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Association between magnetic susceptibilities and hydrocarbon deposits in the Barinas-Apure Basin, Venezuela

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ABSTRACT

We have measured the magnetic susceptibility of 5425 drill cuttings, coming from 20 oil wells distributed in eight fields of the Petroliferous Barinas-Apure Basin (Barinas, Venezuela), seeking evidence of magnetic anomalies associated with the presence of hydrocarbon deposits. The rock samples are located between the near earth's surface and the basement's top (approximately 4000 m). In the magnetic susceptibility profiles, we observed high magnetic susceptibilities at the top of the sedimentary units corresponding to reservoir and source rocks of oil-producing wells, whereas in the case of nonproducing wells we observed low magnetic susceptibilities. A basic statistical analysis of the magnetic susceptibility measurements shows a significant difference between the mean values across producing and nonproducing wells at the correspondent oil-related formations, with a ratio of 4:1 of producing to nonproducing wells. In the producing wells, we have found a relation between the magnitudes of the magnetic susceptibility and the age of the formation; the larger the magnetic susceptibility, the younger the geological stratum. The age and depth of the formations where the cuts were obtained exclude the presence of cultural (human origin) contamination of the samples, suggesting the evidence of authigenic origin of the magnetic minerals due to the reductive effect of hydrocarbons in rocks.

INTRODUCTION

In the last four decades a number of studies have been reported on the magnetic anomalies present in levels near the surface, associated with the presence of underlying hydrocarbon deposits (Thompson et al., 1980; Saunders and Terry, 1985; Saunders et al., 1989, 1991; Benthien and Elmore, 1987; Tompkins, 1990; Foote, 1992, 1996; Ellwood and Burkart, 1996; Liu et al., 1998a, 1998b, 2004; Liu and Liu, 1999). Historically, Steenland (1965), Donovan et al. (1979, 1984) and Saunders and Terry (1985) were the first geophysicists to use the magnetic survey as a complementary method to the conventional survey for oil exploration.

In 1975, a survey was sponsored by the U.S. Geological Survey and directed by Terrence Donovan to measure the magnetic and radiometric fields over the Cement oil field, Caddo and Grady counties (Oklahoma, USA), from a low flying aircraft. Donovan et al. (1979) reported the results of these aeromagnetic investigations together with magnetic susceptibility profiles (depth range of 60–300 m) made from measurements on rock cuttings from wells of the Cement oil field. These authors identified aeromagnetic anomalies on this oil field and attributed them to the presence of abundant diagenetic magnetite resulting from the reduction of the hematite induced by the petroleum reservoir. On the other hand, Reynolds et al. (1991) reported the presence of iron sulfides (e.g. pyrrhotite and greigite) as a possible source of the magnetic anomalies.

Foote (1996) reported the results of an aeromagnetic study made in four different regions of the United States. These studies reveal a connection between the oil/gas producing areas and the anomalously high magnetic susceptibility values measured in vertical well profiles. These anomalous magnetic susceptibilities were possibly produced by different mineral magnetic phases developed in

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sedimentary soils near the surface. Foote (1996) determined that 78% to 90% of the oil/gas producing wells exhibited significant magnetic susceptibility anomalies.

Because many of the studies on the subject were focused on magnetic susceptibility measurements from samples collected at shallow depths, the endogenic or exogenic origin of the magnetic material was not clearly solved (Reynolds, 1982; Machel and Burton, 1991; Gay, 1993; Liu et al., 2004).

Drill cuttings from some Venezuelan and Colombian oil wells were analyzed by magnetic susceptibility (MS), and natural remanent magnetization (NRM) measurements to investigate the possible causal relation between the magnetic anomalies and the hydrocarbon accumulation (Aldana et al., 1999, 2003a, 2003b; Diaz et al., 2000; Costanzo-Alvarez et al., 2000, 2006). The MS profiles were made from 200 m to a depth of about 2000 m. The MS maxima were observed at a depth of about 600 m, which has been interpreted by the authors as resulting from the presence of authigenic magnetite.

In addition, an analysis of drill cuttings from the Guafita oil field (Barinas-Apure Basin, Venezuela) was done using a variety of techniques, such as variable-temperature magnetic susceptibility, Mössbauer effect, electron probe microanalyzer, and scanning electron microscopy (Perez-Perez et al., 2000). This study aimed at determining the iron mineralogy and its distribution in the MS profiles (depth range of 100–1000 m). The analysis of the results indicated that maghemite (γ-Fe_2O_3) was the mineralogical phase responsible for the highest MS values. Along the selected depths, hematite (α-Fe_2O_3), goethite (α-FeOOH), and $FeSO_4 \cdot H_2O$ were also found. Comparison of the $FeSO_4 \cdot H_2O$ concentrations along the MS profiles indicated that the near-surface anomalous zone coincided with the intervals of low concentrations, whereas the sulfate concentration increased at nonanomalous MS zones. This could be due to the in situ transformation from part of the oxides or hydroxides present in the sediments into iron sulfate, and originating from the reducing emanations of the underlying oil deposits. The formed iron sulfate, which is easily soluble in water, can migrate toward shallow levels and reoxide slowly to form maghemite. These results suggest a causal relation between the magnetic anomalies, observed at shallow levels, and the presence of underlying hydrocarbon reservoirs.

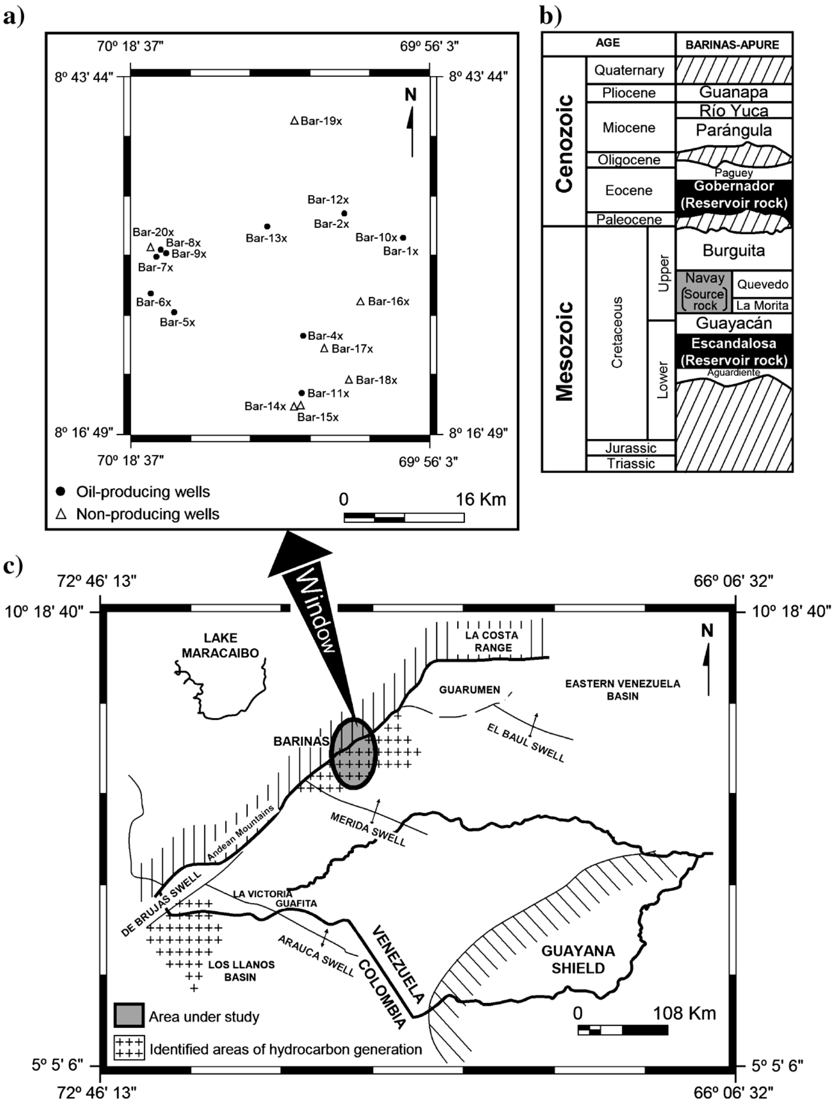

Figure 1. (a) Wells location (Bar-3x well is not shown because it is far away from the main area) (b) Stratigraphic column showing the main formations (modified from Gonzalez de Juana et al., 1980) (c) Geographical setting of the Barinas-Apure Basin showing the location of the area under study.

Saunders and Terry (1985) reviewed some of the theories that explain the formation of diagenetic magnetite. According to Ferguson (1979) and Oehler and Stemberg (1984), the hematite present in the sedimentary rocks is transformed to magnetite in presence of hydrogen sulfide (H_2S), which is commonly produced by anaerobic bacteria that reduce the sulfate anion (SO_4^{2-}) present in hydrocarbons to extract the oxygen required by their metabolisms.

The previous studies motivated us to extend the investigations with data from various oil fields, to find more evidence for the association of magnetic anomalies with hydrocarbon deposits. We undertook the analysis of 5425 samples of drill cuttings from the Barinas-Apure Basin, located in the Barinas State, Venezuela (Figure 1). The sampling was made in 20 oil-producing and nonproducing wells distributed within eight oil fields (Figure 1a). The collection of samples is comprised within the depth range between zero to 4 km, encompassing reservoir and various hydrocarbon source rock formations. The producing formations, Escandalosa and Gobernador of the Barinas-Apure Basin (Figure 1b), are included within this depth range, unlike previous studies in which samples from reservoirs and source rocks were not analyzed (Aldana et al., 1999, 2003a, 2003b; Perez-Perez et al., 2000; Diaz et al., 2000). We have obtained magnetic susceptibility profiles (MS as a function of depth) for each oil well, and analyzed them using basic statistics to characterize the producing and nonproducing wells from the point of view of their magnetic characteristics. We have found anomalously high magnetic susceptibility values below the seal formation and near the top of the reservoir and rock formations in the MS profiles of the oil-producing wells only. To the best of our knowledge, this is the first study of its kind performed on an extensive number of samples from oil wells located within a continental geologic environment, accompanied by a statistical analysis of the MS profiles. Similar studies have been carried out to examine the lithological and stratigraphic variations in magnetic susceptibilities of sediments offshore of Norway, in the northern North Sea and the Norwegian Sea (Mørk et al., 2002).

EXPERIMENTAL

Samples of drill cuttings were provided by Petróleos de Venezuela, S.A. (PDVSA, Petroleum of Venezuela, Caracas, Venezuela). The drilling mud employed in these wells was reported to be a mixture of bentonite and water, without magnetic contaminants. After collection, the drill cuttings were filtered out and completely cleaned of the viscous drilling mud.

We studied a total of 5425 samples in the form of fine unconsolidated rocks associated with a single group of molasses of fluvial-deltaic provenance. The samples were extracted from within a wide depth range of zero to 4000 m from 20 randomly chosen oil wells (13 producing and seven nonproducing) distributed in eight different oil fields of the Barinas-Apure Basin, as shown in Figure 1a. This basin is located in south-western Venezuela, between the Andean Mountains and the Guayana Shield (Figure 1c). It occupies an area of $95,000\ km^2$ and has an important oil production. Figure 1b illustrates the sedimentary stratigraphic section under study and includes sediments ranging in age from the Lower Cretaceous to the Oligocene periods (Gonzalez de Juana et al., 1980). The main geological formations are:

a) Aguardiente and Escandalosa (reservoir rock formation; 6 members) Formations from the Lower Cretaceous period;
b) Guayacán, Navay (source rock; La Morita and Quevedo Members), and Burguita Formations from the Upper Cretaceous period; and
c) Gobernador (reservoir rock formation), Paguey (seal formation), Parángula, Río Yuca and Guanapa Formations from the Tertiary period.

We performed magnetic susceptibility (MS) measurements on sample volumes of $3\ cm^3$ at room temperature, using a homemade AC susceptometer based on an AC mutual inductance bridge. The results are expressed in terms of the dimensionless volume MS intensity. The magnetic field used was 4 nT at a single frequency of 1 kHz. The sensitivity of the instrument was better than 10^{-7} SI (Jorge, 2001). The magnetic susceptibility readings for each sample were repeated five times, and a standard deviation of less than 10% was found for each MS sample average. For each oil well, we obtained a graphical representation of MS as a function of well depth (MS profile).

RESULTS AND DISCUSSION

Figure 2a and b shows the measured MS profiles for two nonproducing wells. These profiles do not exhibit large magnetic susceptibilities at the level of oil-producing formations (approximately 2700 m). The mean MS value calculated from the near-surface zone to the basement depth is approximately 2×10^{-4} SI, which falls within the set of values of the low MS population of oil-producing wells. All MS profiles for oil-producing wells show large magnetic susceptibilities at the level of producing formations (between 3200 to 3400 m), and the value of the mean MS over the entire profile is approximately 6×10^{-4} SI.

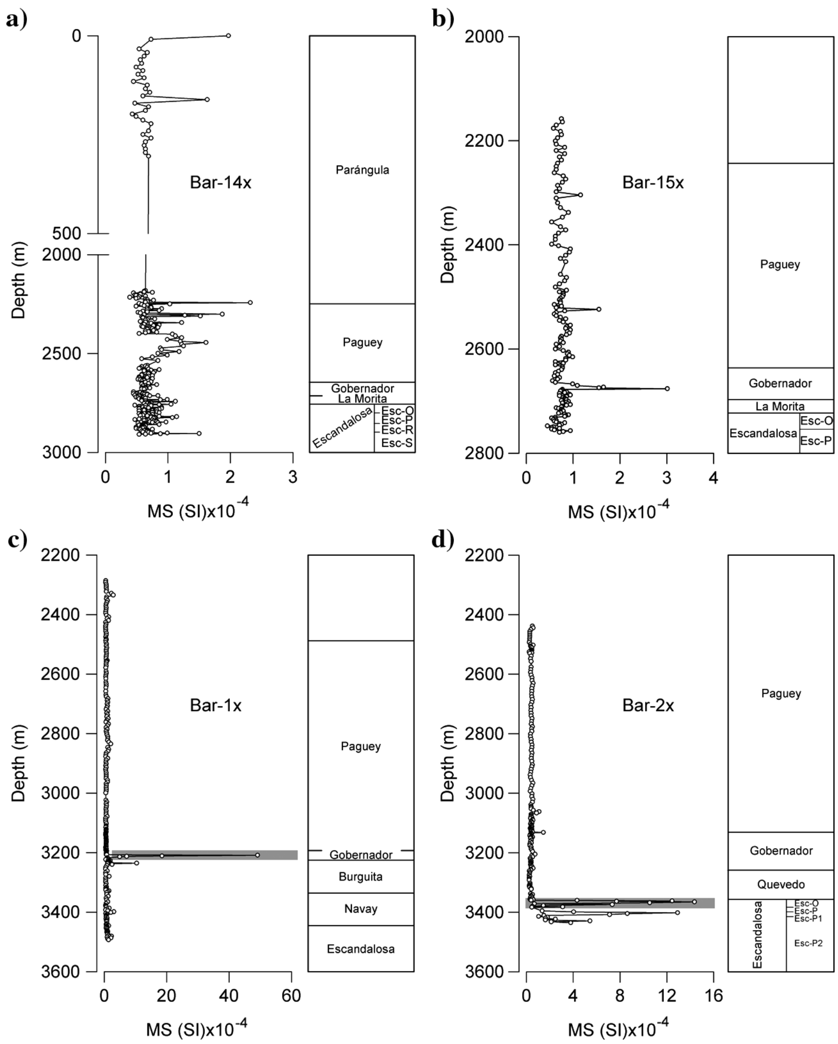

Figure 2. Magnetic susceptibility profiles of drill cut samples for (a) and (b) the nonproducing wells Bar-14x and Bar-15x and (c) and (d) the producing wells Bar-1x and Bar-2x. The right hand side of each graph shows the stratigraphic columns. Note the depths of formation tops for each case. The gray depth interval indicates the oil-producing reservoir.

Figure 2c and d shows typical examples of MS profiles for two oil-producing wells. These wells belong to two different oil fields and two different stratigraphic traps (see Table 1). In both cases, we observed the existence of zones of high and low magnetic susceptibilities in the MS profiles at the oil-producing locations. The low magnetic susceptibilities correspond to the Paguey Formation, which acts as a seal formation of the Barinas-Apure Basin. The highest susceptibilities are present at the overlying formations (Gobernador and Escandalosa) to the producing formations.

For the data shown in Figure 2c and d, the magnetic susceptibility peaks are associated with the producing formations and located preferentially at the overlying formations. Several peaks in the MS profile of the well Bar-2x (Figure 2d) correspond to the Members Esc-O (Escandalosa O), Esc-P (Escandalosa P), Esc-P1 (Escandalosa P1), and Esc-P2 (Escandalosa P2) of the Escandalosa Formation. It is worth mentioning here that the Esc-O Member is currently the only exploited member of the Escandalosa Formation, although each of the other members has proven oil presence. The fact that largest MS values coincide with the sedimentary unit containing the hydrocarbons allows us to consider the possibility that the positive relation could be used to define oil indicators associated with the outlier susceptibility strata or the top of the strata. These magnetic susceptibility peaks are possibly due to the presence of a secondary magnetic mineralogy (e.g., magnetite, Fe_3O_4), which could be produced by a chemical reaction between a primary magnetic mineralogy (e.g., hematite, Fe_2O_3) and a reducing gas (e.g., hydrogen sulfide, H_2S) coming from the underlying hydrocarbon reservoir (Saunders and Terry, 1985).

In the MS profiles exhibiting only a single magnetic anomaly, Figure 2c, no large variations of the magnetic susceptibility values were found along the producing formation. This may be due to the fractures lack and fault systems that contribute to hydrocarbon filtering and, therefore, to the anomaly displacement. The MS profiles exhibiting various anomalies, Figure 2d, and large MS variations above and below the producing formations suggest that a hydrocarbon filtering process or an oil microfiltering left metal traces along the migration path.

Visual microscopic inspection of all the samples that showed the highest MS values and those neighboring samples (extracted from above and below the corresponding depth) indicated that the drill cuttings do not contain residues from the perforation drill or any other metallic contaminants. In addition, we have used Mössbauer spectroscopy on magnetic extracts to identify the iron mineral content. The preliminary results indicate that magnetite is the main iron phase responsible for the magnetic anomalies observed in the MS profiles. This magnetic mineralogical phase has been previously identified by other research groups as the possible source of the magnetic anomalies associated with the hydrocarbon deposits (see, for example, Donovan et al., 1979; Costanzo-Alvarez et al., 2000, 2006).

To perform a statistical analysis of the magnetic susceptibility data, we first separated the MS data according to the geologic formation and well category (producing or nonproducing), from which the measured sample was extracted. Figure 3 shows the average magnetic susceptibility per formation for each well category. Note that we excluded from this analysis the Paguey Formation and the overlying formations, which regularly present low magnetic susceptibilities and are not related to the oil production in this area (i.e.,) these formations are neither source nor reservoir rocks. The most striking feature of Figure 3 is that the average magnetic susceptibility is larger in the oil-producing wells than in the nonproducing wells for all the formations considered. In addition, the sample standard deviations show that the groups of wells are very well separated in every formation. Furthermore, the overall magnetic susceptibility average across all considered formations per well category indicates that oil-producing wells have larger magnetic susceptibilities, with a ratio 4 to 1 (producing to nonproducing wells).

We attributed the differences observed in the MS profiles between the producing and nonproducing wells to the unusual concentrations of magnetic minerals at the oil-producing wells. There are several possible sources of these magnetic minerals in the sediments: (1) they are formed during the sedimentary deposition; (2) they are traces of metals produced by hydrocarbon migrations through faults, microfaults,

Table 1. Oil wells under study.

Class	Wells	Depth (m) Top	Depth (m) Bottom	Samples
Producing oil wells	Bar-1x	2286	3493	257
	Bar-2x	2438	3435	197
	Bar-3x	0	3624	371
	Bar-4x	610	3065	346
	Bar-5x	610	3621	330
	Bar-6x	2292	3814	199
	Bar-7x	622	3746	341
	Bar-8x	2981	3816	199
	Bar-9x	2667	3530	118
	Bar-10x	625	3505	439
	Bar-11x	2213	3350	422
	Bar-12x	2500	3530	315
	Bar-13x	2554	3344	154
		Subtotal of samples 3688		
Nonproducing oil wells	Bar-14x	0	2911	302
	Bar-15x	2158	2760	165
	Bar-16x	3	3060	293
	Bar-17x	716	3005	152
	Bar-18x	1981	3057	216
	Bar-19x	661	3953	213
	Bar-20x	613	3840	396
		Subtotal of samples 1737		
		Total of samples 5425		

and stratigraphic planes; (3) they are a combination of the aforementioned processes; (4) they result from the reductive geochemical environment induced by the hydrocarbons deposits. Figure 1a shows the oil well locations and their categories (producing or non-producing). It can be seen that in some cases both categories are close. For simplicity, let's focus our attention on the MS anomalous zones observed in the group of oil-producing wells, which are localized at the reservoir rock formations. Our results support the authigenic origin of the magnetic mineralogy induced by the hydrocarbons deposits, although we cannot entirely preclude the possibility of minor influence, due to other processes in the formation of magnetic minerals in the sediments. Table 2 shows the number of samples studied (extracted from a depth range 2300–4000 m) for each formation arranged according to decreasing geologic age. In column 4, we list the overall lithological description corresponding to the different formations of the Barinas-Apure Basin. In this table, the Escandalosa Formation has been divided into its respective members, and more than 200 samples for each group of wells were characterized.

Figure 4 shows the mean values of the magnetic susceptibility, their standard deviations, and a linear fitting for the groups of producing and nonproducing wells as a function of the geological age of the formation. In addition, the coefficient of variation was calculated, i.e., the inverse of the intercept multiplied by the standard deviation, expressed in (percentage), for both producing and nonproducing groups, respectively. The coefficient of variation determines the confidence limits which are represented by two gray bands. These bands do not intersect, and their separation indicates a statistically significant result.

Moreover, the difference between the mean values of each formation, corresponding to the nonproducing and producing oil wells, is approximately constant, with a value of $\Delta SM_{mean} = (6 \pm 1) \times 10^{-4}$ SI. That this difference remains constant could be related to the fact that the arrival of hydrocarbons from the source rock on each of these porous rock units occurred simultaneously. The contact of hydrocarbon with the different geological units gives rise to an oxidation-reduction process of equal geochemical intensity.

Also in Figure 4 it is observed that, for oil-producing wells, the mean magnetic susceptibility corresponding to the La Morita Formation, a member belonging to the source rock (Tocco et al.,1997) and rich in organic matter, has the lower value. At the reservoir rocks (Escandalosa Formation and Gobernador Formation) the mean MS values increase. This result could suggest that hydrocarbon seepage and migration from the source rock produces a more reactive geochemical field, thus altering the in situ properties of reactants associated with iron-bearing minerals, changing the rock magnetism. This alteration process is reflected in the mean magnetic susceptibility values, which decrease near the source rock, but increase toward the reservoir rock units. These results are consistent with those indicated by Liu et al. (1998a).

On the other hand, oil and gas explorationists suggest that the aeromagnetic surveys could be used as an exploration tool for locating oil and gas accumulations. The main disadvantages are

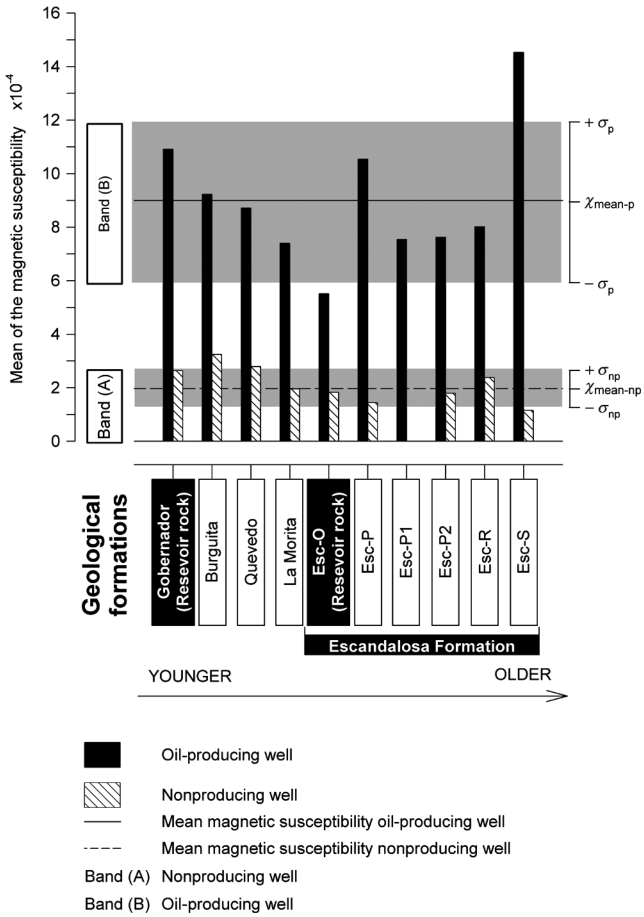

Figure 3. Sample mean of the magnetic susceptibility for the different formations according to well category: producing or non-producing wells. The category mean χ_{mean} includes all formations below the Paguey Formation. The gray band indicates one standard deviation of the samples. The sample mean for the nonproducing wells is $(2.0 \pm 0.7) \times 10^{-4}$ SI, and for the oil-producing wells is $(9 \pm 3) \times 10^{-4}$ SI.

Table 2. Number of drill cutting samples studied per formation with its lithological description.

Formations		Nonproducing wells	Oil-producing wells	Lithological description
Gobernador		111	325	Quartz sandstone
Burguita		20	139	Micaceous sandstone, siltstone, and shale
Quevedo		71	261	Sandstones, shales, and limestones
La Morita		78	71	Shales
Escandalosa	Esc-O	49	68	Sands
	Esc-P	86	100	
	Esc-P1	0	3	
	Esc-P2	9	30	
	Esc-R	52	52	
	Esc-S	16	16	

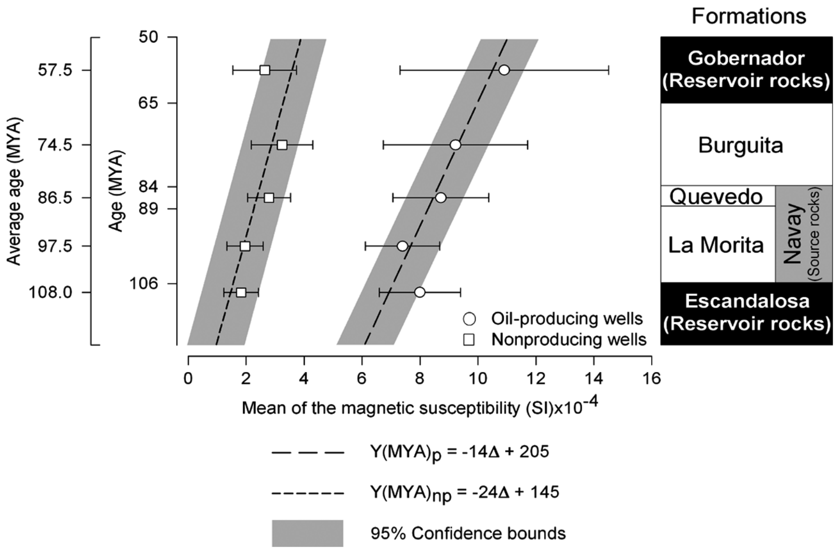

Figure 4. Mean values of the magnetic susceptibility per formation and category (producing and nonproducing wells) plotted against geologic time sequence of the formations. Uncertainty bars indicate the standard deviation of the samples, and the lines show linear functions fitted to the data for the producing and nonproducing wells.

that the magnetic intensity is too small in many cases and that it is very difficult to distinguish them from other magnetic sources. An important question on petroleum research is to understand why the anomalies of susceptibility could be used as an exploration tool.

CONCLUSIONS

We have verified a positive relationship between anomalous large values of susceptibility and the presence of hydrocarbon by using a statistical analysis of the magnetic susceptibility measurements of a particularly large sample of drill cuts. In contrast to related work that sampled rocks close to the surface of oil fields and found near-surface magnetic anomalies, our magnetic susceptibility anomalies are identified for depths in the range of 3–3.5 km, sufficiently far away from possible cultural (human or industry) contamination. The high magnetic contrast of the 13 oil-producing wells appears in the reservoir formations (Escandalosa and Gobernador Formations) where hydrocarbon deposits are found. The MS mean values of the producing wells is four times higher than that of the nonproducing wells, which suggests the presence of magnetic iron minerals caused by the hydrocarbon deposits. In addition, the mean magnetic susceptibility values decrease near the source rock and increase toward the reservoir rock units.

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