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Spatial association analysis between hydrocarbon fields and sedimentary residual magnetic anomalies using Weights of Evidence: An example from the Triassic Province of Algeria

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A B S T R A C T

The presence of near-surface magnetic anomalies over oil and gas accumulations and their contribution to exploration remain somewhat controversial despite encouraging results and an improved understanding of genetic links between hydrocarbon seepage-induced alterations and near-surface magnetic minerals. This controversy is likely to remain since the cause of shallow-sourced sedimentary magnetic anomalies may well be microseepage related, but could also result from other sources such as cultural features and detrital magnetite. The definite way of discriminating between them remains a challenge. In this paper we examine means to deal with this particular purpose using a Bayesian technique known as 'Weights-of-Evidence'. The technique is implemented in GIS to explore spatial associations between known hydrocarbon fields within the central Triassic province of Algeria and sedimentary residual magnetic anomalies. We use the results to show possible application of the method to the recognition of some characteristics (amplitude and width) of anomalies assumed to be induced by hydrocarbon microseepages. Our results reveal strong spatial association with certain typical class of anomalies, confirming therefore hypothesis that hydrocarbon microseepages may result in detectable magnetic anomalies. It is possible to use the anomalies occurring outside the known gas and oil fields to make informed decisions in the selection of new targets for more detailed hydrocarbon exploration.

1. Introduction

Airborne magnetic survey has been used in oil exploration for many decades. It is traditionally applied to quickly and economically screen large areas for mapping depths to basement and bedrock structures that control emplacement of hydrocarbon in overlying sedimentary basins. Recent years have seen a surge in interest for the application of magnetic data to the detection of intra-sedimentary shallow-sourced anomalies associated with hydrocarbon microseepages. It has been well documented that most oil and gas accumulations leak hydrocarbons, creating alteration features close to the surface that can be identified using geochemical methods as well as some geophysical techniques such as gamma-ray spectrometry, induced polarization and magnetic survey (Saunders et al., 1993; Foote, 1996; Schumacher, 2000; Perez-Perez et al., 2011; Curto et al., 2012; Flekkoy et al., 2013).

In the late seventies, it was shown for the first time the presence of near-surface magnetic anomalies over oil and gas fields. It was made independently in Russia by Berezkin et al. (1978) and in USA by Donovan et al. (1979). Advances made in processing aeromagnetic data and an improved understanding of seep mechanisms and alteration processes that result in formation of authigenic (formed in place) magnetic minerals has promoted the magnetic method from a reconnaissance tool of sedimentary basins to a valuable exploration technique. It has a definite role to play as hydrocarbon location tool through detection of short wavelength magnetic anomalies in relationship with hydrocarbon microseepages, either in onshore or offshore basins (Foote, 1996; Burazer et al., 2001; Stone et al., 2004; Curto et al., 2012; Schumacher and Foote, 2014; Menshov et al., 2014). This seep-induced magnetic mineralization has led to some development of analytical methods that allow subtle anomaly identification. Foote (1996) elaborated a method referred to as "Magnetic Bright Spots (MBS)" - which provide valuable clues to an underlying oil or gas accumulation. Studies from onshore and offshore examples reveal stunning results: the exploration leads and prospects associated with MBS anomalies are 4 to 6 times more likely to result in a commercial oil or gas discovery than a similar prospect without such an anomaly (Schumacher and Foote, 2006, 2014). Stone et al. (2004) developed a simple micromagnetic aureole search methodology which is intended to the recognition of annular/aureole-shaped anomalies. The test study from a high-resolution

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aeromagnetic survey performed over Muglad Basin of southern Sudan has successfully revealed an annular anomaly correlating directly with the Jarayan oil field.

Despite the good consistency of results obtained from published studies, this method is not really employed by practicing geophysicists from industry. If data processing techniques can often remove the influence of deep magnetic basement rocks, this is not always the case when it comes to discriminate between the effects of shorter wavelengths anomalies which can result both from authigenic ferromagnetic minerals than possible syngenetic magnetic sources. Certain researchers (Gay and Hawley, 1991; Gay, 1992) remained skeptical about the origin of near-surface intra-sedimentary magnetic anomalies supposedly attributable to hydrocarbon microseepages effect. They reported examples of many false anomalies caused by a detrital magnetite, tuffs, "black sands" in stream channels and cultural contamination from surface and near-surface iron. It is this skepticism that appears to deter many petroleum geophysicists.

Because of this controversy about the presence, origin, and exploration significance of magnetic mineralization associated with hydrocarbon accumulations, we decide to carry out a more analytical and more objective methodology using GIS-based Weights of Evidence (WofE) approach (Bonham-Carter, 1994). This technique is implemented to investigate the genetic links between Sedimentary Residual Magnetic (SRM) anomalies and hydrocarbon seepage environments. The WofE has been extensively applied as successful mineral-potential mapping tool. (Agterberg, et al., 1993; Carranza, 2004; Zeghouane, et al., 2016). However, to our knowledge the present study represents its first application to hydrocarbons exploration. The central Triassic province of Algeria which contains numerous oil and gas producing fields as well as the giant gas-deposit of Hassi R'mel offers an ideal case study.

Our aim was to investigate the spatial association between SRM anomalies and the known hydrocarbon fields within the study area to answer the question whether the spatial distribution of these magnetic anomalies is controlled by the underlying oil/gas fields. First, we use the WofE technique to establish a quantitative characterization of the spatial relationship. Next, we reveal the characteristics (wavelengths and amplitudes) of the type of anomalies assumed to be induced by hydrocarbon microseepages. Finally, we show evidence of the convenience of large-scale aeromagnetic data for such tasks when acquired at relatively low altitude and at suitable accuracy.

2. Hydrocarbon seeps and associated magnetic anomalies

It has long been recognized that most oil and gas accumulations leak hydrocarbons due to high pressures at depth. This leakage occurs vertically or near-vertically from the reservoir to the surface through fractures in rocks and planes of weakness between geological layers or along fault discontinuities (Schumacher, 2010; Salati, 2014). Except some macro-seeps encountered sometimes in certain regions, that manifest themselves as the visible presence of oil and gas seeping to the surface, most of hydrocarbon seeps have no visible and direct evidences of their presence (microseeps), but cause several chemical reactions and microbial oxidation in the rocks and soils and also cause changes in pH and oxidation potential Eh. Such changes in the near-surface soils destabilize many compounds, increase the solubility of the elements and induce mineralogical alterations such as red beds bleaching, clays formation, and creation of secondary carbonates, sulfides, and magnetic minerals (Schumacher, 1996, 2014; Salati, 2014).

Eventov (1997) has reviewed some of the most documented theories concerning the formation of the diagenetic magnetite, caused by hydrocarbon seepages. According to these theories, the hydrocarbon-induced reducing environment can lead to the precipitation of a variety of magnetic iron oxides and sulfides, including magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), pyrrhotite (Fe_7S_8), and greigite (Fe_3S_4). Schumacher (1996) provided a model for hydrocarbon-induced magnetic minerals. In accordance with this model, upward-migrating light hydrocarbons reach near-surface oxidizing conditions; aerobic hydrocarbon-oxidizing bacteria consume methane (and other light hydrocarbons) and decrease oxygen in pore waters. With development of anaerobic conditions, the activity of sulfate-reducing bacteria results in sulfate ion reduction and oxidation of organic carbon to produce bicarbonate ion and reduced sulfur species which in turn combine with available iron to form iron sulfides and oxides. For their part, Machel and Burton (1991) suggested that magnetic minerals could be either produced or destroyed under the influence of hydrocarbons seeps. On the basis of extensive investigations conducted in major oil fields of several basins in China, the results of mineralogical analysis reveal that the enhanced magnetic susceptibility relating to the hydrocarbon microseepages are caused by secondary magnetite and the subsequent low-temperature oxidation products (maghemite) (Liu et al., 2004).

Diagenetic magnetic minerals created by hydrocarbon microseepage have been reported to occur over a wide range in *depth*, from surface soils to strata as deep as 1500 m (LeSchack and Van Alstine, 2002). The identification of anomalous magnetic minerals over oil and gas accumulations has been established by magnetic susceptibility measurements and magnetic mineralogy analysis of surface soils, drill cuttings and cores from oil wells. Saunders et al. (1991) documented increases in magnetic susceptibility that were caused by high concentrations of authigenic magnetic minerals (magnetite and probably maghemite) occurring just below the grass roots. Foote (1996) reported that most magnetically enhanced zones detected in high resolution ground and airborne magnetic surveys over hydrocarbon reservoirs are thought to occur at depths of 60–600 m. Perez-Perez et al. (2011) revealed the presence of authigenic magnetite at a depth of about 600 m by analyzing drill cuttings from Venezuelan and Colombian oil fields.

However, the literature lacks in studies that focus on the horizontal extension of hydrocarbon-induced magnetic mineralization. Only few studies have partially referred to the dimensions of magnetic anomalies associated with these mineralizations. Schumacher and Foote (2014) noted that hydrocarbon-induced mineralization is detectable in broad bandwidth magnetic data acquired at low altitude, without indicating the interval of this bandwidth. Ground survey profiles within productive hydrocarbon areas in Carpathian Foredeep of Ukraine (Menshov et al., 2014) have permitted to highlight seep-induced local magnetic anomalies characterized by a width of about 4 km. Another example of mapping hydrocarbon-induced magnetic anomalies has been published for the Muglad Basin of the Sudan region (Stone et al., 2004); the identified residual intrasedimentary anomalies from a 100 m-altitude airborne survey appear occurring with width in the range of 2–9 km. It is well known that the variation in anomaly width is closely related to the variation of distance (depth + altitude of acquisition) separating the sources from the sensor. The deeper sources produce broader shaped anomalies than those produced by shallower sources. Similarly, the width of anomalies is moreover related to the horizontal dimension of the source. To better be aware of width and gradient steepness of sedimentary residual magnetic anomalies related to hydrocarbon microseepages, we undertook such a study at the Algerian central Triassic province.

3. Materials and methods

3.1. Study area

This study was developed in a region within the Triassic province of Algeria, in fact a large basin located on the northern-central part of the Saharan Platform. It lies at the Northern part of the Oued Mya depression, between 0° 40′–4° 48′E longitudes and 31° 06′–33° 55′N latitudes (Fig. 1). Study area topography is characterized by the presence of several Wadis which flow is from NNW to SSE. The elevation generally ranges from 300 m above mean sea level at southeastern corner of the area to 800–850 m all along the northern margin. The topography of