

Geophysical expression of a buried niobium and rare earth element deposit: The Elk Creek carbonatite, Nebraska, USA

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Abstract

The lower Paleozoic Elk Creek carbonatite is a 6–8-km-diameter intrusive complex buried under 200 m of sedimentary rocks in southeastern Nebraska. It hosts the largest known niobium deposit in the U.S. and a rare earth element (REE) deposit. The carbonatite is composed of several lithologies, the relations of which are poorly understood. Niobium mineralization is most enriched within a magnetite beforite (MB) unit, and REE oxides are most concentrated in a barite beforite unit. The carbonatite intrudes Proterozoic country rocks. Efforts to explore the carbonatite have used geophysical data and drilling. A high-resolution airborne gravity gradient and magnetic survey was flown over the carbonatite in 2012. The carbonatite is associated with a roughly annular vertical gravity gradient high and a subdued central low and a central magnetic high surrounded by magnetic field values lower than those over the country rocks. Geophysical, borehole, and physical property data are combined for an interpretation of these signatures. The carbonatite is denser than the country rocks, explaining the gravity gradient high. Most carbonatite lithologies have weaker magnetic susceptibilities than those of the country rocks, explaining why the carbonatite does not produce a magnetic high at its margin. The primary source of the central magnetic high is interpreted to be mafic rocks that are strongly magnetized and are present in large volumes. MB is very dense (mean density 3200 kg/m³) and strongly magnetized (median 0.073 magnetic susceptibility), producing a gravity gradient high and contributing to the aeromagnetic high. Barite beforite has physical properties similar to most of the carbonatite volume, making it a poor geophysical target. Geophysical anomalies indicate the presence of dense and strongly magnetized rocks at depths below existing boreholes, either a large volume of MB or another unknown lithology.

Introduction

Mineral exploration trends indicate that exploration for deposits in crystalline rocks under sedimentary cover is increasing, as exposed and shallowly buried deposits are discovered less frequently (Witherly, 2012; Williams, 2013). This includes deposits of niobium and rare earth elements (REE), of which few are currently known in North America (Van Gosen and Lowers, 2007; Long et al., 2010). The lower Paleozoic Elk Creek carbonatite in southeastern Nebraska, USA, is an example of a buried intrusion known to have significant niobium and REE mineralization. Exploration studies of concealed deposits and their host rocks require geophysical exploration methods in conjunction with drilling. Gravity and magnetic methods are often useful for studying alkaline igneous systems such as carbonatites because these rocks typically have anomalous physical properties compared with country rocks. The Elk Creek carbonatite was originally discovered through drilling of a prominent gravity high.

Here, high-resolution airborne gravity gradient (AGG) and magnetic data collected in 2012 over the Elk Creek carbonatite are presented and interpreted. A critical part of this study is the systematic collection of physical property data from publicly available core samples. The goal of this case study is to describe the Elk Creek geophysical anomalies in terms of the causative geology, contributing to the understanding of geophysical properties of carbonatites and niobium/REE deposits. This includes describing the nature of anomalies related to the carbonatite at large and anomalies specifically related (or unrelated) to mineralization.

Geologic background

The Elk Creek carbonatite (Carlson, 1972; Carlson and Treves, 2003, 2005) is a 6–8-km-diameter, alkaline-intrusive complex buried under approximately 200 m of Pennsylvanian marine clastic sedimentary rocks in southeastern Nebraska (Figure 1). It is the host of significant niobium and REE deposits (e.g., Long et al., 2010). The carbonatite was emplaced along the

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trend of the 1.1-Ga Midcontinent Rift System, near the northern part of the Nemaha uplift (Burchett, 1982; Carlson, 1997). Uranium-lead dates determined from zircons in the carbonatite range from 540 ± 14 to 480 ± 20 Ma (Farmer et al., 2013). The carbonatite intrudes gneissic Proterozoic country rocks of variable composition. A paleosol lies at the upper surface of the carbonatite. No major faults are known to displace the carbonatite.

The carbonatite complex is composed of several lithologies. Apatite beforite is the volumetrically dominant lithology, followed by undifferentiated mafic rocks (including apparent dikes and sills), syenite, beforite breccia, barite beforite, and a small body of magnetite beforite (MB) (Figure 2). The term *beforite* indicates a carbonatite lithology with dolomite as a primary mineral. Niobium mineralization (typically 1% grade) is primarily associated with the mineral pyrochlore, which in turn is associated with the small-volume MB lithology. The REE mineralization (typically 1% grade) is primarily associated with the barite beforite lithology. The lithologies are known only from borehole cores and legacy reports that are stored by, and available for examination from, the Nebraska Geological Survey. Their estimated relative volumes (this study) are summarized in Table 1.

Spatial and temporal relations between the various lithologies are generally complex and poorly understood. However, a three-stage evolutionary sequence has been proposed on the basis of petrologic evidence (Xu, 1996): (1) A magmatic stage that included emplacement of most of the carbonatite lithologies, syenite, and

mafic rocks that cut at least some of the other lithologies, (2) a deformation and recrystallization phase, characterized by formation of the breccias and recrystallization of dolomite and apatite, and (3) an alteration stage or stages, largely characterized by widespread

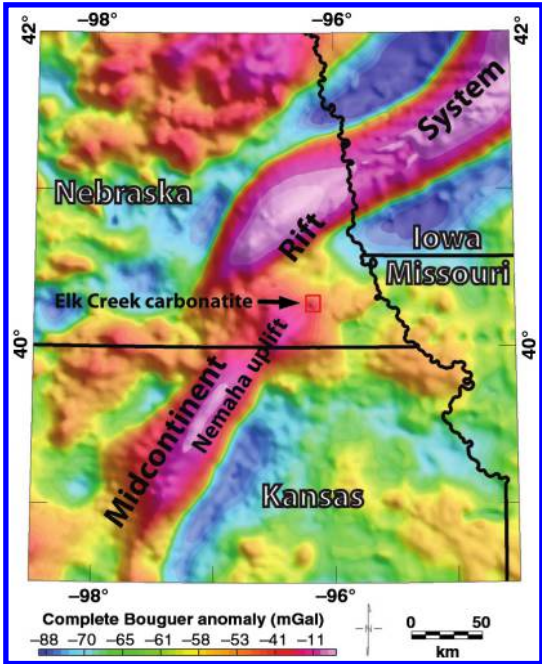


Figure 1. Complete Bouguer gravity map of the region surrounding the Elk Creek carbonatite. Data are from the Pan-American Center for Earth and Environmental Studies (2012). The red box shows the location of subsequent figures.

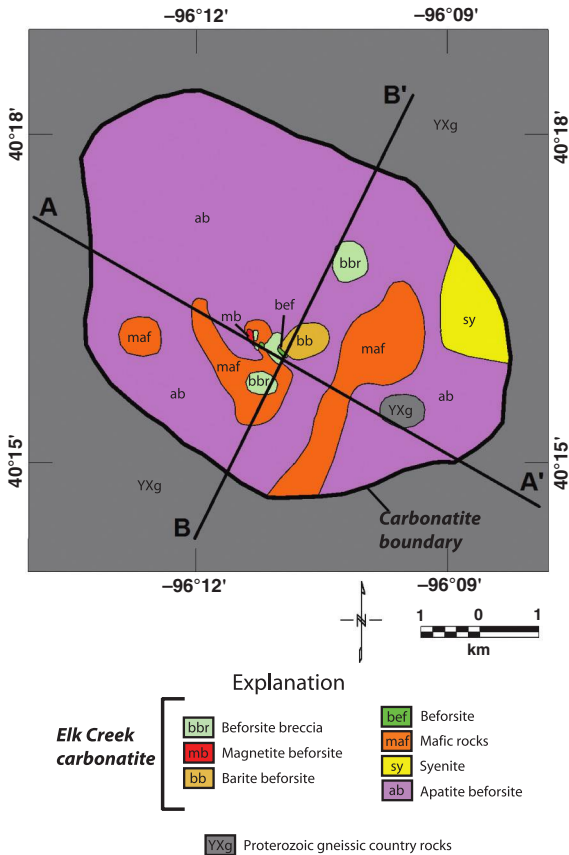


Figure 2. Geology of the Elk Creek carbonatite (this study), as expressed in boreholes at an elevation of 120 m above sea level (roughly 230 m below ground surface). Age relations among the carbonatite units are poorly known, and the ordering of units within the explanation is not meant to imply cross-cutting relations.

Table 1. Lithologies recognized within the Elk Creek carbonatite and their relative volumes (as reported in, and estimated from, public-domain legacy borehole data and reports).

Lithology	Estimated relative volume (%)
Apatite beforite	54
Mafic rocks (undifferentiated)	15
Beforite breccia	15
Barite beforite	6
Syenite	5
Beforite	3
Magnetite beforite	<2
Apatite beforite breccia	1

oxidation. Alteration is observed throughout the Elk Creek cores, and locally is very intense. The timing of the different stages of this evolutionary model is not constrained.

Data

A high-resolution AGG and aeromagnetic survey was flown over the Elk Creek carbonatite in 2012. A fixed-wing platform was used, flying north–south traverse lines with 100-m spacing and draped at a nominal terrain clearance of 100 m.

Airborne gravity gradient and gravity data

The AGG and gravity anomalies reflect lateral variations of density. For vertical components of the gravity field, positive anomalies (or highs) occur over areas of relatively high densities, and negative anomalies (or lows) occur over relatively low-density materials. In AGG surveys, the full gradient tensor of the gravity field is measured (or calculated from partial tensor measurements) from the air, as opposed to traditional gravity field measurements that are normally taken on the ground. Despite the full tensor being measured or calculated, the vertical gravity gradient tensor component (G_{zz}) is the component most commonly shown and displayed because it is visually intuitive. Because AGG data are the derivatives of the gravity field, AGG anomalies better reflect shallower density contrasts than do gravity anomalies, as they emphasize shorter wavelength components of the field that are typically related to shallow sources. The AGG data are processed to remove types of noise inherent to gradiometer systems and measurements, as well as noise common to all types of airborne geophysical data (Dransfield and Christensen, 2013).

Free air vertical gradient AGG data are shown in Figure 3a. The effects of terrain, shown in Figure 3b, are significant and must be removed to isolate the signature of buried sources (such as the carbonatite). A terrain correction density of 2270 kg/m³, a value found to locally minimize terrain effects, results in the terrain-corrected G_{zz} anomalies shown in Figure 3c. The traditional vertical gravity field may be calculated from AGG data, by computing the integral of the measured vertical gravity gradient. However, long-wavelength noise is amplified by this process, and the best practice is to use ground gravity data to recover the longer wavelengths (Dransfield, 2010). In this case, wavelengths longer than 7 km are provided by ground gravity data Pan-American Center for Earth and Environmental Sciences (2012) and added to wavelengths shorter than 7 km calculated from the AGG data (Figure 3d).

The AGG data contain many short-wavelength anomalies, and anomalies of interest are often obscured. In this case, the measured G_{zz} anomalies (Figure 3c) may be considered as the sum of the effects of crystalline basement rocks (including the carbonatite and surrounding Precambrian rocks), Pennsylvanian sedimentary rocks, and possibly noise. The spectral

characteristics of these effects are sufficiently different that the effects of the crystalline rocks may be isolated using matched filtering (Syberg, 1972; Phillips, 2001). The G_{zz} data are shown in Figure 4a, with the short wavelengths unrelated to the crystalline basement rocks removed.

The locations of density contrasts, such as those formed by contacts and faults, can be mapped using the HGM of the gravity field (Cordell, 1979; Cordell and Grauch, 1985). This is based on the principle that gravity gradients will reach maximum values over near-vertical density contrasts. The HGM of the gravity field (Figure 4b) is calculated here using match filtered horizontal tensor components (not shown) measured during the AGG survey, as opposed to being calculated from the gravity field.

Aeromagnetic data

Aeromagnetic anomalies reflect lateral variations of total magnetization, the vector sum of induced and remanent magnetizations (Blakely, 1995; Hinze et al., 2013). Induced magnetization is proportional to magnetic susceptibility and has the same direction as the present day ambient field (inclination 68° and declination 3° in the study area). Remanent magnetization is related to the age and nature of a rock's formation and subsequent geologic history, and may be oriented in a different direction than that of the induced magnetization. Crystalline rocks are typically strongly magnetized (with either or both types), and sedimentary rocks and rocks that have been strongly altered are normally weakly magnetized. Anomalies produced by intrusive igneous rocks normally are dominated by induced magnetization, although mafic and ultramafic intrusive rocks frequently exhibit strong remanence (Clark, 1999).

A reduction-to-pole (RTP) transformation, a standard technique to eliminate displacements related to the dipping magnetic inclination of the earth's field and center anomalies over their sources (Baranov and Naudy, 1964; Blakely, 1995), is applied to the total-field aeromagnetic anomalies over the Elk Creek carbonatite using the present day earth's field direction (Figure 5a). The effects of relatively shallow magnetic sources can be emphasized by calculating the vertical derivative of the RTP anomalies (Blakely, 1995), shown in Figure 5b. Finally, magnetization contrasts may be highlighted using the HGM of the RTP field (Cordell and Grauch, 1985; Grauch and Cordell, 1987; Grauch and Hudson, 2007) (Figure 5c), in a manner similar to that used for the gravity field.

Physical property and assay data

A major part of this study is the measurement of physical properties on drill core samples. A total of 291 dry bulk density and 470 magnetic susceptibility measurements are summarized here (Figure 6a and 6b). Portions of core that are relatively intensely altered are observed to have significantly attenuated densities

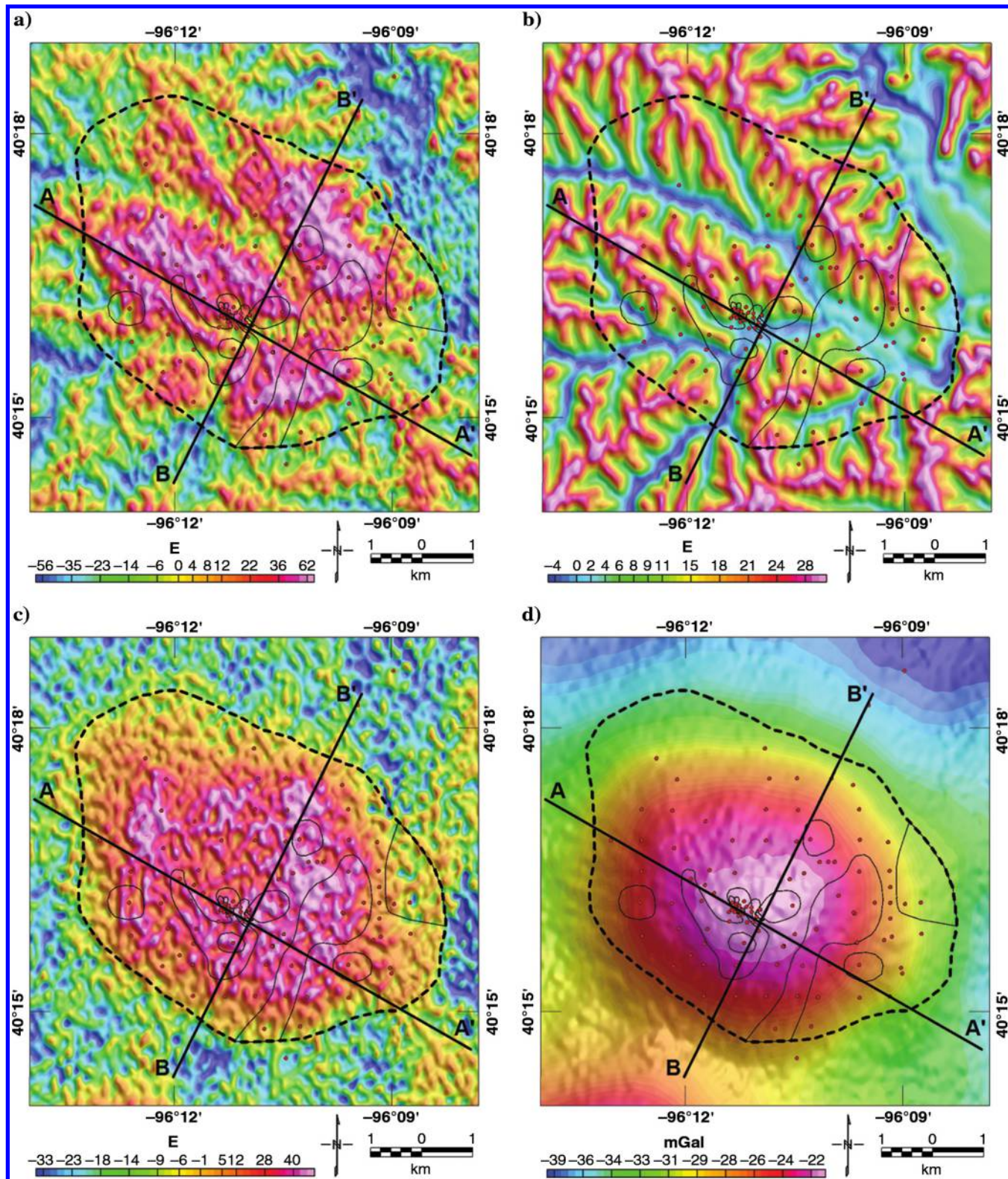


Figure 3. Unfiltered vertical gravity gradient (Gzz) and gravity data. Red dots indicate borehole collar locations. Linework from Figure 2 is shown for spatial reference. The location of profile models A-A' and B-B' is shown. (a) Free-air Gzz data, (b) effect of terrain at the flight surface, computed for a density of 1000 kg/m³, (c) Gzz data, terrain corrected using a density of 2270 kg/m³, and (d) complete Bouguer gravity anomalies computed from AGG and ground gravity data sets.

and magnetic susceptibilities. No information is available on magnetic remanence, which may contribute significantly to the aeromagnetic anomalies. Approximately 16,000 legacy assay measurements are also sorted by lithology for comparison (Figure 6c and 6d).

Qualitative interpretations

Multiple qualitative interpretations are made on the basis of comparing geophysical anomalies with borehole and physical property data, including mapping the carbonatite margin, individual geologic units, and structure.

Mapping the carbonatite

The Elk Creek carbonatite produces an ~60 Eotvos (E) Gzz and ~12 mGal gravity high (Figures 3 and 4). This is expected from density measurements (Figure 5a) that show a 150 kg/m³ mean density contrast between the country rocks and apatite beforite, the most voluminous carbonatite lithology. An ~8 E, ~1-km diameter Gzz high lies over the known extent of the MB. An HGM maximum (Figure 4b) corresponds with the location of the carbonatite margin as loosely constrained by borehole data, although it is narrower in diameter. This effect is interpreted to indicate that the carbonatite narrows with increasing depth, forming a crude funnel shape. The carbonatite does not produce a notable RTP aeromagnetic anomaly (Figure 5a) because most of the

carbonatite volume is weakly magnetized (Figure 6b and Table 1). Locally, the country rocks are more strongly magnetized than the carbonatite, an interpretation supported by magnetic susceptibility measurements (Figure 6b) and a vertical derivative low over most of the carbonatite (Figure 5b). The margin of the carbonatite is interpreted in a manner consistent with the Gzz high (Figure 4a), the HGM of the gravity field (Figure 4b), derivatives of the RTP aeromagnetic data (Figure 5a and 5b), and borehole constraints.

Other geophysical anomalies are produced within the carbonatite. A subtle Gzz low, roughly 1.5 by 1.5 km, near the center of the carbonatite (most easily seen in Figure 4a) is surrounded by local annular highs (wavelengths of 1 km or less) and corresponds to an area of low-amplitude aeromagnetic anomalies (Figure 5A and 5b). It cannot be explained by the known distribution of lithologies. Rather, it is hypothesized that this anomaly represents either (1) a zone of relatively intense alteration compared with the surrounding carbonatite volume, or (2) the local annular highs represent zones of minimal alteration of weakly magnetized lithologies. Gravity data emphasize deeper sources than do AGG data. The highest amplitude part of the gravity high (Figure 3d) is centered on the location of the MB, which is much denser than other lithologies present (Figure 6a). This suggests that a significant volume of similarly dense rocks lies at deeper levels of the

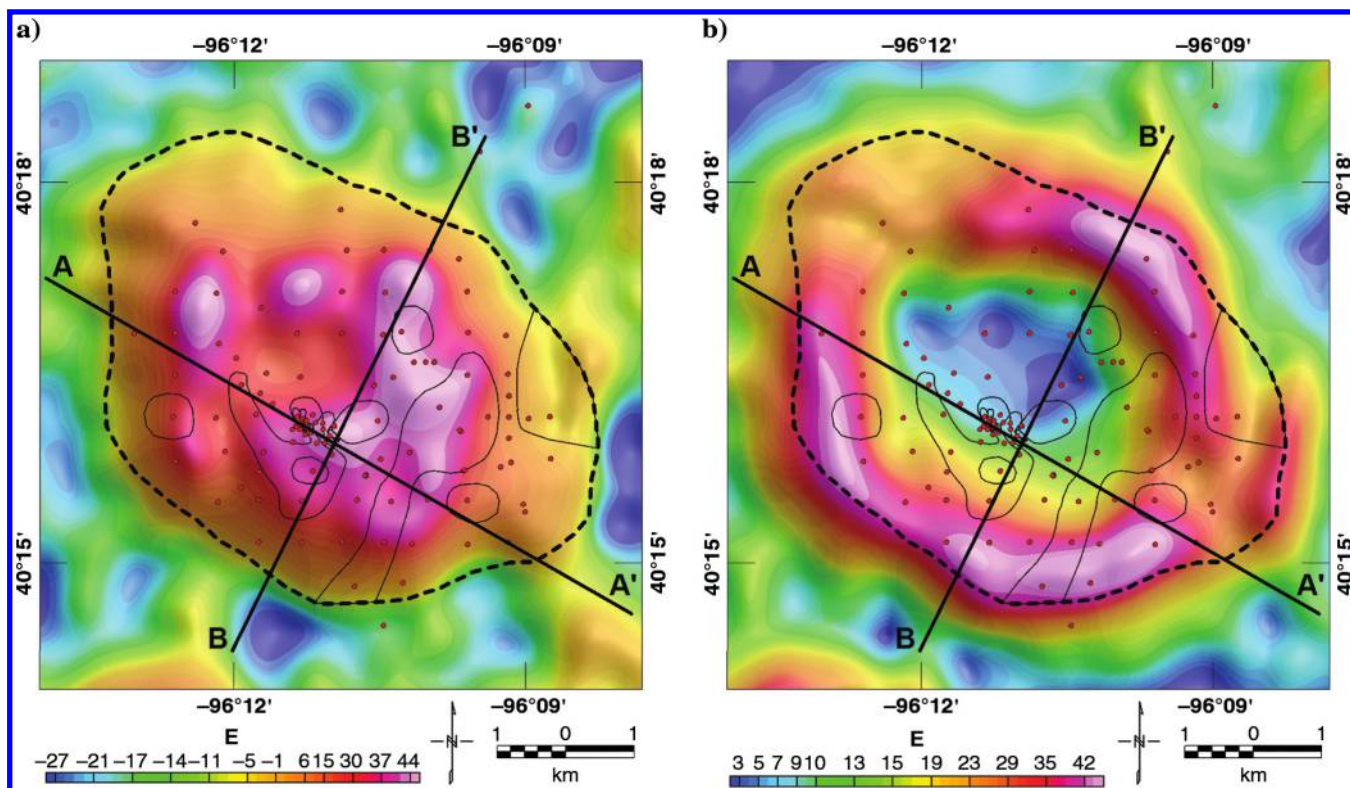


Figure 4. Match filtered AGG data. The red dots indicate the borehole collar locations. Linework from Figure 2 is shown for spatial reference. The location of profile models A-A' and B-B' is shown. (a) Gzz data filtered to remove effects of noise and overlying sedimentary rocks and (b) horizontal gradient magnitude (HGM) of gravity field, calculated from match filtered tensor data.

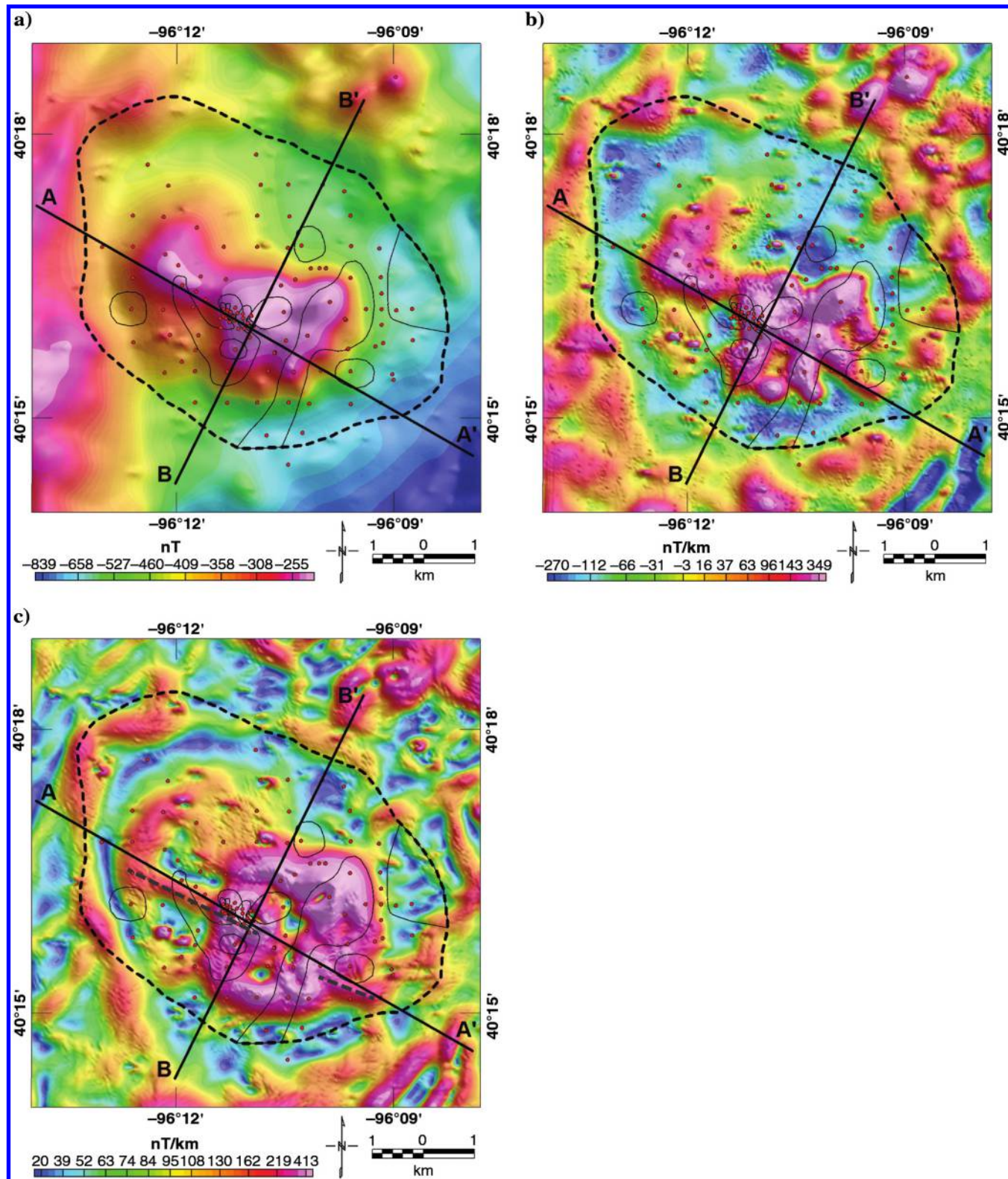


Figure 5. Aeromagnetic data. Red dots indicate borehole collar locations. Linework from Figure 2 shown for spatial reference. Location of profile models A-A' and B-B' shown. (a) Reduced-to-pole total-field magnetic anomalies, (b) vertical derivative of reduced-to-pole total-field anomalies. Very short wavelength anomalies lie over cultural features such as steel bridges and large barns, and (c) HGM of reduced-to-pole total-field anomalies. Dashed gray lines indicate possible faults.

carbonatite. Strong, complex aeromagnetic highs lie over the central area (Figure 5), where two strongly magnetized lithologies are present: Mafic rocks and MB. The mafic rocks are far more voluminous, suggesting that they are the primary source for the magnetic anomalies. However, a large aeromagnetic high in the vicinity of the known location of MB suggests that it may also be an important source in spite of its small (known) volume. This question is addressed in more detail below.

Mapping geologic units and mineralization

To distinguish a particular geologic unit with geophysics, it must have anomalous physical properties that contrast with surrounding units and have a large enough volume. Physical property measurements (Figure 6a and 6b) show that despite several different identified carbonatite units, only three units (or combinations of units) have distinguishable properties: (1) Undifferentiated carbonatite and syenite, including apatite

beforsite, beforite breccia, barite beforite, syenite, beforite, and apatite beforite breccia, which are dense and weakly magnetized, (2) mafic rocks that are somewhat less dense and strongly magnetized, and (3) MB that is very dense and very strongly magnetized. Because MB hosts pyrochlore, the geophysical signature of niobium mineralization is distinguishable if the MB exists in a large enough volume. However, there is little hope for mapping REE mineralization. It is associated with barite beforite, a unit that cannot be distinguished geophysically from the rest of the carbonatite.

Evidence of faulting?

The HGM trends in aeromagnetic data are reliably related to crystalline rocks because the overlying sedimentary rocks are likely very weakly magnetized. Several curved HGM maxima indicate margins of strongly magnetized rocks within the carbonatite, whereas two linear maxima indicate possible northwest-trending faults (depicted in Figure 5c). The locations and trend

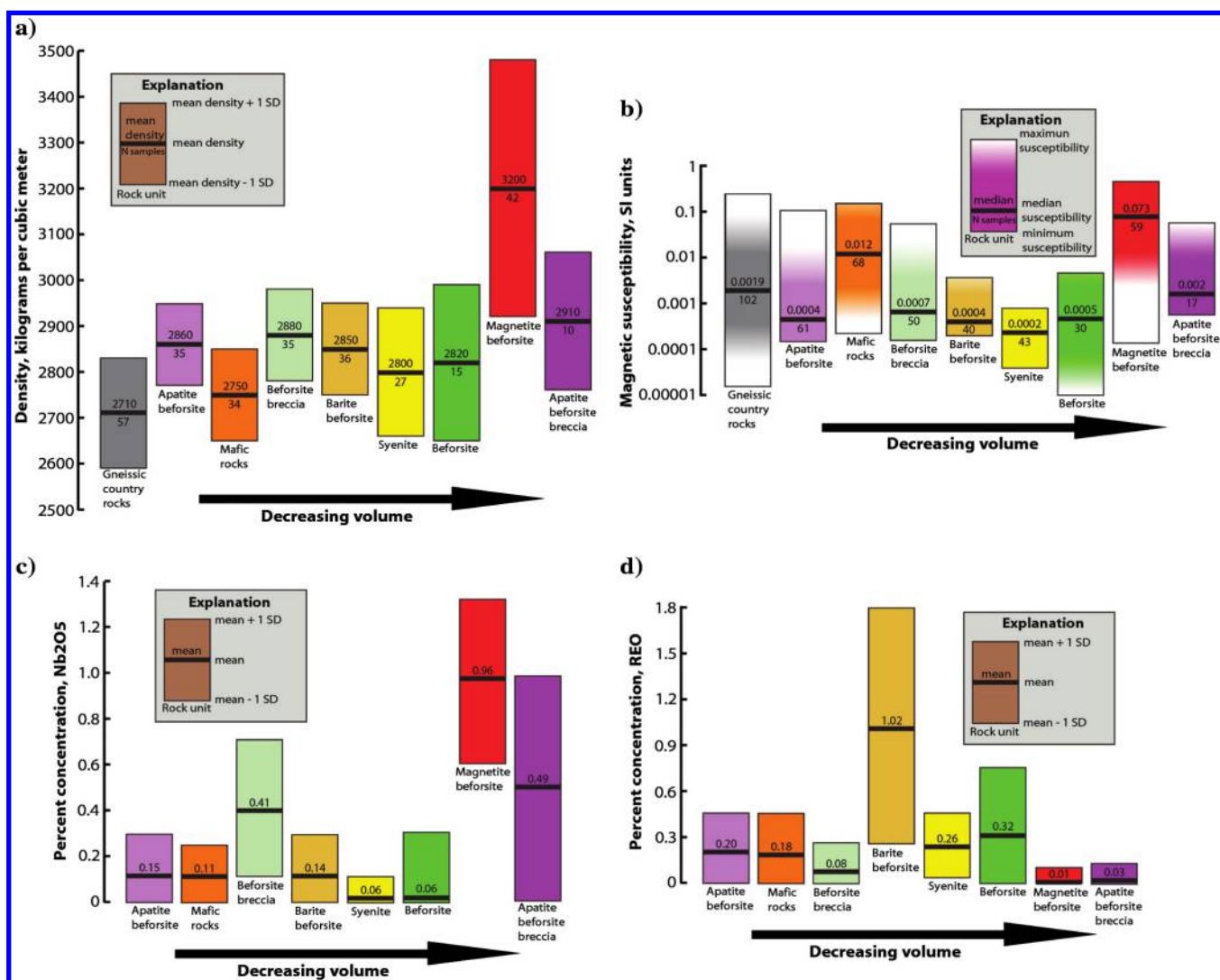


Figure 6. New physical property data and legacy assay data, sorted by lithology. (a) Density, (b) magnetic susceptibility (note log scale), (c) concentration of Nb₂O₅, and (d) concentration of rare earth oxides.

of these possible faults correspond to the location of MB found in boreholes, suggesting structural control on MB localization and niobium mineralization. The MB lithology is not known to exist outside of this area. Structural lineaments relatable to possible faulting within the carbonatite are not strongly expressed in the AGG data (Figure 4b).

Quantitative modeling and related interpretations

To test and refine the qualitative interpretations, two 2.5-D forward profile models of the Elk Creek carbonatite, A-A' and B-B', are constructed (Figures 7 and 8). Such modeling is by nature nonunique, but in this case several constraints help to limit uncertainty. The models use the simplifying assumption that only three units within the carbonatite can be distinguished geophysically: Undifferentiated carbonatite (dominated by apatite beforite and its properties), mafic rocks, and MB. No other units are used in the modeling, except as noted below. The models are initially constructed using

the abundant public-domain boreholes (~100 holes) to constrain the geometry of the uppermost parts of the carbonatite. The first modeling exercise is to manipulate the carbonatite geology to fit those constraints, while also fitting the vertical derivative of the RTP aeromagnetic data. The process of fitting the aeromagnetic, Gzz, and gravity anomalies follows by manipulating the geology at progressively deeper levels. Rather than locally adjusting physical properties and geometries to fit each anomaly curve perfectly, the mean densities and median magnetic susceptibilities are used for each unit (Figure 6a and 6b), and the models are manipulated to give the perceived best overall fit to all types of geophysical data. Median values are used for magnetic susceptibilities because that parameter varies by several orders of magnitude. Variable intensities of magnetic remanence, which is unconstrained, are used (see below). The uncertainty in the geologic interpretations increases at depths greater than the deepest boreholes. Anomalies produced exclusively by the country rocks are not modeled.

The primary Gzz and gravity highs over the carbonatite are easily explained by the density contrast between the country rocks and undifferentiated carbonatite. Fitting the full amplitude of the gravity high requires a carbonatite thickness of 8–10 km (not shown), although this assumes that the density contrast with the country rocks is constant with depth. Hypothetically, a smaller thickness would result from an increasing density contrast with depth.

The aeromagnetic anomalies over the carbonatite primarily reflect the distribution of mafic rocks, with the smaller-volume MB unit making a smaller, yet significant, contribution. The magnetic susceptibilities measured for these units (Figure 6b) are not sufficient to match the amplitude of the anomalies. There are no constraints on the magnetic remanence, but it is thought that these strongly magnetized rocks likely carry some remanence. Therefore, the models assume 1–2 and 2 A/m of normally polarized remanent magnetization (in the modern earth's field direction) for the mafic rocks and MB, respectively, in addition to the induced magnetization that is represented by the magnetic susceptibilities. These are rudimentary estimates, but they do improve the fits to the observed aeromagnetic anomalies.

A small Gzz high lies over the known location of the MB ("MB" in Figures 7 and 8), in the same location as the peak aeromagnetic anomalies. However, the known volume constrained by boreholes

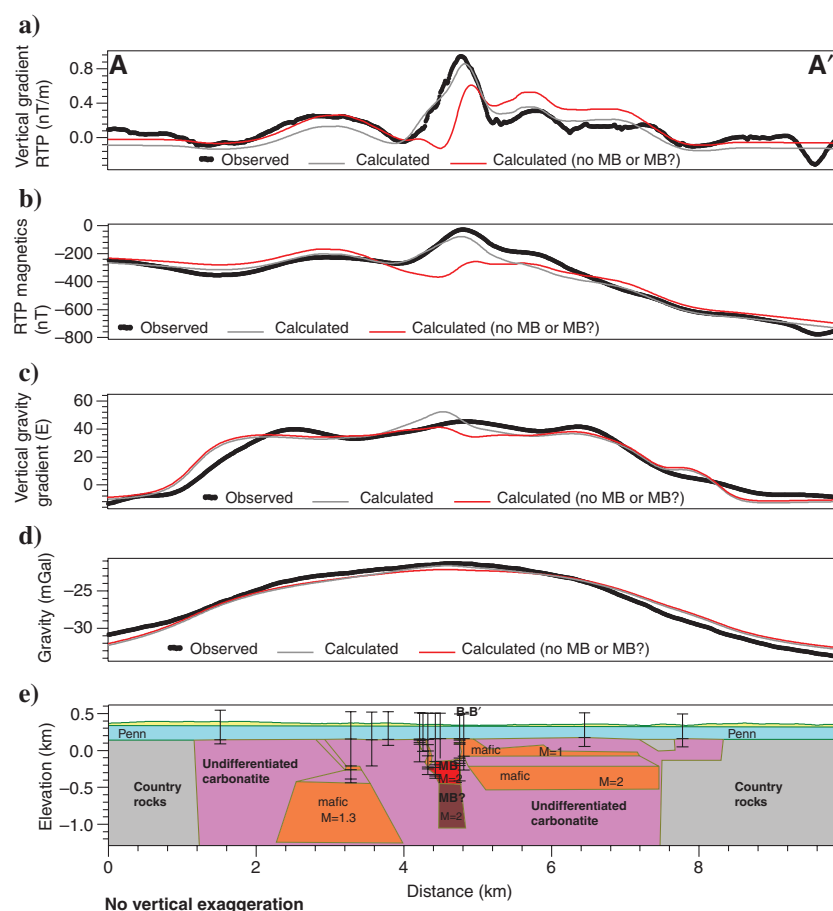


Figure 7. The 2.5D forward model and geophysical responses along A-A'. All units modeled using median magnetic susceptibilities and mean densities (Figure 5a and 5b). Normally polarized remanent magnetizations in A/m (M) shown where used. MB: magnetite beforite. (a) Vertical derivative of reduced-to-pole aeromagnetic anomalies, (b) reduced-to-pole total-field aeromagnetic anomalies. A very deep magnetization contrast, unrelated to the carbonatite, is used to model the long-wavelength regional gravity gradient, (c) vertical gravity gradient (Gzz) data, (d) complete Bouguer gravity anomalies, and (e) geologic model. The vertical gray dashed line indicating a possible fault is missing.

(only some of which fall on the model profiles) is not great enough to fully match the anomalies using known or assumed physical properties. This indicates that more high density and strongly magnetized rocks must exist at depths below the known extent of MB. The geometry of these rocks ("MB?" in Figures 7 and 8) is poorly constrained, but one simple way to model them is with the same properties as, and located immediately under, the known MB. This results in a better match to the Gzz, magnetic, and gravity anomalies. Other geometries and physical properties are possible for these deeper rocks, although any solution must place their greatest mass and magnetization-thickness product under the peak geophysical anomalies. Geologically, these rocks may either represent a greater amount of MB at depth, and by association a greater volume of niobium mineralization, or another dense and strongly magnetized lithology (with unknown mineralization potential) that is not known from borehole data exists. The spatial association with known MB suggests that the former possibility is more likely.

Modeling implies that the known MB and the suspected (deeper) MB are robust geophysical targets. How much of a geophysical response do they produce on their own, or how detectable are they quantitatively? This is addressed by removing them from the forward models and replacing them with rocks that have the same properties as the undifferentiated carbonatite unit. The calculated geophysical responses (red curves, Figures 7 and 8) show decreases in peak aeromagnetic anomaly amplitudes of at least 100 nT, and decreases in Gzz anomaly amplitudes of 10–15 E. The aeromagnetic data are clearly more sensitive to the MB than are the AGG data, due to the unit being orders of magnitude more strongly magnetized than most of the surrounding carbonatite.

Forward modeling does not offer a direct test of the hypothesized relation between faulting and the localization of MB and associated niobium mineralization. However, plotting the location of a possible fault mapped with the HGM aeromagnetic data (Figure 5c) on the model cross sections shows a clear spatial relation between the two (Figure 8).

Other Gzz highs with similar wavelengths occur over the carbonatite (Figure 4a), although they are unassociated with known locations of MB or strong aeromagnetic anomalies. The anomalies form a crude ring-shaped high around a central Gzz low that may be caused by lateral variations of alteration (see

above). The low can be modeled as a zone with a negative density contrast of 250 kg/m^3 compared with the rest of the carbonatite (too small to show at the scale of profile models), although the vertical geometry of this zone is poorly constrained. The possible geologic significance of hypothetically variable alteration is unknown. Could the highs indicate locations of MB that have been missed by borehole exploration? This does not seem likely because they do not directly correspond with large aeromagnetic anomalies, and such anomalies would be expected due to the unit's very strong magnetization.

Conclusions

Geophysical, physical property, and borehole data make a powerful combination for geologic interpretation where the rocks of interest are buried. The lower Paleozoic Elk Creek carbonatite complex in southeastern Nebraska hosts niobium and REE mineralization, and is buried under approximately 200 m of

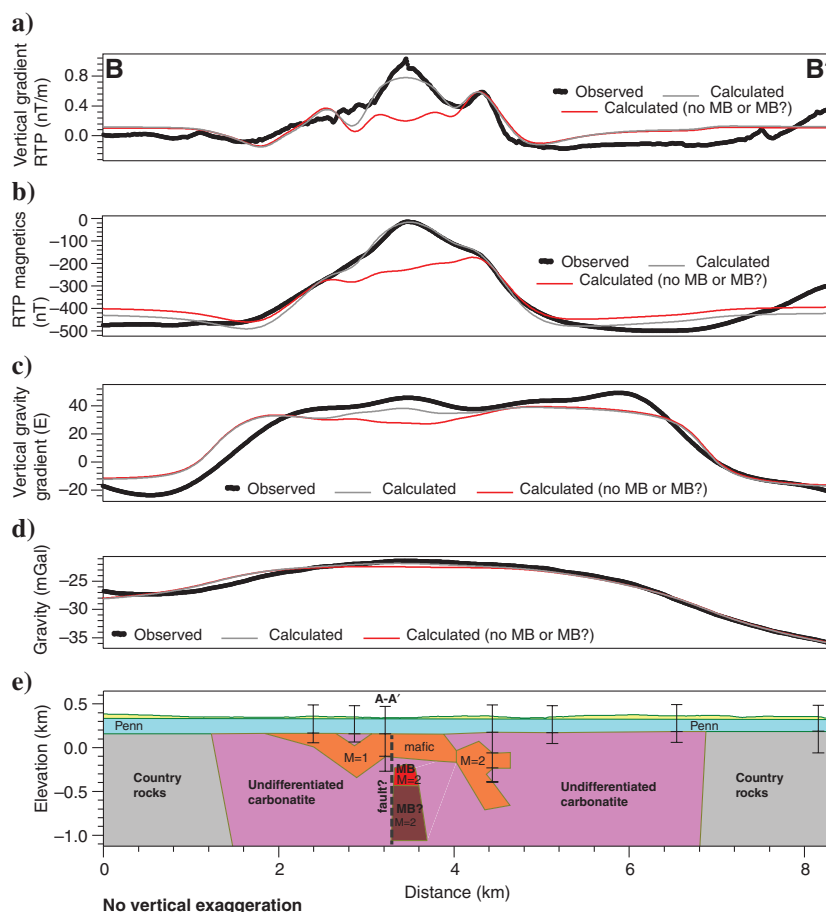


Figure 8. The 2.5D forward model along B-B'. All units were modeled using median magnetic susceptibilities and mean densities (Figure 5a and 5b). Normally polarized remanent magnetizations in A/m (M) are shown where used. (a) Vertical derivative of reduced-to-pole aeromagnetic anomalies, (b) reduced-to-pole total-field aeromagnetic anomalies, (c) vertical gravity gradient (Gzz) data, and (d) complete Bouguer gravity anomalies, and (e) geologic model. A very deep density contrast, unrelated to the carbonatite, is used to model the long-wavelength regional gravity gradient.

sedimentary cover. High-resolution geophysical data, physical property data, and legacy borehole data are combined to explain the carbonatite's geophysical expression because it relates to fundamental structure and mineralization.

The Gzz and gravity highs over the carbonatite are explained by a large density contrast with the gneissic country rocks. Aeromagnetic anomalies are attributed primarily to mafic rocks, with a smaller contribution from MB, a dense and strongly magnetized lithology that hosts niobium mineralization in this complex. Geophysical anomalies indicate that a significant volume of dense and strongly magnetized rocks must exist at a depth below the deepest boreholes. These rocks likely represent more MB and thus niobium mineralization, or could reflect another unknown lithology that is also dense and strongly magnetized. Aeromagnetic lineaments may represent faults, and a suspected fault trends through the area where MB occurs, suggesting that faulting played a role in localizing that particular rock type. Other AGG anomalies with probable sources within the carbonatite are hypothesized to represent variations of alteration. The REE mineralization is primarily associated with barite beforite. However, this unit's physical properties are similar to most of the other lithologies present within the carbonatite, and this rock type cannot be isolated using geophysics.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the United States government.

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References

- Baranov, V., and H. Naudy, 1964, Numerical calculation of the formula of reduction to the magnetic pole: *Geophysics*, **29**, 67–79, doi: [10.1190/1.1439334](https://doi.org/10.1190/1.1439334).
- Blakely, R. J., 1995, *Potential theory in gravity and magnetic applications*: Cambridge University Press.
- Burchett, R. R., 1982, *Tectonics and seismicity of eastern Nebraska*: Nebraska Geological Survey Report of Investigations issue 6, The University of Nebraska.
- Carlson, M. P., 1972, Summary of the Elk Creek anomaly: Nebraska Geological Survey Open File Report.
- Carlson, M. P., 1997, Tectonic implications and influence of the Midcontinent Rift System in Nebraska and adjoining area, in R. W. Ojakangas, A. B. Dickas, and J. C. Green, eds., *Middle Proterozoic to Cambrian rifting, Central North America*: Geological Society of America, 231–234.
- Carlson, M. P., and S. B. Treves, 2003, Characterization and geologic setting of the Elk Creek carbonatite, southeast Nebraska: Presented at 8th International Kimberlite Conference Program, 138.
- Carlson, M. P., and S. B. Treves, 2005, The Elk Creek carbonatite, southeast Nebraska — An overview: *Natural Resources Research*, **14**, 39–45, doi: [10.1007/s11053-005-4677-x](https://doi.org/10.1007/s11053-005-4677-x).
- Clark, D. A., 1999, Magnetic petrology of igneous intrusions: Implications for exploration and magnetic interpretation: *Exploration Geophysics*, **30**, 5–26, doi: [10.1071/EG999005](https://doi.org/10.1071/EG999005).
- Cordell, L., 1979, Gravimetric expression of graben faulting in Santa Fe country and the Espanola basin, New Mexico: Presented at New Mexico Geological Society, 30th Field Conference, 59–64.
- Cordell, L., and V. J. S. Grauch, 1985, Mapping basement magnetization zones from aeromagnetic data in the San Juan basin, New Mexico, in W. J. Hinze, ed., *The utility of regional gravity and magnetic anomaly maps*: SEG, 181–197.
- Dransfield, M. H., 2010, Conforming Falcon gravity and the global gravity anomaly: *Geophysical Prospecting*, **58**, 469–483, doi: [10.1111/j.1365-2478.2009.00830.x](https://doi.org/10.1111/j.1365-2478.2009.00830.x).
- Dransfield, M. H., and A. N. Christensen, 2013, Performance of airborne gravity gradiometers: *The Leading Edge*, **32**, 908–922, doi: [10.1190/tle32080908.1](https://doi.org/10.1190/tle32080908.1).
- Farmer, G. L., R. M. Kettler, and P. L. Verplanck, 2013, Geochemical and isotopic constraints on the age and origin of the Elk Creek carbonatite complex, southeast Nebraska: Presented at Geological Society of America 65th Annual Meeting, 21–7.
- Grauch, V. J. S., and L. Cordell, 1987, Limitations of determining density or magnetic boundaries from the horizontal gradient of gravity or pseudogravity data: *Geophysics*, **52**, 118–121, doi: [10.1190/1.1442236](https://doi.org/10.1190/1.1442236).
- Grauch, V. J. S., and M. R. Hudson, 2007, Guides to understanding the aeromagnetic expression of faults in sedimentary basins: Lessons learned from the central Rio Grande rift, New Mexico: *Geosphere*, **3**, 596–623, doi: [10.1130/GES00128.1](https://doi.org/10.1130/GES00128.1).
- Hinze, W. J., R. R. B. Von Frese, and A. H. Saad, 2013, *Gravity and magnetic exploration*: Cambridge University Press.
- Long, K. R., B. S. Van Gosen, N. K. Foley, and D. Cordier, 2010, The principal rare earth elements deposits of the United States — A summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report, 2010-5220.

- Pan-American Center for Earth and Environmental Sciences, 2012, <http://gis.utep.edu/>, accessed 30 October 2012.
- Phillips, J. D., 2001, Designing matched bandpass and azimuthal filters for the separation of potential-field anomalies by source region and source type: Presented at 15th Geophysical Conference and Exhibition, ASEG.
- Syberg, F. R. J., 1972, A Fourier method for the regional-residual problem of potential fields: *Geophysical Prospecting*, **20**, 47–75, doi: [10.1111/j.1365-2478.1972.tb00619.x](https://doi.org/10.1111/j.1365-2478.1972.tb00619.x).
- Van Gosen, B. S., and H. A. Lowers, 2007, Iron Hill (Powderhorn) carbonatite complex, Gunnison County, CO — A potential source of several uncommon mineral resources: *Mining Engineering*, **59**, 56–62.
- Williams, N., 2013, Mineral exploration under deep cover: Presented at Geological Society of America 125th Anniversary Annual Meeting and Expo, 271–7.
- Witherly, K., 2012, The evolution of minerals exploration over 60 years and the imperative to explore undercover: *The Leading Edge*, **31**, 292–295, doi: [10.1190/1.3694895](https://doi.org/10.1190/1.3694895).
- Xu, A., 1996, Mineralogy, petrology, geochemistry and origin of the Elk Creek carbonatite, Nebraska: Ph.D. thesis, University of Nebraska–Lincoln.

A biography and photograph of the author are not available.