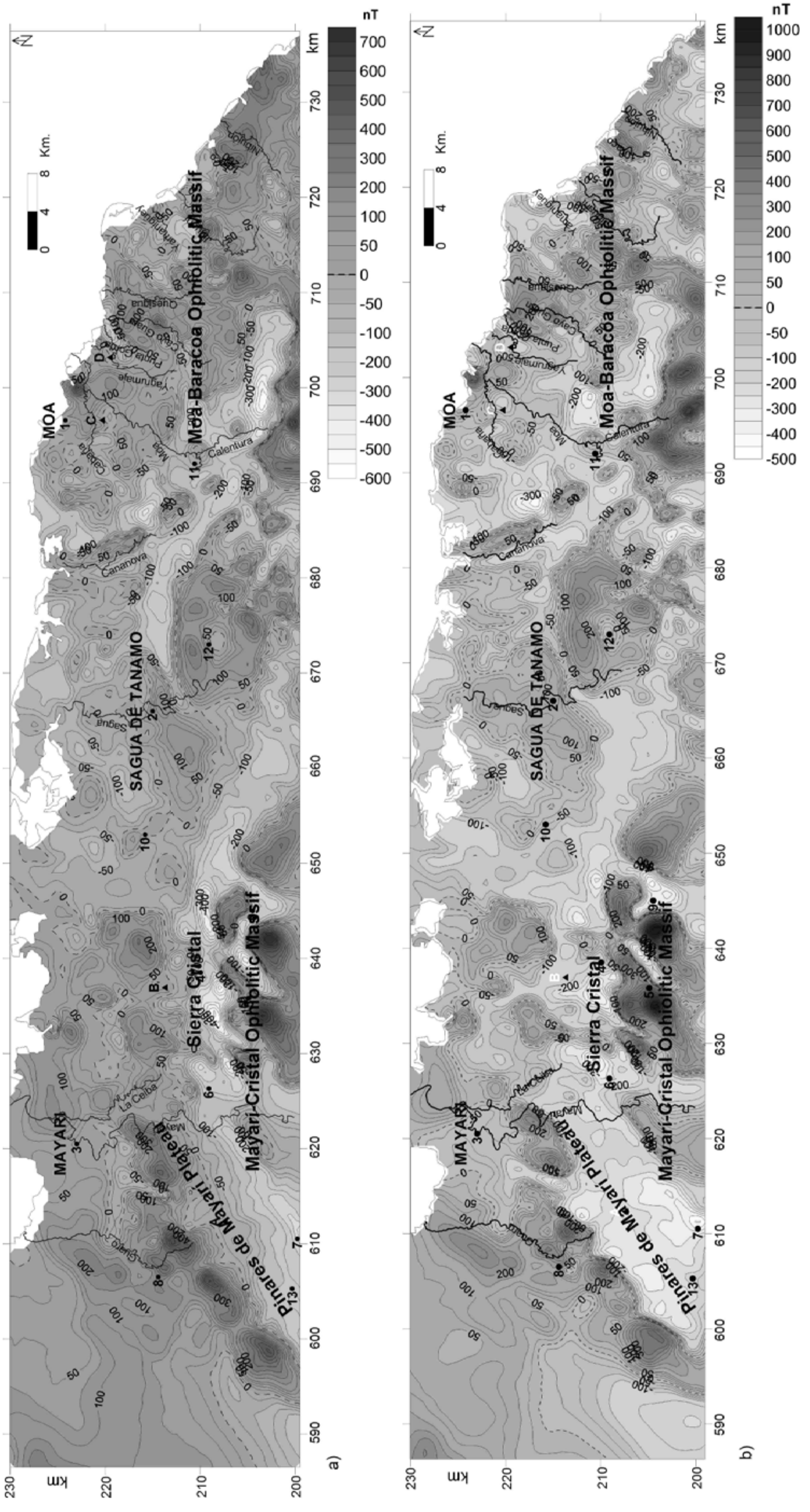


Fig. 4. a, Map of ΔT of the Mayarí-Sagua-Moa region; b, Map of ΔT reduced to the pole of the Mayarí-Sagua-Moa region. Towns: 1, Moa; 2, Sagua de Tánamo; 3, Mayarí; 4, Sierra Cristal; 5, Cayo Verde; 6, Hicotea; 7, Piloto Abajo; 8, Guamutas; 9, Moreiros; 10, La Güira; 11, Calentura Abajo; 12, Castro; 13, Pinares de Mayarí. Fe+Ni laterites deposits: A, Pinares de Mayarí; B, Nícaro; C, Moa; D, Punta Gorda.

ophiolitic rocks the variations in thickness of the ophiolitic sect (cumulative or tectonites) are better defined (Iturralde-Vinent, 1996a; Proenza, 1997; Proenza *et al.*, 1999a, b, c), which is important when prospecting for chromite deposits, since these deposits are usually inserted in dunites and harzburgites in the upper part of the basal tectonites of the ophiolitic sequences, including the so-called transition area (Nicolas and Prinzhofer, 1983; Proenza *et al.*, 1998a, b, 1999a, b). Positive values of the magnetic field where there are outcrops of serpentinized peridotites or gabbros suggest thick tectonite layers, while negative values in gabbros indicate greater thickness of the cumulative section or a combination with other rocks underlying the low magnetization. Negative values in serpentinized rocks represent evidence of minimum thickness and the existence at depth of rocks of the cumulative level, volcano-sedimentary or both. In Cretaceous volcano-sedimentary rocks the negative values indicate a maximum thickness and an absence deep of serpentinitic rocks, while in the Paleogene volcano-sedimentary and the sedimentary rocks it suggest thickness, of the Cretaceous volcanic basement or of both rock groups. Finally positive values of the field in Cretaceous volcano-sedimentary outcrops indicate a maximum thickness that overlies the ultrabasic rocks, evidencing their allochthonous character.

The variations in thickness of the serpentinized ultrabasic rocks, according to the behavior of the magnetic field, is shown in Figure 5.

Over the lateritic deposits the magnetic field generally presents negative values, suggesting little thickness of serpentinitic bodies on which these deposits are developed (Karlsen and Olesen, 1996). They are usually found in outlying areas of the ophiolitic massif where a tectonic horst exists which has caused erosion of the most superficial lithology, or both conditions at the same time (Batista, 1998; Batista and Rodríguez, 2000).

Different areas of hydrothermal alteration are reported in the region (Ramayo, 2001, 2003; Rodríguez-Vega, 1998; Vila, 1999; Batista and Ramayo, 2000a, b). Here the magnetic field possesses negative intensities smaller than -25 nT and aligned anomalies related to fault systems (Figure 1). Such results agree with geophysical studies carried out previously in this region (Batista, 1998; Batista and Rodríguez, 2000). The importance of the delimitation of those areas resides in that they can be associated to secondary mineralization in precious metals. The presence of gold has been reported by Vila (1999) and Batista and Ramayo (2000a, 2000b). On the other hand, great damage may be caused to the metallurgical process by the presence of siliceous material in the laterites (Rojas and Beyris, 1994). These alterations also offer information on the regional tectonic and physical-chemical conditions in the interior and surroundings of the rocks (Utada, 1990).

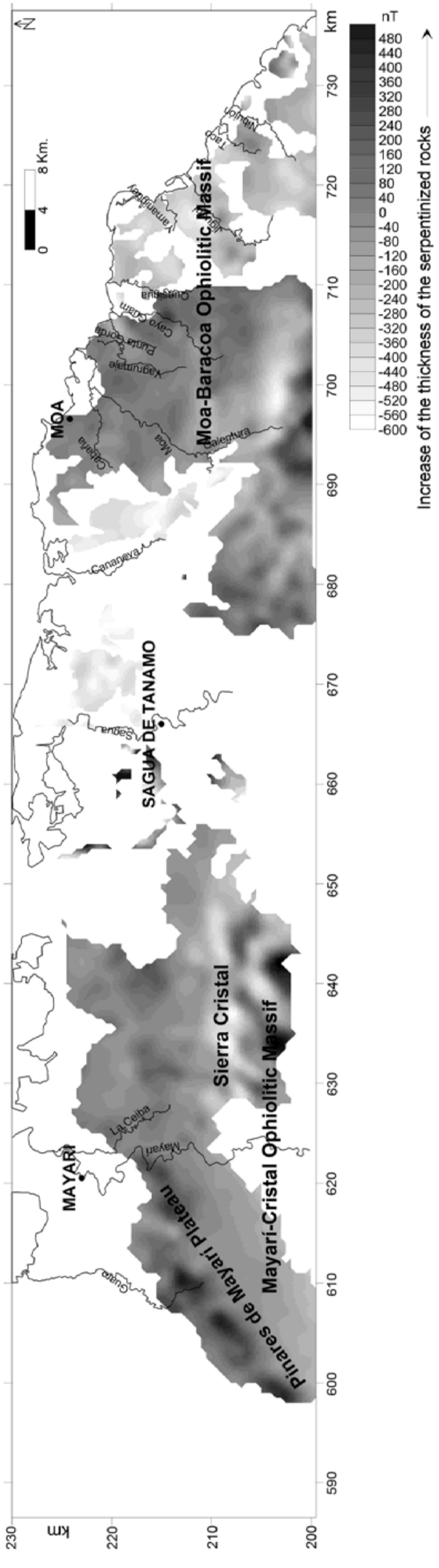


Fig. 5. Variations in the thickness of the serpentinized ultrabasic rocks according to the intensities of the magnetic field.

Shaded relief maps of ΔTrp and horizontal gradients

In the contour and relief maps of ΔTrp (Figure 4 and 6) and of the horizontal gradients (Figure 7 and 8), we find anomalous areas with northeast and northwest direction, which could be related to the main fault systems in the region (Figure 1), in agreement with Naidu and Mathew (1998), in a different region of the world. The high gradients observed in areas of change of polarity of the magnetic field, suggest abrupt contacts between the geologic bodies. The aligned areas that show positive values of the field are indicative of an increment of magnetization, caused in ultrabasic rocks, by an increase of serpentinization or the existence at depth of serpentinitic peridotites, according to work carried out in the study region (Chang *et al.*, 1990, 1991; Batista, 1998; Batista and Rodríguez, 2000; Batista *et al.*, 2002) and in other parts of the world (Best *et al.*, 1998; Goussev *et al.*, 1998; Hassan *et al.*, 1998; Peirce *et al.*, 1998). In ophiolites and volcano-sedimentary rocks the negative values in the anomalous areas can be related to the existence of hydrothermal alterations (Utada, 1990; Locke *et al.*, 1994; Alva-Valdivia *et al.*, 1997; Batista, 1998; Batista and Rodríguez, 2000; Alva-Valdivia and Urrutia-Fucugauchi, 1998; Chernicoff and Paterlini, 1998) or of less magnetic rocks in the depth (Batista, 1998; Batista and Rodríguez, 2000).

Some anomalous areas do not coincide with the fault systems, but they may be are related to tectonic structures not described, as there are deep structures without appreciable reflection at the surface or passive old structures, keeping in mind that such structures evolve in time and depth. These elements lead us to consider those anomalous areas for future geologic investigations. There are other structures that are not reflected in the magnetic field, because they are not associated to processes that alter the magnetization of the rocks or because these embrace small areas at the scale of the survey. The behavior of the magnetic field for most of the structures suggests positions, longitudes and forms that agree with the geologic and tectonic maps (Batista, 1998; Batista and Rodríguez, 2000).

Vertical gradient of ΔTrp

Figure 9 shows maps of the first and second vertical gradient of ΔTrp, in which appear different positive anomalies that reflect the existence of small and shallow geologic bodies with an appreciable magnetic behavior, which may provide information on shape, depth, extension, direction, etc. of the layers (Henderson, 1992; Best *et al.*, 1998; Chernicoff and Zapata, 1998; Nash, 1998). In the higher order gradients those anomalies are accentuated, indicating the existence in surface of the bodies that produce them (Gunn *et al.*, 1998). In the serpentinized peridotites we may observe many anomalies, some being elongated with northeast and northwest direction like the fault systems, others are found in areas of intersection of faults. These anomalies are due to an increment of serpentinization of the rocks (Chang *et al.*, 1990, 1991; Logachev and Zajarov, 1986), in agreement with works carried out in other regions of the world (Nash, 1998). In other parts of the region the anomalies are linked to gabbros and volcanic rocks or the proximity of serpentinized rocks.

Maps of upward continuation of ΔTrp

Starting from the geologic features and the results of previous geophysical work in the region we find in the same outcrops, fundamentally ophiolitic rocks to depths that oscillate between 2 and 3 km according to Fonseca *et al.* (1985), Quintas (1989), Chang *et al.* (1990, 1991), Batista (1998) and Batista *et al.* (2002).

We select heights of 250, 500, 750, 1500, 1800, 2200 and 4000 meters (Figure 10) for an analysis of upward continuation.

When the recomputed elevation increases, the behavior of the magnetic field depends on the characteristics of the largest and deepest geologic bodies, that is to say, the effect of the superficial rocks is eliminated (Gunn *et al.*, 1998). This transformation of the magnetic field has been used in numerous investigations with the objective of finding the deep structure of a region, as well as to separate the effect of different geologic objects of interest (Chang *et al.*, 1990, 1991; Pearson, 1996; Best *et al.*, 1998; Hassan *et al.*, 1998; Zaigham and Mallick, 2000; Batista *et al.*, 2002). In the study region initially the most important variations take place for the heights of 250, 500 and 750 m, which attenuate the small anomalies, of relatively shallow character and the effect of small bodies that produce them. In the case h = 250 m, the negative anomaly located to the northwest of the Pinares de Mayarí Plateau, is attributed to gabbros whose attenuation indicates depths of 250 m. In positive anomalies of serpentinized peridotites located to the southwest of Sierra Cristal and in the surroundings of Sagua de Tánamo and Moa town, this attenuation indicates that the thickness is less than 250 m except where anomalies with negative sign (north and south of Sagua de Tánamo town) in areas of serpentinized peridotites indicate the existence of a less magnetic lithology near the surface. Some investigators have suggested to the south of the Sagua-Moa region some ophiolites on volcanic rocks (Campos, 1983; Murashko and Lavandero, 1989). The bodies related to these anomalies possess depths around 250 m. For h = 500 m, the negative anomaly located northwest of Pinares de Mayarí Plateau in gabbros show the same depth. The attenuation of positive anomalies in Sierra Cristal and other areas in the surroundings of Moa and Sagua de Tánamo town, and on volcano-sedimentary rocks in this last town, suggests a depth

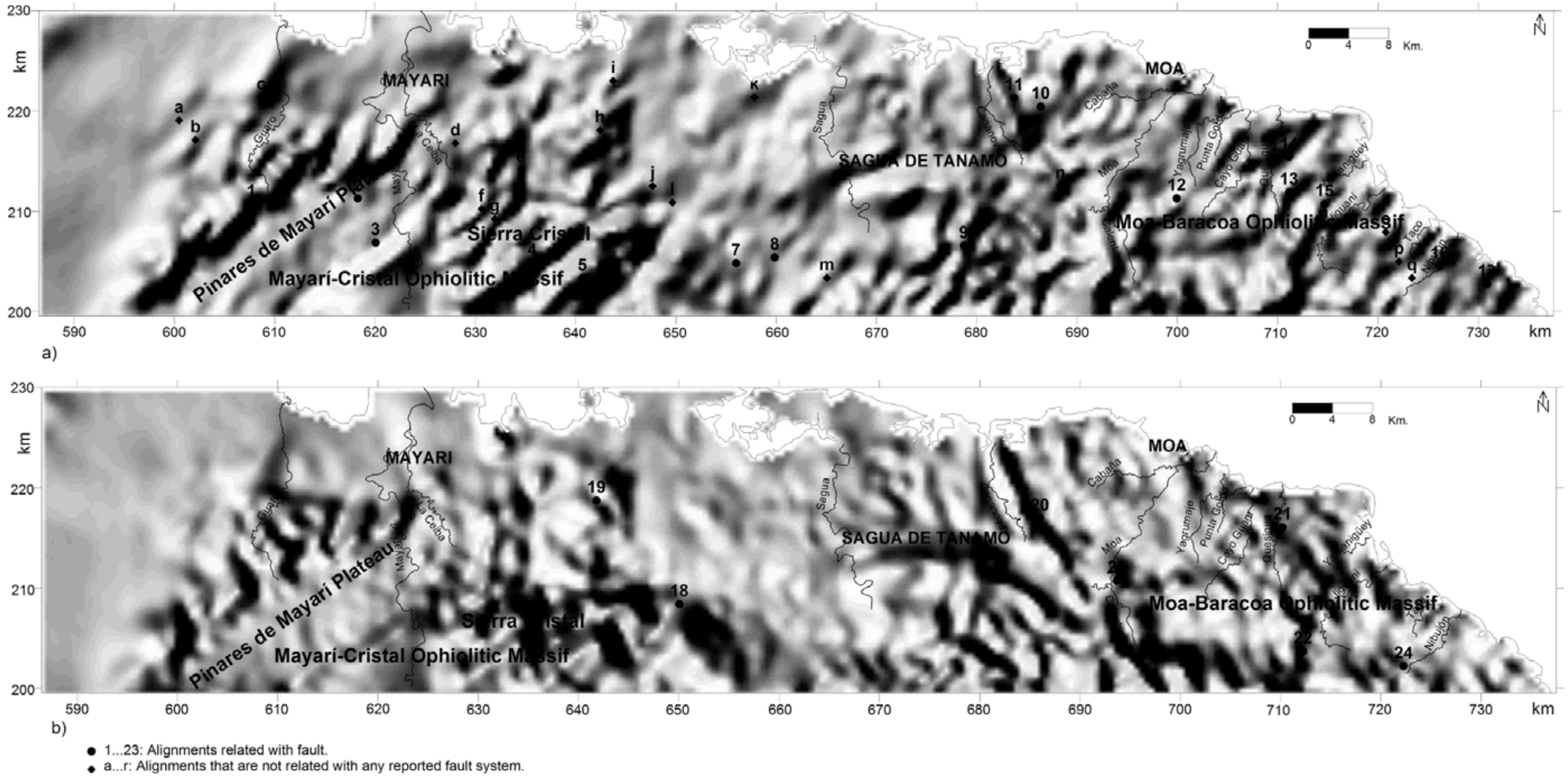


Fig. 6. Relief map of ΔT reduced to the pole (ΔTrp) of the Mayarí-Sagua-Moa region. a, ΔTrp illuminated from NW. b, ΔTrp illuminated from SW.

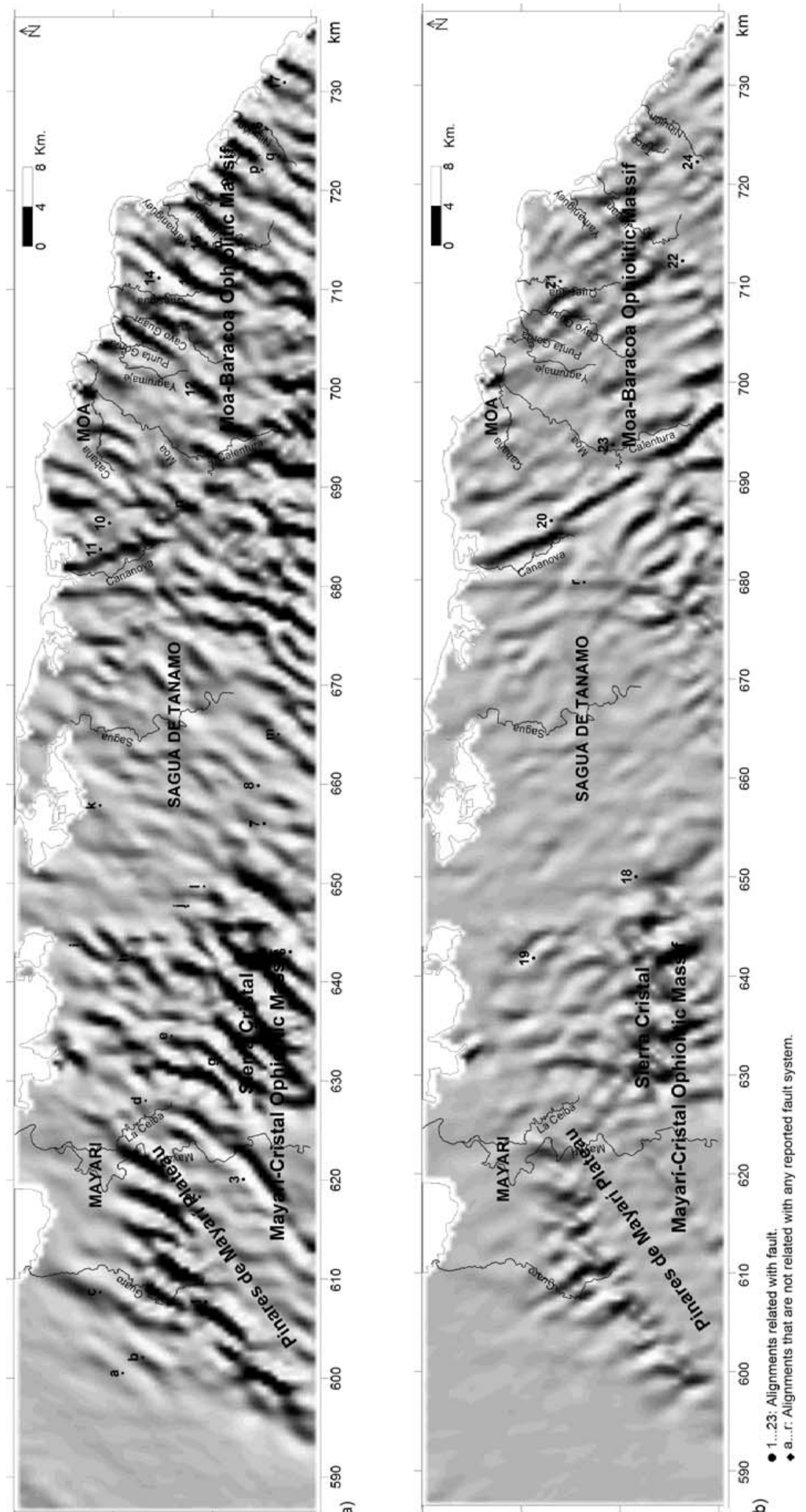


Fig. 7. Map of ΔTx of the Mayarí-Sagua-Moa region. a, ΔTx illuminated from W; b, ΔTx illuminated from SW.

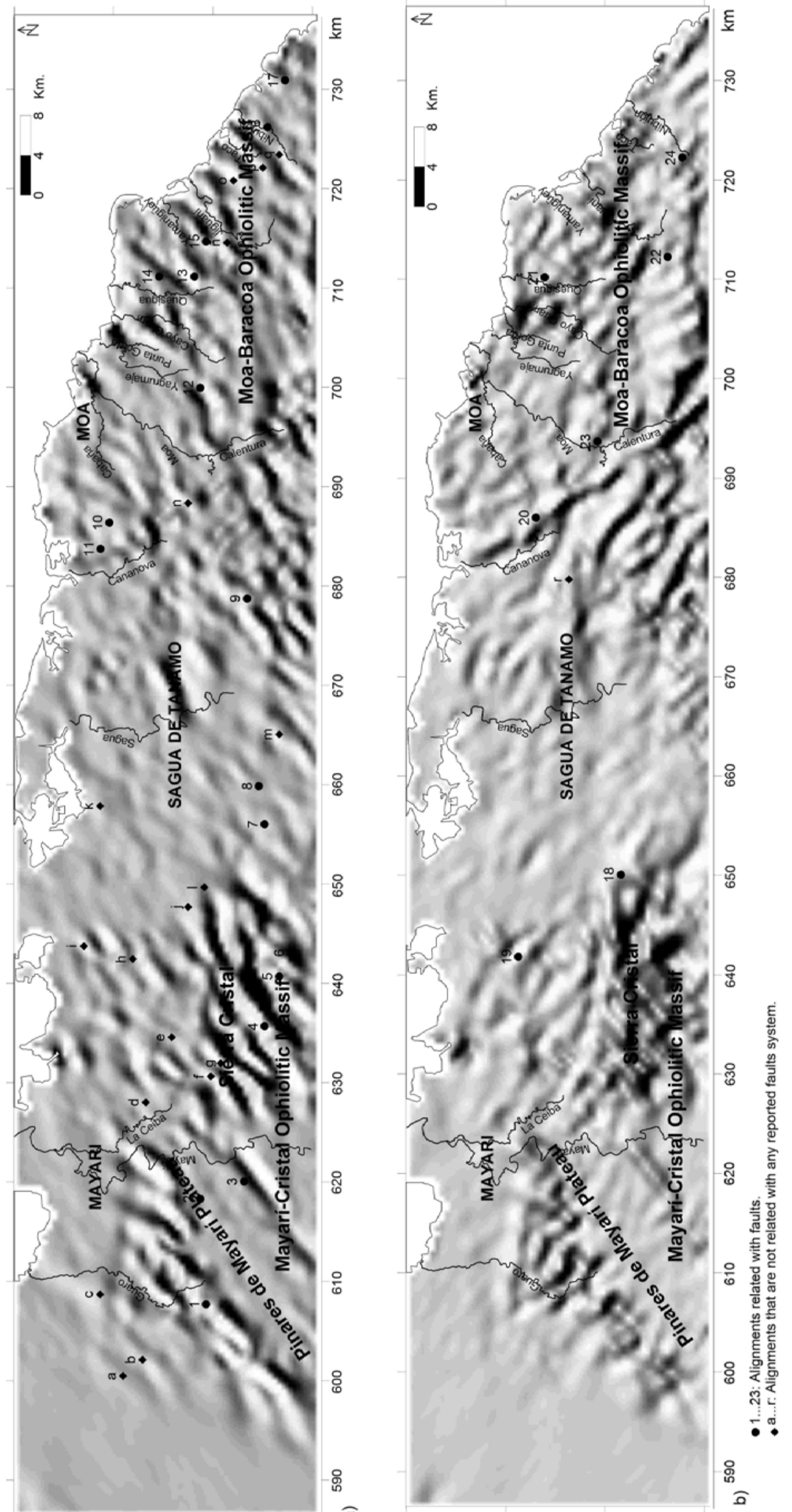


Fig. 8. Map of ΔTy of the Mayarí-Sagua-Moa region. a, ΔTy illuminated from SE; b, ΔTy illuminated from SW.

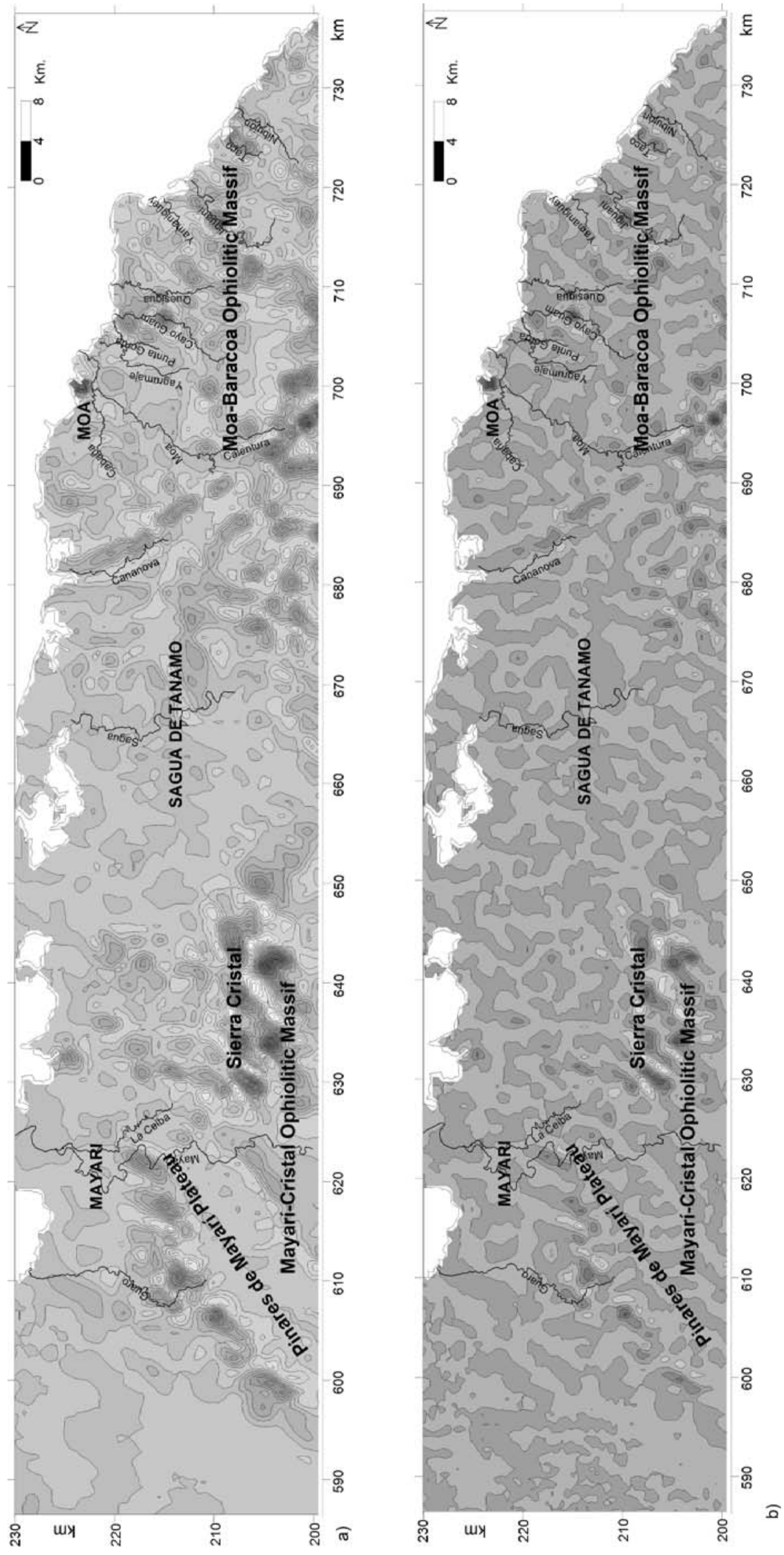


Fig. 9. Map of ΔTz (a) and ΔTzz (b) of the Mayarí-Sagua-Moa region.

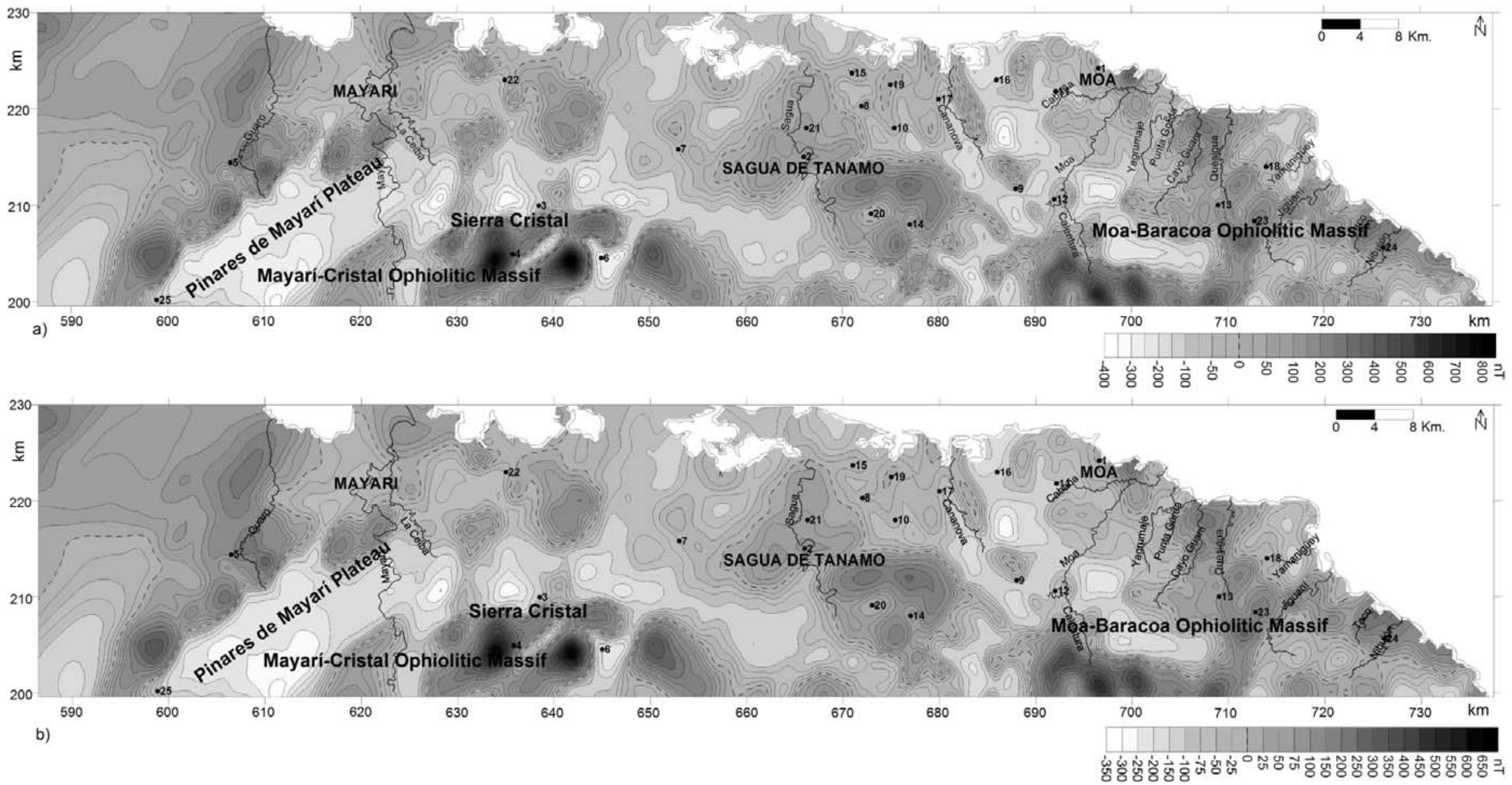
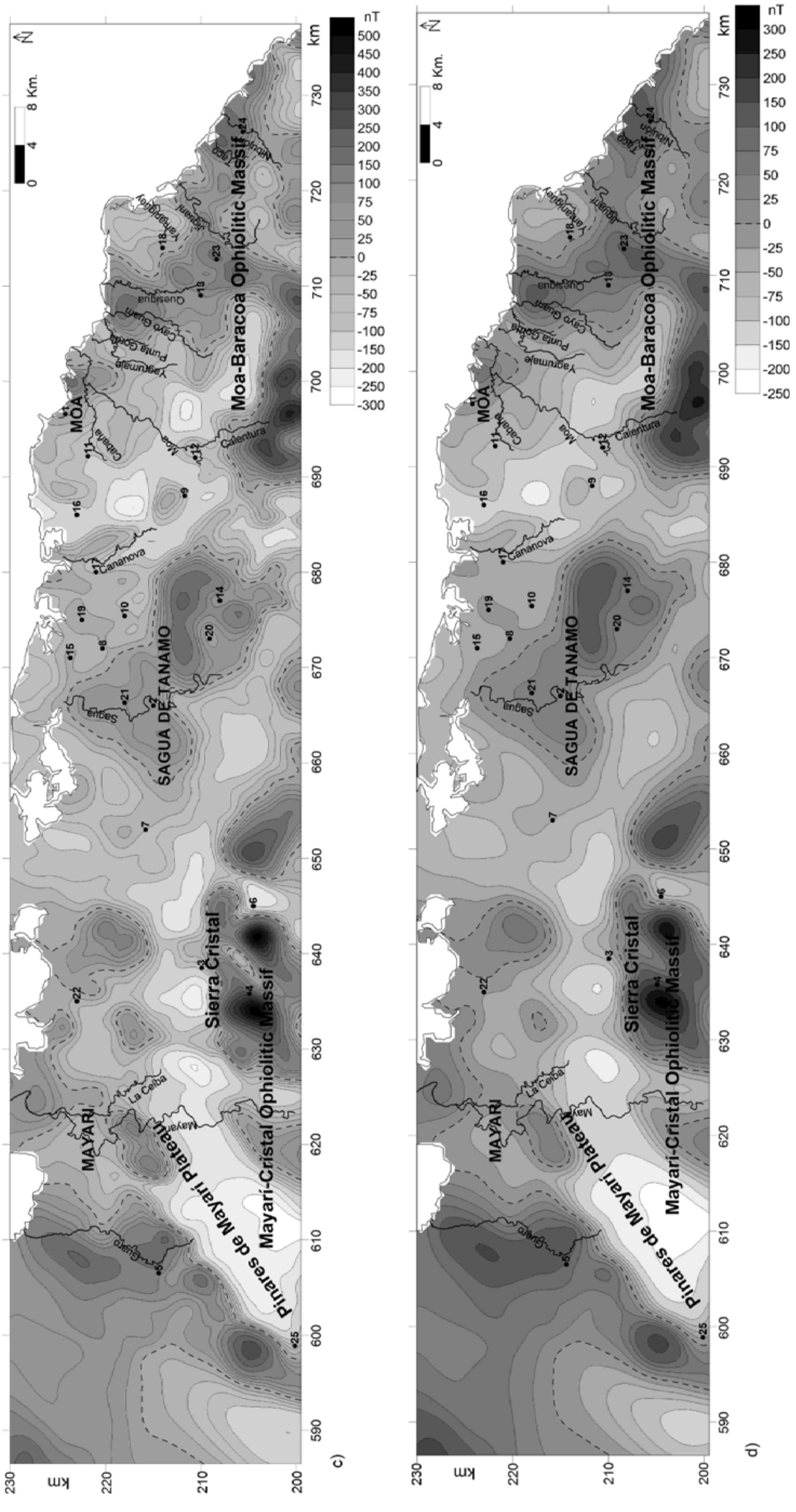


Fig. 10. Upward Continuation Map of the Mayarí-Sagua-Moa region. a, h=250 m; b, h=500 m; c, h=750 m; d, h=1500 m; e, h= 1800 m; f, h=2200 m; g, h= 4000 m. Towns: 1, Moa; 2, Sagua de Tánamo; 3, Sierra Cristal; 4, Cayo Verde; 5, Guamutas; 6, Moreiro; 7, La Güira; 8, Quemado de Aguacate; 9, Caimanes; 10, Barbarú; 11, Centeno; 12, Calentura Abajo; 13, Quemado del Negro; 14, Hato Viejo; 15, Cayo Acosta Dos; 16, Yaguaneque; 17, Cananova; 18, Cayo Grande; 19, Melena Ocho; 20, Castro; 21, Paso de la Vaca; 22, Levisa; 23, La Penda; 24, La Vega de Taco; 25, Sierra de Nipe.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Moa-Baracoa Ophiolitic Massif
Mayarí-Cristal Ophiolitic Massif
Pinares de Mayarí Plateau
Sierra Cristal
SAGUA DE TANAMO
MOA
MAYARÍ
La Ceiba
Mayarí
Guaro
Sagua
Cananova
Cabaña
Moa
Calentura
Yagrumaje
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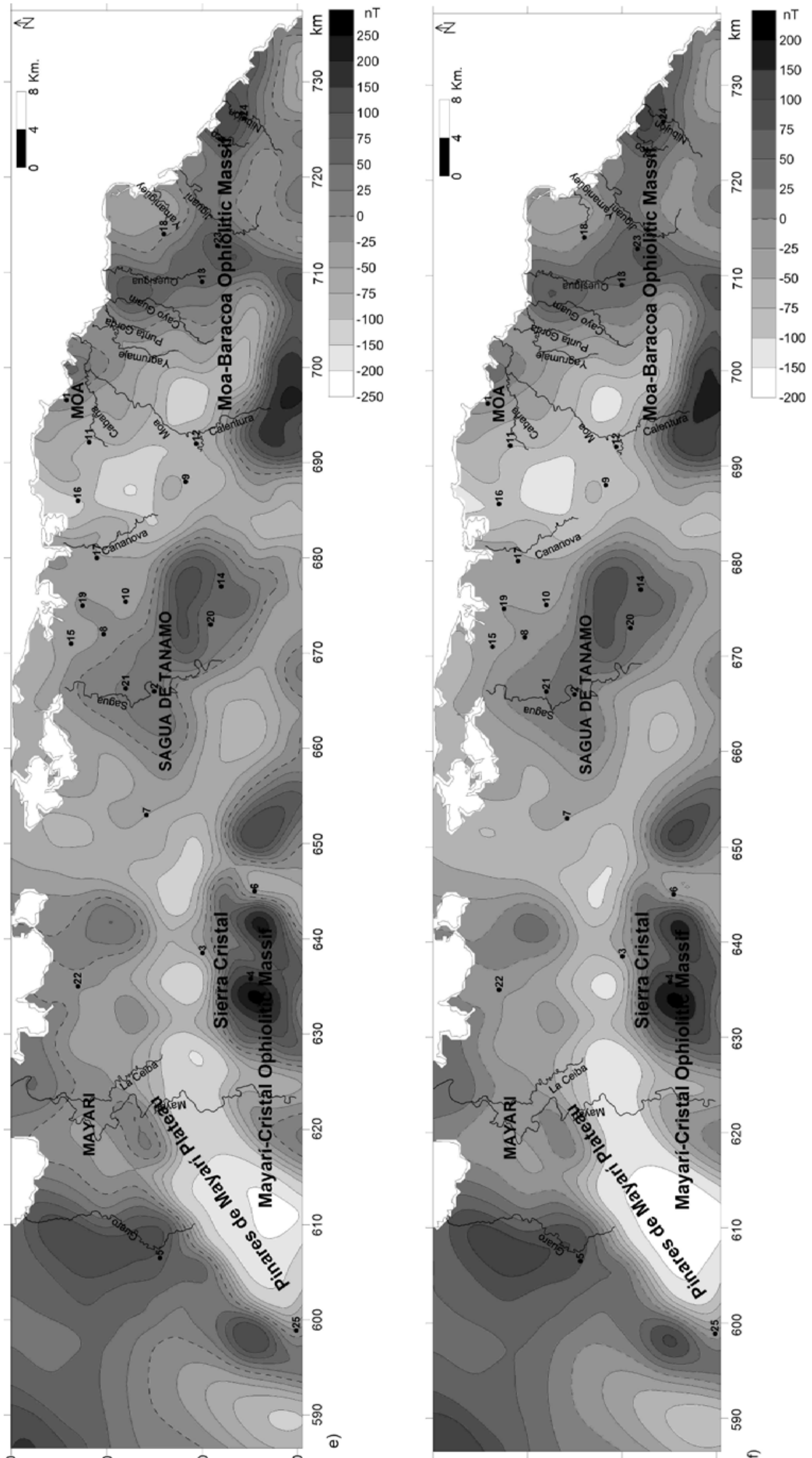
Cayo Guam
Quesigua
Jiguaní
Yamanigüey
Nibujón
Jaguaní

Fig. 10. (c,d) .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-200
-250
MOA
SAGUA DE TANAMO
MAYARI
Moa-Baracoa Ophiolitic Massif
Sierra Cristal
Mayarí-Cristal Ophiolitic Massif
Pinares de Mayarí plateau
Cananova
Cabaña
Moa
Calentura
Yagrumaje
Punta Gorda
Cayo Guam
Quesigua
Jiguaní
Yamanigüey
Sagua
La Ceiba
Mayarí
Guaro
Nibujón

Fig. 10. (e, f) .

of around 500 m for the serpentinized peridotites. The positive anomaly observed east of Moa town on serpentinized peridotites surrounded by gabbros confirm the results obtained from the map of ΔTrp, on a great depth of the gabbros and around 500 m depth of serpentinitic areas inside them. Finally, other anomalies are caused by bodies with larger depths around 750 m. The most significant are northeast and southwest of Sagua de Tánamo and Moa town, respectively, where volcano-sedimentary rocks outcrop in the first locality and serpentinized peridotites in the second. The last two areas are linked with a system of faults of northwest-southeast direction. Negative values are observed south of Sagua de Tánamo town, related to sedimentary rocks outcrop. For levels over 750 m no significant variations are observed until the interval 1500-1800 m, where the positive anomaly located on serpentinized rocks attenuates to the east of Mayarí town, suggesting a maximum depth of these rocks in this interval. At elevations of 2200 to 4000 m variations suggest that most of the peridotite bodies extending to such depths possess a metamorphic basement rich in magnetic minerals, as in other regions of the world (Logachev and Zajarov, 1986; Batista *et al.*, 2002). The areas where the serpentinitic bodies are deeper or their magnetized metamorphic basement is closer to the surface, are located to the northwest of Pinares de Mayarí Plateau, in the Sierra Cristal, north of Sagua de Tánamo town, and south and southeast of Moa town where mountainous relief prevails with a combination of tectonic movements and erosion levels.

The areas of important negative values and of smaller thickness of the serpentinized peridotites and deeper rocks of low magnetization are located south of Sierra de Nipe.

Figure 11 shows the main results obtained from the aeromagnetic survey interpretation.

RESULTS AND CONCLUSIONS

The aeromagnetic survey confirms the validity of the application of such surveys for areas of high geologic complexity in ophiolitic rocks.

Variations in thickness and lithology, of the two fundamental levels of the ophiolitic section defined the basement. Areas were also defined where the Cretaceous volcano-sedimentary rocks over on serpentinized peridotites. The high intensities of the magnetic field suggest that south of the Sierra Cristal the serpentinized rocks reach their maximum thickness or present a magnetic metamorphic basement near the surface. To corroborate this idea, detailed studies or deeper drilling in the region would be necessary. On lateritic deposits the magnetic field presents negative values, suggesting thin serpentinitic bodies in outlying areas of the ophiolitic massif or where a tectonic horst has caused

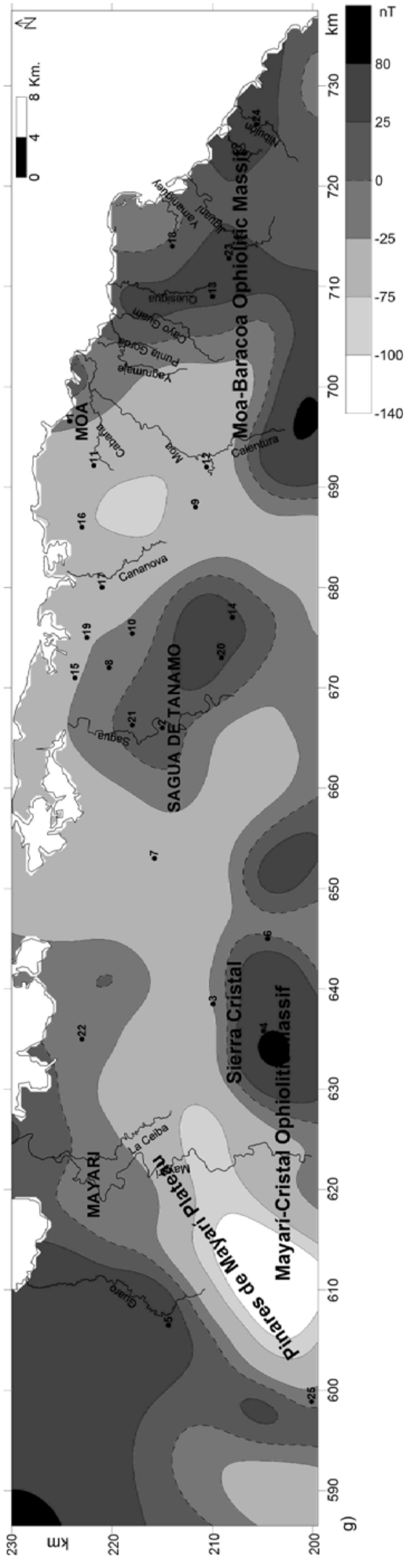

Fig. 10. (g) .

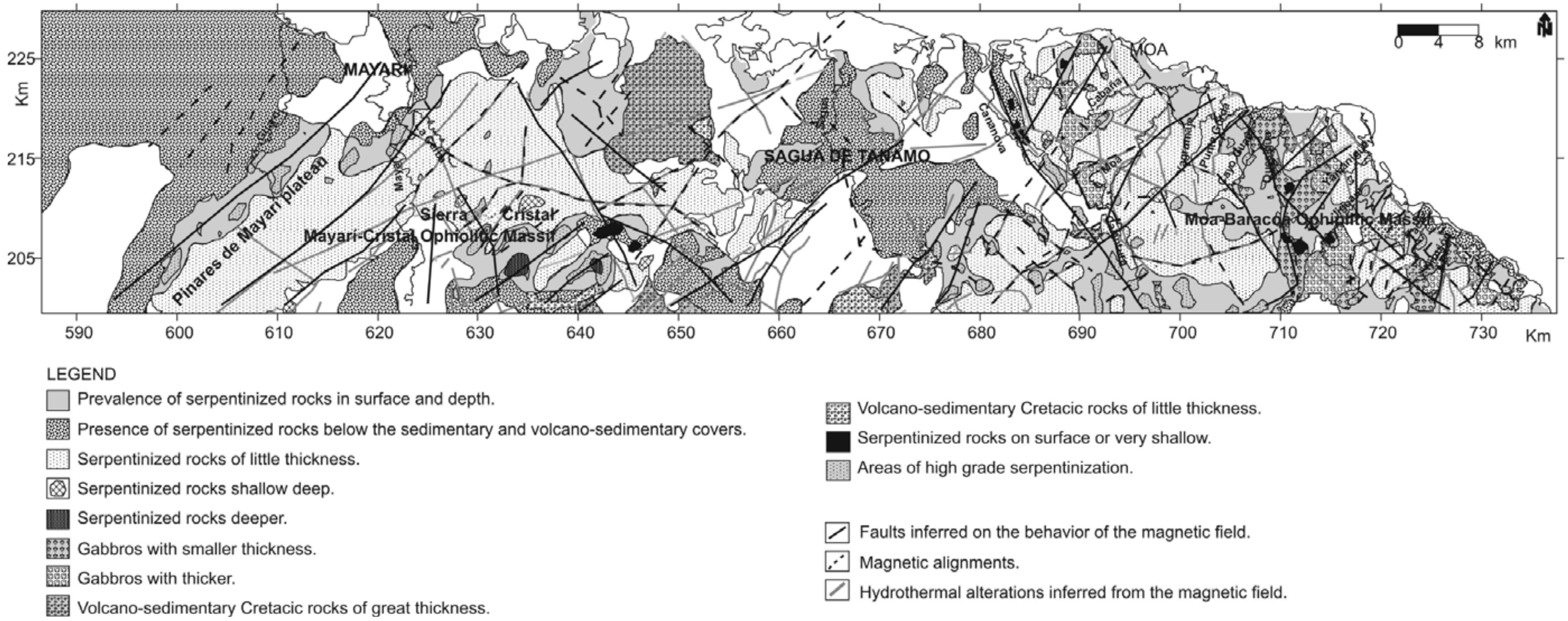

Fig. 11. Interpretation scheme of the aeromagnetic data.

the erosion of the cover. Lengthened anomalous areas, aligned anomalies and high gradients are reflected in the magnetic field.

Areas of probable hydrothermal alterations were defined, to assist in future prospecting for metals and exploitation of Fe+Ni laterites deposits. Tectonic windows were defined as well as sectors with increase of serpentinization along faults, and the proximity to the surface of ultrabasic rocks.

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José Alberto Batista Rodríguez
Instituto Superior Minero Metalúrgico de Moa.
Las Coloradas, Moa. Holguín, Cuba
Tel. (53)(24)(6)8190, Fax: (53)(24)(6) 2290
E-mail: jabatista@ismm.edu.cu