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# Effective Use of Non-Seismic Methods for Petroleum Exploration

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**Problem:** What can be done when you have basement outcropping along narrow basins, in a frontier area with no wells, little geophysical knowledge but abundant oil seeps indicating a potential petroleum system? Your choices are either: a) forget it and turn your back on the area (as many of us have done in the past), b) scratch your head and throw out possible explanations, or c) use a systematic approach of gathering both geological and geophysical understanding, from a regional to play-concept perspective, thereby improving your chances for locating a wildcat discovery well, ahead of your competitors.

To walk away is an easy decision owing to the abundance of (oftentimes) significant risks. However, the line between caution and balanced risk should be drawn using a scientific approach. This approach might be based on your company being the first to explore a new play, and thereby being the one who takes the lion’s share of the risk. Seismic methods are unsurpassed as a single-method exploration tool, but can be extremely expensive, especially in regions of rugged terrain (upwards of US$ 40,000/line km). Non-seismic methods provide an excellent means for analysis of regional and frontier areas, and for outlining prospective basins at favorable economic costs and with rapid acquisition rates.

Designing your seismic program to include the addition of potential field data (e.g., gravity, magnetics, MT, EM) can extend your exploration budget, and add new and important constraints to the interpretation of seismic data, with the value-added benefits typically more than offsetting the minimal added expense.

Figure 1: Location of study Area ( Shown in yellow)

**Exploration Example:**
We present here a case study from the Upper Magdalena basin in Colombia (see Figure 1). This study involved a methodical, detective-like approach that included both seismic and non-seismic methods, with the non-seismic methods being airborne gravity and magnetics, magnetotellurics (MT) and radar data.

**Geologic Setting:** The Upper Magdalena Basin in Colombia is a prolific oil province formed by the uplifting of the Cordilleras produced by the Andean Orogeny. The present Magdalena River runs between the Central and the Western Cordillera and forms a 12,000 sq. km basin in its upper course with a stratigraphic register from Paleozoic rocks up to Present. From North to South it can be divided into four sub-basins: the Honda basin (where Cretaceous, Tertiary and Present sediments cover older rocks), the Girardot basin (where pre-Cretaceous to Present rocks are observed in outcrop), the Neiva basin (the most prolific oil province in the region where a large thickness of producing sediments is found), and finally, the Southern Magdalena Basin.

South of the town of Garzon, the Upper Magdalena Basin is closed by exposures of pre-Cretaceous rocks of Paleozoic age. Cretaceous and Tertiary sediments form three narrow sub-basins: The Saladoblanco, the Tarqui and Suaza depressions (Fabre, 1992). No oil in commercial quantities has been discovered to date in these basins. However, numerous oil seeps and tar-impregnated beds have been known for centuries there. How do we explain petroleum generation along narrow basins, with basement exposed and covering most of the surface? Good geochemical correlation between oil seeps and extracts from the Villeta shale, and the presence of hydrocarbons in the Cretaceous Caballos and Guadalupe sandstones, demonstrate that oil generated by the Villeta formation migrated throughout the area.

The Colombia National Oil Company, ECOPETROL, recognized that “petrolization” of the area should be accomplished through an exploration program by combining an old-fashioned approach (regional to detailed geological/geophysical methods) with modern application of technologies such as remote sensing; in this case, an airborne gravity and magnetic survey. Non-seismic, particularly airborne methods, can provide a cost-effective, fast approach to investigate the hypothetical petroleum system. This work can then be followed by more detailed (and costly) seismic prospecting to determine the best location for the initial well program.

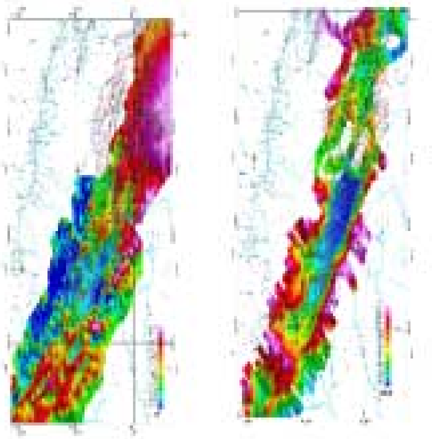

Figure 2:
Left:Magnetic anomaly, reduced to the pole (RTP)
Right:Gravity anomaly map for the entire Upper Magdalena basin.
The merge between different vintages is noticed on the RTP, and between land and aero-gravity data on the Bouguer anomaly map.

**Gravity And Magnetics.** Gravity and magnetic data, when acquired by an aircraft, come in very handy when you are asked to explore over 3 million acres, in a short amount of time. In 1995 Ecopetrol designed a regional gravity and magnetic survey over the entire Putumayo and Upper Magdalena Valley area. Special care was taken during the survey planning stage so that data coverage was sufficient along the foothills areas. This condition was required in order to detect the possible presence of sediments under basement rocks. Such conditions can result as a product of the thrust tectonics that gave origin to important traps north in the same foothills, producing the Guando, Cusiana, Cupiagua and other fields.

The survey area is comprised of a long narrow valley with peaks on the north side reaching in excess of 4,000 metres. The survey planning was constrained by the safety requirements of the flight crew and equipment and also the need for the highest resolution geophysical data obtainable. By modifying the program layout it was determined that the two requirements mentioned above could be best achieved by flying at a fixed barometric altitude of 3280 metres. Fugro-LCT was commissioned to acquire, process and interpret the airborne gravity and magnetic data utilizing their state-of the-art system.

Interpretation of the magnetics data required the reduction to the pole (RTP) (Figure 2, left side), using a special methodology developed for this project, which takes into account the fact that wide magnetic latitude variations occur over the study area (which is about four degrees in latitude). These variations hinder the application of normal single-latitude reduction to pole operators.

Figure 3: Magnetic provinces in the Upper Magdalena - Putumayo Basins.

It was interesting to notice that intrusives were clearly identified; the interpretation included separating these from basin targets. The map is dominated by a large positive anomaly at the North, the clear expression of the Sumapaz massif (Paleozoic rocks). Southward from there we distinguish at least three different structural provinces: the Northern magnetic provinces (See Figure 3, Zones A, A$^1$ and A$^{11}$) of the Central Cordillera, Natagaima Arch and Eastern Cordillera, the "central" Upper Magdalena Basin (Zone C in Figure 3) enclosed by Central Cordillera igneous rocks and the Garzon Massif, and finally the Putumayo foredeep (Zone B). The N-NE trends noticed on the RTP map correspond on the surface with dominant compressional faults such as the La Plata, Altamira, Garzon-Suaza and many others.

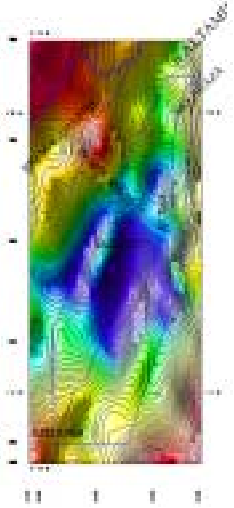

Figure 4:Acevedo Block: Gravity data (C.B.A) Blue line NW – SE shows location of the MT profile

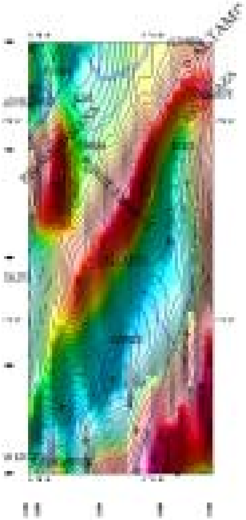

Figure 5:Acevedo Basin, Reduced to Pole Magnetic Anomaly.

Fugro-LCT also provided Ecopetrol with a 3D Euler interpretation of depth to magnetic basement, which yielded a good calibration with the existing wells where available.

A further interpretation of the main structural elements, when combined with the gravity data, provides valuable insights about the geological setting. The final products included the Isostatic residual gravity anomaly, which helped to define basin geometries and main structural elements such as faults, anticlinal and synclinal configurations and 3-dimensional features associated in the region with dense intrusives.

The Bouguer Anomaly map, (Figure 2 right side) shows a large blue expression dominating the center of the map, which depicts the deep Neiva depocenter. This central anomaly is surrounded by red (positive) anomalies; the easternmost anomaly is related to the Garzon Massif (where pre-Cambrian exposures occur) and the westernmost anomaly is related to the Central Cordillera (igneous outcrops).

Two sub-basins, detected by this survey in the southernmost region, are discussed in the following sections. The portions of the gravity and magnetic data from Figure 2 covering this detailed area are shown in Figures 4 (Bouguer gravity) and 5 (RTP magnetics). These basins are named the Tarqui (Western) and the Suaza (Acevedo) sub-basins (eastern). Although known for decades, they didn't receive commercial attention until we started to put the geophysical pieces together as part of this study. The blue outline indicates the Acevedo basin, where numerous oil seeps occur.

When combined with geological knowledge, one can learn from known features in order to predict unknown structures. This is the case with thrust faults, which can be depicted both on gravity and magnetic anomaly maps. One indicator of sediments present under thrust faults is the fact that the anomalies appear "incomplete", or asymmetric in character. From an examination of these anomalies, the interpreter gets a sense that half of the anomaly is missing, this being caused by the masking effect of the gravity signal of the thrusted units. A combination of magnetic depth estimation methods such as 2D Euler, Werner deconvolution etc, helps the interpreter define the mismatch of basement depths on both sides of the given fault.

Figure 6: Acevedo Basin, SAR image. Faults shown from left to right:Altamira, Acevedo, Guayabal and the Garzon - Suaza Megashear.

**Remote Sensing:** The start of the structural interpretation began with the available SAR data. When combined with the knowledge gained from the potential fields data, we can construct an interpretation of the structural setting. The sense of thrusting, displacement of strike slip and the amount of throw on normal faults can be inferred, while lithologic discrimination helps to differentiate between positive anomalies of prospective interest and intrusive bodies not suitable for oil accumulations.

The combined interpretation using geology, remote sensing and potential fields provides the basis for construction of possible Play Maps, where initial assessment of the types of trapping involved can help to rank the different areas of interest. We combined these maps with overlays of known oil fields and oil seeps to allow the interpreter to understand the trends and missed plays. Finally, we ranked the areas in terms of acreage, kitchen volume and facilities, which contribute to building a portfolio for further exploration, be it directly by the landowner or suitability for farm out.

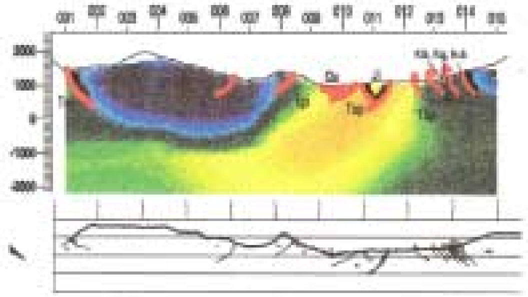

Figure 7: Acevedo Basin, MT Profile. For location see Figure 5. Blue colors represent highly resistive beds, related with basement, while yellow and green areas are more conductive, sedimentary layers. Geology is overlaid for comparison.

The Acevedo basin, previously called the Suaza basin by Fabre, is shown in Figure 6. Well-defined inverse faults match well with the potential fields interpretation, and the shape of the anomalies predict sediments overlaid by basement rocks (which are pre-Cambrian rocks in the East of this image). One factor puzzled the explorationists in this area for many years: the rocks laying on the surface and covering most of the central part of the basin had previously been mapped as Jurassic rocks, thus posing intriguing questions about their origin: How did they get there? Are they rooted? Is there additional prospective sediment beneath? Fabre had spoken about the "klippe" theory, which in brief form implies basement rocks hanging over younger sediments, but being isolated from the main roots by erosional or tectonic events. The work discussed above achieved the goal of focusing our attention on some specific play concepts and narrowing our region of study. The gravity and magnetic interpretation and modeling results provided some interesting possible answers to some of these issues, but we desired additional, independent confirmation of the play potential, prior to invoking either expensive seismic, drilling, or both.

**Magnetotellurics (MT):** While this geophysical tool has been used successfully for some decades by the mineral and environmental industry, oil-oriented applications are very young (even though Vozoff discussed applications in sedimentary basins in the early 70's). In Colombia we saw the application of traditional MT in the recognition of the Amazonas and the same Upper Magdalena by Amoco during the late 1980's.

In order to define whether prospective sediments were present under the above-mentioned "klippes" and determine the angle of the inverse faults, we chose to apply the MT method, selecting Geodatos, a Chilean Company to perform this work. Their method is called Continuous Electromagnetic Profiling, or CEP (see results in Figure 7). Based on the apparent resistivity of rocks, the CEP method seeks to correct for static problems present in typical MT measurements due to variations in resistivity produced by surficial sources. The idea of CEP was first devised by Bostick in 1986 and later on developed by Torres-Verdin and Bostick in 1992.

We had studied in 1993 the feasibility of MT for identifying prospective sediments beneath thrust faults, covered by basement-related rocks. This early work yielded promising results. In the current play concept, older rocks, usually highly resistive, hang over and cover younger, less conductive sediments. Thus the study setting presents a good scenario for resistivity / CEP MT methods.

The geometry of the trap itself can't be mapped with detail, but an accurate measure of the angle of thrusting, and the extent and depth of sediments under the hanging wall were judged to represent sufficient information to warrant further exploration expenditures. The next logical step was to acquire seismic data, taking into special account model-driven acquisition design parameters such as cable length, source and resolution, based on the results from the integrated gravity, magnetic and MT modeling and interpretation. Seismic acquisition and standard processing was followed by PSDM imaging constrained with geologic modeling.

Prior to shooting the data, we took advantage of the CEP results and the gravity and magnetics 2D modeling and map interpretations, to build models and apply ray tracing techniques in order to predict migration apertures and anticipated-to-be poorly illuminated areas. **This step alone saved ECOPETROL enough line-kilometers of seismic coverage to pay for the entire investment in gravity, magnetic and MT data.** (Seismic acquisition costs in the difficult terrain associated within Colombia can escalate to values in excess of 40,000 US dollars per line kilometer). Thus in addition to the interesting and useful geological and geophysical information that was achieved with the gravity, magnetic and MT data, the benefit in optimizing the layout of costly seismic was enough to immediately justify the cost (with a very short return on investment time frame).

**Seismic Acquisition**: Existing seismic data acquired by EUROCAN in the late 1980's, had shown reflections under the Jurassic beds of the Saldaña Formation. Interpreters at that time were unable to understand these events. But now, with the confirmation from the CEP and gravity and magnetic results, new high-quality seismic data were acquired with cable lengths up to 8 kilometres, a source produced by 8 kgs of dynamite and specially designed arrays. As a result, we were able to predict the sedimentary sequence and, based on seismic character, propose a model for the basin, with amazing insights about the amount of prospective sediments being buried by older rocks. This type of compressive tectonics provides the elements to form traps under the thrusting, most of them with their own closure.

Interpreters within Ecopetrol started to map promising structures that may hold vast amounts of hydrocarbons. In 1999 we added some geochemical studies based on soil samples, and the results matched extremely well with the predicted structures described above. Another non-seismic technique that would have assisted in this area would be radiometrics derived from a gamma ray spectrometer, which could be co-located with the airborne gravity and magnetic instrumentation. This data might have confirmed the presence of oil indicators leaking from the main structures.

**Present Work:** The time for drilling the first wells is quickly approaching. Acknowledging the high risk (and high potential), a strategy was developed for bringing in partners with important knowledge and technical expertise. As a result, Ecopetrol farmed out the entire southernmost sub-basins of the Upper Magdalena Basin.

Ecopetrol has interested parties including Canadian Talisman in the Acevedo region, TotalFinaElf Exploration just North of Acevedo and other major players. Emerald has taken the lead by making discoveries in the overthrust play, and Talisman is poised to follow suit in the coming months.

**Conclusions:** Significant structures seen at the surface, obvious productive anticlines and well known targets in oil bearing provinces have been already drilled. Less obvious traps remain reserved for those who are willing to challenge and change existing paradigms.

Integration is becoming the modern approach to today's complex exploration environment. Independent geophysical methods, such as gravity, magnetics, magnetotellurics and seismic are used in synergy to help reduce the risk associated with frontier exploration. These independent methods help constrain the interpretation of the seismic data, helping to reduce the uncertainty in difficult to image areas - places where others have feared to venture.

One major benefit to the study discussed here was that the modelling and interpretation of the seismic, gravity and magnetics and MT involved a closely coordinated group effort. In this way, new ideas were driven by a variety of both seismic and non-seismic geophysical methods, testing other methods and, accordingly, the ideas were either dismissed or strengthened in a truly real-time integrated exploration sense.

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