Review Article

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Non-seismic and non-conventional methods of exploration for oil and gas in Cuba: a review

Abstract

In oil and gas exploration, a decisive aspect is constituted by vertical microseepage of light hydrocarbons on gas-oil accumulations and the modifications that they produce in the surface environment (fundamentally, soils). Non-seismic and non-conventional exploration methods are responsible for detecting and mapping these modifications in the surface environment, thus complementing the complex of conventional methods with subsurface geological-structural mapping (~ 500m), the basis for a reduction of areas, with the consequent increase in the effectiveness of investigations and the reduction of risk in exploration. Unfortunately, the acceptance of these methods and their results is still going through a bad time, since the community of explorers and geoscientists who use seismic as their main investigative-exploratory tool still reject them or use them very limitedly. The aforementioned methods most used in Cuba are: Remote Sensing, Gravimetry, Aeromagnetometry, Unconventional Morphometry, Aerial Gamma Spectrometry and the Redox Complex. Also, Surface Geochemical Exploration is used with various direct methods. In relation to international literature, the processing and interpretation of geophysical-geochemical information in our country has innumerable theoretical-methodological inventions and innovations, totally Cuban. The work presented offers a current overview of the aforementioned methods in Cuba, based on a systematization-generalization of their information in almost a decade. The physical-chemical-geological premises that support the different methods, the main methodological characteristics have been addressed, and the most important geological tasks and their main results have been briefly examined on: the presence of biogenic methane; offshore exploration; support for geological mapping; the exploration of asphalt and bituminous rocks; exploration in land blocks; the exploration of sedimentary basins and; naphtha and gas exploration.

Keywords: gas-oil accumulation, micro seepage, non-seismic and non-conventional exploration methods, remote sensing, gravimetry, aeromagnetometry, unconventional morphometry, aerial gamma spectrometry, redox complex

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Introduction

In oil and gas exploration, a decisive aspect is constituted by vertical microseepage of light hydrocarbons on gas-oil accumulations and the modifications that they produce in the surface environment (soils, fundamentally). Among these modifications are: increased content of metallic elements (V, Ni, Fe, Pb and Zn); increased Magnetic Susceptibility; decreased Redox Potential and Spectral Reflectance, both reduced by the background; presence of minimums of the K/Th Ratio with maximums of U (Ra), mostly in its periphery; presence of residual (local) geomorphic and magnetic maximums and remote sensing anomalies, among others. The non-seismic and non-conventional methods of exploration (NSNCME) are in charge of detecting and mapping these modifications in the surface environment, thus complementing the complex of conventional methods with a reduction of areas and very valuable information: the possible load of hydrocarbons in a seismic structure and/or the presence of subtle stratigraphic traps. Unfortunately, the acceptance of the NSNCME and its results in oil and gas exploration is still going through a bad time, since the community of explorers and geoscientists who use seismic as their main investigative-exploratory tool still reject them or use them very limited.

In the international field, the most recognized and cited literature[1–5] on these methods emphasizes various non-conventional techniques, basically dealing with the modifications produced by the microseepage of light hydrocarbons in the soils over gas-oil accumulations. To a lesser extent, they focus support on subsurface geological-structural cartography (~500m) of the territory, the basis for mapping favorable areas for hydrocarbons with the determination of local perspective sectors (reduction of areas). Also, in relation to this literature, the processing and interpretation of the geophysical-geochemical information discussed in this article has numerous inventions and theoretical-methodological innovations, totally Cuban.

The NSNCME most used in Cuba are: Remote Sensing, Gravimetry, Aeromagnetometry, Non-conventional Morphometry, Aerial Gamma Spectrometry and Redox Complex. Also, Surface Geochemical Exploration is used with various direct methods. This complex of methods has as main purposes, in addition to the reduction of areas, the elevation of the effectiveness of the investigations with a reduction of the risks in the exploration.

During the reduction of areas, non-seismic exploration methods lead to the cartography of not a few favorable sectors, given by the contours of spatially close of AGS Anomalous Complex groupings (possible hydrocarbon microseepage). The resulting total anomalous picture is verified with the Generalized Response Models (GRM) on the known accumulations (reservoirs), previously determined, in order to establish the sectors that must be recognized and evaluated on land with a profile of the Redox Complex plus the direct geochemical techniques. Only very few perspective sectors are derived, where the presence of hydrocarbons at depth is established or not, mainly from the anomalous indications of Soil geochemistry (basically vanadium and nickel) and from the results of direct geochemical methods.

In oil and gas exploration, the two most important geological tasks that are undertaken simultaneously with the use of NSNCME are: support for subsurface geological-structural mapping (~500m) of the territory and mapping of favorable areas for hydrocarbons with the determination of the local perspective sectors. Thus, in Cuba, for the 2014-2022 period, various NSNCME GeoSoft Oasis Montaj Projects (processing and interpretation) have been prepared for different onshore oil blocks (6, 7, 8A, 9, 9A, 13, 14, 15, 17, 18, 21, 21A and 23) which are currently subject to constant review and reinterpretation. Also in the same period, this type of project has been carried out for the entire Cuban Island Platform (marine oil blocks) but only considering non-conventional Morphometry as an exploration method. Exceptionally, in very specific cases, gravimetry and aeromagnetometry have been processed, due to the difficulties for the availability of this information.

Various publications (monographs and scientific articles) on the results of the application of the NSNCME in Cuba serve as background and mandatory references to this work: Pardo Echarte and Rodríguez Morán,[6] (The Redox Complex); Pardo Echarte and Cobiella Reguera,[7] (Exploration in onshore blocks and naphtha exploration); Pardo Echarte, Reyes Paredes and Suárez Leyva,[8] (Offshore exploration by unconventional morphometric methods); Pardo Echarte, Rodríguez Morán and Delgado López,[9] (NSNCME for oil and gas in Cuba); Pardo Echarte,[10] (Exploration in land blocks) ; Pardo Echarte, Valdivia Tabares and Fajardo Fernández,[11] (Exploration of asphalt and bituminous rocks); Pardo Echarte et al.,[12] (Geological-structural mapping and favorable sectors for oil and gas in Cuba); Pardo Echarte, Delgado López and Morales González,[13] (Exploration of sedimentary basins); Pardo Echarte et al.,[14] in press (Presence of biogenic methane); Pardo Echarte, Rodríguez Morán and Fajardo Fernández,[15] (Exploration in land blocks); Pardo Echarte, Hechavarría Govin and Rodríguez Morán,[16] (Geological-structural mapping); Domínguez Sardiñas, Jiménez de la Fuente and Pardo Echarte,[17] (Gas exploration).

The work presented offers a current overview of the NSNCME for oil and gas in Cuba, based on a systematization-generalization of the information of these methods in almost a decade. In it, the physical-chemical-geological premises that support the different methods have been addressed; its main methodological characteristics and; the most important geological tasks and their main results have been briefly reviewed. Thus, the tasks of: the presence of biogenic methane; offshore exploration; support for geological mapping; the exploration of asphalt and bituminous rocks; exploration in land blocks; the exploration of sedimentary basins and; naphtha and gas exploration, are addressed.

Development

Physical-chemical-geological premises

In Cuba, from the petrophysical point of view, the high average density of Jurassic-Cretaceous carbonates, volcanic, granitoids and ophiolites justifies that their top elevations cause low-amplitude local gravimetric maximums. In the same way, due to the high magnetic susceptibility of ultrabasites and sometimes of granitoids, they present a very prominent anomalous response in the magnetic field and its derivatives.

From the point of view of Surface Geochemistry, according to Price (1985), Schumacher,[2] Saunders et al.[5] and Pardo Echarte and Rodríguez Morán,[6] the premises that support the application of geophysical-geochemical-morphometric methods of exploration for oil and gas are the following:

The migrating hydrocarbons are oxidized by microbial action, creating a reducing environment and producing mainly CO_2 and H_2S, which drastically changes the pH/Eh of the system, as well as the stability fields of the different mineral species present in that environment. These changes result in precipitation or solution and remobilization of various mineral species and elements, causing secondary mineralization of calcium carbonate and silicification. The latter result in denser surface materials, resistant to erosion and resistive (geomorphic anomalies and resistivity maximums are formed). In this way the rock column above an oil accumulation becomes significantly and measurably different from that of the laterally equivalent rocks, forming a type of “chimney”.

In seas, diagenetic carbonates can form slabs, rubble, large mounds and pillars, hard soils, or carbonate cements that fill porosity, all of which give rise to positive residual relief.

According to Pardo Echarte, Reyes Paredes and Suárez Leyva,[8] the morphometric methods used to assess the hardening of surface rocks on hydrocarbon deposits should consider the detection of geomorphic anomalies (local morphometric maximums) of low amplitude, of the order from the first meters to the first tens of meters and with dimensions equal to or greater than 0.5 km in diameter. For this, the residualization or regional-residual separation of the relief is required from the Digital Elevation Model (DEM). This residualization or separation of these two components consists of evaluating the regional characteristics and finding the local anomalies (residuals) by subtracting the regional effects from the corresponding relief or DEM. The objective of the residualization is focused on obtaining an ideal map to define the position, geometry and amplitude of the local geomorphic anomalies sought. After having tested on ground targets with graphical methods, sliding averages and polynomial fits, all with limited results, the idea of testing, directly, with upward analytical continuation (UAC) arose. In the calculation, the elevation was modified between 100 and 1000 m, obtaining the best solutions for the known targets on land and a few at sea, with the height of 500 m.

The decomposition of clay is responsible for the radiation minima reported on oil and gas accumulations: potassium is leached from the system towards the edges of the vertical projection of the accumulation, where it precipitates resulting in a halo of high values. Thorium remains relatively fixed in its original distribution within the heavy insoluble minerals; hence, minimums of the K/Th ratio are observed surrounded by maximums on the microseepage foci in the area of gas-oil deposits. For the most part, maximum U (Ra) is observed on the periphery of these foci. The grouping of anomalous complexes linked to these microseepage foci can determine, depending on the scale of work, the outline of plays, leads or prospects.

Regarding the role of hydrogen sulfide, its very presence conditions the formation of a column of reducing environment (minimum of Redox Potential) on the accumulation. This reducing environment in turn favors the conversion of non-magnetic iron ores into more stable magnetic (diagenetic) varieties such as magnetite, maghemite, pyrrhotite, and griegite. They are responsible for the increase in the Magnetic Susceptibility of rocks and soils and consequently for the presence of subtle local magnetic maximums on the accumulation. The coprecipitation of iron and/or manganese with calcite in carbonate cements on marine hydrocarbon deposits also results in an increase in Magnetic Susceptibility and Polarizability.

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Materials and methods[11]

Materials

The materials that are normally used and their sources are the following:

a. Grids of the gravimetric and aeromagnetic field at a scale of 1: 50 000 and aerial gamma spectrometry (channels: It, U, Th and K) at a scale of 1:100 000 of the Republic of Cuba.[18]

b. Digital Elevation Model (DEM) (90x90 m) taken from Sánchez Cruz et al.,[19] with source at: http://www.cgiar-csi.org/data/srtm-90m-digital-elevation.

c. LANDSAT 7 satellite images of the Republic of Cuba and their interpretation.[20]

d. Digital Maps of the Hydrocarbon Shows and the Oil Wells of the Republic of Cuba at a scale of 1: 250 000.[21,22]

e. Digital Geological Map of the Republic of Cuba at a scale of 1:100,000[23], used for the purposes of geological interpretation.

The processing of the geophysical information is carried out using the Oasis Montaj software version 7.01. The processing and interpretation of the data from the Redox Complex is carried out with the Redox System (Database and Software).[24]

Methods

Non-seismic geophysical exploration methods used in Cuba

The non-seismic geophysical exploration methods used in Cuba are:

i. Remote sensing (RS)

ii. Gravimetry (Gb)

iii. Aeromagnetometry (DT)

iv. Aerial Gamma Spectrometry (AGS). The latter is also classified as an unconventional geophysical-geochemical method together with the Redox Complex.

Remote sensing

In an area where there are hydrocarbon microseepage, an acid-reducing medium takes place, which favors the clay and iron layers to be altered. Thus, for example, clays change from montmorillonitic to kaolinitic. For its part, ferric iron (Fe^{+++}) becomes ferrous iron (Fe^{++}). A secondary carbonation process also occurs. All these alterations of the environment are reflected by tonal anomalies in the satellite images.

The unconventional way of processing the ASTER (15m resolution) and LANDSAT 7 (30m resolution) images, indistinctly, is related to the subtle darkening of the ground by the presence of metals, which is expressed in weak negative residual anomalies of Spectral Reflectance within the Visible Band (band 1). These anomalies are reflected in the so-called "Redox Scenarios". In the processing, band 1 is converted to Spectral Reflectance values, when analyzing. Then the background value (average) for the area where the target is located is subtracted from the entire territory. As a result, an image with residual Spectral Reflectance values (transformed) is obtained, which is conveniently reclassified to highlight the anomalous area (with negative values). The aforementioned procedure constitutes an innovation-generalization of the results of the Redox Complex regarding the use of Reduced (residual) Spectral Reflectance (RSR) in soil samples.

Gravimetry

The gravitational field (Bouguer Reduction, 2.3 t/m^3) is subjected to the regional-residual separation from the Ascending Analytical Continuation (AAC) for the heights of 500, 2000 and 6000m, given by the depth order of the possible oil and gas targets and seismic studies, although for geological-structural mapping, the first vertical derivative (GbVD) and the total horizontal derivative (GbTHD) are used, as the latter allows mapping the different tectonic alignments (faults) present.[9]

The geological-structural cartography based on the regionalization of the GbVD field distinguishes different zones of intense maximum values, maximums, intermediate values, minimums and intense minimums. The maximums and intense maximums can, as a rule, be basically associated with the presence of carbonates and ophiolites (occasionally, some granitoids), respectively. The minima and intense minima can be associated with the sediments of the basins (or structural depressions) and with the sequences of the Tectono-Stratigraphic Units (TSU) of terrigenous-carbonate composition. The salt structures mapped by the AGS and the DEM are revealed by minimum values of the GbVD field.

The residual field at 500m (Gbres500) and the GbVD allow the cartography of subtle local gravimetric maximums, associated with structural uplifts of carbonates and/or volcanics, with gas-oil interest.

Aeromagnetometry

The magnetic field is subjected to Pole Reduction (DTpr) and to the first vertical derivative (DTprVD). From these fields, the geological-structural cartography is carried out based on their regionalization, by distinguishing the areas of maximum, intermediate and minimum values. The maximum values, as a rule, respond to the presence of ophiolites and the minimum to the sediments of the basins or structural depressions. The tectonic alignments (faults) are determined from the total horizontal derivative (DTprTHD). Occasionally, weak local maximums related to diagenetic magnetic minerals associated with light hydrocarbon micro-seepage processes are observed.

Also, regional-residual separation is performed from the AAC at 500m, with the purpose of revealing deeper magnetic targets. Finally, quantitative estimates of the depth to magnetic targets under the sediments are made from the derivative of the inclination of the magnetic field (TDR).[9]

Unconventional geophysical-geochemical exploration methods used in Cuba

Aerial gamma spectrometry

In the AGS, the minima of the K/Th ratio (fundamentally from the minima of K) and the local maxima of U (Ra) are mapped, the latter mostly on its periphery, with the purpose of indicating the localities linked with possible active zones of vertical microseepage of light hydrocarbons.[9] In addition, known salt structures are reflected, mapped by zones of increased K values. Hydrocarbon-favorable areas are plotted from the outline of spatially close AGS Anomalous Complexes.

The redox complex

It is integrated by a set of techniques: Redox Potential, Magnetic Susceptibility, Spectral Reflectance and Soil geochemistry. The foundations of this complex of methods are collected in a Patent[10] and in a Protected Work (Redox System).[24]

The Redox Complex is a complex of unconventional geophysical-geochemical exploration techniques, used for the indirect detection and evaluation of various objects of a metallic nature (such as accumulations of hydrocarbons, due to the presence of V, Ni, Fe, Pb, Zn), which is based on the Geochemical Principle of the Vertical Migration of Metal Ions.

It is indicative of the physical-chemical processes and/or of the modifications of the environment that take place in the upper part of the cut, direct on the metallic occurrences, conditioned by the diffusion halos of light hydrocarbons and other satellite elements (metal ions) that they reach the surface. Its objective is to establish the possible presence of hydrocarbons in the depth and its main characteristics (degree of preservation of the possible accumulation and estimates of the depth and quality of the hydrocarbon).

The exploration strategy of this complex of techniques is based on considering a set of Scenarios (Structural Maps by seismic, Satellite Images (including Redox Scenarios), Maps of Potential Fields, AGS and DEM), from the which complexes of anomalous indications are established (favorable areas resulting from an integrated prospective cartography) to which a cross-sectional recognition profile is traced for ground verification by the Redox Complex and other direct geochemical techniques.

Geological tasks and their results

Presence of biogenic methane

According to Pardo Echarte et al.,[15] an important aspect to consider during oil and gas exploration using indirect geophysical-geochemical methods is the possibility of obtaining false anomalies caused by biogenic methane deposits. This is because microseepage of biogenic gas accumulations produces several anomalies, such as soil magnetic carbonate, radiation minima, and others, which are identical to anomalies created by microseepage from a thermogenic hydrocarbon reservoir. Hence, when the objective of the investigation consists of determining the presence of hydrocarbons in the depth of a study area, it is necessary to use a varied and sufficient set of indirect and direct geophysical-geochemical techniques, in order to be able to discriminate the nature thermogenic or biogenic of the hydrocarbons.

Biogenic hydrocarbons are generated by biological processes or during the early stages of alteration of recent marine sediments. Biological sources include terrestrial plants, phytoplankton, animals, bacteria, macroalgae, and microalgae. Its chemical composition has the characteristic that it presents hydrocarbon chains of 15 to 35 carbon atoms (C_{15} to C_{35}), since the compounds from C_3 to C_{14} are absent in living organisms. In addition, they have odd carbon chains in greater abundance than even carbon chains.

On the other hand, the composition of Natural Gas is made up of mixtures of essentially pure hydrocarbons up to mixtures with non-hydrocarbon gases whose main components are nitrogen, carbon dioxide (CO_2) and hydrogen sulfide (H_2S). The predominant compound is methane and its source is reduced soluble organic matter and perhaps CO_2.

A set of indirect and direct geophysical-geochemical methods possible for this purpose can be the following:

a) Environmental and geological field observations.

b) Kappametry and Soil geochemistry (belonging to the Redox Complex).

c) Recording of field gases.

d) Determination of fats and oils.

e) Liquid chromatography for determination of aliphatic and aromatic fractions.

f) Gas chromatography coupled to Mass Spectrometry.

The results of the research by Pardo Echarte et al.[15] (Figure 1), allowed establishing the presence of light hydrocarbons (mainly methane gas) of a biogenic nature accumulated in the shallow depth of the study area (south of the Guanahacabibes Peninsula, Pinar del Río province). This prevented the continuation of the exploratory tasks, highlighting the need and validity of the integrated use of indirect and direct geophysical-geochemical techniques. The finding was based on:

a. The results of the Soil geochemistry (The V/Ni ratio exhibits low values [<4 mg/Kg]).

b. Recently formed hydrocarbons exhibit a high level of odd-numbered n-alkanes.

c. They are the result of the contribution of detritus from terrigenous plants (predominance of n-paraffins in the C_{23}-C_{33} region).

d. Aromatic compounds are not present in significant proportions (>>4mg/kg).

e. Total absence of biomarker compounds (acyclic isoprenoids and extended Hopanes).

f. Absence of n-paraffins below C_{15}.

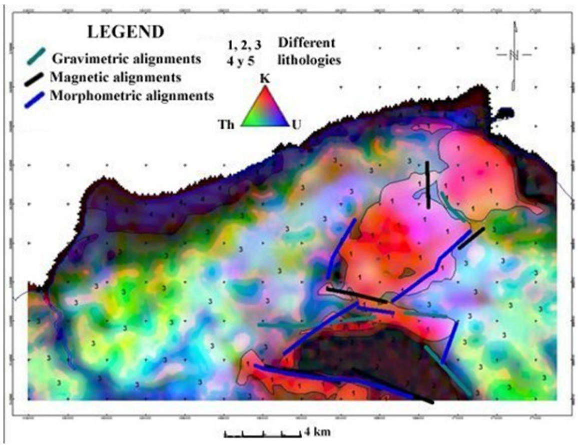

Figure 1 Antiformic structure devoid of vegetation and profile measured at the limits of a natural gas leak south of the Guanahacabibes Peninsula, Pinar del Río province. Taken from Pardo Echarte et al.[15]

Offshore unconventional morphometric exploration

According to Pardo Echarte, Reyes Paredes and Suárez Leyva,[8] the processing of the DEM (90x90 m) provides a quick form of preliminary offshore oil and gas exploration, being useful to focus on the areas to be surveyed with other complementary unconventional methods (Magnetic and Induced Polarization) from whose complex results the most expensive volumes of detailed 2D-3D seismic would be argued.

The totally marine study region is located in the western region of Cuba, between Morro-Cabañas and Varadero-Cárdenas, also known as the Northern Cuban Oil Strip (NCOS). The NCOS covers the coastal strip of the provinces of La Habana, Mayabeque and Matanzas, including the adjacent aquarium, about 5 km wide and 150 km long, where most and the largest deposits in the country have been discovered.

The geological task posed to the non-conventional morphometric processing and interpretation of the study area (Santa Cruz-Puerto Escondido sector) consisted of establishing geomorphic anomalies linked, presumably, to gas-oil targets of the Camajuaní and Placetas Tectono-Stratigraphic Units (TSU) of carbonated-terrigenous composition.

The DEM (90x90 m) was subjected to the regional-residual separation from the UAC at 500 m (DEMres500) and to the first vertical derivative (DEMVD), equivalent, but a little more resolute. To plot the morphotectonic alignments, the total horizontal derivative (DEMTHD) of the DEM (90x90) was used. The local morphometric maxima (geomorphic anomalies) and their amplitude relative to the background (less than or equal to 30m) were determined from the DEMres500 and DEMVD fields.

As a result, the mapped geomorphic anomalies seem to be linked to zones of active microseepage of light hydrocarbons over the gas-oil accumulations located, preferably, to the south of the presumed thrust fronts, mapped by the morphotectonic alignments (Figure 2). The figure also shows the outline of the main known oilfields.

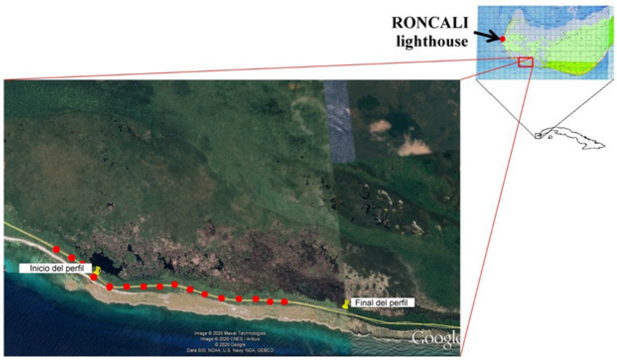

Figure 2 Geomorphic anomalies and their amplitude relative to the background (<=30m) and morphotectonic alignments of the study area (Santa Cruz-Puerto Escondido sector). The outline of the main known oilfields is also shown. Modified from Pardo Echarte, Reyes Paredes and Suárez Leyva.[8]

Support for geological mapping at a scale of 1: 50 000

According to Pardo Echarte, Hechavarría Govin and Rodríguez Morán,[15] the use of geophysics in support of geological cartography is very old. Traditionally, aeromagnetic data has been the main aerogeophysical parameter used. However, its use combined with apparent resistivity (Aerial Electromagnetic Survey-AEM) and Airborne Gamma Spectrometry (AGS) data achieves a much more useful product for this purpose. Potentially, other geophysical methods can be used to solve specific geological problems, particularly structural ones (detection of contacts and faults and delimitation of geological bodies), such is the case of gravimetry.

As a rule, field geological observations complemented with remote sensing information are insufficient for the purposes of subsurface geological cartography of a territory, particularly when its structural framework is very complex. In these cases, the assistance of geophysical-morphometric interpretation is essential. In this sense, it is known that potential fields help, basically, to the structural-tectonic deciphering of the territory and, to a lesser extent, to the lithological cartography of the different geological units present, resulting in the inverse contribution of aerial gamma spectrometry.

In the study region (sector of the northern coast of the provinces of Mayabeque and Matanzas), the gravimetric and aeromagnetic data potentially allow the identification of different geological-structural features: by minima, those associated with uplift of rocks of the North American Continental Margin (NACM) (within of the Cuban North Folded and Thrust Belt (CNFTB)) and to structural depressions (D); by maximums, those associated with the presence of the Zaza Terrane (Hatten et al., 1988), that is, volcanic+ophyolites (V). On the other hand, the DEM (90x90m) seems to reflect some outstanding geological-structural features inherited in the relief. Meanwhile, the alignments of potential fields and morphometric allow to trace the main tectonic limits of the territory.

The research used an integrated approach that considers the application of gravi-magnetic methods and non-conventional morphometry to map the subsurface geological structure (up to ~500 m depth), while to map the surface lithological composition based on the radioactive nature of the residual soils, the AGS is used.

As a result, the subsurface geological structure (~500 m) of the territory was mapped (Figure 3). This is how they are recognized: structural depressions, uplift of NACM rocks, tectonic limits, presence of volcanic+ophiolites and the possible extension in depth of outcropping geological bodies. In addition, the superficial lithological composition was established and mapped from the radioactive nature of the residual soils present (Figure 4), allowing to establish the presence of rocks with potassium feldspar, clay, carbonate with phosphatization, gabbro-serpentinite and of marshy deposits.

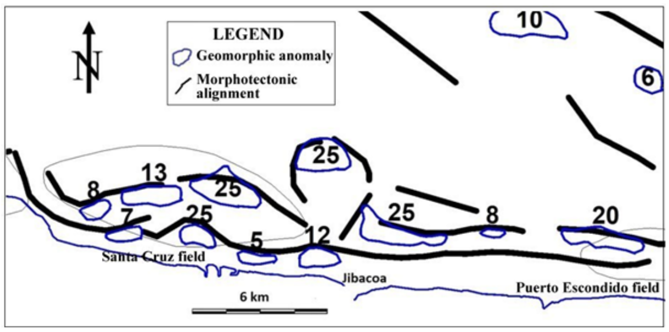

Figure 3 Diagram of the geological structure of the territory based on the integrated interpretation of geophysical and morphometric data. Taken from Pardo Echarte, Hechavarría Govin and Rodríguez Morán.[15]

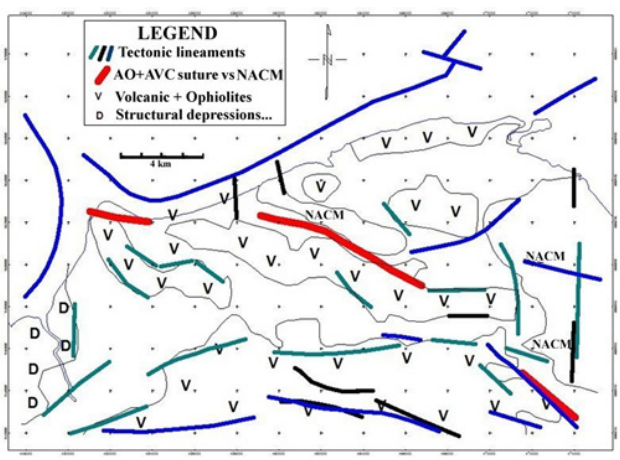

Figure 4 Lithological cartography from the Ternary Map (K, Th and U). Taken from Pardo Echarte, Hechavarría Govin and Rodríguez Morán.[15]

Exploration of asphalt and bituminous rocks

According to Pardo Echarte, Valdivia Tabares and Fajardo Fernández,[11] in the most diverse territories the exploration activity of asphalt and bituminous rocks involves considering the dichotomy in the physical-chemical-geological response of these two mineral forms, one liquid and one another solid. Thus, the presence of asphaltic rocks can be distinguished in the gamma spectrometry by minima of the uranium and total gamma intensity channels, due to the fact that the uranium and radioactive contribution, in general, is suppressed by the liquid nature of the mineral, equivalent to that of the petroleum. In contrast, the response of bituminous rocks (bitumens and asphaltites, solids) is uraniferous and slightly anomalous in the total gamma intensity channel (TGI), given the nature of organic matter. However, both types of rocks (asphalt and bituminous) have a similar expression in minima of the magnetic field reduced to the pole, maxima of apparent resistivity and minima of the Redox Potential. The dissimilar physical-chemical-geological response between solid and liquid hydrocarbons is well represented in the studied area (Municipality of Martí, Matanzas province), allowing to define in advance the nature and general characteristics of the hydrocarbon to be prospected.

The purpose of the research was to map the possible development zones of asphalt and bituminous rocks in the study region within the tectonic-structural framework in which they unfold. For this, the gravimetric, magnetic (DTrp), morphometric and aerial gamma spectrometry data of the territory were considered.

In the AGS, the minimums and maximums of the U(Ra)-TGI channels were determined, which were compared with the local minimums of the DTrp channel following a discriminatory purpose, in order to indicate the locations associated with the most probable areas of asphalt and bituminous rock development. In addition, the known asphalt and bituminous occurrences of the territory were considered.

The results of the AGS cartography, within the framework of the known asphalt and bituminous occurrences, are offered in Figure 5. It shows the minimums and maximums of the U(Ra)-TGI channels, together with the local minimums of the DTrp channel. Thus, two main favorable areas are established: one to the north, linked to asphalt occurrences and another to the south, of greater proportions, linked to bituminous occurrences. The geological-structural picture for these two favorable areas is different. Also, four presumably bituminous areas were mapped, of smaller proportions, spatially intermediate between the two previous main ones. The highest density of mapped tectonic alignments (gravimetric, magnetic and morphometric) is concentrated within the limits of the two main favorable areas determined, which could explain the high migration of hydrocarbons towards the surface with its consequent entrapment, oxidation and degradation in the form of asphalt and bitumen (the latter, in a sector with recent uplift, judging by the DEM data)

Non-seismic exploration in an onshore block

According to Pardo Echarte, Rodríguez Morán and Fajardo Fernández,[15] it is known that non-seismic exploration methods offer necessary and important information on the geological-structural cartography of the territories and on the presence in them of active microseepage vertical zones of light hydrocarbons, witnesses of possible accumulations at depth. That is why the benefits in the use of non-seismic exploration methods, integrated with geological and petroleum data, translate into a better understanding of the geology, as well as a better evaluation of the possible targets of interest and the exploration risk.

In this way, the geological task posed to the research consisted of supporting the geological-structural cartography and of favorable areas for the occurrence of hydrocarbons from an integrated geophysical-morphometric interpretation in the region of an onshore oil block in Central Cuba.

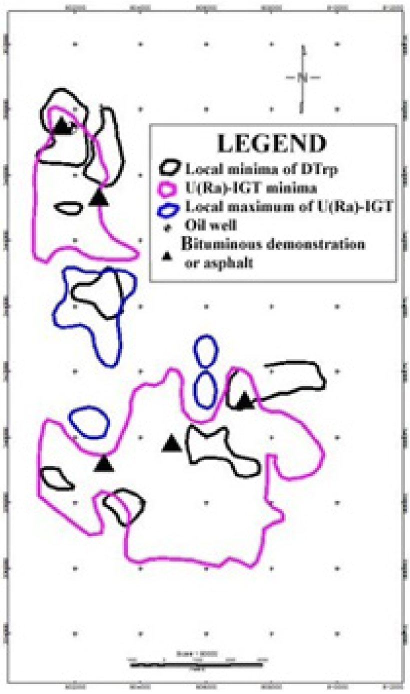

Figure 5 AGS mapping results (minimum and maximum of U(Ra)-TGI channels, together with local DTrp minima). In addition, the known occurrences of the territory are observed. Taken from Pardo Echarte, Valdivia Tabares and Fajardo Fernández.[11]

There is a well-established regularity in Cuba regarding the role of potential fields, unconventional morphometry and AGS in this type of geological task: the former basically help the geological-structural deciphering of the territory and AGS together with gravimetry and morphometry associated, allow to map the presumable active zones of vertical microseepage of light hydrocarbons on the possible accumulations of hydrocarbons.

The data used were: gravimetric and aeromagnetic fields at a scale of 1: 50 000 and AGS at a scale of 1:100 000; DEM (90x90m); maps of oil wells and hydrocarbon shows at a scale of 1: 250 000; and geological map at scale 1: 250 000.

As a result, the integrated gravi-magnetic, non-conventional morphometric and AGS interpretation in the territory allowed to recognize:

a. Different tectonic boundaries.
b. The magnetic expression of the crystalline basement of the Bahamas Platform.
c. The presence of volcanic + ophiolites (which in practice are indistinguishable in their magnetic behavior, only their limits being recognizable).
d. Synorogenic and postorogenic basins.
e. Structural uplifts of rocks of the NACM within the CNFTB, corresponding to the development zones of the Camajuaní and Placetas Tectonic Stratigraphic Units (TSUs), judging by the respective northern parallel strips of favorable areas observed within them.

f. Possible structural uplift of NACM rocks within a presumable Southern Fold Belt (SFB), judging by the presumed belt of favorable areas, with sublatitudinal direction, observed within the Cretaceous Volcanic Arc (CVA).

The results of the integrated prospective cartography, within the framework of known hydrocarbon shows and tectonic alignments (gravimetric) of the territory, are presented in Figure 6.

In general, all the mapped anomalous localities are located south of the Remedios TSU, which reinforces the criterion of gas-oil interest in oil and conventional gas from the Camajuaní and Placetas TSUs.[10]

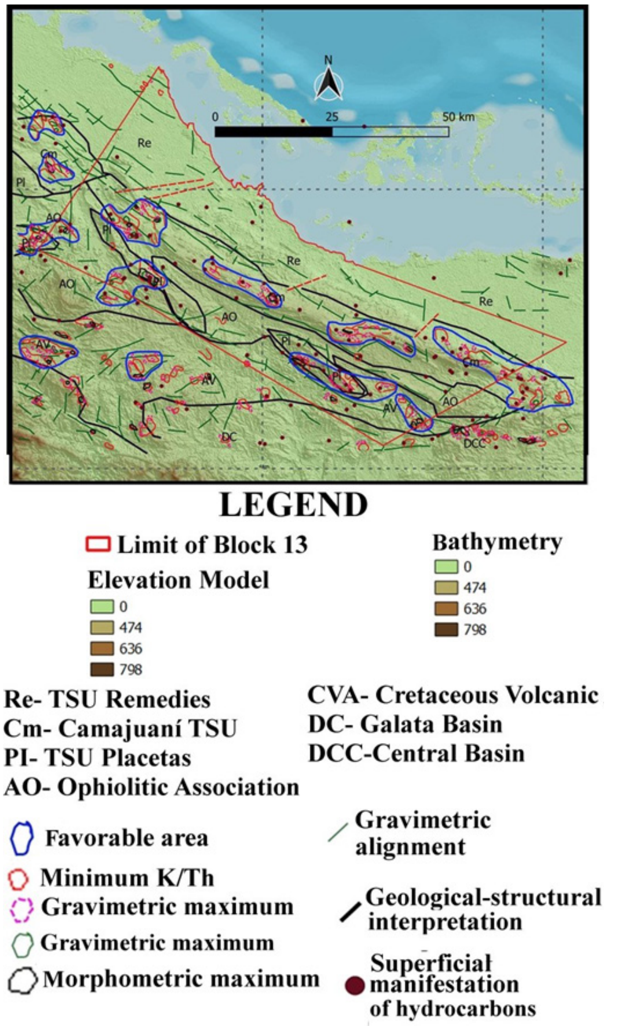

Figure 6 Integrated prospective cartography, in order to establish favorable sectors for the occurrence of hydrocarbons in the study area (Central Cuba). The results of the AGS cartography were considered together with the associated gravimetric and morphometric local maximums. Taken from Pardo Echarte, Rodríguez Morán and Fajardo Fernández.[15]

Exploration of sedimentary basins

According to Pardo Echarte, Delgado López and Morales González,[15] sedimentary basins are a traditional objective for oil and gas exploration in all territories. The cartography of its sedimentary thickness is an essential element to consider, but this information is not always available due to the limited volume and quality of seismic work and drilling carried out. The sedimentary basins of western Cuba have a magnetic basement made up of sequences of volcanics + ophiolites from the Zaza Terrane.[25] The cartography of the sedimentary thicknesses and the composition of the basement can be established from the processing and interpretation of the potential field data. For this, the research used an integrated approach that considers the application of methods to determine the depth to the magnetic basement, such as the derivative of the inclination of the magnetic field (Inclination-Depth Method) and 2D physical-geological modeling of potential fields. For its part, the integrated prospective cartography, in order to establish the favorable sectors for the occurrence of hydrocarbons in the study region, considered the results of the AGS cartography together with the local morphometric maximums.

Judging by past geological and geophysical information,[26] the real limits of the basins and sub-basins known in western Cuba cover both zones of minimum values and non-anomalous field as well as zones of maximum values, of the vertical derivative of the gravitational field (Gb250VD). However, it was decided to offer, in Figure 7, a version of the possible limits of the deepest parts of the basins from the gravimetric data. It also presents the depth to the magnetic basement by magnetic (Inclination-Depth Method) and wells data.

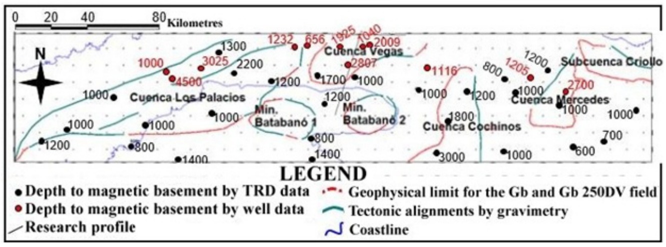

Figure 7 Approximate limits of the deepest parts of the structural depressions in the study area (western Cuba) according to the Gb (gravitational) and Gb250VD fields. In addition, the depth to the magnetic basement is presented by magnetic (Inclination-Depth Method) and by wells data. Taken from Pardo Echarte, Delgado López and Morales González.[15]

The results of the 2D physical-geological modeling of potential fields by a study profile are presented in Figure 8. The 2D physical-geological model essentially reflects the base and top of the main rock packages, showing their envelope. They simplify the geological characteristics present, in order to group several folded and thrust formations. The root mean square error obtained in the modeling of the gravitational field was 0.417 and in that of the magnetic field it was 62.6.

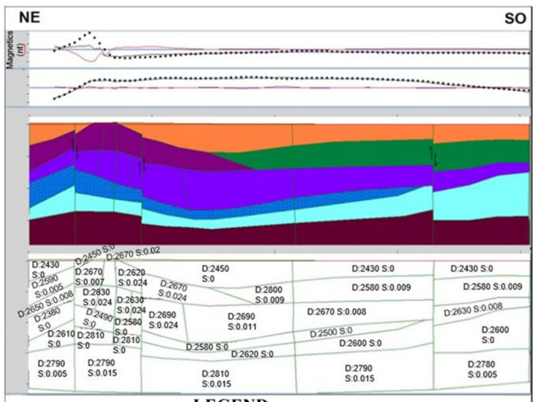

Figure 8 2D physical-geological model of potential fields for a study profile. D- Density; S- Magnetic Susceptibility. Taken from Pardo Echarte, Delgado López and Morales González.[15]

The results of the integrated prospective cartography, within the framework of the hydrocarbon shows and tectonic (gravimetric) alignments of the territory, are presented in Figure 9. These contemplate a group of three AGS anomalous complexes (Favorable Sector 1), two of them with associated morphometric anomalies in the Los Palacios Basin region, and a group of four AGS anomalous complexes (Favorable Sector 2), associated to a NW-SE striking fault by aeromagnetometry, in the Madruga region, Vegas Basin.

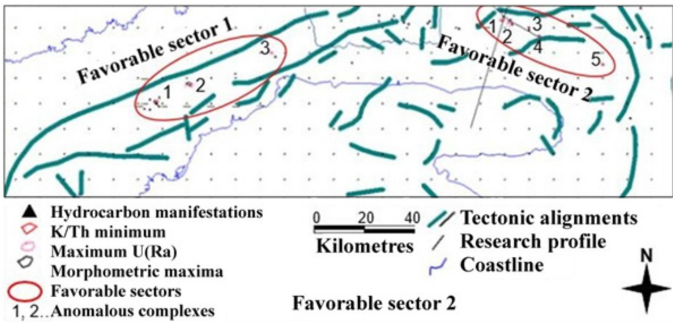

Figure 9 Integrated prospective cartography, in order to establish favorable sectors for the occurrence of hydrocarbons in the study region (western Cuba). The results of the AGS cartography together with the local morphometric maxima were considered. Taken from Pardo Echarte, Delgado López and Morales González.[15]

Naphtha exploration

According to Pardo Echarte et al.,[12] the Motembo naphtha deposit[27,28] was discovered between the years 1880-81. The naphtha accumulation zones correspond to the fractured serpentinite zones, small in size and with little or no communication between them. Currently, the original deposit is depleted.

In the southeast (SE) sector of Motembo, bounded to the east by a N-NW trending tectonic dislocation that apparently could have served as a migration route for hydrocarbons in the area, an anomalous complex (AC) of non-seismic methods is observed, with an extension of 2-3km^2 (Figure 10), made up of:

a. A minimum of the K/Th ratio (in red).
b. A maximum of U(Ra) (in pink), coincident with the minimum of K/Th ratio.
c. A remote sensing anomaly (RS) (in grey-green).

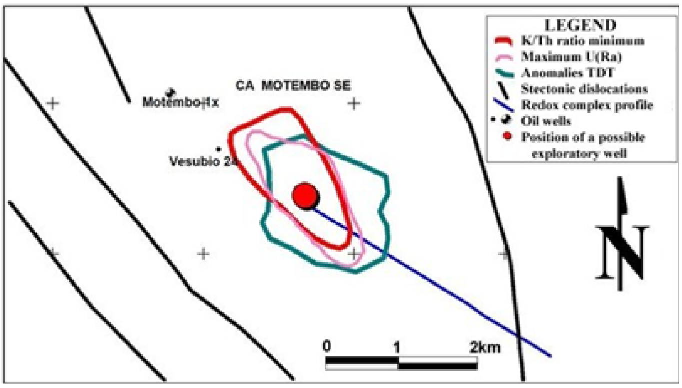

Figure 10 AC Motembo Southeast: in red, minimum of the K/Th ratio; in pink, maximum of U(Ra); in greyish-green, RS anomaly; in black, tectonic dislocations, by gravimetry; in blue, profile of the Redox Complex; the black dots correspond to the oil wells; the red dot indicates the position of a possible exploratory well. Modified from Pardo Echarte and Cobiella Reguera.[7]

The uraniferous nature of this AC, close to the edge of the ophiolitic massif, should be noted as of interest, revealing a very probable relationship with hydrocarbons. Near the town (NW), two oil wells were drilled.[29,30] The first, very close to the aforementioned AC, with a depth of 381m, had entries of naphtha at 327m and light oil at 342m. The second, more distant from the AC, with a depth of 1941m, had slight gas shows.

The results of the recognition work by the Redox Complex (Figure 11), according to a profile (blue line in Figure 10), were positive (anomalous) according to the Soil geochemistry at the western end, within the AC area (K/ Th-U(Ra)-RS), where the anomaly remained open. Notable increases are appreciated, in more than three to four times the local background of V, Pb and Zn. In addition, another narrow anomalous zone is observed at the eastern end of the profile, linked to the previously mentioned N-NW trending tectonic dislocation, which confirms its possible role as a migration route for hydrocarbons in the area.

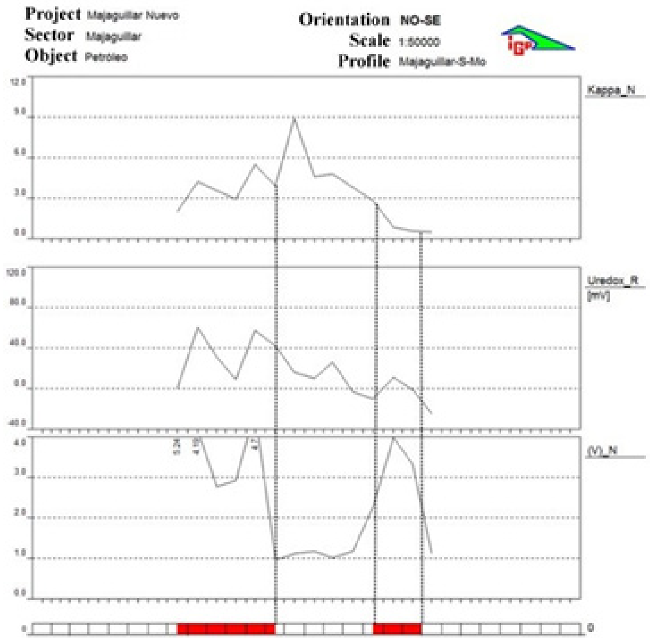

Figure 11 Results of the recognition profile with the Redox Complex. Anomalous Soil geochemical results (red bars) over AC Motembo SE (western end of the profile) and over the N-NW striking tectonic dislocation at the eastern end of the profile; the distance between points is indicative. Taken from Pardo Echarte and Cobiella Reguera.[7]

According to this information, the possible Naphtha target linked to the aforementioned AC, with an area of 2-3km^2, would be found shallow (300-400m) in crushed ophiolites, covered by massive ophiolites. This would represent an objective of limited scope, given its scarce exploitable resources, but with high interest, given the ease of operation and the high quality of the expected hydrocarbons.

Gas exploration

According to Domínguez Sardiñas, Jiménez de la Fuente and Pardo Echarte (in press), the integration of various exploratory methods, particularly non-seismic and non-conventional methods, is essential when evaluating the gas potential of an area. Thus, for gas exploration in the Motembo region, Villa Clara province, geochemistry, potential fields, aerial gamma spectrometry and remote sensing were considered. A Geographic Information System was used for gravimetric data, aerial gamma spectrometry, Aster satellite images, and chromatography for gas analysis.

In general, the integration carried out from the different non-seismic and non-conventional methods points to the presence of gaseous hydrocarbons towards the southeastern part of Motembo, in the region associated with carbonates. The gases in the area have multiple origins: those corresponding to the southeast region indicate that they are the consequences of an active and intense exudation and correspond to high gravimetric, airborne gamma spectrometry and remote sensing anomalies.

The integration of the results indicates the presence of three anomalous gaseous zones, probably, associated with surfaces altered by the existence of hydrocarbons that migrate to the surface. Of these areas, the one located furthest to the southeast is the one with the best representation and size (Figure 12).

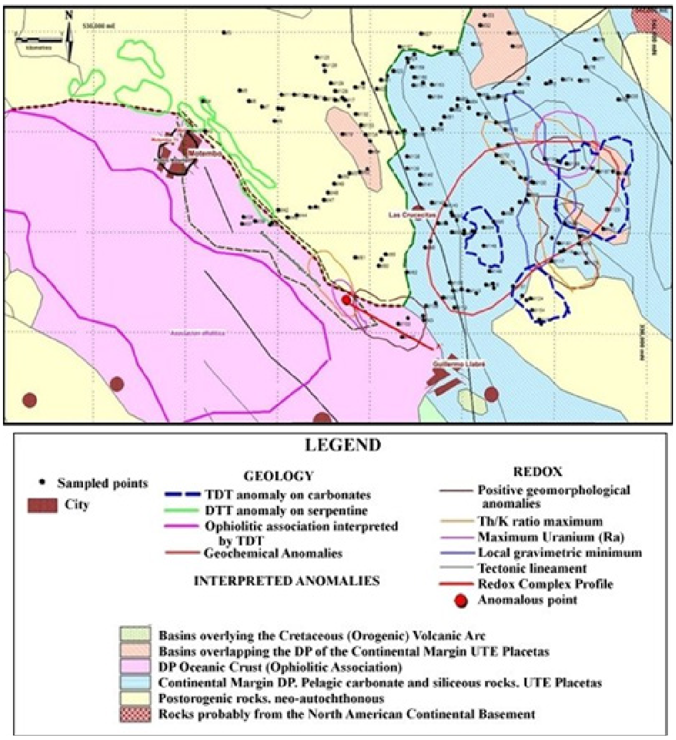

Figure 12 Integration of the results by the methods used in the Motembo area. Taken from Domínguez Sardiñas, Jiménez de la Fuente and Pardo Echarte (in press).[31]

Conclusion

i. The work presented offers a current overview of the NSNCME for oil and gas in Cuba, based on a systematization-generalization of the information of these methods in almost a decade in the country. In it, the physical-chemical-geological premises that support the different methods have been addressed, as well as their main methodological aspects and the most important geological tasks and their main results have been briefly examined. From the latter it is derived that the NSNCME for oil and gas used in Cuba are effective for solving the geological tasks posed.

ii. The NSNCME used in Cuba are: Remote Sensing, Gravimetry, Aeromagnetometry, Unconventional Morphometry, Aerial Gamma Spectrometry, Redox Complex and some direct geochemistry techniques. The aforementioned complex has as a novelty the integration of methods, all of them based (with the exception of Gravimetry) on the anomalous physical-chemical response of the environment against the microseepage of light hydrocarbons on the gas-oil accumulations in depth. This complex of methods has the purpose of subsurface geological-structural cartography (~ 500m), the basis for the reduction of areas, achieving an increase in the effectiveness of investigations and a decrease in exploration risks.

iii. In relation to the international literature, it emphasizes various non-conventional methods dealing, fundamentally, with the modifications produced by the microseepage of light hydrocarbons in the soils on the accumulations and to a lesser extent, they focus on the support of subsurface geological-structural cartography (~500m) of the territory, base of the mapping of favorable areas for hydrocarbons with the determination of the local perspective sectors. Also, the processing and interpretation of the geophysical-geochemical information discussed in this article has numerous theoretical-methodological inventions and innovations not considered in the international literature.

iv. During the reduction of areas, the aforementioned methods lead to the cartography of favorable sectors, given by groups of AGS Anomalous Complexes (possible hydrocarbon microseepage), which must be recognized and evaluated on land, subsequently, by the Redox Complex and other direct geochemical techniques. From this, only very few perspective sectors are derived, where the possible presence of hydrocarbons at depth is established, basically, from the anomalous indications of Soil geochemistry and the aforementioned direct geochemical techniques.

v. In the opinion of the authors, this document should be a recommended reference for all explorers and geoscientists in the oil industry inside and outside our country.

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Conflicts of interest

None.

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