Airborne Gamma Ray Surveying in Hydrocarbon Exploration

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Summary

Subsurface hydrocarbon deposits influence the concentration and distribution of naturally occurring radioactive elements at the Earth's surface through a combination of microseepage, groundwater movement, and electrochemical convection cells. The resulting gamma ray patterns can be effectively mapped using airborne gamma ray spectrometry. Normalizing K and U to Th in a newly developed mathematical algorithm called GammaPro provides an effective and low cost method to enhance the usefulness of radiometric data and thereby increases the odds of exploration success when combined with more conventional exploration methods such as seismic.

Introduction

Petroleum exploration is dominated by seismic methods. While seismic data are unsurpassed for imaging trap and reservoir geometry, they yield little information about whether or not a trap is charged with hydrocarbons. Integrating radiometric survey data with seismic and other more conventional geological, geochemical, and geophysical data can substantially improve the success rate of on-shore exploration wells.

In addition to differentiating various sedimentary units based on their radioactive properties by ground, well-logging, and airborne methods, gamma ray measurements have been applied directly to hydrocarbon exploration since at least the 1950's (Sikka and Shives, 2002) with varied success. Recent advances in sensor technology, digital data acquisition, GPS positioning, computer processing, and awareness of physical and chemical reactions surrounding hydrocarbon deposits have greatly increased the effectiveness and reduced the cost of airborne gamma ray surveys for hydrocarbon exploration. By understanding how the complex but predictable mobility of radioelements corresponds with hydrocarbon accumulations, radiometric maps can indicate the presence (or equally important, the absence) of oil and gas in the subsurface.

Theory and/or Method

Earth's crust contains variable concentrations of the naturally radioactive elements potassium (K), thorium (Th), and uranium (U). These radioelements (and their daughter products) emit gamma radiation which can be quickly and inexpensively measured with gamma spectrometry methods (Bailey and Childers, 1977). Critically, each radioelement can be detected independently so that the nuclear chemistry of the gamma source can be determined. Gamma radiation data are useful in many applications including geological mapping, soil studies, mineral exploration, and environmental monitoring but have been rarely applied to hydrocarbon exploration.

Airborne radiometric data are collected by fixed wing aircraft or more rarely helicopters flying in a grid-like pattern at a specified flight height, speed, and line spacing. The area to be surveyed needs to be much larger than the target area while the line spacing is sufficiently dense to produce the desired resolution. On-board sodium iodide scintillation counters measure gamma energy and the digital data stream is recorded with GPS position data. Channels for total gamma count, U, Th, and K are accumulated individually, usually at one second intervals corresponding to 30 to 60 meters across the ground, depending on aircraft speed. The data are corrected for flight height, air temperature, humidity, cosmic noise, Compton scattering, and radon effects to provide maps showing total count and individual radioistope concentrations (equivalents for U and Th). The resulting data will almost certainly be influenced by surficial features such as changes in lithology, soil type, moisture, vegetation, standing water, overburden thickness, topography, and cultural effects. Conventional processing, including the generation of isotope ratio and ternary maps, helps to reduce surficial effects, but more advanced processing is required to increase reliability of hydrocarbon detection.

Morse and Zinke (1995) and Armstrong and Heemstra (1973) observed that subsurface hydrocarbon deposits produce anomalously low total radiation patterns over an otherwise radioactive Earth. Saunders, et al (1993) noted that U and K distributions provided more reliable indications of hydrocarbons while Th remained constant.

Surficial radiation patterns related to buried hydrocarbon deposits result from a combination of light oil and gas microseeps, bacterial action, groundwater movement, redox boundaries, and pH changes resulting from the physical and chemical disequilibrium between oil and gas accumulations with their host rocks (Morse and Zinke, 1995; Klusman, 1993; Pirson, 1979; Machel and Burton, 1991; Schumacher, 1996; Sikka and Shives, 2002; LeSchack and van Alstine, 2002, and many others). Over millions of years, diagenetic properties of hydrocarbons alter the physical, chemical, and biological characteristics of rocks and soil at the surface. Methods to map these surficial changes (Klusman, 1985; Schumacher, 2011) including soil gas detection, iodine chemistry, and gamma ray spectrometry (radiometrics) have been used with mixed success. Of these survey methods, only airborne radiometrics is able to cover large areas of ground with uniform data, but surficial influences have traditionally made gamma data difficult to interpret (Saunders, et al, 1993).

The distribution and concentration of the three most common radioactive isotopes K, Th, and U at the Earth's surface are influenced by, among other things, the presence or absence of underlying hydrocarbon accummulations. Solubility and mobility of uranium are related to its valent state (Bailey and Childers, 1977). When micro-sized bubbles of gas released from a hydrocarbon deposit under pressure escape near-vertically through a network of groundwater-filled joints and bedding planes related to differential compaction, U^{+6} is carried to the surface where it is reduced to U^{+4} by organic compounds, precipitated, and becomes immobile. K is affected by groundwater pH. Carbonic and organic acids generated by low pH hydrocarbons destroy clay minerals, releasing K to ascending groundwater, with possible interaction from redox electrochemical convection cells. Th is believed to be more stable in the presence of hydrocarbons, microseepages, groundwater movement, and convection cells. Complex interactions between the three radioelements in the weathering environment yields distinctive radioactive patterns on the surface above hydrocarbon accumulations, presenting a situation where geophysics can be used to effectively map geochemistry.

Hydrocarbon accumulations are not the only factor affecting surface radiation patterns. Individual radioelement distributions will typically show patterns corresponding with surface features including topography, moisture, soil, and vegetation. Ratio and ternary maps are an improvement, but effects unrelated to the presence or absence of hydrocarbons must be reduced to yield useful information. Complex mechanisms affecting the distribution of surficial gamma sources and the underlying relationships with hydrocarbons encouraged the development of GammaPro, a proprietary multivariate processing algorithm combining channels for U, Th, and K with the following observations and benefits:

1. U and K are influenced by Eh and pH changes introduced by hydrocarbon seeps and related electrochemical convection cells.
2. U and K are normalized with reference to Th, as Th is believed to be unaffected by the presence or absence of hydrocarbon accumulations while having similar radiation responses.
3. Gamma energy from Th, U, and K is consistent when modified by local variations in vegetation, overburden thickness, topography, and moisture.
4. Reduces effects of variable host lithologies.
5. Reduces surficial effects of vegetation, outcrop, topography, and moisture.

6. Reduces contamination by radon gas.
7. Recognizes different radioelement specific activities (the quantity of gamma energy per gram of element).
8. Th is used as a constant, as it is mostly immune to changes in pH and Eh.
9. Combines three radioelement channels into one simplified database and map.
10. Data are directly interpretable in terms of surface chemistry.
11. Increases reliability in discriminating prospective from non-prospective ground.
12. Absolute values are not as important as relative values and anomaly shapes.
13. Yields easily identified “hot” colors which correspond with known hydrocarbon reservoirs and prospective ground.

GammaPro algorithms are still experimental and can be modified to suit different geological and surficial environments.

Examples

We have had the privilege of collecting and processing 25,000 line km of airborne gamma ray and magnetic data over prospective ground in Saskatchewan, Nebraska, Tennessee, and Kentucky. Results show a strong but imperfect correlation with known hydrocarbon reservoirs and prospective ground.

Conclusions

Variations of uranium, potassium, and thorium can be measured by cost-effective airborne radiometric methods and correlated with the presence or absence of hydrocarbons at depth in terrestrial environments. The ability to discriminate between prospective and non-prospective ground, using appropriate data collection, processing, and interpretation, is an attractive exploration benefit. Advanced computer processing techniques such as multi-channel GammaPro technology help improve reliability and are easily modified to meet local conditions.

While seismic and gravity methods remain the dominant geophysical tools for hydrocarbon exploration, radiometric surveys have been shown to be useful if processed and interpreted correctly. Radiometric surveys respond to near-surface gamma anomalies resulting from hydrocarbon seeps and electrochemical convection cells, and are therefore unable to predict depth to a productive zone. If the depth to a favorable horizon is known, such as from nearby well logs or seismic data, then radiometric data can be used to substantially increase the odds of exploration success. Aeromagnetic data can be collected during radiometric flights to provide structural detail. Additional seismic and gravity data will provide integrated exploration tools to further reduce risk, especially in basins where seismic data have had difficulty identifying traps.

Airborne radiometric data are best collected in dry conditions over flat, uniform ground with minimal vegetation and industrial/agricultural disturbances. No geophysical technique is perfect, and careful interpretation is required.

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