Delineating Pixels of Natural Hydrocarbon Micro-Seepage Induced Alterations and Anomalies in Overlying Soils and Sediments in Ugwueme, with ASTER Data and Band Ratio Technique

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Abstract

The earth’s underlying hydrocarbon-bearing reservoirs frequently leak. These reservoirs leak because of their inadequate sealing, and at high pressure, oil and gas escape vertically or nearly vertically to the earth’s surface as seepage. Micro-seepages on the earth’s surface cause oxidation-reduction reactions, which cause anomalies in the soils and sediments beneath them. Remote sensing (RS) and geographic information systems (GIS) are important tools for investigating hydrocarbon micro-seepage-induced changes and anomalies in overlying soil and sediments. In this study, ASTER remote sensing data was adopted to delineate pixels of hydrocarbon micro-seepage-induced anomalies in Ugwueme, south-eastern Nigeria. Band Ratio (BR) was used as a spectral enhancement technique to detect alterations and anomalies in the overlying soil and sediments. ASTER BR of 2/1 improves ferric iron; (5+7)/6 improves clay minerals; (1+4)/(2+3) improves ferrous iron; and 4/(6+9) improves gypsum.

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The study highlights that BR is an excellent spectral enhancement technique for delineating areas of alterations and anomalies induced by hydrocarbon micro-seepage.

Keywords: alterations, anomalies, ASTER data, band ratio, hydrocarbon micro-seepage

Introduction

The earth’s underground petroleum reservoirs are often saturated with oil and gas, concealed within the earth’s impermeable reservoir [1-5]. As a result of differences in pressure, these oil and gas leaks migrate vertically or nearly vertically along geological faults, fractures, and layers of rocks to shallow levels and finally to the earth’s surface as seepages [6-9] (Fig. 1). The vertical movement of oil and gas through geological faults and fractures and within the sub-surface bedding plane is known as the “chimney effect” [10-13]. Through its passage, the chimney effect often generates oxidation-reduction reactions that produce anomalies in overlying soils and sediments. Microbial and mineralogical anomalies, as well as changes in the electrical and magnetic characteristics, often occur at the near surface and on the surface of overlying sediments and soils [14-17]. Among these anomalies and alterations, red bed bleaching (conversion of Fe³⁺ to Fe²⁺) [18-20], clay minerals (conversion of feldspar to clay minerals, such as kaolinite) [21-23], carbonates (the presence of Fe²⁺ rich minerals (conversion of feldspar to clay minerals, such as kaolinite) [21-23], carbonates (the presence of Fe²⁺ rich carbonates, such as siderite), [24-27], and ferrous iron enrichment [28-30] often express diagnostic spectral characteristics, which can be detected and interpreted with remote sensing technology [31-33]. The description of these anomalies and alterations as represented in Fig. 1 is highlighted as follows [8, 34-36]:

(a) Red bed bleaching: Red beds or sediments often appear reddish if they contain iron oxide (hematite). When hydrocarbon seepage comes into contact with reddish sediments, it degrades the iron oxide and bleaches them. Bleached sediments frequently include more siderite and pyrite and less ferric iron [37-39].

(b) Clay mineral precipitation: In areas of hydrocarbon micro-seepage, clay minerals like illite and smectite frequently transform into kaolinite. Kaolinite-rich sandstone exhibits brighter values in the band ratio image [40-42].

(c) Prevalent carbonate minerals: Carbonate minerals are created when calcium or magnesium oxides present in sediments react with carbon dioxide emerging from micro-seepage. As a result, carbonate mineral concentrations rise in micro-seepage milieus. The calcium and magnesium content of the parent materials, in contrast, governs the development of carbonate minerals [43-45].

(d) Present of magnetic minerals: The synthesis of ferrous minerals is stimulated by reducing the ferric iron level in a micro-seepage-impacted environment. The precipitation of pyrrhotite, magnetite, greigite, and maghemite has been observed in numerous hydrocarbon micro-seepage fields [46-48].

Hydrocarbon seepage found on the earth’s surface may be macro- or micro-seepage [7, 49, 50]. Etiope [14] documented that Link [51] was the first scientist to have distinguished hydrocarbon seepage as either micro-seepage or macro-seepage. According to Etiope [14], macro-seepages are the visible onshore or offshore manifestations of oil, gas, and mud volcanoes, whereas micro-seepages are the invisible remains of light hydrocarbons that cause mineral alterations [52-54]. They are dominated majorly by methane (CH₄) and lightly by ethane (C₂H₆), propane (C₃H₈), butane (C₄H₁₀), and pentane (C₅H₁₂) gases [55-57]. At the surface, these hydrocarbon gases interact with the environment and produce mineralogical and botanical anomalies [58-60]. Long-term contact of hydrocarbon micro-seepage with overlying soils and sediments often alters their mineral composition, thereby producing changes in their pH, mineralogy, chemical, and physical properties [61-63]. These changes are manifested by changes in the color, hardness, radioactivity, magnetic, and electric properties of the rock minerals [64, 65]. Long-term exposure to hydrocarbon micro-seepage in the soil and sediments often results in local anomalous redox zones, which promote a wide range of mineral and chemical changes [66, 67]. Another important form of hydrocarbon seepage is active and passive seepage [52]. While active hydrocarbon seepage is associated with the subsurface, where oil and gas leak in large quantities into shallow soils and sediments as well as into the overlying water column, passive hydrocarbon seepage refers to areas or zones where subsurface oil and gas are inactively seeping [68-70]. Globally, hydrocarbon oil and gas seeps, and their diverse surface expressions are seen in sedimentary basins that contain oil and gas reserves [71-73].

The traditional techniques for studying hydrocarbon micro-seepage-induced alterations in soil and sediment have been extensively studied. These techniques, which include geophysical and geochemical analyses, are expensive, time-consuming, and destructive, and they are only suitable for selected observations within the vicinity of drilling sites in active oil fields [74-77]. Remote sensing offers a quick, cheap, and non-destructive solution for studying hydrocarbon micro-seepage manifestations at or near the earth’s surface [54, 78]. Although remote sensing techniques cannot directly identify micro-seepage, they can detect patterns of large-scale modification [59, 68]. In the past few decades, researchers have employed spectral enhancement techniques such as false color composite (FCC), band ratio (BR), and principal component analysis (PCA) to identify areas of surface-based alterations and anomalies induced by hydrocarbon micro-seepage on soil and sediments [79, 80].
In this study, the overall aim was to apply the BR algorithm and Advanced Space-borne Thematic Emission and Reflection Radiometer (ASTER) data to delineate pixels of mineral alterations and anomalies induced by natural hydrocarbon micro-seepage in Ugwueme. Field observation is an integral part of the study. Fieldwork was carried out in the study area to ascertain the hydrocarbon micro-seepage-prone zone.

ASTER is a multispectral sensor found on the Earth’s Observing System (EOS) Terra platform that measures electromagnetic radiation from the surface in 14 bands [81-84]. Case studies by Salati et al. [85], Rowan et al. [86], Poumandari et al. [87], and Rockwell et al. [88] have shown that ASTER data has successfully been used to delineate pixels of alterations and anomalous minerals by utilizing their emissivity, absorption, and reflection features in the SWIR and TIR regions of the electromagnetic spectrum [86, 89]. Ugwueme is a developing town situated in Enugu, in the southeastern part of Nigeria. The area is cited as being on fairly elevated terrain, covering an area of about 82 km on a scale of 1 to 25,000 km [90, 91]. Ugwueme is accessible by a laterite road and can be found between latitudes 6°0'00" N and 6°07'00" N and longitudes 7°24'00" E and 7°30'00" E in geographic coordinates [8, 92].

Materials and Methods

Description of the Study Area

The study area “Ugwueme” is situated on a fairly leveled elevation between latitudes 6°0’00" N and 6°07’00" N and longitudes 7°24’00" E and 7°30’00" E in Enugu, South-Eastern Nigeria. The region falls under the Tropical Wet and Dry Climate “AW” of the Koppen climate classification scheme [3, 6]. The wet season lasts from April to September, while the dry season runs from November to March of the following year. The dry season is characterized by little rainfall, high sunshine, and dryness. During the wet season, Ugwueme experiences heavy rainfall, with a record of 1,800 mm, which results in significant floods, soil leaching, erosion, severe outwash, groundwater penetration, and percolation. According to studies, this climatic circumstance is thought to be the primary reason for the oil seepage that flushed out from the tar sand as heavy, viscous, and sticky crude within the study area [3, 6]. The temperature is high in the area, and during the dry weather, it rises up to 26.6ºC.

Geological Settings of the Study Area

The geological setting of Ugwueme is explained in the study geology map (Fig. 2). The study area and its environs are underlain by four formations and five main lithological facies. These formations are the Awgu Shale, Owelli Sandstone, Mamu, and Ajali Formations. The main lithological facies associated with the study area are the heterolith sediments, dark gray shale, coarse grain, medium grain, and whitish cross-bedded sandstones [92, 93]. The Awgu shale is documented to be up to 300 ft. thick. The formation is made of bluish-gray, well-bedded shale with occasional intercalations of yellow, pale, fine-grained sandstones and thin-shell limestone [3, 94]. The Owelli sandstones are mostly ferruginous and are characterized as medium-to-coarse-grained sandstones [3, 93]. Toward the Awgu location, the Owelli sandstone is estimated to be about 130 m thick, resting conformably on the Awgu shale [52, 93]. The Mamu Formation (Lower Coal Measures)
is dated from the Lower to Middle Maastrichtian and is between 100 m and 1000 m thick. These formations are characterized by the alternation of coal seams with sandstone, siltstone, mudstone, and rare shale. The Ajali Formation is composed of friable and thick medium- to coarse-grain sandstones that are poorly sorted and whose conformability is above that of the Mamu Formation [92].

**Data Sources and Pre-Processing**

ASTER is a one-of-a-kind sensor that records electromagnetic radiation in 14 district bands with 15-m, 30-m, and 90-m spatial resolutions in the visible-near infrared (VNIR), shortwave infrared (SWIR), and thermal infrared (TIR) (Table 1) [95-97]. With a spatial resolution of 15 m, 30 m, and 90 m, the sensor has three VNIR bands ranging from 0.52 µm to 0.86 µm, six SWIR bands ranging from 1.60 µm to 2.43 µm, and five TIR bands ranging from 8.125 µm to 11.65 µm. The wavelength areas of VNIR, SWIR, and TIR offer spectral resolution concerning rocks and minerals [98, 99]. The VNIR area of the ASTER sensor is very effective in detecting iron-oxide minerals containing Fe$^{2+}$ or Fe$^{3+}$ ions. Altered rocks and minerals containing hydroxyl (OH) and carbonate (CO$_3$), such as Al-OH, Fe-OH, Mg-OH, and carbonate minerals, exhibit different absorption signatures in the SWIR region. The Earth Resources Observation and Science (EROS) Center in the United States and the Earth Remote Sensing Data Analysis Center (ERSDAC) in Japan offer ASTER products.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Band No.</th>
<th>Spectral Range (µm)</th>
<th>Spatial Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIR</td>
<td>1</td>
<td>0.52–0.60</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.63–0.69</td>
<td>30</td>
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<tr>
<td></td>
<td>3N</td>
<td>0.78–0.86</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td>0.78–0.86</td>
<td></td>
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<tr>
<td>SWIR</td>
<td>4</td>
<td>1.60–1.70</td>
<td></td>
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<tr>
<td></td>
<td>5</td>
<td>2.145–2.185</td>
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<td></td>
<td>6</td>
<td>2.185–2.225</td>
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<td>8</td>
<td>2.295–2.365</td>
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<td></td>
<td>9</td>
<td>2.360–2.430</td>
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<tr>
<td>TIR</td>
<td>10</td>
<td>8.125–8.475</td>
<td>90</td>
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<td>11</td>
<td>8.475–8.825</td>
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<td>8.925–9.275</td>
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<td>14</td>
<td>10.95–11.65</td>
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[100-102]. Two ASTER preprocessing approaches are cross-talk correction of ASTER-SWIR bands and layer stacking of VNIR-SWIR bands into a unique nine-band data cube. The cross-talk phenomenon has a tremendous impact on the ASTER-cross-talk SWIRs. This phenomenon changes radiance measurements within the SWIR area as a result of ASTER’s instrumental difficulties, resulting in deceptive reflectance spectra and mineral misidentification [103, 104]. Crosstalk can be decreased by utilizing the crosstalk correction program at www.gds.aster.ersda.c.or.jp. To convert pixel radiance within the sensor into the reflectance of the surface data, the ENVI (Environment for Visualizing Images) version 5.1 software’s rapid line of site atmospheric analysis of spectral hypercubes (FLAASH) module and thermal atmospheric correction of ASTER TIR emittance bands were used [105, 106].

Methods

To give the anomalous surface mineral assemblages more prominence in the study, the subset images were processed with the band ratio (BR) technique in order to delineate pixels of mineral anomalies and alterations. Band-rationing (BR) is a useful remote sensing technique for identifying spectral changes in minerals [80, 89]. It’s a multispectral image analysis that involves dividing one spectral image band by another in arithmetic terms [16, 58, 107]. The ratio of spectral reflectance measured in one spectral image band to spectral reflectance measured in another spectral image band is the outcome of this arithmetic division [62, 108]. After removing atmospheric factors such as haze from the image, band rationing improves the contrast between the objects by dividing the brightness values at peaks and troughs in a reflectance curve. Compositional information is enhanced through spectral band rationing, whereas other sorts of information about the earth’s surface are suppressed. This approach is great for emphasizing characteristics or materials. Equation (1) depicts the basic equation for calculating the band ratio technique [52, 109].

$$B_R = \frac{B_1}{B_2}$$

Where $B_1$ and $B_2$ represent the specific image bands, while $i$ and $j$ denote the digital numbers (DN) situated in the bands. In this study, band ratios (BR), an important spectral enhancement technique, were calculated using various bands in ASTER data to improve the spectral signatures of alteration and anomalous minerals [63]. ASTER BR of 2/1 enhances ferric iron [85]; (5+7)/6 enhances clay minerals [110], after [51]; (1+4)/(2+3) enhances ferrous iron [88]; and 4/(6+9) enhances gypsum [85].

Fig. 3. a) False color composite (FCC) map, formed by the BR images; b) Alteration zones elucidated in the study geology map. c) BR of 2/1 enhances ferric iron; (5 + 7)/6 enhances clay minerals; (1+4)/(2+3) enhances ferrous iron; and 4/(6 + 9) enhances gypsum.
Results and Discussion

Fig. 3a) shows the false color composite (FCC) map. The FCC maps in the study are formed by the BR images to indicate ferric iron, ferric oxides, gypsum, and clay minerals as channels of red (R), green (G), and blue (B), respectively. The alteration zones are represented by small spheres, as shown in Fig. 3b), and are highlighted in green. The field sample measurement is represented by a small, dark-colored square, which is elucidated in the study geological map. Fig. 3c) depicts the enlarged portion of the FCC map that clearly distinguishes ferric iron, clay minerals, ferrous iron, and gypsum mineralogical alterations with band ratio index. Their description is highlighted below:

Ferric iron index: Ferric iron minerals exhibit high reflectance at ASTER band 2 and broad absorption at the NIR wavelength (ASTER band 1). To depict ferric iron mineral pixels in the study area, the ASTER band ratio index of 2/1 is employed. In this study, the FCC of the band ratio, which displays ferric iron, is green.

Clay mineral index: Clay minerals frequently exhibit high reflectance abilities in ASTER bands 5 and 7, as well as vibrational Al-OH absorption characteristics in band 6. In addition to this, clay-bearing locations within the study area were delineated with ASTER BR (5+7)/6. In the study, clay pixels are highlighted in pink.

Ferrous iron index: Ferrous iron materials have high reflectance properties at ASTER bands 1 and 4 as well as an absorption feature in the VNIR wavelength of ASTER bands 2 and 3. To depict ferrous minerals in the study area, the ASTER BR (1+4)/(2+3) is employed. In the study, ferrous iron is delineated with a blue color.

Gypsum index: Gypsum displays high reflectance at ASTER band 4 and absorption at ASTER bands 6 and 9. Thus, in the study, ASTER BR 4/(6+9) is utilized to discriminate gypsum, with a red color from the study area background pixels.

Conclusions

Remote sensing is a useful technique for analyzing and modeling hydrocarbon micro-seepage-impacted areas. The technique is cheap, rapid, and non-destructive, and it can be used to delineate areas of mineralogical and botanical anomalies. Anomalies and alterations in soil and sediment can be found on the earth’s surface in a variety of ways. Within these forms, red bed bleaching, ferrous iron enrichment, clay minerals, and carbonate alterations exhibit abnormal spectral signatures, which can be analyzed with remote sensing tools. In this study, the band ratio (BR) algorithm was the technique used with the ASTER sensor to delineate areas of surface mineral alterations and anomalies induced by hydrocarbon micro-seepage in Ugwueme. ASTER BR of 2/1 enhances ferric iron; (5+7)/6 enhances clay minerals; (1+4)/(2+3) enhances ferrous iron; and 4/(6+9) enhances gypsum. The study highlights that BR is an excellent spectral enhancement technique for delineating areas of alterations and anomalies induced by hydrocarbon micro-seepage.

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Conflict of Interest

The authors declare no conflict of interest.

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