Applications of magnetic methods in oil and gas exploration

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Magnetic methods have been used in oil and gas exploration since the 1920s but, for most of that period, only to investigate major fault zones and map basement rocks. However, recent advances imply that now, under favorable conditions (and especially in combination with other geophysical and geochemical methods), magnetic techniques can play a bigger role in locating oil and gas fields.

This article will briefly review the conventional application of magnetic methods and evaluate their potential for possible direct detection of oil and gas accumulations. The examples used to illustrate my views have been taken from published articles and I have made every attempt to cite the authors in the following.

Structure associated anomalies related to magnetic fault blocks. In the Mesozoic and Cenozoic eras, the rigid basement of the North China Basin underwent strong and widespread fault blocking. The basement uplifts produced lateral magnetization contrasts and in some cases the faulting could be associated with magnetization contrasts with the basement. Thus, possible oil and gas traps correlate with gravity and magnetic anomalies.

The Niutuozhen anomaly is a typical basement block anomaly. A corresponding gravity high is situated on the steep gradient slope between the positive and negative peaks. The offset between the gravity and magnetic anomalies is caused by the oblique magnetization of the source. The core of the uplift is mainly Precambrian magnetic crystalline basement rocks which are overlain by Paleozoic carbonates. Figure 1 shows an interpretive cross section of the uplift associated with the Niutuozhen anomaly. The major fault (on the southeast side of the uplift) is associated with significant oil deposits.

The previous example, and the next three examples, were taken from "Aeromagnetic anomalies and prospective oil traps in China" by Y. X. Zhang (GEOPHYSICS, 1994).

The Hejian aeromagnetic anomaly is related to the uplifted basement block composed of Archean gneissic granites and Middle-Proterozoic carbonates. The block is tilted and faulted in the west with a displacement of nearly 3000 m. Oil and gas have accumulated mainly in the Middle-Proterozoic dolomite (Figure 2).

The magnetic anomalies associated with this uplift often have amplitudes in excess of 100 nT. Associated gravity anomaly highs are about 10 mGal. These anomalies can be delineated without further processing.

Structure-associated anomalies related to volcanic rocks. The aeromagnetic map of the giant Daqing Dome (the largest oil field in China) has many local highs (amplitudes often 40-50 nT). The depth of the sources is 3-5 km. A well with depth of 4188 m encountered Upper Jurassic magnetic andesite and basalt with thickness up to 104 m (Figure 3), which produce a local magnetic high.

The Northern Dagang area consists of a fault block composed of Paleozoic limestones and Mesozoic volcanics. The northeast trending positive magnetic anomaly

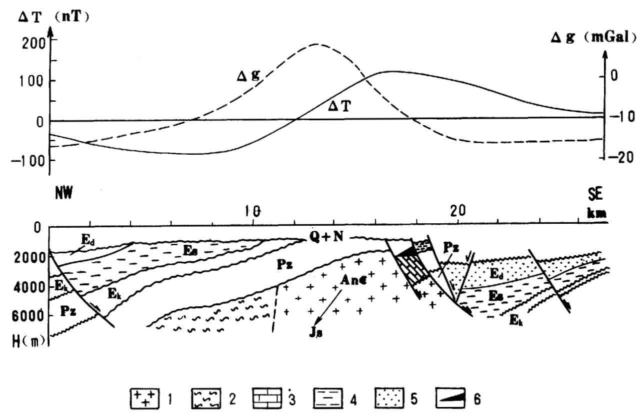

Figure 1. Cross-section and gravity magnetic profiles across the Niutuozhen uplift. The major fault on the southeast side of the uplift is associated with oil deposits adjacent to Paleozoic carbonates. (1) Precambrian magnetic crystalline basement rocks, (2) Precambrian schist and gneiss, (3) Paleozoic carbonate rock, (4) Paleogene mudstone, (5) Paleogene sandstone, and (6) oil reservoir. (From Zhang, GEOPHYSICS, October 1994).

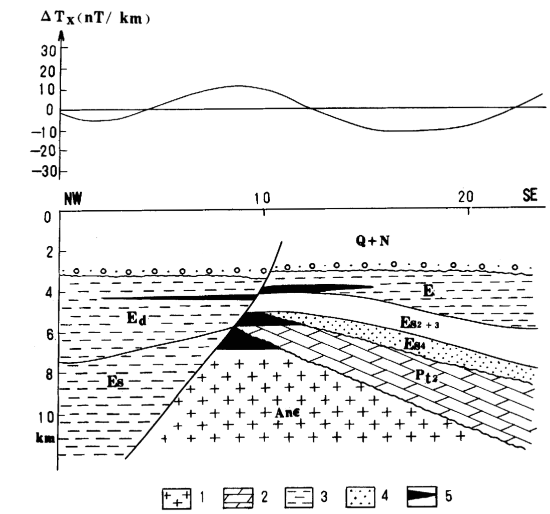

Figure 2. Cross-section and magnetic profile from Hejian. (1) Precambrian gneissic granites, (2) Mesoproterozoic dolomite, (3) Paleogene mudstone, (4) Paleogene sandstone, and (5) oil reservoir. (From Zhang.)

has an amplitude of 7-25 nT. A well penetrated, at 1638 m, a Mesozoic basalt which had a thickness of several tens of meters. Since the basalt layers occur along a fold-axis controlled by a major fault, the related anomalies coincide well with the Dagang structure itself (Figure 4).

Structure-associated anomalies related to magnetic sedimentary formations. In the south part of the South Peten Basin in southern Belize, the main exploration target is the Coban formation of Cretaceous age. This is a prolific producer in neighboring Guatemala.

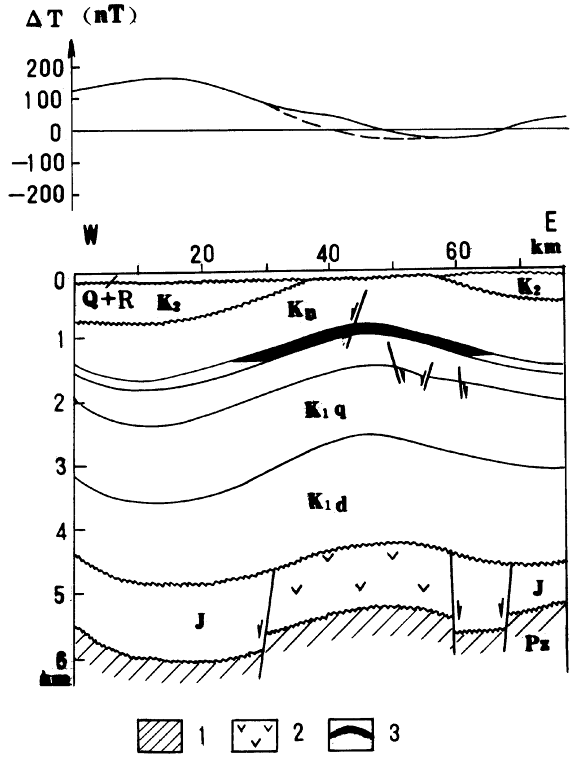

Figure 3. Cross-section of the Daqing Dome with magnetic profile. Dashed line is regional that was removed to isolate the anomaly of interest. (1) Paleozoic basement, (2) Jurassic volcanic rocks, (3) Cretaceous clastic rocks, and (4) oil reservoir. (From Zhang.)

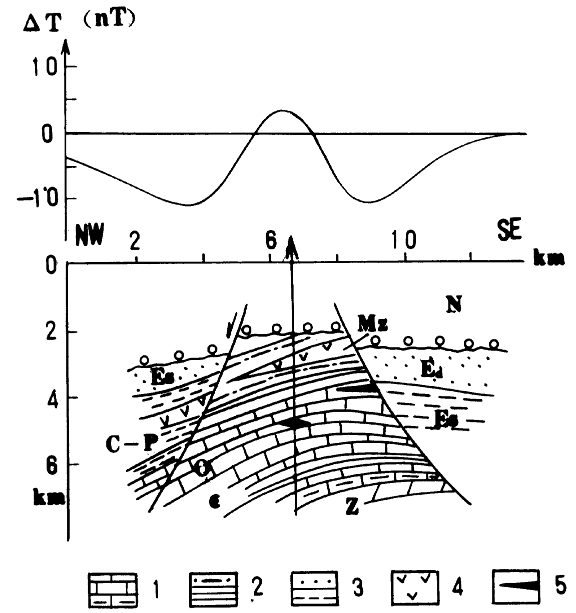

Figure 4. Cross-section of northern Dagang structural zone with magnetic profile. (1) Lower Paleozoic limestone/dolomite, (2) Phanerozoic siltstone/shale, (3) Paleogene sandstone/mudstone, (4) Mesozoic volcanic rocks, and (5) oil reservoir. (From Zhang.)

High frequency magnetic anomalies, not expected in this area due the great depth to the basement (3000-6000 m), were recorded (Figure 5, Figure 6). A previous interpretation of the data attributed these anomalies to igneous sills and dikes, but their pervasive occurrence over a large area and their consistent wavelengths suggested folded magnetic sedimentary beds. It was established that indeed there was a highly magnetic bed in the lower Eocene Toledo formation near the top of the sedimentary section. See "Syngenetic magnetic anomaly sources: Three examples" by S. P Gay Jr. and B. W. Hawley (GEOPHYSICS, 1991).

The Monkey River well, drilled in 1979 and with a total depth of 3507 ft, in the eastern part of the area showed that the magnetic interval had a thickness of 490 m and that susceptibility averaged 220 × 10^{-6} units. Petrographic analysis of the grains showed that a large percentage was andesite, a

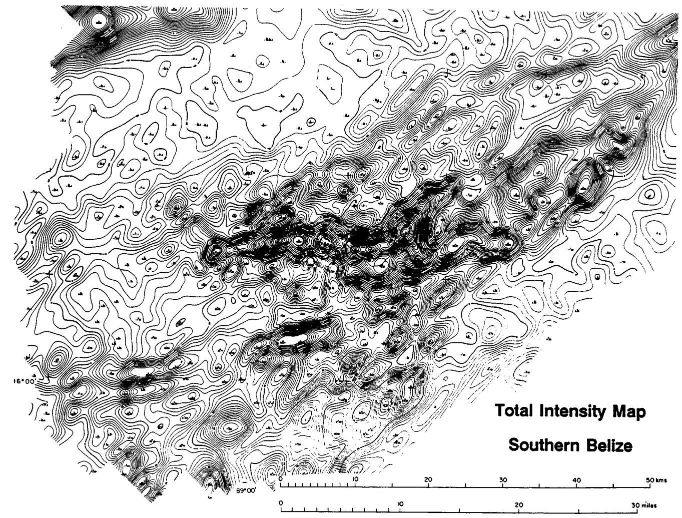

Figure 5. Total intensity map of the south Peten Basin in southern Belize. High-frequency anomalies were not expected in this area due to the great depth to basement. Contour interval is 2.5 nT. (From Gay and Hawley, GEOPHYSICS, July 1991.)

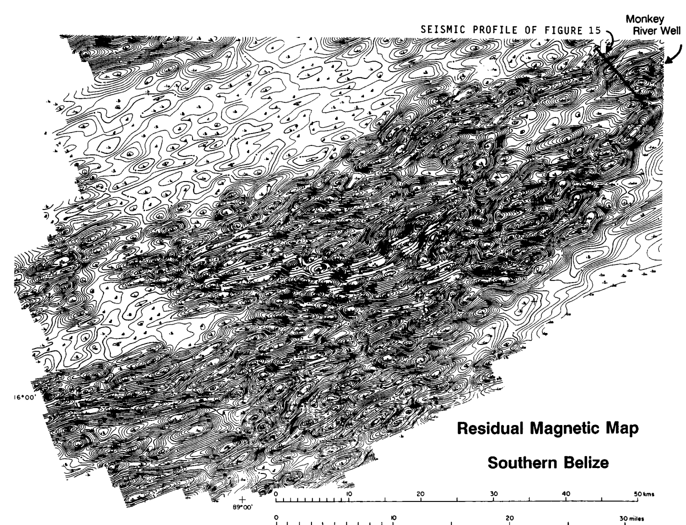

Figure 6. Profile residual map south Peten Basin. The magnetic highs and lows are caused by the magnetic Toledo Formation of lower Eocene age, which has been folded into a series of anticlines and synclines in the south Peten fold-thrust best. Contour interval is 0.5 nT. (From Gay and Hawley.)

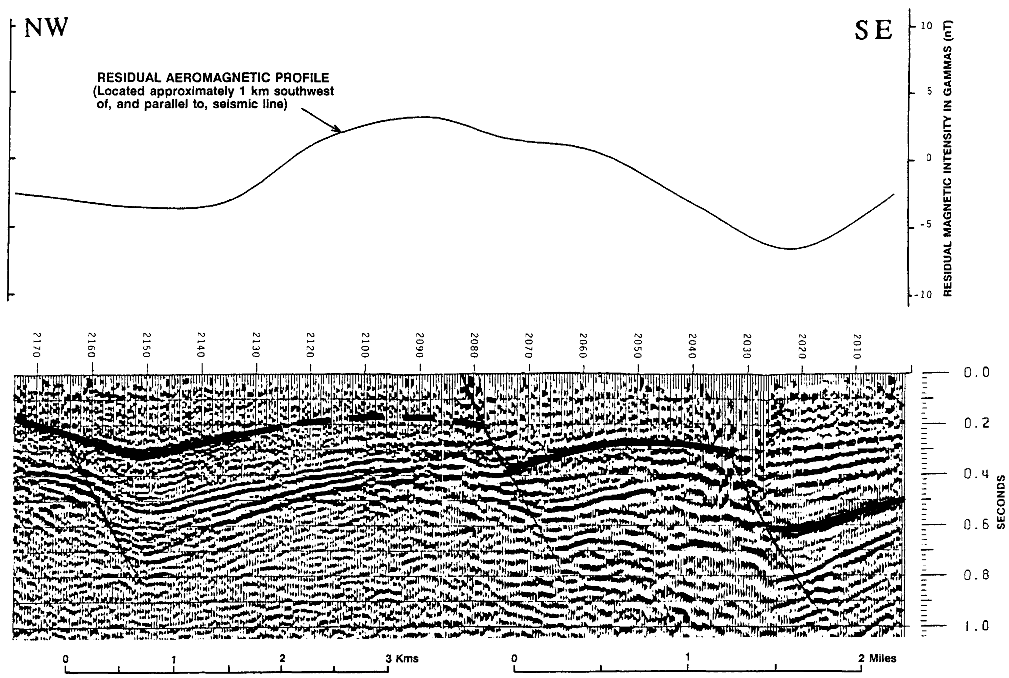

Figure 7. Seismic section and accompanying residual magnetic profile southwest of the Monkey River structure in southern Belize. The magnetic interval (measured in a well 3.4 km northeast of the section) is 490 m and has an average magnetic susceptibility of 220 X 10^{-6} cgs units. This interval occurs high in the section close to the position of the marked reflector. Note the excellent correspondence of this reflector and the magnetic profile. (From Gay and Hawley.)

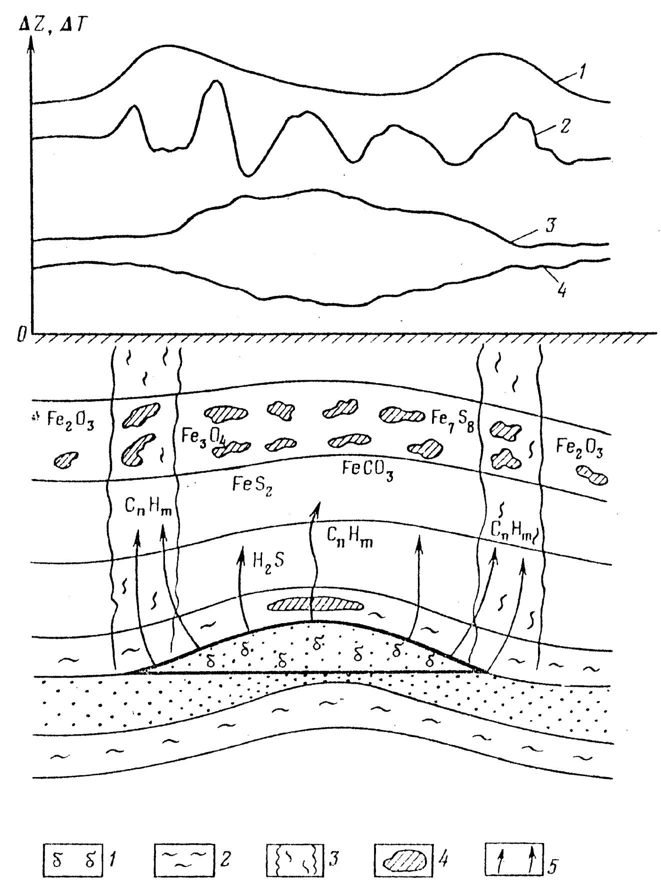

Figure 8. Conceptual model. (1) oil accumulation, (2) seal, (3) zones of subvertical inhomogeneities, (4) secondary magnetic bodies, and (5) migration path of hydrocarbons. (Modified from Berezkin et al.)

rock common in volcanic flows which generally contains several percent magnetite. A comparison of the final residual map with seismic data, especially in the offshore portion, revealed that the residual magnetic highs correspond very closely to seismic highs. The target Cretaceous beds lie 200-400 m below the magnetic Toledo formation, so there is generally a small (but predictable) horizontal offset between the residual magnetic highs and the structures of economic interest. Figure 7 shows a magnetic profile along one seismic line; correlation with shallow seismic reflector is excellent.

Direct detection of oil and gas. The use of magnetic methods for direct or semidirect location of oil and gas is based on the detection of diagenetic magnetite, caused by hydrocarbon seepage. The presence of magnetic bodies over oil and gas accumulations has been established for many producing areas. Some of these bodies are shallow (less than 1000 ft; some are rather deep (greater than 3000 ft).

Some of the theories concerning the formation of this diagenetic magnetite were reviewed by D. F. Saunders and S. A. Terry in "Onshore exploration using the new geochemistry and geomorphology" (*Oil and Gas Journal*, 1985). According to these authors, hematite in the sediments overlying petroleum accumulations is converted to magnetite by chemical reduction due to hydrogen sulfide formed by sulfate-reducing bacteria in the presence of hydrocarbon gases. Hydrogen sulfide can be generated in shallow reservoirs by alteration that results from the introduction of anaerobic bacteria by descending meteoric waters. The bacteria selected their food from the hydrocarbons and deliver oxygen by the reduction of sulfate ions in the invading waters.

Another possibility is that reduced iron in solution combines with hematite and water to form magnetite, and a third possibility is that ferrous ions produced at some depth may migrate upward into an oxydizing zone. Slow oxidation may directly produce magnetite.

The conversion of nonmagnetic hematite to magnetite creates anomalous "ripples" on the aeromagnetic total field record which can be readily identified in the data processing. Saunders and Terry showed four such profiles over known fields. The diagenetic magnetic signal is recognized by its longer "wavelength" (compared to background noise) and its higher amplitude. The very long basement effects and very short cultural sources were removed or highly suppressed by data processing.

The Russian model, summarized by Berezkin et al. in "Aeromagnetic survey in oil and gas geological prospect-

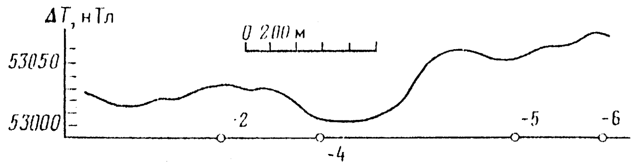

Figure 9. Magnetic profile over Saribikulskoe bitum field. o = induced polarization points. (Modified from Berezkin et al.)

ing" (published in Russian in *Geology of Oil and Gas,* 1993) is a little bit different. They connected the appearance of magnetite with reorganization of siderite. They also have a different point of view on the role of microorganisms in the formation of magnetite. The Russians feel the main role played by the microorganisms involves the oxidation of hydrocarbons, which leads to the formation of the simplest organic acids, carbonic acids, etc. which, in turn, chemically react with minerals in surrounding rocks.

The Russian approach to the interpretation of magnetic anomalies over oil and gas accumulation is more flexible than the one used in many other areas, such as the U.S. Berezkin et al. cite four different kinds of magnetic anomalies which are found over oil and gas fields (Figure 8):

1) Double hump anomaly: The result of subvertical zones with more intensive hydrocarbon migration than in the center of the field. Very often pyrite is formed over the center of the field and this will make the anomaly even more evident. In my opinion, this type of anomaly could also be associated with fractured reservoirs.
2) The "ripples" described by Saunders and Terry.
3) Positive anomaly. Caused by uniform magnetism over the whole field with higher intensity in the middle.
4) Negative anomaly. Caused by formation of pyrite instead of magnetite. This might be the result of the migration of hydrogen sulfide (H_2S).

When dealing with anomalies 1 and 4, a combination of the magnetic method with IP to map shallow zones of pyrotization over oil and gas accumulations could be very beneficial. See "A review of some experience with induced-polarization/resistivity method for hydrocarbon survey: Successes and limitations" by B. K. Sternberg (GEOPHYSICS, 1991). The integration of these inexpensive methods could confirm the anomalous zone and help understand what kind of magnetic anomaly could be expected.

Figure 9, over Sarabiculskoe bitume field in Tatarstan (Russia) is an example of anomaly 1. The bitume accumulation is at a depth of 150 m. The t curve has two maximums at the edge of the accumulation and a minimum at the center. The minimum is probably associated with the presence of pyrite. An IP survey, done at the same time, shows an increase in apparent polarization from 2% at the edge of the field to 4% at the center. Increased polarization is known to be caused by the presence of pyrite.

Figure 10 over the oil-producing Kotovsky reef in Russia is an interesting example of anomaly 3.

The Russian approach might indicate that some previous work on direct detection of hydrocarbons should get a "second look." For example, Busby et al. looked for only high frequency, low amplitude anomalies, type 2, in the Formby area in England. See "A search for direct hydrocarbon indicators in the Formby area" (*Geophysical Prospecting*, 1991). However, based on their published data, this looks more like a case of anomaly 1. IP studies over this field would be quite interesting.

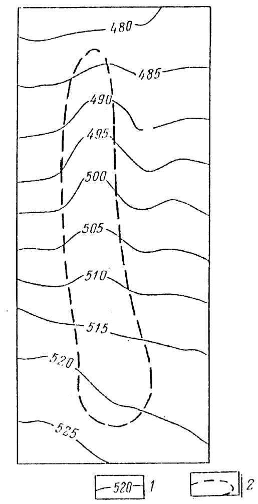

Figure 10. (right) T magnetic map over Kotovsky oil-producing reef in Volvograd district of Russia, (1) magnetic contours of ΔT, and (2) area of oil production. (Modified from Berezkin et al.)

Discussion. The magnetic method has well established theory, acquisition techniques, interpretation processes and data are available all over the world. However, this method has a poor reputation among many practicing geophysicists. One reason is that, in many cases, data interpretation may still be more art than science.

From my point of view, the best way to utilize the magnetic method is in a manner that integrates its information with that of other geophysical and geochemical methods.

The effective combination of gravity and magnetic methods for structural interpretation was illustrated by the examples from China. However, this combination could also be used to directly confirm the presence of oil and gas because the gravity effect resulted from the difference in density between the water-saturated and hydrocarbon-saturated parts of the reservoir. The combined gravity effect of oil and gas (especially gas) in the producing part of the field could reach more than a milligal.

Many benefits can result from a union of seismic and magnetic methods. Their integration for structural interpretation was shown in this article in the example from Belize. A very interesting synergy of three methods is described in "Empirical observations relating near-surface magnetic anomalies to high-frequency seismic data and Landsat data in eastern Sheridan County, Montana" by J. A. Andrew et al. (GEOPHYSICS, 1991). It shows that most fields have an associated near-surface magnetic anomaly. Other near-surface magnetic anomalies occur in conjunction with seismic events which correlate with producing intervals. In this case, the use of the different types data in combination aided recognition of the important anomalous features in each data set.

Finally, in areas where only magnetic data are available, I recommend a two-stage approach to interpretation. First is traditional structural interpretation and the second is the attempt at direct detection of hydrocarbons. For the second stage, the effects of Precambrian rocks and basement topography and of surface and near-surface cultural iron contamination and volcanics should be removed.

Conclusions. When conditions are favorable, the magnetic method can be effective in oil and gas exploration. It is, also, relatively inexpensive and readily available.

The magnetic method has a long history of success in providing information about structure, but recent developments have shown it can provide evidence of oil and gas accumulations. This information can, and should, be integrated with other geophysical and geochemical methods. When confirmed by another geophysical method (especially seismic), magnetic anomalies can be very attractive targets for exploratory drilling. LE

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