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Correlating biodegradation to magnetization in oil bearing sedimentary rocks

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Abstract

A relationship between hydrocarbons and their magnetic signatures has previously been alluded to but this is the first study to combine extensive geochemical and magnetic data of hydrocarbon-associated samples. We report a detailed study that identifies a connection between magnetic mineralogy and oil biodegradation within oil-bearing sedimentary units from Colombia, Canada Indonesia and the UK.

Geochemical data reveal that all the oil samples are derived from mature type-II kerogens deposited in oxygen-poor environments. Biodegradation is evident to some extent in all samples and leads to a decrease in oil quality through the bacterially mediated conversion of aliphatic hydrocarbons to polar constituents. The percentage of oil components and the biodegradation state of the samples were compared to the magnetic susceptibility and magnetic mineralogy. A distinct decrease in magnetic susceptibility is correlated to decreasing oil quality and the amount of extractable organic matter present. Further magnetic characterization revealed that the high quality oils are dominated by pseudo-single domain grains of magnetite and the lower quality oils by larger pseudo-single domain to multidomain grains of magnetite and hematite. Hence, with decreasing oil quality there is a progressive dominance of multidomain magnetite as well as the appearance of hematite. It is concluded that biodegradation is a dual process, firstly, aliphatic hydrocarbons are removed thereby reducing oil quality and secondly, magnetic signatures are both created and destroyed. This complex relationship may explain why controversy has plagued previous attempts to resolve the connection between magnetics and hydrocarbon deposits.

These findings reinforce the importance of bacteria within petroleum systems as well as providing a platform for the use of magnetization as a possible exploration tool to identify subsurface reservoirs and a novel proxy of hydrocarbon migration.

1. INTRODUCTION

Direct hydrocarbon exploration has been an area of active research for decades and although links between magnetics and hydrocarbons have been alluded to through both large and small spatial scale research (e.g., Donovan et al., 1979; Benthien and Elmore, 1987; Elmore and Crawford, 1990; Aldana et al., 2003, 2011; Venkatachalapathy et al., 2011) neither an unambiguous relationship nor a plausible mechanism has been identified.

1.1. Observations

Aeromagnetic studies for exploration of hydrocarbon reservoirs assume that magnetic anomalies at shallow depths could be associated with the chemical alteration of

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magnetic minerals within a reducing environment in underlying hydrocarbon reservoirs (Donovan et al., 1979).

Well core, soil and fluid studies associated with hydrocarbons have also been a topic of growing research, especially with magnetic mineral characterization (e.g., Díaz et al., 2000; Gonzalez et al., 2002; Aldana et al., 2003; Ivakhnenko and Potter, 2004; Costanzo-Á lvarez et al., 2006; Liu et al., 2006; Rijal et al., 2010; Aldana et al., 2011; Venkatacha-lapathy et al., 2011; Rijal et al., 2012). These studies have identified a number of relationships between magnetic properties and hydrocarbons such as high magnetic susceptibility (χ) anomalies only associated with the presence of hydrocarbons relative to background readings, and magnetic susceptibility correlations to physical and chemical properties of oils, e.g., density, viscosity, sulfur content and diagenetic settings.

Several studies (e.g., Díaz et al., 2000, 2006; Guzman et al., 2011) identified positive correlations between extractable organic matter (EOM), organic matter free radical concentration (OMFRC) and magnetic susceptibility, proposing that the areas of magnetic anomalies represent broad reducing bands with the presence of asphaltenes suggesting that secondary minerals are formed by a bacterial reducing process. These studies mainly looked at samples above oil reservoirs, identifying magnetic differences within samples spanning several geological formations. Machel (1995) created a detailed report on magnetic mineral assemblages in diagenetic environments associated with hydrocarbon plumes.

However, magnetic susceptibilities in these studies show inconsistent and poorly constrained relationships with hydrocarbons. This uncertainty has provided a barrier to the effective application of magnetic survey techniques in petroleum exploration.

1.2. Mechanisms

It has been suggested that chemical alteration of iron oxides to authigenic magnetite and/or iron sulfides could cause relative increases or decreases in the magnetic signal (Donovan et al., 1979; Elmore and Leach, 1990; Reynolds et al., 1990a,b; Reynolds et al., 1991; Saunders et al., 1991 Foote, 1996; Leblanc and Morris, 1999). One study by Elmore et al. (1993) reported an increase in total magnetization through the diagenetic formation of magnetite in host rocks with little magnetization before hydrocarbon infilling. A reduction in total magnetization was also recorded in units where the formation of magnetite caused the destruction of relatively larger proportions of hematite. Other processes have also been identified that could result in magnetic anomalies (Machel and Burton, 1991; Gay, 1992; Machel, 1995, 1996). Díaz et al. (2000) suggested these anomalies are a result of hydrocarbon gas leakage from below, resulting in a net transfer of electrons from altered organic matter to Fe(III).

Magnetite and pyrrhotite are the more stable minerals under anaerobic/reducing conditions compared to higher stabilities for goethite and hematite under aerobic/oxidizing conditions (Machel and Burton, 1991; Machel, 1995). The introduction of fluids such as hydrocarbons are already known to sometimes result in diagenetic remagnetization e.g., Elmore et al. (2001) and results suggest that on a large scale, anomalous magnetic susceptibility associated with low EOM abundances can form around reservoirs due to the formation of secondary magnetic material. There are still many uncertainties however related to the mechanisms for producing magnetic signatures in oil deposits and their adjacent environments. One key unknown is the nature of the magnetic signature of oil reservoirs themselves.

1.3. Biodegradation

The likely relationship between the presence of hydrocarbons and authigenic magnetite formation is further complicated by the oil biodegradation, chemical alteration of magnetic minerals and continued migration of oils within the reservoir. Biodegradation is primarily an oxidation process, which is controlled by conditions needed to support microbial life (Connan, 1984). Biodegradation therefore needs a number of factors to occur; (1) sufficient porosity and permeability for water mobility; (2) temperatures should be <80 °C to support the microbes, and (3) H_2S levels and salinity should be suitable for either aerobic or anaerobic bacteria (Connan, 1984; Palmer, 1993; Blanc and Connan, 1994). Due to these conditions, it can be assumed that biodegradation typically increases towards the surface; however, biodegradation can increase with vicinity towards an oil–water contact potentially increasing with depth (Head et al., 2003; Larter et al., 2003).

In this study, oil impregnated samples have been assessed and compared to magnetization to identify any relationships. The work is distinct from previous studies because (1) it mainly investigates a series of samples from a variety of reservoirs and (2) it uses geochemical analyses to directly identify oil quality and biodegradation state. These results are then compared with magnetic characterization data. Our findings have direct relevance to studies that use magnetic susceptibility and identify a clear correlation between mineral magnetism and detailed oil chemistry. The work discriminates between previously proposed mechanisms and supports future use of magnetic data in hydrocarbon exploration.

2. SAMPLES

Samples were collected from four sources: (1) Wessex Basin, Dorset, UK, (2) Saltarín 1A well, Llanos Foreland Basin, Colombia, (3) Athabasca, Alberta and Plover Lake, Saskatchewan, Canada and (4) Kabungkan and Lawele, Buton Island, Indonesia (Fig. 1). These samples were selected because of their variation in biodegradation, however, retrieving oil free samples from the same geological facies was possible for the UK Osmington Mills samples. A brief overview of the geological settings are outlined below.

Fieldwork was conducted in the Wessex Basin, Dorset, UK (Fig. 1a) (Selley, 1992) where samples were collected from oil stained outcrops. The Wessex Basin is characterized by the presence of an anticlinal feature at the surface and is part of a system of linked Mesozoic basins trending across Southern England and Northern France (Underhill and Paterson, 1998). Inversion of the basin depocenters