Airborne gamma-ray spectrometry inversion signatures of Hicks Dome area

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Summary

The inversion of airborne gamma-ray spectrometry (AGRS) data has been studied and demonstrated to be a good alternative to the standard processing approaches. This study explores an inversion-based processing of radiometric data collected as part of an airborne geophysical survey over the Hicks Dome, IL area. Hicks Dome is located within the Illinois-Kentucky Fluorspar District (IKFD). The IKFD includes a large, mineralized area of carbonate-hosted fluorite deposits classified as Mississippi Valley-type (MVT) mineralization as well as fluorite that is associated with Permian age alkalic rocks. Hicks Dome, which is an igneous intrusive complex, has potential for several critical minerals including fluorite ± rare earth elements (REEs), barite, titanium, niobium, and beryllium. The REEs occur primarily in phosphate minerals including fluorapatite, monazite and xenotime. Other REE-bearing fluorcarbonate minerals of the bastnaesite group including parasite and/or synchysite are present in Hicks Dome samples. Accessory minerals like monazite typically contain small amounts of thorium, which can be measured by the AGRS surveys. Thorium can then be used as a proxy to map the potential for REEs in the right geologic environments.
The investigation of radioelement concentrations from the high-resolution airborne radiometric survey has yielded insightful results. For example, the relative concentration of equivalent thorium (eTh) to potassium (K) is highlighted by the eTh^^{2}/K ratio and identifies rocks and soils with low potassium levels. These findings not only elucidate eTh anomalies associated with the Hicks Dome complex but also underscore the importance of considering elemental interrelationships for a comprehensive understanding of the geological landscape. Noteworthy anomalies in uranium and thorium, both near the dome and to the north, provide valuable insights into the geological intricacies and mineralogical variations within the surveyed area. This study summarizes the AGRS thorium map as a good mapping tool for setting the stage for further exploration and a deeper understanding of the geological nuances and potential REE mineralization in the Hicks Dome vicinity.

Introduction

Airborne gamma-ray spectrometry (AGRS) plays a pivotal role in geophysical and geological mapping, serving as a crucial tool for mineral exploration and comprehensive lithological distribution mapping (Davis & Guilbert, 1973; Grasty, 1979; Dickson & Scott, 1997; Shives, 2015; Weihermann et al., 2021). AGRS assesses the naturally occurring radioactivity emitted in the form of gamma - rays from rocks and weathered materials, reaching depths of up to 30-45 cm. The primary sources of gamma radiation originate from the decay series of potassium-40 (40K), uranium-238 (238U), and thorium-232 (232Th) (Minty, 1997; Wilford, 2002; IAEA, 2003). Radiation measurement for uranium and thorium relies on their daughter elements, bismuth-214 (214Bi) and thallium-208 (208Tl). Results are reported in parts per million (ppm) as equivalent uranium (eU) and equivalent thorium (eTh). Potassium (K) is measured by 40K and its results are reported in percentage (%). This technique not only contributes to mineral exploration but also enhances the understanding of lithological distributions, showcasing its significance in contemporary geological investigations. Traditional exploration methods utilized for identifying potential alkaline igneous source rocks have typically involved high-resolution airborne and surface gamma-ray spectrometry for the detection of thorium (Th) and uranium (U) contents. These approaches also encompass magnetic surveys to emphasize the presence of magnetite, gravity surveys to distinguish dense lithologies, and heavy-mineral studies (Lottermoser, 1991).
AGRS data inversion, explored since 1969 by Kogan et al. 1971 and others (Tammenmaa et al., 1976; Gunn, 1978; Crossley & Reid, 1982; Schwarz, 1992; Minty & Brodie, 2015; Druker, 2017; Weihermann et al., 2021), offers an alternative to standard processing. The method used here enhances the signal-to-noise ratio, providing improved contrast between radioelements. Notably, the AGRS inversion, which accounts for the footprint of the gamma-ray detector, surpasses the standard point-by-point method in standard processing. This advancement is underscored by its inclusive analysis of the gamma-ray signal across the entire sampling area, rather than solely beneath the aircraft. It also includes the real flight height of the survey. The details of the inversion can be found in Weihermann et al., 2023.
The Hicks Dome area has been studied for rare earth mineral concentrations in ultramafic alkaline rocks and their weathered regolith (Wilson, 2019; Denny et al., 2015).

Hicks Dome

Hicks Dome is located in Hardin and Pope Counties, Illinois and lies within the larger Illinois-Kentucky Fluorspar District. It was produced by igneous processes that gave rise to both a prominent topographic high and a structural upwarp. This geological feature is characterized by a concentration of ultramafic dikes, sills, plugs, and intrusive breccias, attributed to alkaline and potentially carbonatitic magmatism, which was accompanied by explosive volatile release (Potter et al., 1995; Denny et al., 2008; Moorehead 2013; Plumlee et al., 1995). The sedimentary-hosted fluorite deposits in the Illinois-Kentucky Fluorspar District, are classified as Mississippi Valley-type (MVT) deposits (Denny et al., 2008; Moorehead 2013). The MVT-related fluorite is characterized by vein-type or bedding replacement deposits hosted in carbonate rocks that contain distinctive mineralogy and associated alteration. Diverging from typical MVT systems, these deposits feature a prevalence of fluorite over galena and sphalerite. The igneous-related fluorite occurs in breccias at Hicks Dome and is related to magmatic processes (Denny et al., 2008; Moorehead, 2013).

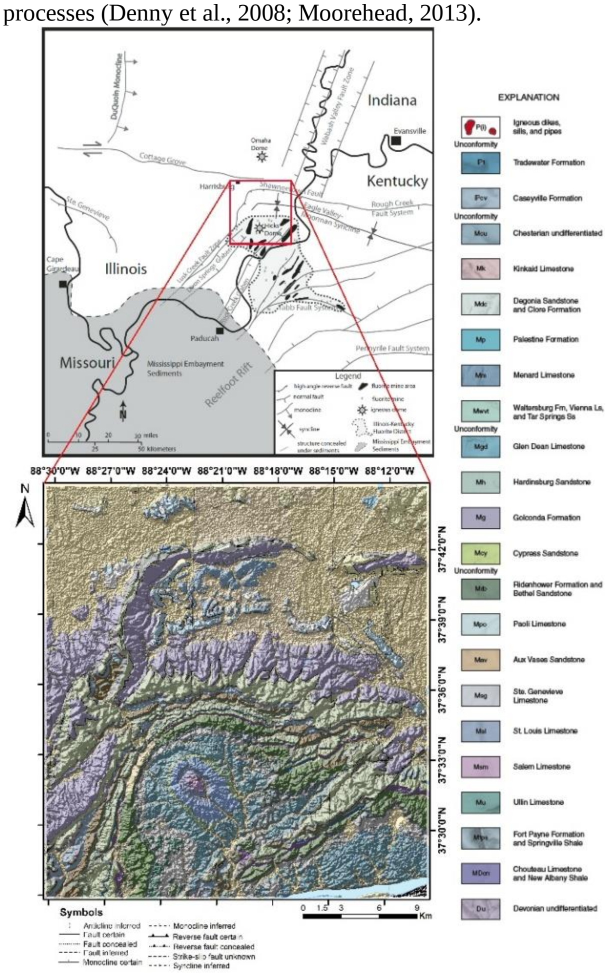

Figure 1: Simplified Illinois-Kentucky Fluorspar District map, with the indication of the study area in red. (Modified from Denny et al., 2008; Denny & Seid, 2014).

AGRS Inversion Processing

We analyzed data collected as part of the U.S. Geological Survey's Earth Mapping Resources Initiative (Day, 2019). Data were collected along flight lines spaced at 200 m over an area that covered southern Illinois, western Kentucky, and southern Indiana (McCafferty & Brown, 2020). We selected the region that includes Hicks Dome (Figure 1). The potassium (K), uranium (eU), and thorium (eTh) channels underwent inversion-based processing. The inversion methodology used is detailed in Weihermann et al. (2021, 2023). Typically, basic maps of the radioelements (K, eU, eTh), after undergoing the inversion, result in improved differentiation of the eTh, eU, and K concentrations related to primary lithologies. Statistical outcomes for K, eU, and eTh are displayed in Figure 2.

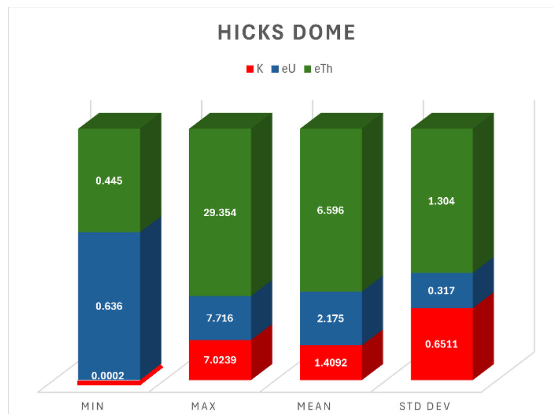

Figure 2: Statistical representation after inversion of the K (%), eU (ppm) and eTh (ppm) of the Hicks Dome study area.

Thorium exhibits a strong influence in rocks, regolith, and soils across the region, characterized by the highest maximum, mean, and standard deviation. In contrast, eU displays elevated minimum values and overall higher concentrations. Potassium, on the other hand, registers the lowest values among the three elements within the study area. The heightened values of eTh and eU, particularly eTh, provide corroboration for findings in prior studies (Ford et al., 1988; Verplanck & Gosen, 2011; Antunes & Ferreira, 2021), indicating that elevated concentrations of both elements, especially eTh, are frequently observed in carbonatites and REE-bearing alkaline intrusions. This insight aligns with established evidence supporting the prevalence of high eTh values in such geological formations. The basic maps of K, eU and eTh are displayed in Figure 3. Potassium exhibits slightly elevated concentrations over Hicks Dome, with lower values in the topographically lower elevations around the dome (Figure 3a). Notably, the northern region of the study area displays elevated K

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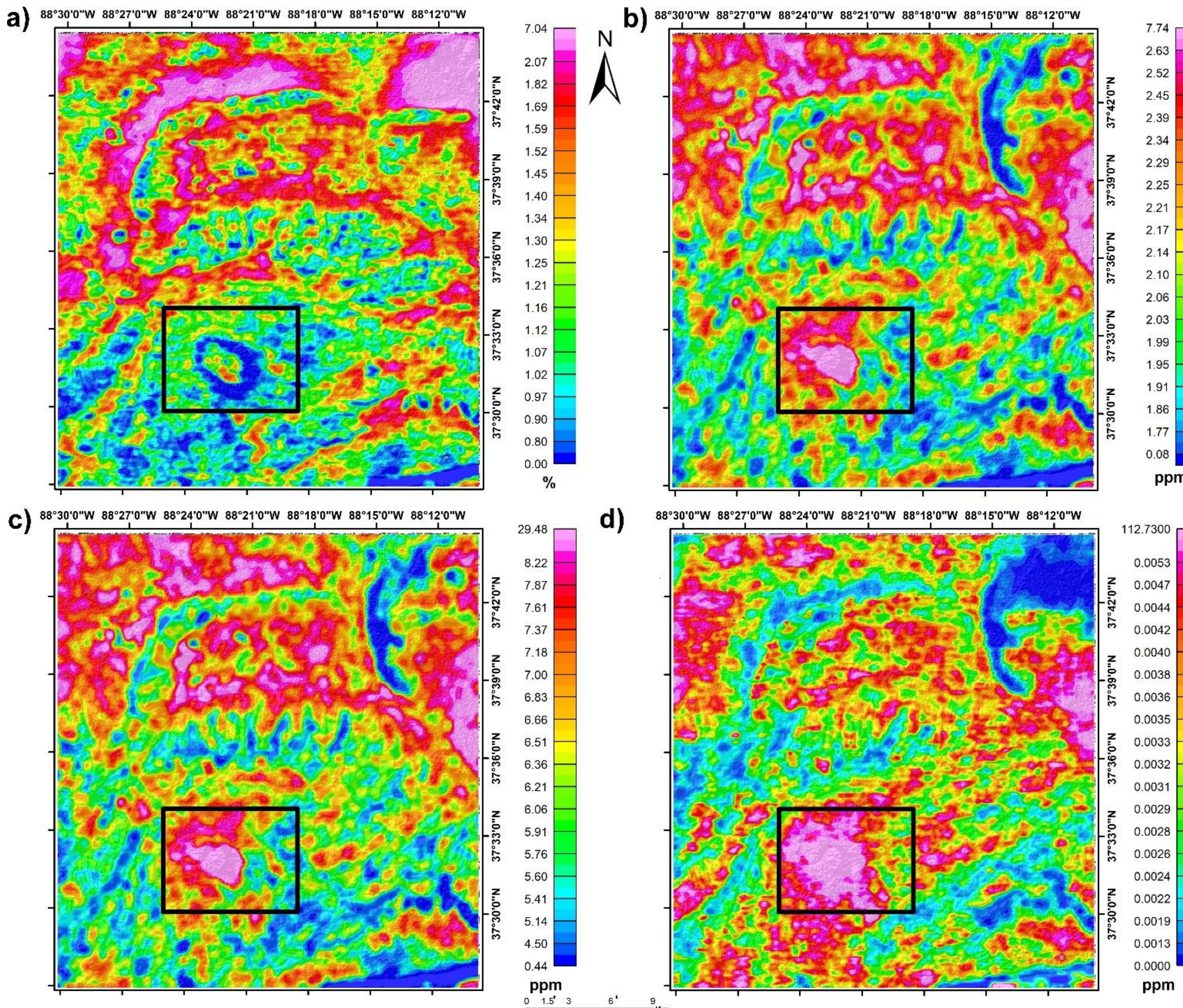

Figure 3: AGRS Inversion maps. a) Potassium, b) Uranium, c)Thorium and d) Ratio eTh^2/K. The black square represents the approximate location of Hicks Dome.

anomalies attributed to the Quaternary cover and late Pennsylvanian shales and sandstones.

Thorium exhibits a notable anomaly associated with Hicks Dome and displays additional anomalies in the northern section of the study area. Similarly, uranium maps a mostly coincident anomaly with the eTh and outlines the dome.

The eTh^2/K ratio provides insight into the relative concentration of thorium to potassium, leveraging the fact that K exhibits the lowest concentration in the area. This ratio amplifies the visibility of an eTh anomaly associated with Hicks Dome.

These maps, produced using the high-resolution radiometric survey data, can act as a starting point to investigate the REE potential of the Hicks Dome area by revealing notable concentrations of eTh in the limited exposed alkalic rocks and in the more extensive regolith that covers the igneous complex shown in Figures 2, 3c, 3d. REEs are predominantly extracted from ores and minerals inherently enriched with uranium and thorium. Detecting eTh anomalies provides a valuable method for locating enriched regions of rare earth elements within Hicks Dome.

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The presence of elevated thorium in the area has the potential to be used as a proxy to map higher concentrations of REE-bearing primarily monazite, bastnaesite and xenotime found in the breccias and regolith.

Figure 4 shows an anomaly map illustrating the distribution of elevated K, eU, and eTh across the study area. The anomalies were delineated using a criterion of the mean plus three standard deviations. Notably, three distinct anomalies domains are discernible in the region. The first is situated in the central region of Hicks Dome, characterized by elevated levels of thorium and uranium. The second domain is allocated across the central part of the study area and is characterized by elevated eTh and K values. Lastly, the third domain, located to the north of the dome, correlates elevated levels of eTh, K, and eU and occurs over the late Pennsylvanian shales and sandstones. Importantly, the coincident eTh and eU anomalies occurring on northwest side of Hicks Dome could be related to increased concentrations of monazite, xenotime and bastnaesite.

Future studies will compare geochemical data with our results.

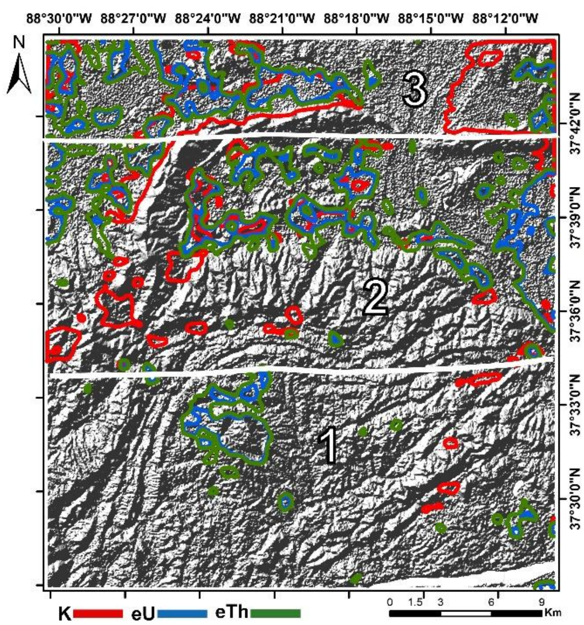

Figure 4: Anomalies map of Potassium (red), Uranium (blue) and Thorium (green) of the study area.

Conclusions

Our analysis of potassium, uranium, and thorium from the airborne survey has revealed distinct patterns and anomalies that can be used to guide geologic mapping and mineral exploration. The eTh^2/K ratio, which emphasizes the relative concentration of thorium in relation to potassium, expands the extent of the eTh anomaly over Hicks Dome, suggesting a broader area for rare earth element exploration. This derivative product also considers the region's lower potassium levels. These findings not only spotlight specific anomalies associated with high thorium within Hicks Dome but underscores the significance of considering the interplay between different radioelements to comprehend the geological characteristics of the surveyed area. The observed anomalies in uranium and thorium, both in proximity to the dome and in the northern part of the region, provide valuable insights into the geological complexities and mineralogical variations within the study area.

The inversion-based processing of radiometric data has revealed three major radioelement domains. The first domain within Hicks Dome exhibits heightened concentrations of eTh and eU; the second domain is located over the central part of the study area and is characterized by moderate potassium and high thorium; the third domain correlates with increased thorium, potassium, and uranium. These findings enhance our understanding of the area and underscore the potential of high-resolution AGRS data to guide further ground exploration and investigation in these specific anomaly domains.

Acknowledgments

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