Satellite-Based Detection of Hydrocarbon-Induced Surface Alterations in Alkaleri and Kirfi Local Government Areas, Bauchi State, Nigeria

Aduojo Atakpa[1], Ndanusa Shaibu[2], Shehu Suraju[3], Umoru Sumaila[4], Muhammed Zuerat Ojonugwa[5]
Sani Yakubu Abdulaziz[6], Kakuru Ayuba Kake[7], Obadigie Augustine Prest[8]
[1,2,3,4,5,6,7,8]*National Space Research and Development Agency (NASRDA), Abuja, Nigeria*

***Abstract*—Hydrocarbon microseepage induces measurable mineralogical, geochemical, and biophysical alterations at the Earth's surface, offering detectable signatures that satellite-based remote sensing can exploit for non-invasive petroleum exploration. This study applies a multi-criterion spectral prospectivity analysis within the Alkaleri and Kirfi Local Government Areas (LGAs) of Bauchi State, Nigeria using Sentinel-2 Harmonized Surface Reflectance imagery processed on the Google Earth Engine (GEE) cloud-computing platform. A cloud-free composite was generated from scenes acquired between January and December 2023, filtered to less than 10% cloud cover. Six spectral indicators of microseepage-induced surface alteration were computed: the Clay Index (B11/B12), Iron Oxide Index (B4/B2), Hydrocarbon Stress Index (HSI; derived from Red Edge bands (B6 and B5), Normalized Difference Vegetation Index (NDVI), Shortwave Infrared–Near Infrared Moisture Anomaly Index, and a final weighted composite Hydrocarbon Prospectivity Index (HPI). All indices were normalised and fused through a mean-reduction overlay to generate a continuous prospectivity surface. The study demonstrates that the systematic convergence of multiple independent spectral proxies substantially reduces false positives and enhances exploration targeting relative to single-index approaches. The study provides a cost-effective reconnaissance framework for basin exploration in structurally complex sedimentary settings, with direct applicability for prioritising drilling targets within the study area.**

***Index Terms*—Hydrocarbon, microseepage; Sentinel-2; Google Earth Engine; prospectivity**

I. INTRODUCTION

Satellite-based remote sensing has emerged as a transformative approach for detecting surface alterations induced by hydrocarbon microseepage, offering cost-effective and non-invasive alternatives to traditional ground-based exploration methods. Hydrocarbon microseepage refers to the vertical migration of petroleum compounds from subsurface reservoirs to the surface through faults, fractures, and permeable pathways, causing detectable chemical and mineralogical changes in overlying soils and sediments (Saha, 2022). These alterations manifest as anomalous concentrations of clay minerals, ferrous iron, and carbonate minerals, which can be identified through multispectral and hyperspectral satellite imagery. Recent studies have demonstrated that Landsat-8 Operational Land Imager (OLI) data, when processed using band ratio and principal component analysis techniques, can effectively delineate clay and ferrous iron-rich areas associated with hydrocarbon seepage, achieving precision scores exceeding 52% in correlation with existing well locations (Cetin et al., 2025). The integration of spectral enhancement techniques such as the Crosta method enables the identification of mineral alteration zones that serve as indirect indicators of subsurface petroleum accumulations, particularly in inaccessible terrains where conventional field surveys are logistically challenging.

The advent of next-generation hyperspectral satellite missions has significantly advanced the detection capabilities for hydrocarbon-induced surface alterations. The Environmental Mapping and Analysis Program (EnMAP) hyperspectral sensor, with its 224 contiguous bands and 30-meter spatial resolution, has demonstrated superior performance in mapping mineralogical footprints of petroleum microseepage systems compared to traditional multispectral platforms. Elhaei and Asadzadeh (2025) utilized EnMAP data to characterize diagnostic absorption features associated with microseepage-induced alterations in the Qom region of Iran, successfully identifying partial to complete bleaching of hematite from redbeds, formation of secondary goethite, and development of montmorillonite, calcite, and Fe^{2+}-bearing chlorite across affected zones. These findings align closely with field observations and laboratory spectroscopy, highlighting the advantages of spaceborne imaging spectroscopy for mapping diagenetic mineralogical alterations in sedimentary strata. Furthermore, comparative analyses between multispectral Sentinel-2 imagery and hyperspectral data have shown that while multispectral sensors can detect general alteration patterns, hyperspectral instruments provide the spectral resolution necessary to distinguish between specific alteration minerals associated with hydrocarbon microseepage, thereby reducing false positives and improving exploration targeting (El-Hadidy et al., 2022; Jenny et al., 2023).

II. MATERIALS AND METHODS

The study utilized the Google Earth Engine (GEE) cloud-computing platform to perform a multi-criteria prospectivity analysis hydrocarbon within the Alkaleri and Kirfi Local Government Areas of Bauchi State, Nigeria. The primary dataset consisted of Level-2A Sentinel-2 Harmonized Surface Reflectance imagery acquired between January 1 and December 31, 2023. To ensure high spectral quality, the image collection was filtered for cloud cover (less than 10% per scene), and a median reducer was applied to generate a cloud-free composite of the study area. This composite was subsequently clipped to the administrative boundaries defined by the FAO GAUL 2015 Level 2 dataset.

The methodological framework involved the calculation of six distinct spectral indices to identify geological and geochemical indicators of resource presence. Vegetation health was assessed via the Normalized Difference Vegetation Index (NDVI), while moisture anomalies were identified through a Short-Wave Infrared (SWIR) and Near-Infrared (NIR) normalized difference. Specifically, a Hydrocarbon Stress Index (HSI) was derived using Red Edge bands (B6 and B5) to detect geobotanical stress associated with microseepage. Furthermore, mineralogical markers were isolated using the Clay Index (B11/B12) and Iron Oxide Index (B4/B2).

The final prospectivity model was constructed through a weighted data fusion approach. Each primary indicator: NDVI (inverted to represent stress), HSI, Clay Index, Iron Oxide Index, and Moisture Anomaly was normalized to a consistent range using a unit scale transformation to ensure equal weighting. These layers were then aggregated using a mean reduction function to produce a Final Prospectivity layer. The results were visualized using a multi-layered color-coded mapping system and exported at a spatial resolution of 20 meters for further geospatial analysis and field validation.

III. RESULTS AND DISCUSSION

Clay Index Analysis

The Clay Index map reveals anomalous concentrations of clay minerals, particularly around the Jagudi and Kukar regions, indicating intense hydrothermal alteration (Figure 1).. Hydrocarbon microseepage induces acidic reducing environments that alter feldspars to clay minerals such as kaolinite and illite, serving as reliable surface indicators of subsurface petroleum accumulations (Asadzadeh & de Souza Filho, 2020). The spatial distribution of elevated clay index values aligns with fault zones that act as conduits for vertical hydrocarbon migration, where the conversion of original rock-forming minerals to secondary clay assemblages creates distinctive spectral absorption features in the shortwave infrared region (Elhaei & Asadzadeh, 2025). These clay alteration zones represent diagenetic changes induced by long-term leakage from reservoir traps, making them critical targets for detailed seismic surveys and drilling operations in the Benue Trough region.

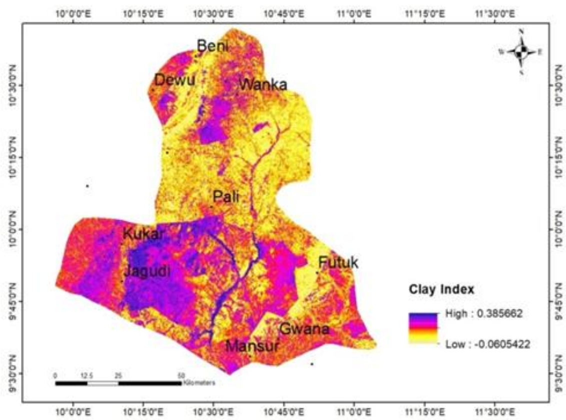

Figure 1. Clay Index

Hydrocarbon Stress Index Evaluation

The Hydrocarbon Stress Index map displays vegetation anomalies characterized by spectral signatures of physiological stress, particularly visible in the peripheries of producing fields around Wanka and Pali (Figure 2). This index captures vegetation degradation resulting from root-system absorption of hydrocarbon compounds and associated soil contamination, which reduces chlorophyll production and alters leaf cellular structure (Garain et al., 2021). The anomalous stress patterns correlate with subsurface structural features, where faults facilitate the upward migration of light hydrocarbons that create reducing soil conditions toxic to vegetation (Al-Jabri et al., 2023). High index values (cyan/green zones) indicate areas where vegetation exhibits abnormal spectral responses consistent with petroleum-induced stress, offering a cost-effective reconnaissance tool for identifying prospective hydrocarbon accumulation zones prior to detailed geophysical surveys.

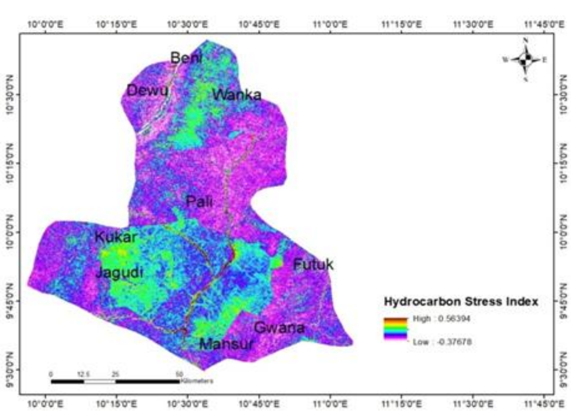

Figure 2. Hydrocarbon Stress Index

Iron Oxide Index Interpretation

The Iron Oxide Index map illustrates the distribution of ferric iron minerals, with high-value zones in the northern regions around Beni and Dewu, indicating unaltered oxidized sediments, while anomalously low values suggest bleached zones (Figure 3). Hydrocarbon microseepage promotes the diagenetic reduction of ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}), causing the bleaching of redbeds and depleting hematite concentrations in surface sediments directly above reservoirs (Asadzadeh & de Souza Filho, 2020). The spectral contrast between bleached (reduced) and unaltered (oxidized) zones enables the delineation of potential petroleum traps, as the reducing environment created by seeping hydrocarbons selectively destroys iron oxide coatings on soil particles and sand grains (Elhaei & Asadzadeh, 2025). These iron oxide depletion zones, when correlated with structural lineaments, provide compelling evidence of active hydrocarbon seepage systems.

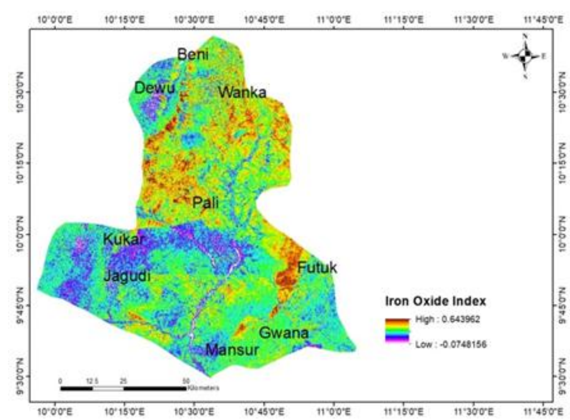

Figure 3. Iron Oxide Index

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) map reveals significant vegetation health variations, with anomalously low values around Pali and Futuk indicating stressed vegetation potentially associated with subsurface hydrocarbon seepage (Figure 4). Hydrocarbon microseepage induces vegetation stress through soil chemistry alterations and microbial oxidation of seeping gases, which reduces photosynthetic pigment concentrations and leaf area index, thereby lowering NDVI values compared to background vegetation (Garain et al., 2021). The spatial correlation between low NDVI anomalies and known fault systems suggests that vegetation indices effectively detect hydrocarbon-induced ecological disturbances, particularly in agricultural and grassland areas where healthy vegetation provides a strong spectral baseline for anomaly detection (Al-Jabri et al., 2023). These vegetation stress patterns serve as indirect indicators of petroleum accumulations, complementing mineralogical alteration mapping in integrated exploration campaigns.

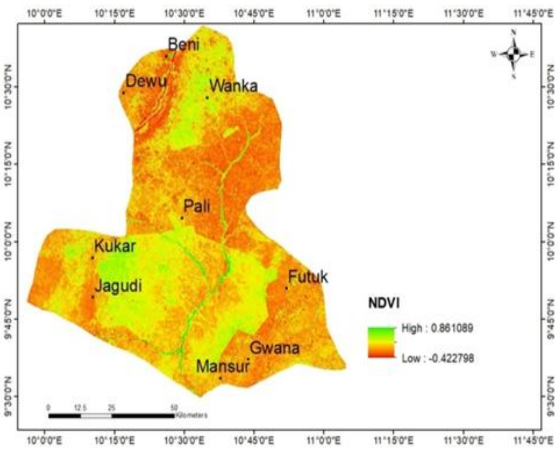

Figure 4. Normalized Difference Vegetation Index (NDVI)

Soil Moisture Index Analysis

The Soil Moisture Index map demonstrates hydrological anomalies across the study area, with distinctive moisture retention patterns around Gwana and Mansur that may indicate hydrocarbon-induced soil alterations (Figure 5). Hydrocarbon seepage modifies soil moisture characteristics through the formation of hydrophobic barriers created by petroleum compounds and alteration of soil porosity via diagenetic mineral changes, affecting evapotranspiration rates and surface moisture content (El-Hadidy, 2022). Anomalous moisture zones correspond to areas of clay mineral enrichment and iron oxide depletion, suggesting that integrated analysis of soil moisture with other alteration indices enhances the detection of microseepage zones (Asadzadeh & de Souza Filho, 2020). These moisture anomalies, particularly when identified using multispectral remote sensing, provide valuable reconnaissance data for prioritizing high-potential areas for detailed hydrocarbon exploration in frontier basins.

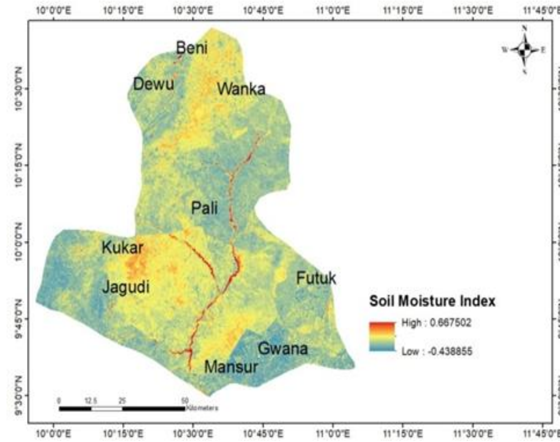

Figure 5, Soil Moisture Index

Hydrocarbon Prospectivity Index map

The Hydrocarbon Prospectivity Index map illustrates the spatial integration of multiple microseepage-induced spectral anomalies including clay mineralization, iron oxide alteration, vegetation stress, and soil moisture variations into a unified favorability model using weighted overlay analysis. The resulting classification, ranging from very low to very high prospectivity, effectively delineates priority targets within the Benue Trough, where high-potential zones concentrate around structural lineaments and zones of diagenetic alteration, particularly in the Jagudi and Wanka areas (Figure 6). This multi-criteria decision analysis approach synthesizes individual diagnostic indicators into a composite index that reduces exploration uncertainty by highlighting areas where multiple anomalies converge, consistent with GIS-based weighted overlay methodologies that assign hierarchical importance to spectral predictors (El-Hadidy, 2022). Recent applications demonstrate that combining hyperspectral and multispectral indices through advanced integration techniques significantly enhances the detection of microseepage-induced mineralogical footprints compared to single-parameter analyses, enabling precise mapping of hydrocarbon migration pathways (Elhaei & Asadzadeh, 2025). Furthermore, the validation of these prospectivity models against known structural controls and geochemical anomalies confirms their reliability for frontier exploration, as integrated remote sensing-geophysical approaches have successfully delineated hydrocarbon prospect areas in structurally complex basins by correlating surface alterations with subsurface accumulations (Garain et al., 2022). The delineation of very high prospectivity zones aligns with established petroleum system models where the juxtaposition of altered zones and structural traps indicates active hydrocarbon leakage from deep reservoirs (Asadzadeh & de Souza Filho, 2020).

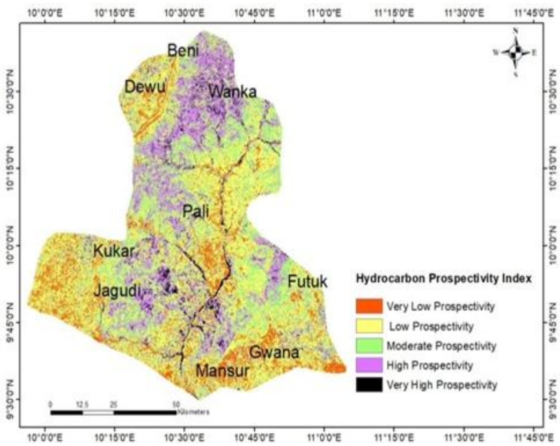

Figure 6. Hydrocarbon Prospectivity Index

IV. CONCLUSION

This research successfully demonstrates the efficacy of integrating multispectral remote sensing indices including Clay Index, Hydrocarbon Stress Index, Iron Oxide Index, NDVI, and Soil Moisture Index into a comprehensive Hydrocarbon Prospectivity Index for delineating microseepage-induced surface anomalies within the Benue Trough. The weighted overlay analysis reveals distinct spatial patterns of hydrocarbon favorability, with high to very high prospectivity zones concentrated around structural lineaments in the Jagudi, Wanka, and surrounding areas, where convergent anomalies in clay mineralization, iron oxide depletion, vegetation stress, and soil moisture alterations indicate active vertical hydrocarbon migration from subsurface accumulations. These findings validate that the spectral responses of surface materials serve as reliable proxies for petroleum-induced diagenetic changes, enabling the identification of prospective zones prior to expensive drilling operations. The methodology provides a cost-effective reconnaissance tool for frontier basin exploration, significantly reducing exploration risk by prioritizing areas where multiple independent microseepage indicators coincide with favorable structural settings, thereby offering a robust framework for integrating remote sensing technology into conventional petroleum exploration workflows in structurally complex sedimentary basins

REFERENCES

[1] Al-Jabri, K., Al-Mulla, Y., Melgani, F., & Stefanakis, A. (2023). Remote sensing analysis for vegetation assessment of a large-scale constructed wetland treating produced water polluted with oil hydrocarbons. Remote Sensing, 15(24), 5632. https://doi.org/10.3390/rs15245632

[2] Asadzadeh, S., & de Souza Filho, C. R. (2020). Characterization of microseepage-induced diagenetic changes in the Upper Red Formation, Qom region, Iran. Part II: A new insight using reflectance spectroscopic analysis. Marine and Petroleum Geology, 117, 104387. https://doi.org/10.1016/j.marpetgeo.2020.104387

[3] Asadzadeh, S., & de Souza Filho, C. R. (2020). Characterization of microseepage-induced diagenetic changes in the Upper Red Formation, Qom region, Iran. Part II: A new insight using reflectance spectroscopic analysis. Marine and Petroleum Geology, 117, 104387. https://doi.org/10.1016/j.marpetgeo.2020.104387

[4] Cetin, M., Aydinli, H.O., Pashaei, M.H. et al. Remote sensing techniques for hydrocarbon Micro-Seepage detection in Raman Mountain, Turkey. Environ Earth Sci 84, 215 (2025). https://doi.org/10.1007/s12665-025-12239-8

[5] El-Hadidy, S. M. (2022). Detecting hydrocarbon micro-seepage and related contamination probable prospect areas deduced from a comparative analysis of multispectral and hyperspectral satellite images. Journal of King Saud University - Science, 34(5), 102192. https://doi.org/10.1016/j.jksus.2022.102192

[6] El-Hadidy, S. M. (2022). Detecting hydrocarbon micro-seepage and related contamination probable prospect areas deduced from a comparative analysis of multispectral and hyperspectral satellite images. Journal of King Saud University - Science, 34(5), 102192. https://doi.org/10.1016/j.jksus.2022.102192

[7] El-Hadidy, S.M., Alshehri F., Sahour H., Abdelmalik K. W. (2022). Detecting hydrocarbon micro-seepage and related contamination, probable prospect areas, deduced

from a comparative analysis of multispectral and hyperspectral satellite images (34) , doi: 10.1016/j.jksus.2022.102192

[8] Elhaei, Y., & Asadzadeh, S. (2025). Mapping the mineralogical footprints of petroleum microseepage systems in redbeds of the Qom region (Iran) using EnMAP hyperspectral data. Remote Sensing, 17(12), 2088. https://doi.org/10.3390/rs17122088

[9] Elhaei, Y., & Asadzadeh, S. (2025). Mapping the mineralogical footprints of petroleum microseepage systems in redbeds of the Qom Region (Iran) using EnMAP hyperspectral data. Remote Sensing, 17(12), 2088. https://doi.org/10.3390/rs17122088

[10] Elhaei, Y., & Asadzadeh, S. (2025). Mapping the mineralogical footprints of petroleum microseepage systems in redbeds of the Qom Region (Iran) using EnMAP hyperspectral data. Remote Sensing, 17(12), 2088. https://doi.org/10.3390/rs17122088

[11] Garain, S., Mitra, D., & Das, P. (2021). Detection of hydrocarbon micro-seepage prospects using Landsat 8-based vegetation stress analysis in part of Assam-Arakan Fold Belt, NE India. Arabian Journal of Geosciences, 14(1), 1–16. https://doi.org/10.1007/s12517-021-08376-6

[12] Garain, S., Mitra, D., & Das, P. (2022). Mapping hydrocarbon microseepage prospect areas by integrated studies of ASTER processing, geochemistry and geophysical surveys in Assam-Arakan Fold Belt, NE India. International Journal of Applied Earth Observation and Geoinformation, 111, 102558. https://doi.org/10.1016/j.jag.2022.102558

[13] Jenny P.G.E., Precious V. G. M., Riva K. P. V., and Jun L. E. G. (2023). Mapping potential areas for hydrocarbon microseepage in Lower Agusan River Basin, Caraga, Philippines using Sentinel 2 imagery, Proc. SPIE 12977, Eighth Geoinformation Science Symposium Geoinformation Science for Sustainable Planet, 129771H (29 January 2024); https://doi.org/10.1117/12.3009576

[14] Saha, S. K. (2022). Remote sensing and geographic information system applications in hydrocarbon exploration: A review. Journal of the Indian Society of Remote Sensing, 50(10), 1557–1576. https://doi.org/10.1007/s12524-022-01540-9