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Geological-Structural Mapping and Favorable Sectors for Oil and Gas in Cuba

Non-seismic Exploration Methods

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ISSN 2191-589X ISSN 2191-5903 (electronic)
SpringerBriefs in Earth System Sciences
ISBN 978-3-030-92974-9 ISBN 978-3-030-92975-6 (eBook)
https://doi.org/10.1007/978-3-030-92975-6

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The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

After a little more than the first billion years, from the first stage of consolidation of our planet, the movement of the tectonic plates began to govern its evolution. This mechanism of global planetary dynamics would lead to the intensification of the recycling of terrestrial materials, climate changes and biological diversification on Earth. Thus, a particular geodiversity and biodiversity appear as the distinctive signature of our current world.

In the region that we know as the Caribbean, the processes and mechanisms of physical and biological evolution have left their mark since at least the beginning of the Mesozoic and up to the present day. With the birth of the "Tethys Sea", between the continental, North American and South American margins, the first magmatic and sedimentary rocks of the primitive Caribbean emerged. The Proto-Caribbean region would occupy an area, perhaps a million square kilometers in its beginnings; to develop and reduce itself to the present day, perhaps to a space barely equivalent to a quarter or a fifth. Subduction would lead to the disappearance of most of the materials that existed here; the tectonic accretion of the lands belonging to some paleogeographic domains against others, would lead to the shortening of the regional profile, and at the same time, to its thickening in parts.

The Cuban geological substrate, originated during the evolution of this intense geodynamic context, represents a complex, highly diverse set of lithic materials reduced to a geotectonic and structural strip, attached to the southern margin of the North American continent. Here the remains of several paleogeographic domains converged. Namely, elements of the intraoceanic volcanic island arc systems, which were born, developed and disappeared during the Cretaceous and Paleogene periods; relics of oceanic crusts; of intraoceanic rift systems and associated sediments; of metaphorized continental lands; intramontane and piggy backs basins; of foreland basins; and postorogenic coverage until recent. As is understandable, the original relationships between the aforementioned geological–geographical elements are today very difficult to restore in a coherent reconstruction. Thus, Cuban geosciences have had, historically, and to date, immense cognitive challenges: establishing regularities and useful hypotheses in economic practice, such as the exploration of natural resources essential for the development of our country.

Today the geological substrate of the Cuban territory is assumed, in general, as parallel tectonostratigraphic strips, more or less narrow, ridged and folded, imbricated in several mantles, forming complex structural stacks, in a sublatitudinal direction, segmented and accreted along from the southern margin of the North American continent—Bahamas platform to the north, and from the Mayan continental block—Yucatan platform to the west. Under these conditions, hydrocarbon exploration in particular faces the compression of past oil systems, their evolutions and, most importantly, the establishment of their elements in the current geotectonic situation and structure. The identification of source rocks, the types of original organic matter, the conditions of genesis for the oils and their migrations and dismigrations over time; the types of traps and the nature of the reservoirs, the flows and migration routes; and local and regional seals, the possible volumes of hydrocarbons contained, among others, etc., are goals assumed by generations of Cuban and foreign geoscientists, already for almost a century of work.

The surface shows, tar springs and natural asphalt, were the direct indicators of the existence of hydrocarbons in a given area, but the search for economically significant accumulations, through the drilling of exploratory wells, in occluded deposits, would be the most promising challenge. But only the knowledge of the geological premises was quickly insufficient to obtain optimal results in oil exploration. Thus, geophysical methods decisively complete the answer to such challenges. The diversification of its applications, based on natural physical fields, had promising advances for exploration. Well logging methods reinforced the interpretation of lithologies, their properties, limits and thicknesses of different units traversed, allowing the characterization of reservoirs and testing the most promising correlations.

At present, the theoretical and technological advances that are presented to us are truly impressive, however, the increasing depth of exploration, the already described high geological complexity of the Cuban territory, the surprising variability in the types of reservoirs (carbonates, serpentinites, volcanic rocks and others) and the need to achieve high economic efficiency, among other pressures, require a complex, holistic approach to current gas-oil exploration work. Thus, the integration, increasingly sophisticated and creative with the use of new software, of all available data and methods, is shown as the most advisable way to search for oil and gas in Cuba. The research team that offers us this scientific contribution dedicates their efforts to this cardinal objective.

The authors value that the investigations in oil and gas exploration take into account the most classical components that characterize the geological-geophysical-geochemical “macro” aspects, those that are more evident and better accepted. However, they maintain that there are indicators considered “micro”, less evident and not widely accepted, but that they can play an important complementary role to the first, with the common and main objective of achieving greater efficiency in

new discoveries. To solve this last task, they assume the so-called unconventional geophysical-geochemical exploration methods. The authors base their line of study, developed in decades of work, on the existence of microseepage of light hydrocarbons in the vertical, which lead to superficial modifications on accumulations in the subsoil, such as seismic structures or stratigraphic traps, charged. Hence, the need to achieve a detection and mapping of the areas affected by microseepage; and, in addition, contribute to recognize the geological–structural context of its occurrences.

It is known how expensive it is to acquire and process high-quality modern seismic information, carried out with the use of sophisticated and highly specialized technology. On the other hand, the present team of researchers, in order to fulfill their task, promote the use of non-seismic exploration methods used in Cuba: remote sensing, gravimetry, aeromagnetometry, airborne gamma spectrometry (AGS) and morphometry (non-conventional) from Digital Elevation Model 90 × 90 m. They clarify that the AGS also classifies as an unconventional geophysical-geochemical method along with the Redox Complex. In addition, they process gravimetry, aeromagnetometry and morphometry at a scale of 1:50000, AGS at a scale of 1:100000, and ASTER and LANDSAT satellite images (with resolution of 15 and 30 m, respectively). The result to be achieved is the reduction of areas for more effective exploration, which also leads to risk reduction. From the implementation of these methods, the perspective sectors for oil and gas are obtained once the integration with the corresponding geology and seismic has been carried out.

In the western region of Cuba, with several land exploration blocks, geological-structural cartography, based on gravi-magnetic and morphometric data, establishes possible structural highs that alternate with depressed areas. The authors achieve a version of the mapping of favorable sectors of interest related to conventional oil and gas in the Tectonostratigraphic Units of Camajuaní and Placetas, associated with the Continental Margin of North America. The proposal is based on the presence of a complex of anomalies of geophysical-morphometric indicators, considering minimums of the K/Th ratio and local maximums of U (Ra) in its periphery, remote sensing anomalies, as well as local gravimetric, magnetic and morphometric maxima.

In areas with microseepage near the Motembo oil field and the Menéndez-Bolaños area, in the province of Villa Clara, they were corroborated by data from surface geochemical surveys with the presence of gas in soils. These areas of possible hydrocarbon microseepage were achieved from the study of the latest indirect indices through the analysis of optical images. In another case, in the Majaguillar area, another area with microseepage was identified, with similar patterns, supported by the interpretation of a complex of non-seismic and non-conventional methods.

The well-known Central Basin of Cuba has been one of the important oil regions of the country, distinguished by its peculiarities in the exploration and extraction of hydrocarbons, given by reservoirs in effusive and clastic volcanic rocks. This is a first-order structure, regional in nature, it had its development in relation to the evolution of the La Trocha fault system. This last tectonic element has had a long existence, dividing the substratum of the Cretaceous volcanic arc, participating in regional thrust

and folding and influencing the diastrophism of the crust, elevation and subsidence of blocks, erosion and sedimentary accumulation, regional, etc. In this context, the authors point out that the 2D physical-geological models of potential fields have the objective of clarifying the deep constitution of the territory, given the interest in finding conventional oil and gas from the Tectonostratigraphic Units of Camajuaní and Placetas, in the sediments of the Continental Margin of North America. From this it is inferred that the hydrocarbons known in the area are products of migration from the underlying bedrock, related to the basin-platform slope sequences. Several sectors are defined as perspective, to be contrasted with the seismic information.

The authors evaluated several areas that meet, according to their results, the geological-oil premises for the presence of large accumulations of high-quality oil. For their study, they used more than 2000 rock samples, more than 200 oil for physicochemical analysis and biomarker testing, and 27 organic extracts of bedrock for geochemical correlations. Only those areas with high thermal evolution of oil were taken. As a result, they determined the types of oils of families I and II of Cuban crude oils, which indicate the presence in the subsoil of an Upper Jurassic-Lower Cretaceous tectonic plate; and Family III, indicating the presence in the subsoil of the Lower-Upper Cretaceous tectonic plate. Among the areas analyzed, there are exploratory blocks in the Central Basin, which meets all the premises for the presence of large accumulations of high-quality oil. According to the work team, in the rest of the assessed areas there is variation in thermal maturity, increasing the risk of finding deep accumulations with high-quality commercial crude.

For more than three decades, the main authors (MEPE, ORM) have accumulated vast experience in the application of the most varied geophysical methods, in geophysical-geochemical mapping, in geological-structural and tectonic regionalization, among others. The development of techniques and methods for studying the Redox Potential with different uses; and in the last two decades, the integration of the Redox Complex with its introduction in research associated with the exploration of hydrocarbons in the country and other regions. The foregoing has led to a solid conceptual foundation and innovation in integrative methods and techniques, with holistic interpretations and demonstrated practical scope. They even have experience in the development of their own software, to solve tasks in their daily work.

The present volume *Geological-Structural Mapping and Favourable Sectors for Oil and Gas in Cuba. Non-seismic Exploration Methods* groups and consolidates a new vision on the knowledge in the integration of data and information, applicable in the exploration of hydrocarbons in Cuba. The extensive experience of the main authors of the work team, both as researchers in different areas of application of geophysical-geochemical-geological studies, as well as professors in higher education centers in Cuba and abroad, they endorse the consistent scientific conceptualization of the content that is offered to us. The young researchers, accompanying those wise men, broaden the horizons of the approaches used in the studies carried out and provide comprehensiveness to the consolidated results.

Finally, I would like to congratulate the guides and participants in this book, and a call to attention to those decision makers, responsible for supporting the application of the methods, techniques and concepts demonstrated here reliably. I thank Dr. Manuel Pardo Echarte for the privilege of having the opportunity to review this valuable contribution.

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Preface

In solving any problem of geological exploration, it is essential to use a holistic approach, that is, to consider the integration of the parts or components subject to investigation. As a rule, these components characterize the "macro" geological-geophysical-geochemical aspects (large, more evident and better accepted) and the "micro" ones (small, less evident and little accepted). Usually, for the study of the latter, the so-called non-conventional geophysical-geochemical exploration methods are used. In the particular case of oil and gas exploration, the nucleus of the "micro" aspects is characterized by the microseepage of light hydrocarbons, with a vertical nature on the gas-oil accumulations, as well as, by the modifications that occur in the superficial medium as a result of it. Thus, the problem lies in the need of detection and mapping of microseepage, complementing the conventional methods with a valuable information: the possible hydrocarbon charge in a seismic structure and/or the presence of subtle stratigraphic traps. Also, it is of interest to know the geological-structural framework where microseepage occur. The non-seismic exploration methods used in Cuba are: remote sensing, gravimetry, aeromagnetometry, airborne gamma spectrometry (AGS) and morphometry (non-conventional, from the Digital Elevation Model 90 $\times$ 90 m). The AGS also classifies, as a non-conventional geophysical-geochemical method, together with the Redox Complex. In the work, gravimetry, aeromagnetometry and morphometry at a scale of 1:50000, AGS at a scale of 1:100000, and ASTER and LANDSAT satellite images (with 15 and 30 m resolution, respectively) are processed. The purposes of the referred complex of methods are to reduce areas, increasing the effectiveness of exploration with a decrease in its risks. From the implementation of these methods, perspective sectors for oil and gas are obtained once the integration with geology and seismic has been carried out. The work presents a brief theoretical account of the methods and, as practical results, a set of perspective sectors of possible interest for exploration.

It is known that non-seismic exploration methods offer necessary and important information on the geological-structural mapping of the territories and on the presence in them of vertical areas of active microseepage of light hydrocarbons, witnesses to possible accumulations at depth. That is why the benefits of using these methods,

prior to their integration with geological and seismic data, translate into a first approximation, valid for an initial understanding of geology and mapping of favorable areas of possible gas-oil interest. Such are the objectives of the investigation at the western Cuba region (land exploration blocks 6, 7, 8A and 9A). To meet these objectives, gravimetry and aeromagnetometry at a scale of 1:50000 and 1:250000, AGS at a scale of 1:100000, (ASTER satellite images) and the Digital Elevation Model 90 × 90 m of the territory were processed. For the geological interpretation, the Digital Geological Map of the Republic of Cuba at a scale of 1:100000 was used. The geological-structural cartography of the study region, based on the gravi-magnetic and morphometric data, establishes possible structural highs which alternate with depressed areas. A version of favorable sectors mapping of gas-oil interest (linked to conventional oil and gas from the Camajuaní and Placetas Tectonostratigraphic Units) is based on the presence of a complex of geophysical-morphometric indicator anomalies. It considers: minimums of the K/Th ratio and the local maxima of U (Ra) in its periphery; remote sensing anomalies as well as; local gravimetric, magnetic and morphometric maxima. The work presents an account of the processing and interpretation of non-seismic exploration methods and, as practical results, the foundation of the main favorable sectors of possible interest for exploration. The geological-structural cartography of the study region, based on gravi-magnetic and morphometric data, allowed to clarify the structural picture of the territory, where geological structures of Cuban direction (SE-NW course) and others of SW-NE and latitudinal (EW) course predominate.

The remote sensors allow the analysis of the terrain in order to identify indications of possible hydrocarbon microseepage in soils and sediments. Microseepage are invisibly hydrocarbon escapes that are manifested on the surface through changes in the reflectance, stress on vegetation, abnormal concentrations of kaolinite, iron oxides and carbonate alterations. The objective of the work is to identify areas of possible hydrocarbon microseepage from the study of the last four indirect indices through the analysis of optical images. The digital processing of multispectral images, Aster, Landsat 7 and 8 consisted of Red Green Blue (RGB) combinations, band ratios and integration and analysis of the information in the Geographic Information System. Spatial-temporal studies of Normalized Difference Vegetation Index (NDVI), analysis of thermal reflectivity images of the surface related to the stress of the vegetation and studies of mineralogical anomalies were carried out at a scale of 1:50000. Areas with microseepage near the Motembo oilfield and the zone of Menéndez in Villa Clara province were interpreted, being corroborated by data from surface geochemical surveys with the presence of gas in soils. Another area with microseepage was identified in the Majaguillar area, with similar patterns to the previous ones, which was supported by the interpretation of a complex of non-seismic and non-conventional methods. In addition to these, other areas were interpreted with a lower degree of confidence but with characteristics very similar to those already established.

The Central Basin of Cuba was the largest oil-producing region in the country during the 1960s. However, after the 1990s with the discovery of the Pina oilfield, there has been no other significant discovery. Exploration failures are considered to be conditioned, in part, by the high geological complexity of the region and by the

volcanic nature of the sequences present, which limit the depth of reflection seismic research. Thus, the problem lies in the need to use 2D physical-geological modeling of potential fields in order to help clarify the deep constitution of the territory, given the interest for finding conventional oil and gas from the Tectonostratigraphic Units (TSUs) of Camajuaní and Placetas at the sediments of the North American Continental Margin. Geological and petrophysical data, seismic data and potential fields of the northeastern region of the Central Basin of Cuba were evaluated in the preparation and interpretation of three 2D models of potential fields: one that is longitudinal to the basin and two that cut the Cristales and Pina oilfields, respectively. As a result, from the 2D physical-geological models, the hypothesis of the existence in the whole basin of carbonates from the North American Continental Margin, considered as source rock, is validated. According to the models, the top of these rocks is located, at the Pina sector, between 2.98–4.3 km, while at the Jatibonico-Cristales and Catalina sectors they range between 5.55–6.6 km and 6.2 km, respectively. In addition, their thickness decreases from north (5 km) to south (1.3 km) and, conversely, the one of Zaza Terrain. This reinforces the hypothesis of the best prospects for finding conventional oil from the Camajuaní and Placetas TSUs in the Pina sector.

Cuba has been producing oil since 1936. The first fields produced good-quality crude, but with little production due to bad reservoirs (ophiolites). Later, better reservoirs were discovered (Mesozoic carbonates) with large resources, but with poor quality oil. So far, no large reserves of high-quality oils have been discovered in Cuba. The objective of this study was: to evaluate areas that meet the petroleum-geologist premises for the presence of large accumulations of high-quality oil. For that reason, 2038 rock samples (for rock-eval studies), 207 oil samples (for physicochemical and biomarkers analysis) and 27 organic extracts from source rock (for oils—source rock correlations) were used. The petroleum systems exploratory method was followed. Only those areas with high thermal evolution oils were taken into account (Exploratory blocks 21-23, Block 7, Block 6, Block 13 and Blocks 17-18). It is concluded that the presence of families I and II of Cuban oils indicates the presence of the J_3-K_1 tectonic sheet; Family III of Cuban oils, indicates the presence of the K_1-K_2 tectonic sheet. The premises that an area must meet for the existence of large accumulations of high-quality oil are: oil with high thermal evolution, rich in sulfur and protected from biodegradation, Veloz Group-type reservoirs. Of the areas evaluated, Block 21-23 is the one that meets all the premises for the presence of large accumulations of high-quality oil. In the rest, there is variation in thermal maturity, increasing the risk of finding deep accumulations with high-quality commercial crude, and also, presence of reservoirs that have not demonstrated large reserves (Camajuaní Tectonostratigraphic Unit).

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Contents

1 Non-seismic and Non-conventional Exploration Methods for Oil and Gas in Cuba: Perspective Sectors 1
1.1 Introduction 3
1.1.1 Physical–Chemical–Geological Premises 4
1.2 Materials and Methods 5
1.2.1 Materials 5
1.2.2 Methods 6
1.3 Results and Discussion 10
1.3.1 Western Cuba, Motembo SE Sector 11
1.3.2 Central Cuba, Oeste De Ceballos and La Vigía Sectors, Central Basin 16
1.3.3 Central-Eastern Cuba, Maniabón Sector 20
1.4 Conclusions 22
References 23

2 Geological–Structural Mapping and Favorable Sectors for Oil and Gas in Western Cuba Through Non-seismic Exploration Methods 25
2.1 Introduction 27
2.1.1 Geographical Location 27
2.1.2 Land Exploratory Blocks 7, 8A and 9A 28
2.1.3 Regional Geological Model 28
2.1.4 Geological Task 31
2.1.5 Physical–Chemical–Geological Premises 32
2.2 Materials and Methods 33
2.2.1 Information and Its Sources 33
2.2.2 Methods and Techniques 33
2.3 Results 33
2.3.1 Information Processing and Interpretation 33
2.4 Discussion 40
2.4.1 Land Exploratory Block 6 40