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Gravity and Magnetic Investigations into Possible Economic Mineral Deposits within the Northwest St. Francois Terrane, Southeastern Missouri

Brandon Todd Ives

GRAVITY AND MAGNETIC INVESTIGATIONS INTO POSSIBLE ECONOMIC MINERAL DEPOSITS WITHIN THE NORTHWEST ST. FRANCOIS TERRANE, SOUTHEASTERN MISSOURI

A Masters Thesis

Presented to

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In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Geospatial Sciences in Geography and Geology

By

Brandon Todd Ives

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GRAVITY AND MAGNETIC INVESTIGATIONS INTO POSSIBLE ECONOMIC MINERAL DEPOSITS WITHIN THE NORTHWEST ST. FRANCOIS TERRANE, SOUTHEASTERN MISSOURI

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ABSTRACT

The exposed Precambrian St. Francois Mountains in southeast Missouri are a well-studied terrane of rhyolites, granites, and basaltic dikes, but much of the buried basement lithology west of the exposed region is still poorly delineated. The western St. Francois is host to large hydrothermal Pb-Zn and Fe-oxide ore deposits, some of which were located with previous geophysical investigations. The economic ore deposits specifically in the Pea Ridge Mine in Washington County contain known economic minerals and rare earth element deposits. In order to further investigate the Precambrian basement lithologies and the possible locations of additional economic ore deposits, a gravity survey was conducted during the summers of 2013 and 2014, collecting over 700 new gravity stations. The new gravity data were merged with previous gravity data showing anomalies that with further processing (e.g., wavelength filtering and derivative analysis) and 2.5-D computer modeling some of the basement lithologies were better defined and previously unknown gravity maximums were identified. The 2.5-D models allowed the development of answers to questions raised by the complete Bouguer gravity anomaly map which also gives insight into the history of the region during the Precambrian after the collapse of the central pluton. The Pea Ridge Mine and many of the other Fe mines are located over gravity minimums, and low density bodies in the Precambrian below the denser ore bodies compensated for the low gravity anomalies. Additionally, the low density bodies may give a greater understanding into the origins of the hydrothermal ore deposits themselves.

KEYWORDS: geophysics, gravity, magnetic, St. Francois Mountains, Missouri, economic minerals, rare earth elements, mining, Precambrian

This abstract is approved as to form and content

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Chairperson, Advisory Committee
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INTRODUCTION

Southeastern Missouri has a geologic history featuring early tectonism forming the Mesoproterozoic era St. Francois Mountains (Kisvarsanyi, 1980). This was followed by subsidence of the volcanic terrane, leading to a long period of erosion and deposition as the area became an inland sea until the uplift of the Ozark Dome, beginning in the middle Paleozoic and ending in the early Mesozoic (Unklesbay and Vineyard, 1992; Brown, 2005). This geologic history has left a variety of lithological structures both above and below ground, the latter of which are still only partially known. Understanding the underlying lithology and geometry is paramount to understanding the geologic and tectonic history of the region. Over time, the fractures in the Precambrian basement rocks may have led to the development of some of the richest iron, lead, and associated economic mineral deposits found in North America, developed through chemical processes and hydrothermal alteration of the basement rocks (Horrall et al., 1993; Nold et al., 2013). This study is specifically interested in the location of possible rare earth element (REE) deposits and the use of geophysical techniques to constrain their known boundaries in the subsurface.

An initial series of igneous extrusive events 1.5 billion years ago started the foundation from which the St. Francois Mountains developed (Kisvarsanyi, 1980). As volcanic activity in the area ended during the Precambrian period, the region became an inland sea and the deposition of the nearshore Lamotte Sandstone began, followed later by the creation of an offshore carbonate bank, the Bonneterre Formation, which surrounded the highpoints, creating islands of exposed igneous basement (Gerdemann

and Myers, 1972). One of these islands contains known occurrences of REEs that were created through physical and chemical alteration of the igneous basement rocks and transported through fractures and fissures forming breccia pipes adjacent to the main magnetite ore body in the lower depths of the Pea Ridge Mine (Nuelle, 1998; Gow et al., 1994). A greater knowledge of the lithology and geometry of these basement igneous rock bodies below the sedimentary structures is important, and knowing how they are arranged in the subsurface is a way to identify possible locations of other REE-bearing ore bodies in the northwest St. Francois terrane.

Geophysical methods are one of the ways to gain knowledge of the buried crystalline basement terrane. For larger deeper structures seismic and magnetotelluric methods are used to aid gravity methods in creating a more detailed interpretation of the subsurface lithologies. The breccia pipes containing the REE deposits are 700 meters below the surface and are only 30 square meters in cross section, thus in comparison to the ore bodies surrounding them, they are not very large or deep (Seeger et al., 2001). Because of the size of the breccia pipes, other, less coarse, geophysical methods must be used. Previously, aeromagnetic and isolated gravity surveys have been performed and combined with well-core data to create the current maps of sedimentary deposits and the upper igneous basement (Kisvarsanyi, 1981).

In the winter of 2014 a new aeromagnetic and aerogravity survey was performed as part of a United States Geological Survey (USGS) project titled Setting and Origin of Iron Oxide-Copper-Cobalt-Gold- Rare Earth Element (Fe-Cu-Co-Au-REE) Deposits of Southeast Missouri (USGS, 2013). The methods used for that research are a combination of new gravity data, combined with earlier gravity and magnetic data allowing the

development of a multifaceted geological and geophysical signature of the probable locations of REE deposits.

The resulting maps of combined data show definite improvements in the delineations of the past basic gravity contour maps. Some anomalies mapped have increased in scope and magnitude when the new data is added to the previous data, where others have lessened. This shows that by improving the station spacing and number of data points in the region the gravity anomalies can become better defined. In the simple Bouguer gravity anomaly maps the changes are obvious and further processing and modeling has accentuated these differences. After wavelength filtering, the gravity anomalies found on the Bouguer gravity anomaly maps become more apparent as regional-scale trends. To help identify smaller anomalies a second derivative was applied that emphasized small changes in the data over the area. Two and one-half dimensional (2.5-D) models were created to represent the possible lithological compositions and geometry representing the anomalies within the research area. Three models were created: 1) a west-to-east profile passing through the Pea Ridge area, 2) a north-to-south profile passing through Pea Ridge and the Huzzah gravity maximum anomaly, and 3) a west-to-east profile through the Huzzah anomaly.

CHAPTER 1

1.1 Mineralogical Overview

This study is focused on the location and extent of economic mineral deposits and derived associated metals, particularly REEs, in or near the crystalline basement of the St. Francois terrane. The Viburnum Trend lead-zinc deposits (galena, sphalerite, and chalcopyrite) found in the dolomite of the Bonneterre Formation are some of the largest in the world and overshadow other significant deposits of zinc, copper, cobalt, nickel, and cadmium (Erickson et al, 1981). As associated minerals, these other economic ores are also useful as indicators for the location of possible REE deposits. Outside the Viburnum Trend are the extensive magnetic iron deposits that are most likely the result of hydrothermally altered apatite (Nold et al, 2013). Hydrothermal alteration is a common type of low-grade metamorphism that alters the chemical and crystallographic structures of the currently emplaced rocks and minerals. Large hydrothermal origin REE deposits exist around the world, but Pea Ridge is the only known one in the United States (Gow et al, 1994).

REE minerals have been known for over 200 years, but profitable refinement has only occurred in the last 50 years (Castor and Hendrik, 2006). REEs are a group of 17 elemental minerals starting with scandium, yttrium, and the entire lanthanoid series. REEs are subdivided into two major groups: the light REE cerium group (Sc, La, Ce, Pr, Nd, Pm, Sm, Eu, and Gd), and the heavy REE yttrium group (Y, Tb, Dy, Ho, Er, Tm, Yb and Lu). The heavier REE group is scarcer and move valuable, both economically and industrially, than the more common light REE group (Castor and Hendrik, 2006).

The importance of REEs increases every day as the use of high-tech devices grows. Because of REEs' usefulness in such a broad range of applications and consumer goods, their increase in use is considered a significant economic indicator of growth (Castor and Hedrick, 2006). Their use is not just in consumer products such as modern high-capacity batteries and LED light bulbs, but they are also highly sought after for industrial and military applications in which hard, strong-wearing materials are vital (Seeger, 2013). Modern electric and hybrid automobiles, wind power generators, medical imaging machines, as well as the magnets, memory, and glass in smart phones are just a few of the daily uses of REEs today. As society relies increasingly on electronics and technology REEs become more important. Finding viable REE deposits within the United States is a vital component to economic and industrial independence going into the future.

The word "rare" in the name is actually a misnomer, as some REEs, cerium in particular, are more common than silver, tin, or molybdenum, but REEs are quite difficult to refine from the ores that contain them, thus making them scarce in their final usable form (Castor and Hedrick, 2006). In 1998, China began restricting the export and processing of REE-bearing mineral ores and this has led countries worldwide to expand the search for their own deposits. Before China's rise to dominance of the worldwide market of REE mining and processing in the 1980s, Mountain Pass, California, was the largest REE mine in existence (Castor and Hedrick, 2006). Mountain Pass and the Chinese Bayan Obo mine are both large above ground open-pit mines, whereas Pea Ridge is a traditional deep shaft mine. Although the Mountain Pass deposits are of a higher grade, the Bayan Obo mine produces over 25 times more REE-bearing ore (Castor

and Hedrick, 2006). The Pea Ridge deposits are of even higher grade than the Mountain Pass ore deposits, and while smaller in bulk the Pea Ridge resources could add a significant amount to the known US quantities (Long et al, 2010).

The known REE-bearing ores at Pea Ridge are contained within four breccia pipes at the designated 2275' level inside a weak fracture zone located between the main magnetite body and a lightly altered rhyolite body (Figs. 1 and 2) (Sidder et al, 1993). The sizes of the pipes are irregular, but the dimensional area is as much as 60 meters by 15 meters with unknown vertical extent, with a minimum of 120 meters known (Seeger et al., 2001). The breccia pipe deposits have been known since at least the mid-1970s, and multiple projects have taken place to try and identify and map the deposits, including a recent highly detailed multi-level mapping project undertaken by the USGS and Missouri Geological Survey (MGS) (Whitten and Yancey, 1990; Seeger, 2013).

1.2 Study Area

The northwestern St. Francois terrane is the focal point for this regional geophysical investigation using combined information from past geophysical studies in the area and well cores (Fig. 3). The St. Francois Mountains are the exposed basement of the southwestern boundary of the Eastern Granite-Rhyolite province near the boundary with the Southern Granite-Rhyolite province (Rohs and Van Schmus, 2007). The earliest emplaced igneous bodies in the St. Francois region were comprised of extrusive rhyolite and trachyte ash-flow tuffs, followed by alkali granites, which make up the bulk of the volcanic deposits found in the St. Francois region (Kisvarsanyi, 1981). Intruding these large emplaced massifs is a series of porphyritic ring granites surrounding the original

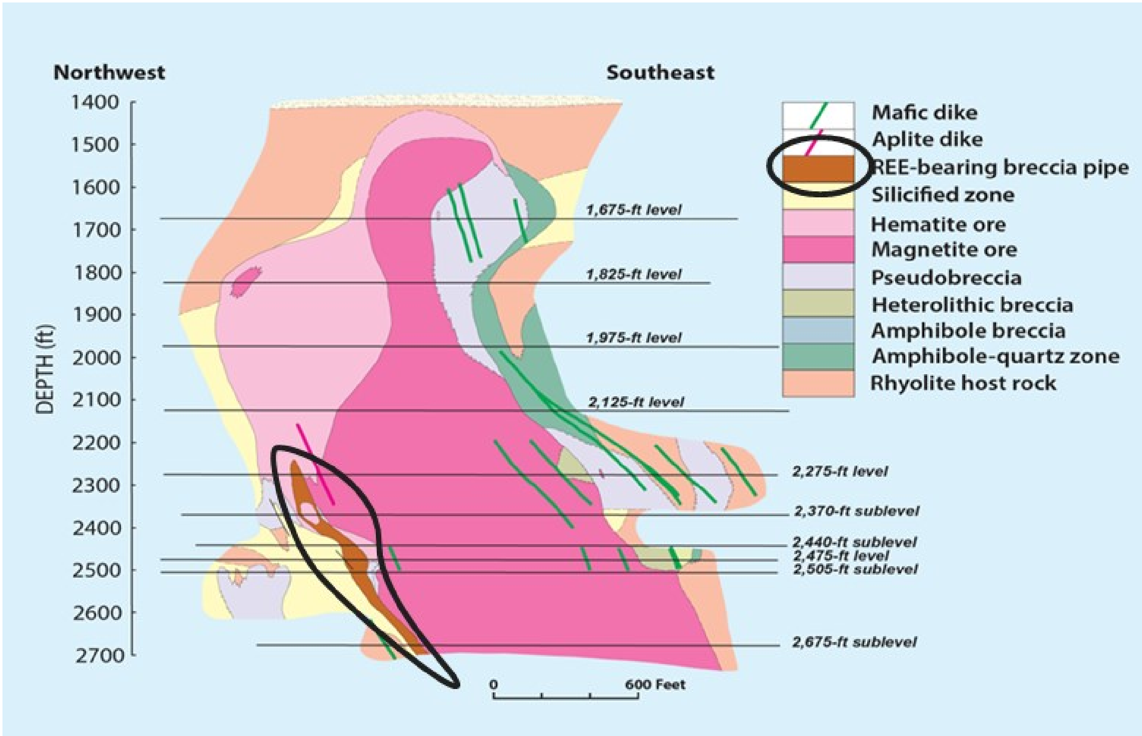

Figure 1. Vertical geologic cross-section of the Pea Ridge mine (USGS, 2013). REE-Bearing breccia pipe adjacent to main magnetite body highlighted.

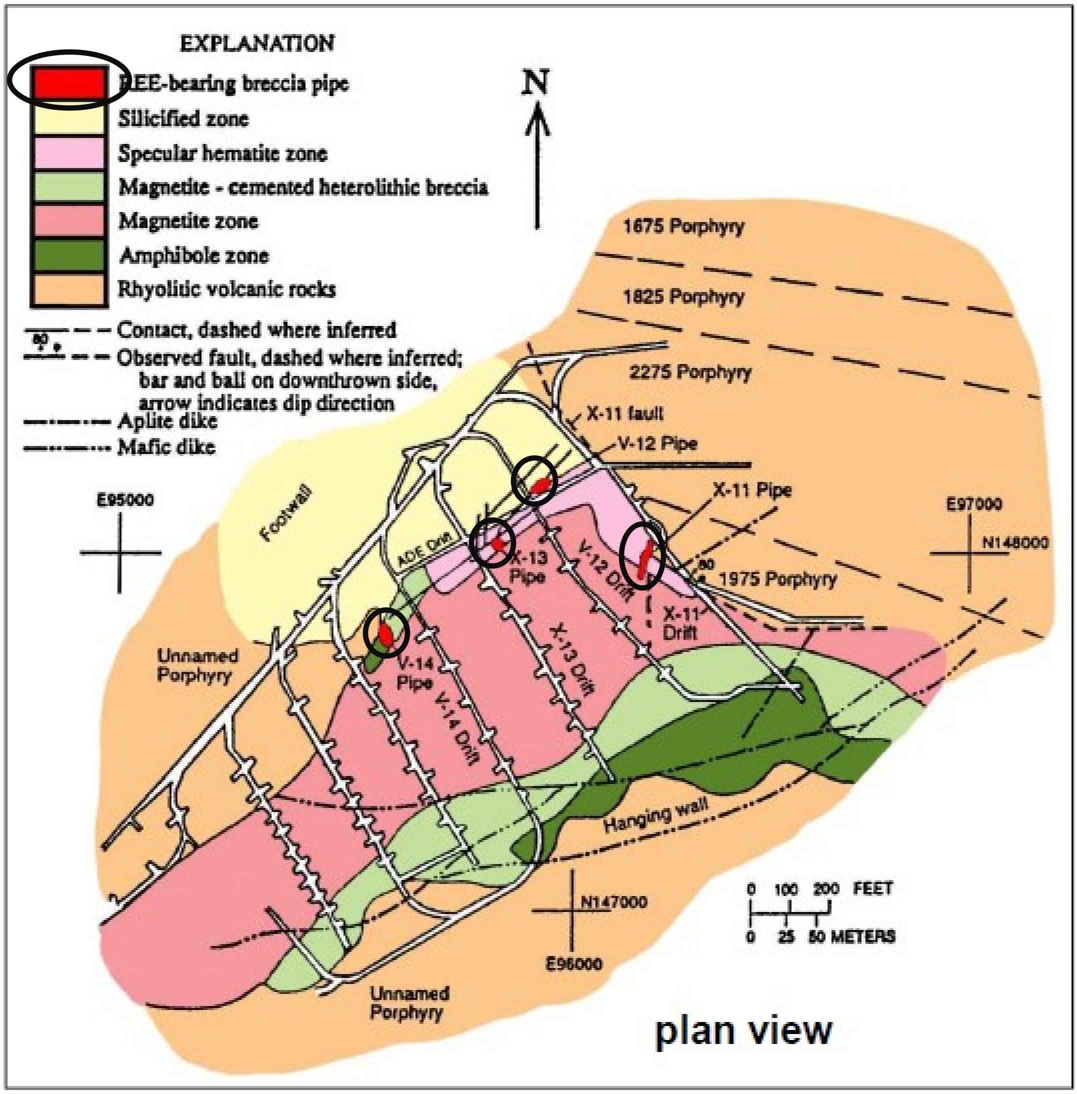

Figure 2. Horizontal geologic cross-section of the Pea Ridge mine 2275’ depth (Seeger, 2013). REE-Bearing breccia pipes adjacent to main magnetite body highlighted.

rhyolitic flows and granitic plutons, with the last series of intrusions being of the tin-type granites well known in the region (Kisvarsanyi, 1981). Some of these igneous bodies can be seen on the surface as exposures of the central plutons and ash-flow tuffs, and are some of the oldest outcrops in the United States. It is the unexposed continuation of those lithologies with which this survey is most concerned.

The northwest St. Francois Mountains region has a long history of economic resource extraction, and although mining in the Viburnum Trend has declined dramatically as the use of lead has declined worldwide, other areas have become more important (Erickson et al., 1981). Even the once important and prosperous iron mines -- that served the region for generations, such as Pilot Knob and Iron Mountain, have been closed after more than 150 years of mining in the region, because of the lack of financial profitability (Unklesbay and Vineyard, 1992).

The central study area of the Pea Ridge Mine, which is a deep shaft mine, was the richest of all the iron-ore-bearing mines in the area after all the above-ground deposits were depleted three generations ago (Long et al, 2010). After decades of profitable extraction a precipitous decline in the price of iron decreased profitability in the 1990s and led to the closure of the mine, with the lower levels being flooded. Bankruptcy was filed in 2001 (Long et al, 2010). Today the mine has one shift a week which only processes the remaining tailings piles. A renewed interest in developing REE deposits in the United States has, however, brought attention to the known REE deposits in Pea Ridge (Nulle et al, 1998).

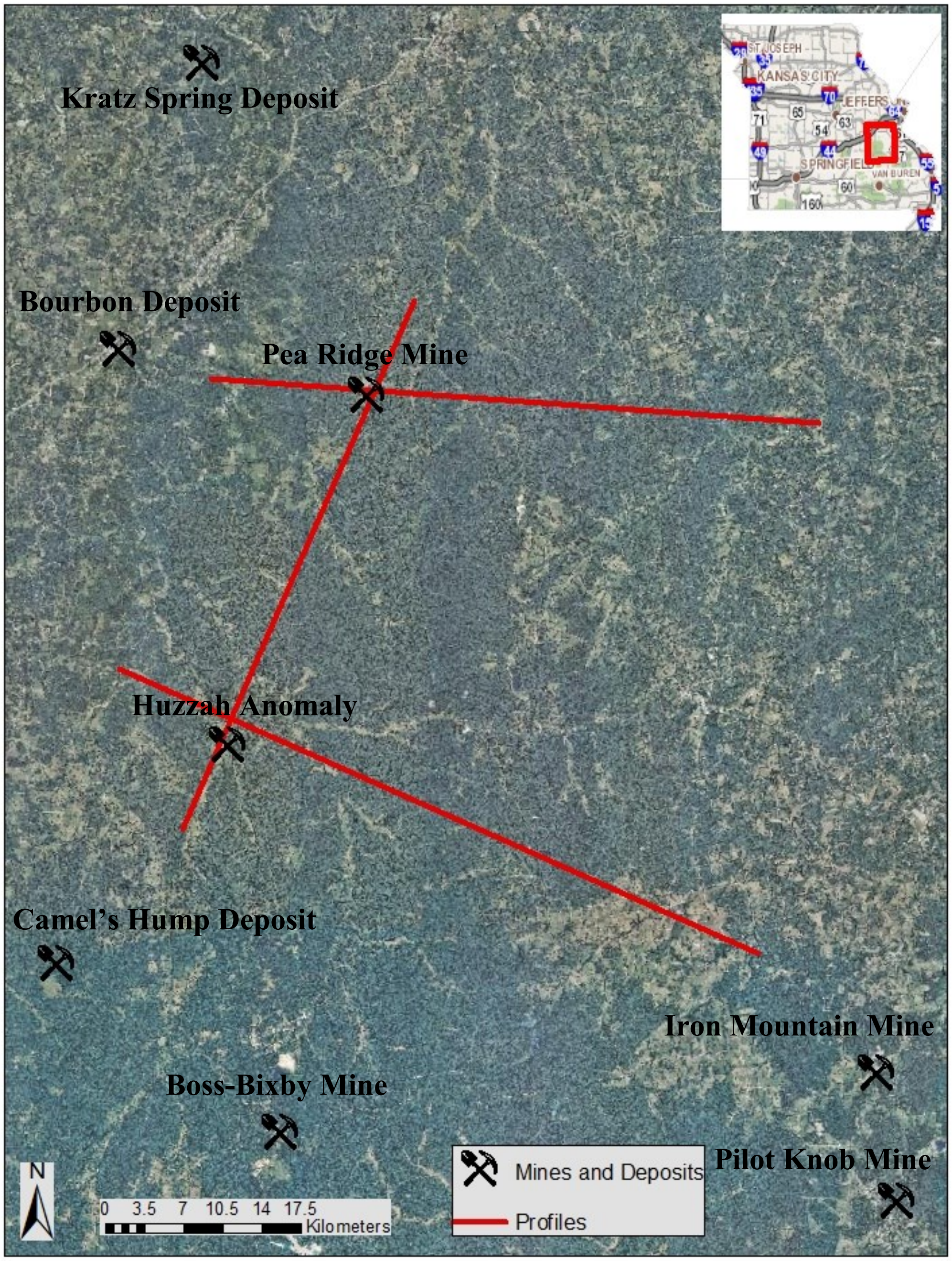

Figure 3. Geographic location of research area. Basemap from Missouri Department of Transportation (MODOT.com) and adapted from Missouri Spatial Data Information Service (msdis.missouri.com)

1.3 Previous Geophysical Studies

The most comprehensive geophysical surveys in Missouri began in the 1930s with magnetic traverses along highways, and later the WPA (Works Progress Administration) collected gravity data in areas of interest determined during the earlier magnetic highway traverses (Cordell, 1979; Cordell and Knepper, 1987). By the 1970s, aeromagnetic surveys covered almost the entire state, augmenting the earlier groundwork. Most of the significant magnetic anomalies in the St. Francois region were identified by the earlier aeromagnetic data which ranged from 400 m to 8 km line spacing (Fig. 4). Thus the information and interpretation was regional at best, and these early data were the basis of much of the literature until recently (Cordell and Knepper, 1987; Hildenbrand et al., 1996).

Other large-scale geophysical projects, such as Earthscope (a nationwide broadband seismic project to study the United States lithosphere) or NASA's satellite-based Gravity Recovery and Climate Experiment (GRACE), are very good for isolating large regions of interest for further study but are not useful in regional studies, or even smaller local-scale investigations. To get an idea of the subsurface structure researchers need detailed in-situ data collection to correlate their results with other data collection methods. Shah et al. (2013) provide an example of such a project, as they describe researching undeveloped economic mineral deposits in southeast Alaska using multiple geophysical techniques and correlating the results to core samples collected from drill holes. They detail the use of magnetotelluric, aeromagnetic, and magnetic susceptibility of drill-hole samples and combine those results with gravity and density data to create detailed plan-view and cross-profile maps and derive models from those maps. The

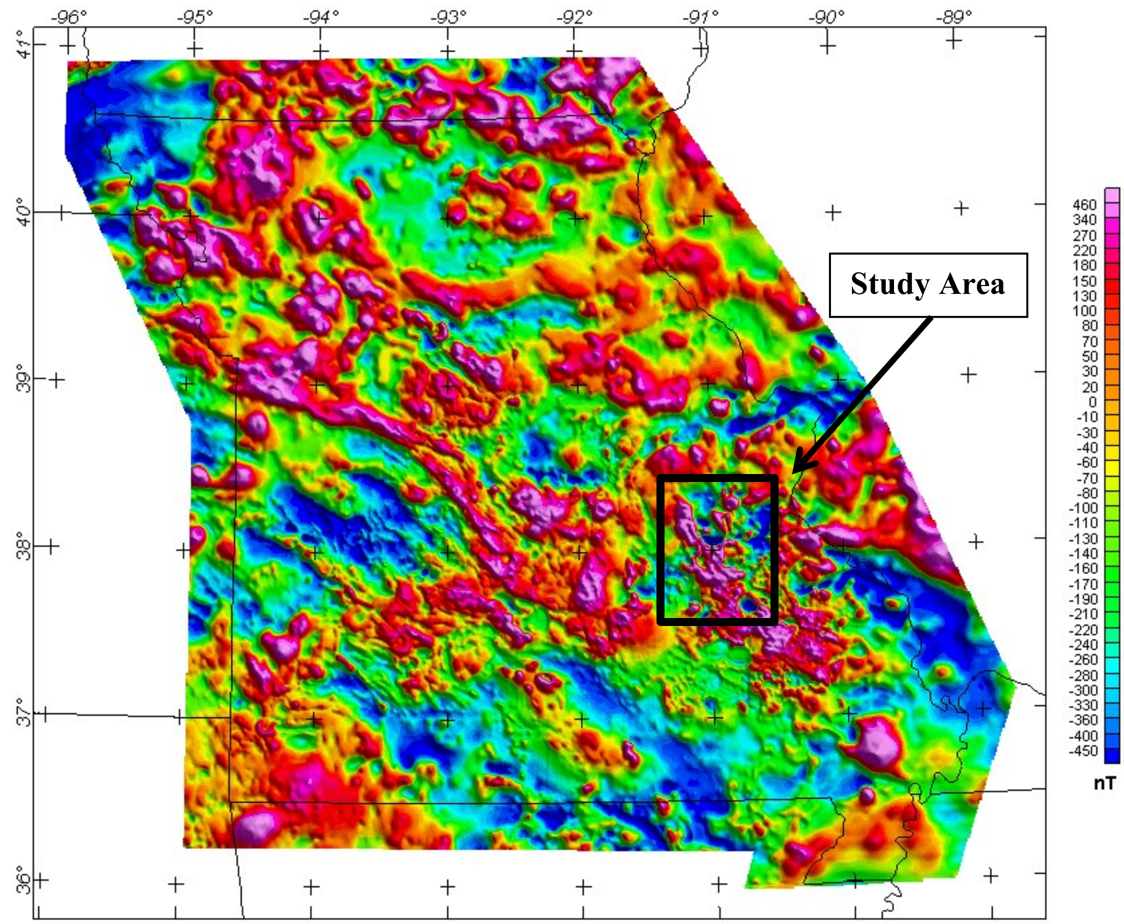

Figure 4. Total-field magnetic map of Missouri. The black border represents the extent of the magnetic anomaly maps used in this study Figures: 11, 12, 14, 15, 16, 17, 19, and 20 (USGS, 2013).

research into the northwestern St. Francois terrane is similar to the southeast Alaska project, but with more of an emphasis on the gravity and magnetic data interpretation, and well-log data are used to refine the possible lithologies and their densities to aid in the removal of the effect of the overburden sediments on the gravity readings of the crystalline basement.

What is known about the basement in the St. Francois region comes from drill-core samples, scattered outcrops and interpretations of previous magnetic anomaly maps (Hildenbrand et al., 1996; Kisvaranyi, 2007). Defining large regional lithologies hidden under the Paleozoic sediments away from the exposed outcrops is how geophysics is commonly used. Variations in lithology, depth and geometry create different geophysical signatures that can be identified and correlated in a similar manner to physical stratigraphic correlation done typically at the surface between outcrops. The difficulty is in balancing the number of geophysical stations and the amount of area to be covered so that the resolution of the data is good enough to refine the boundaries of the hidden lithology. Also, access to the area of study can be difficult if the area is rugged or heavily wooded— as is the case in the northwest St. Francois region—which is why many surveys use airplanes and helicopters for the collection of gravity and magnetic data, but that method of collection may have poor spatial resolution.

1.4 Research Purpose

This research project does not pinpoint specific emplacements of the minerals and ores of interest, but was to aid in refining the locations of possible emplacements that exploratory drillers may then sample for further investigation and confirmation. It is the

proverbial needle-in-a-haystack problem, trying to find possible small deposits in a large geographic area, in which different subsurface lithologies and geometries can produce the same geophysical signature at the surface.

Geophysical models are non-unique and interpretive, and they rely on other types of observations and refinements to better understand the various possible solutions provided by the data. To better refine the models the gravitational effect of the sedimentary overburden from the crystalline basement rocks was subtracted to give a more localized reading of what the gravity is in the basement terrane. Because the topography of the surface of the basement does not mirror the ground surface, the changes in elevation and effect of the sedimentary layers can have noticeable effects on the Bouguer gravity anomaly maps produced with data collected at the surface. Next is comparing the new in-situ gravity data to aeromagnetic data collected in the past. Using other processing techniques, such as bandpass and derivative filtering and the creation of isostatic residual maps, anomalies of significance have been accentuated, either local or regional, further delineating areas of possible REE deposits for core sampling in the future.

Over 700 in situ gravity station readings were recorded during the summers of 2013 and 2014 throughout the northwest St. Francois area with half-mile spacing between stations. Those stations were added to other gravity data from the University of Texas at El Paso Pan American Center for Earth and Environmental Studies (UTEP PACES) gravity database to create Bouguer gravity anomaly maps. The maps were then compared with local gravity and magnetic data of the Pea Ridge Mine area, in combination with other regional studies. These other studies included historical

aeromagnetic surveys and a recent aeromagnetic and aerogravity survey done by the USGS during the winter of 2013-2014. The combined data was processed using a variety of software and methods to isolate geophysical markers that can be applied to the region as a whole and identify possible locations of other REE deposits.

The maps and models are only one part of the overall research. Other important outcomes from this thesis are a greater understanding of the subsurface lithology and geometry of the northwest St. Francois terrane. Furthermore this research has added a large number of data points to the current body of knowledge that is lacking on the western side of the St. Francois Mountains.

CHAPTER 2

2.1 Regional Geological History and Precambrian Development

A detailed knowledge of the subsurface lithologies and geometry of a study area is essential for creating and interpreting geophysical models. Various lithological compositions can present the same gravity or magnetic anomalies at the surface, but by comparing multiple geophysical methods (e.g., seismic, magnetotelluric, etc.) and using drill core sample evidence as constraints, the possibilities are narrowed substantially. Additionally, using previous geological and geophysical studies allows a more thorough and nuanced approach to the development of geophysically-based models.

The St. Francois terrane (Fig. 5) is a remnant of Precambrian collapsed calderas and volcanic activity consisting of the crystalline remains of ash-flow tuffs and rhyolite flows, granitic central plutons and ring intrusions, and makes up the majority of the basement lithology (Kisvaranyi, 1981). There are some exposures cropping out at the zenith of the Ozark Dome (Kisvarsanyi, 1980) (Fig. 6). Earlier studies of the region have been generally focused on the eastern side of the St. Francois Mountains, mainly the Reelfoot Rift and Mississippi Embayment. These investigations have focused on the seismic history and possible hazards of the New Madrid Fault Zone and looking into the history of the development of the embayment (Hildenbrand, 1985; Langenheim and Hildenbrand, 1997; Csontos et al., 2008). The western side has been investigated mostly with interest in economic minerals, specifically within the Viburnum Trend lead-mining district (Gerdermann and Myers, 1972; Graf, 1984; Garven et al., 1999; Bradley and Leach, 2003).

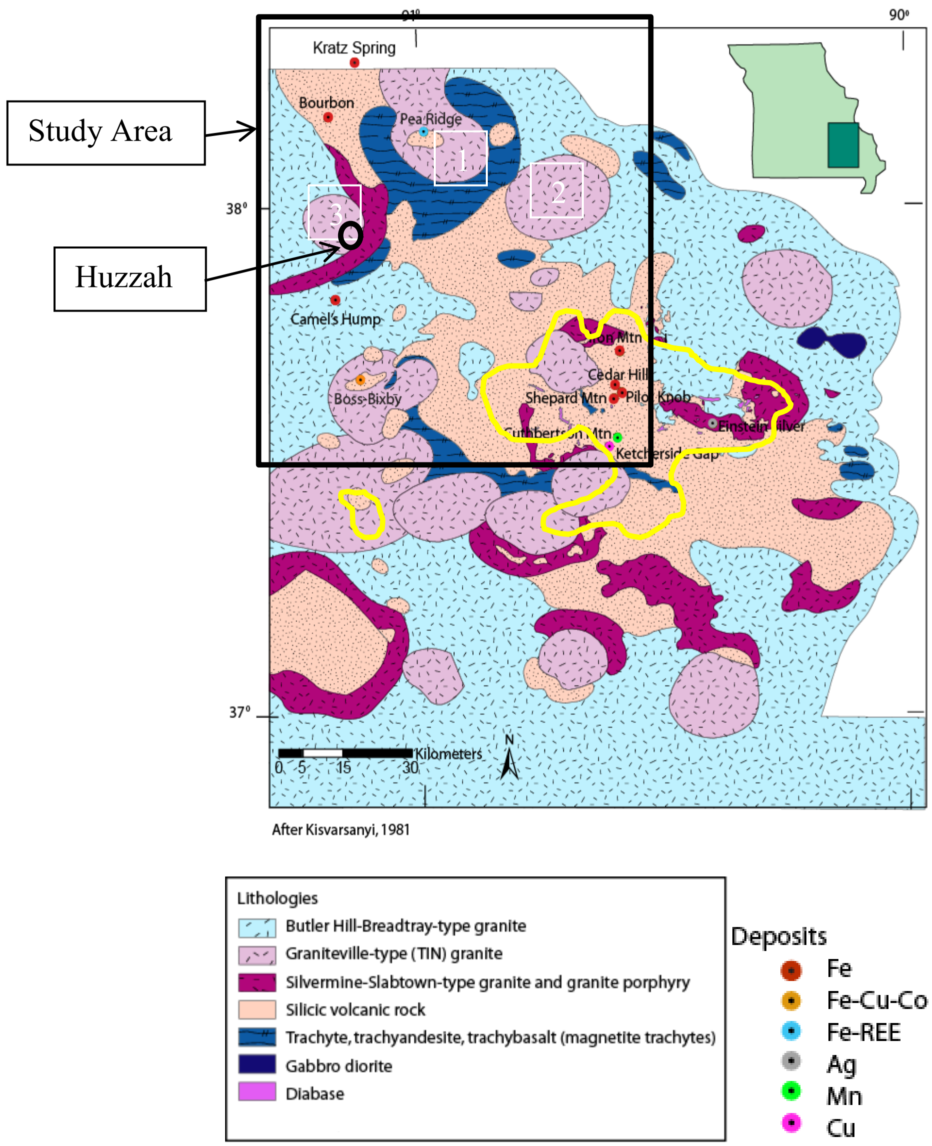

Figure 5. Precambrian geology of southeast Missouri (USGS after Kisvarsanyi, 1981). Outlined box represents study area. The approximate location of the Huzzah anomaly is marked. Yellow outline is the approximate location of exposed Precambrian outcrops. Numbers represent calderas referred to final models (Figs. 20a, 20b, and 20c).

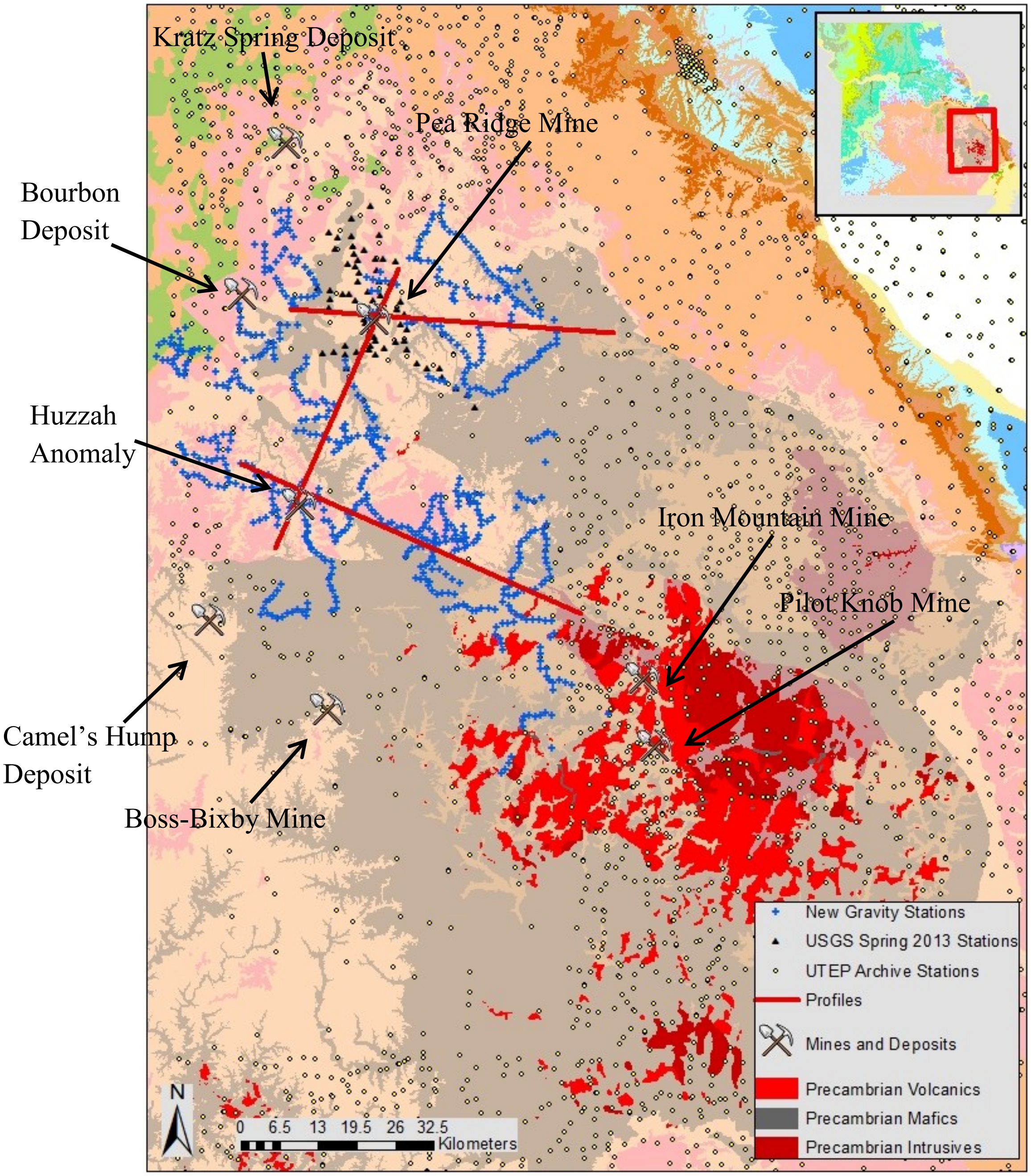

Figure 6. Bedrock map of study area covering the entire St. Francois region with the locations of all gravity stations. Bedrock adapted from Missouri Spatial Data Information Service msdis.missouri.com. Red areas are outcrops of the Precambrian terrane.

The St. Francois region has undergone extensive change over time that included the Ouachita orogeny on its southern flanks, combined with other continental and regional tectonic events which altered the area dramatically during the last 1.5 billion years (Braile et al., 1986; Van Schmus et al., 1996). Locally, the formation of the St. Francois Mountains and active local volcanism started with the creation of the Eastern Granite-Rhyolite Province, which covers Illinois, Indiana, parts of Michigan, Ohio, Kentucky, Tennessee, and southeast Missouri, in the Mesoproterozoic (1.47±0.03 Ga), and finished with mafic intrusions between 1.258 Ga and 904 Ma (Kisvarsanyi, 1981; Van Schmus et al., 1996; Rohs, 2013).

There have been few studies on the northwest St. Francois terrane, and most targeted studies have been mostly in search of the limits of known geology of economic interest (Gerdemann and Myers, 1972; Cordell, 1979; Gleason et al., 2000; Groves et al., 2010). Studies on the basement geology of the St Francois Mountains have generally been concerned with the depth of the sediments to the basement, the mineralogical and general lithological make-up at the nonconformable surface of the basement, and using gravity and magnetic anomalies to infer the basement lithologies (Stewart, 1968; Cordell, 1979; Kisvarsanyi, 1979; Pratt et al., 1992). What lies below the deeper surface of the known basement is even more poorly understood. There is a suggestion that below the Eastern Granite-Rhyolite Province is an older extension of the eastern part of the Central Plains Orogen consisting of 1.6 to 1.8 Ga granites and rhyolites (Sims and Petermar, 1986). Stewart (1968) conducted a seismic refraction survey with two long profiles, both running roughly west-to-east. One profile was in north-central and the second in southeastern Missouri crossing the St. Francois region. In the seismic profile from St.

Genevieve to Gladden, Missouri, passing near the research area, some evidence was found for two granitic layers dipping westward, though the dip did not represent a strong signal in the recorded shots (Stewart, 1968).

The earliest exposed remains of the tectonic history of southeast Missouri include exposures of some of the oldest Precambrian rock in the south-central United States, and the only surface exposures of the Eastern Granite-Rhyolite Province (Van Schmus et al., 1996). Studies using U-Pb age dating of zircons have found the earliest crystallization of the central pluton at 1.48 ±0.02 billion years (Sims et al., 1987). Using paleomagnetic data Meert and Stucky (2002) developed a similar date of the crystallization of the central pluton. Other plutons later developed during periods of resurgent doming, creating a series of knobs around the central volcanic region (Kisvarsanyi, 1981; Sides et al., 1981).

To the southeast of the St. Francois Mountains is the Reelfoot Rift, the central tectonic feature of the New Madrid Seismic Zone. Because of its history of earthquake activity and the basis for the creation of the Mississippi Embayment, this eastern side of the St. Francois Mountains has been studied extensively (Hildenbrand, 1985; Braile et al., 1986; Langenheim and Hildenbrand, 1997; Csontos et al., 2008). Although there are no exposed outcrops of the Reelfoot basement rocks, it is believed that they are of the same composition as the St. Francois granites and rhyolites (Braile et al., 1986). Magnetite rich granites and syenite formed around and within the ‘knobs’ of the St. Francois Mountains, helping set the stage for the development of the rich mineral deposits that developed later (Kisvarsanyi, 1980, Lowell, 2000).

Within the study area there have been repeated igneous intrusions along with cycles of eruption, uplift, subsidence, and erosion into the Paleozoic, which are central to

the understanding of the possible lithological geometries in the basement (Hildenbrand, 1985; Lowell, 2000). Initial periods of regional uplift as evidenced by the multiple calderas consisting of alkali rhyolite ash-flow tuffs and the consolidation of biotite Butler Hill and Breadtray granites were followed by the collapse of the calderas and the intrusion of the amphibole-bearing, Silvermine and Slabtown granites, and later syenite, into the extensive fractures and ring dikes post-collapse (Kisvarsanyi, 1980). The cycle of doming and collapse was repeated with the addition of extensive hydrothermal activity, granite porphyries surrounding the older volcanic rocks, and the two-mica tin Graniteville granites intruding as a final stage of doming (Kisvarsanyi, 1980). The various granites and developmental timeline, including the final dozen caldera complexes, can be seen in Figure 5. The earliest St. Francois volcanics are mixed in with the Precambrian sedimentary Centralia and Quanah sequences and only light metamorphism has taken place within those original sequences, and this has been shown as a lack of high temperature activity around the region during the later stages of volcanism (Pratt et al., 1992). As tectonic activity slowed, the entire region was exposed and underwent extensive erosion, creating a large nonconformity before being inundated by seawater in the upper Cambrian to begin the deposition of the Lamotte Sandstone (Gerdemann and Myers, 1972).

2.2 Paleozoic Deposition and Mineralization

Overlying the igneous terrane is a thin skin of mostly Cambrian and Ordovician near-shore and carbonate-shelf deposits which formed from alternating transgressive-regressive sedimentary cycles, and ranging in thickness from 0 to over 1500 meters

(Gerdemann and Myers, 1972). Regional volcanic activity did not completely end in the Precambrian, but it did signal the start of a tapering-off of the tectonism in the region (Braile et al., 1986). Proterozoic mountain building and uplift of the Precambrian terrane created the source material for the extensive deposition that formed the basal sandstone. Starting in the late Cambrian the region was covered by an inland sea with the high points of the eroded Precambrian volcanics forming islands, and these islands created material for filling in the valleys through fracturing, weathering, and erosional processes (Gerdemann and Myers, 1972). The post-volcanic Cambrian period was the beginning of the deposition of the Lamotte Sandstone and Bonneterre Formation in a shallow sloping shelf in the tropical inland sea (Erickson et al., 1981). This latter period deposition that tops the eroded surface of the crystalline basement as a nonconformity does not relate directly to the undiscovered mineralized deposits of economic interest located in the facies below, but is contextually important for understanding what lies below those sedimentary sequences. Within the study area the bedrock is composed mostly of upper Cambrian and lower Ordovician sedimentary units with some Precambrian igneous outcrops exposed at the center of the Ozark Dome. On the eastern side of the St. Francois Mountains are scattered outcrops of younger Mississippian and Pennsylvanian sediments that have been preserved because of faulting associated with the Mississippi Embayment (Braile et al., 1986; Hildenbrand et al., 1985).

The sedimentary lithologies have been of significant interest to researchers as they are the host to the world-class lead deposits in the Old Lead Belt and the New Lead Belt, known as the Viburnum Trend, and are referred to as Mississippi-valley-type lead-zinc deposits (Leach and Rowan, 1986; Garven et al., 1999). These deposits were thought

to have formed during the late Paleozoic Ouachita orogeny where hydrothermal brines were formed within the foreland Arkoma Basin and were transported northward and deposited mainly within the Bonneterre Formation (Leach and Rowan, 1986; Garven et al., 1999). The lead and zinc deposits are for the most part found in the Bonneterre Formation and also contain other economic minerals, such as barite, silver, and copper as associated minerals (Gerdemann and Myers, 1972; Erickson et al., 1981). With a decrease in industrial lead use over time, other economic mineral ores have become more important, and most of those ores are found in or near the crystalline igneous basement. Additionally, more recent investigations into carbon, cobalt, and nickel hydrothermal deposits between the basal Lamotte Sandstone and the Bonneterre Formation garnering interest, and while not as large as the other Lead Belt deposits, they still contain significant quantities that may prove economically viable in the future (Horrall, et al., 1993).

2.3 Economic Mineral Development in the Precambrian Basement

One of the focuses of this thesis is investigating and isolating undeveloped or undiscovered areas with probable economic mineral ores as part of a USGS project on economic ore deposits of southeast Missouri (USGS, 2013). Missouri has a strong history of mining beyond the sedimentary-derived ores, as iron-ore deposits are second only to the lead-zinc deposits in terms of economic value in southeast Missouri (Unklesbay and Vineyard, 1992). The first iron furnace in the region was built in 1815, and initially iron ores were mined from large surface exposures of hematite hosted in the igneous basement rocks at Iron Mountain and Pilot Knob. As those deposits were depleted they were

replaced with smaller surface deposits and the first underground iron mine at Pea Ridge (Unklesbay and Vineyard, 1992).

The Pea Ridge Mine in Washington County, 60 miles southwest of St. Louis, provides a detailed source of mineral and lithological information for the basement that can be used to extrapolate to other similar lithologies in the region. Pea Ridge is a large hydrothermal magnetite deposit that was found as a magnetic anomaly in 1950, and then developed in the late 1950s as a deep shaft mine (Gow et al., 1994; Long et al., 2010). Of particular interest within the Pea Ridge Mine are four large breccia pipes containing very high grade REE ores with an average yield of 12%. These deposits were never developed and the mine went bankrupt in 2001 (Grauch et al., 2010; Long et al., 2010). The REE yields are high, but the deposits are also rich in the much rarer heavy range of REEs, possibly making Pea Ridge a very important United States deposit as China continues to restrict exports of REEs for use in their own domestic manufacturing (Grauch et al., 2010; Castor and Hendrik, 2006).

The mineral emplacement of the REEs and magnetite body in Pea Ridge is well known and is contemporaneous with the regional volcanism. Using U-Pb dating gives a date range from 1.473±0.003 Ga to 1.466±0.004 Ga (Menuge et al., 2002). This agrees with Gleason et al. (2000), who used neodymium dating (ε_{ND}). Dating with an initial date of 1.465 Ga, the ore values of magnetite is +3.3, hematite +3.6, early REE apatite +3.9, and the REE bearing xenotime +5.1 (Gleason et al., 2000). the numbers represent a younger formation chronologically from the initial date with smaller number being closer to the initial date. The age dates for the development of the known ore deposits coinciding with the earliest magmatic activity strengthens the possibility of other similar

activity within the Precambrian St. Francois region. Since the entire region has had multiple periods of doming, caldera collapse, and intrusions, whatever magmatic activity developed the Pea Ridge deposits would have also been active throughout the region.

The mapped lithology around Pea Ridge is not unique, though it does seem to have more of the syenite intrusions than the other plutonic bodies making up the Precambrian St. Francois Mountains (Fig. 5) (Kisvarsanyi, 1981). This lends credence to the possibility that Pea Ridge is not a unique deposit, and that the conditions for the development of other REE-bearing ores in other places is quite likely. Adding to this evidence are geophysical readings throughout the region which contain similar trends in the data to those found around Pea Ridge. In this research gravity and magnetic data combined with the known lithology and geologic history and are used to create a geophysical signature that can be developed into non-unique models along profiles of interest.

CHAPTER 3

3.1 Field Data Collection

During the summer of 2013 and 2014 over 700 new gravity stations were collected around the northwest St. Francois Mountains and the Pea Ridge Mine region using a Lacoste and Romberg model G gravity meter (accurate to ±0.02 mGal) and Topcon GB-1000 DGPS (elevation accuracy ±0.05 meters) (Fig. 6). The stations were collected at an average spacing of one-half mile and recorded along public roads, as most of the area is in the heavily forested Mark Twain National Forest or private land with little or no access. Cuba and Farmington, Missouri were used as the absolute base stations, and three other local base stations were established to be used at the start and end of each day to determine the instrumental drift of the gravity meter. Twenty to twenty-five stations were recorded each day. In addition, differential GPS stations were recorded at each station to determine the station's latitude, longitude, and ellipsoidal elevation.

3.2 Data Processing

The GPS data were corrected to a base station at Farmington, Missouri and geoidal elevation corrections were applied using US Geoid09 model. The GPS data were merged with the gravity station readings and reduced using the 1967 International Gravity formula (Morelli, 1976). The Bouguer and free-air corrections were applied using sea level as the datum and 2.67 g/cm^3 as the density reduction. Terrain corrections were computed using the SRTM (Shuttle Radar Tomography Mission) 90 m DEM data

and the Oasis-Montaj terrain correction program to distances out to 167 km. The resulting Bouguer gravity anomaly data was gridded with 10 second spacing (approximately 200 meters) using a minimum curvature technique and contoured at 5 mGal intervals.

The magnetic data were acquired from the USGS data archive (Bankey et al., 2002) which compiled the datasets from over 1000 historical magnetic surveys into one searchable archive. For processing details of the data see Bankey et al., (2002). The total-field magnetic data were then gridded at a 10 second spacing (approximately 200 meters) and were reduced to pole (removing the dipolar effect of the Earth's magnetic field) and contoured at 250 gamma intervals (Figs. 7 and 8).

Once the data have been processed, the next step is to construct anomaly maps and to interpret these maps. Modern geophysical representations start with a plan-view map detailing high and low amplitude anomalies within a selected range using color scales. In the past, shaded relief or contour maps were the most common form of representing the data to give an overall view of the study area (Cordell, 1979; Guinness et al., 1983). Advances in digital image processing and computing have allowed the maps to become more detailed along with the subtlety of shading and improvements of color being added to maps (Cordell and Knepper, 1987, Shah et al., 2013). Once the plan-view is created, cross-sectional profiles can be extracted from the known data traverses and used to create subsurface models; combining multiples of these profiles can be used to create models in 2.5- and 3-D (Mickus and Keller, 1992; Hildenbrand et al., 1996). With the increased resolution of GPS data, the physical locations of survey stations identified on the maps have become more accurate and have made it much easier to combine multiple map layers (Shah et al., 2013; Shoberg and Stoddard, 2013).

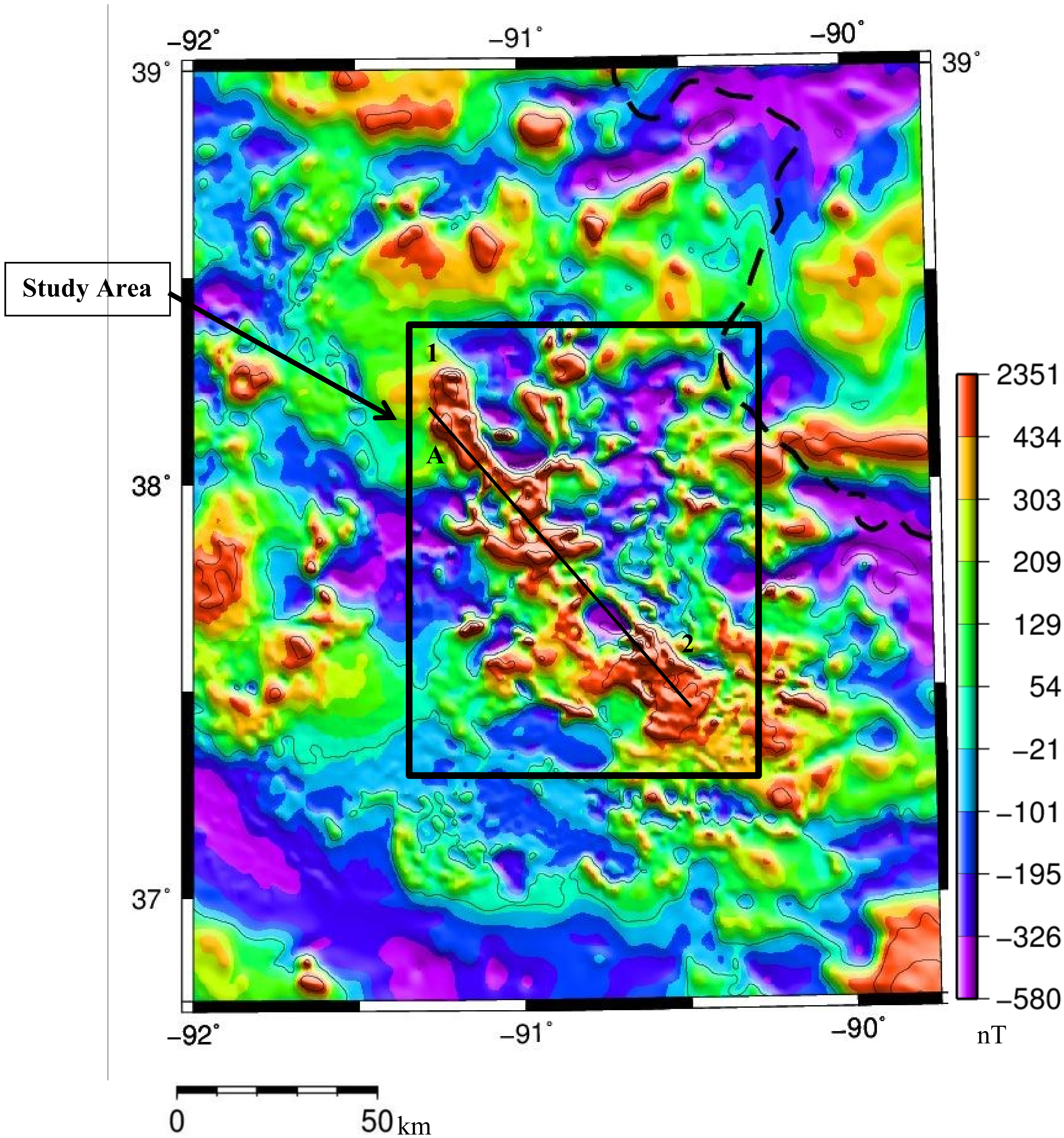

Figure 7. Total-field magnetic intensity map of the northwest St. Francois region. The black border represents the extent of the magnetic and Bouguer gravity anomaly maps. Line A shows the general trend discussed in the text. Areas 1 and 2 are differences between the total-field and RTP maps discussed in the text.

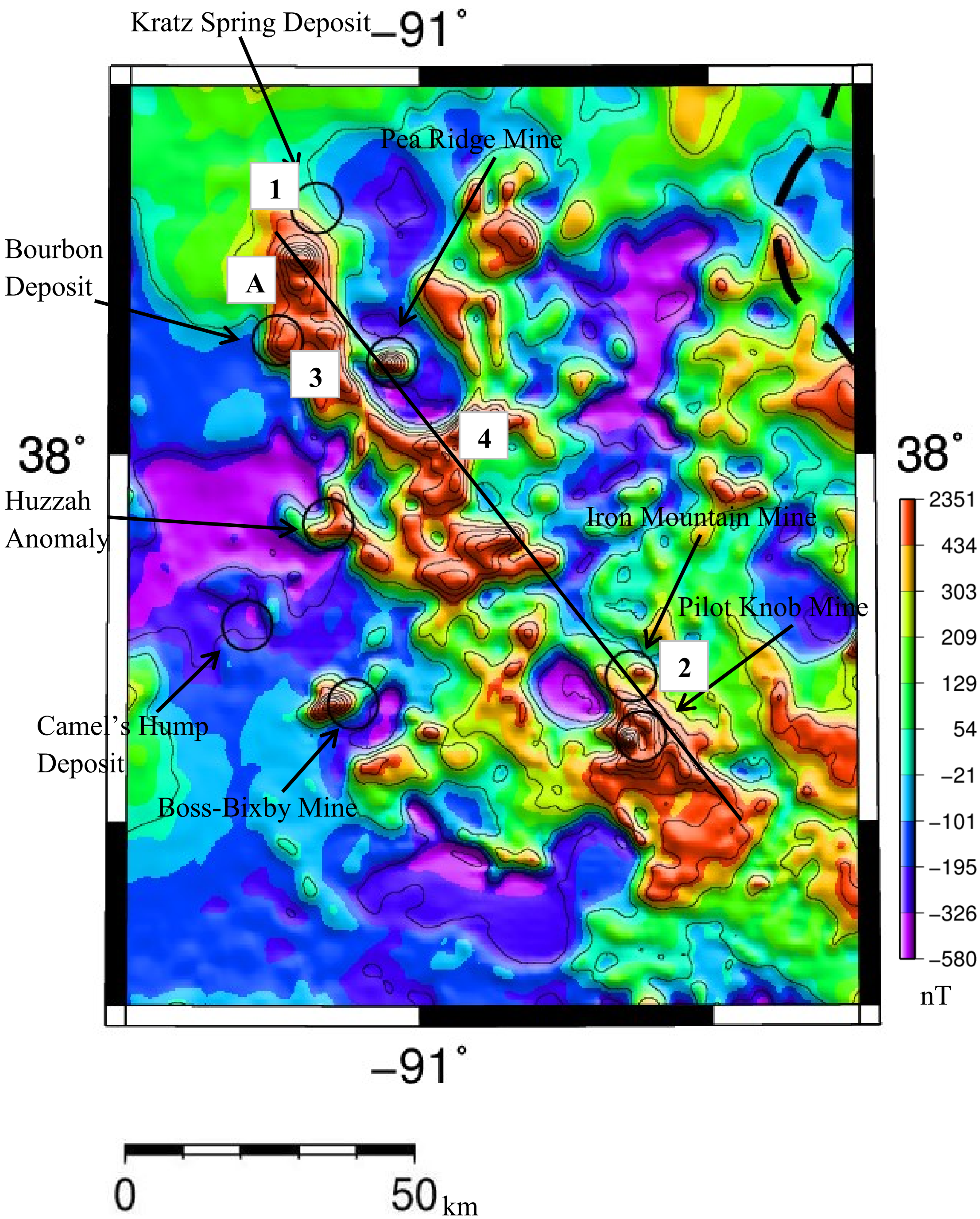

Figure 8. Reduced-to-pole magnetic anomaly map of the study area. Line A shows the general trend discussed in the text. Areas 1 and 2 are differences between the total-field and RTP maps discussed in the text. Areas 3 and 4 represent igneous ring intrusions mapped in Figure 5.

Combining many different representations in a single map can give extremely detailed views into the data and area of research. Shah et al. (2013) combined station locations and contour lines onto a color field map and then laid the combined images onto a shaded-relief topographic map. Such detailed representations allow a variety of separate pieces of information to be shown together for a much deeper understanding of the displayed area and allow a more effective interpretation by the reader.

3.3 Magnetics

Magnetic geophysical investigations are similar to gravity studies as they are both potential fields, so the same interpretation methods can be applied to both. Magnetic field strength relies on the dipole nature of a magnetic field and the application of Coulomb's First Law to determine magnetic force. In geology, minerals have a wide range of magnetic susceptibilities which is a physical property of the mineral measured in the magnetic method. Most minerals with high susceptibilities are Fe-Ti oxides with the majority of minerals (e.g., quartz and feldspars) having low susceptibilities (Lowe, 1999). Using a magnetometer, the total magnetic field can be measured which is the combination of the Earth's internal field and the induced field caused by magnetic minerals (Burger et al., 2006). The interpretations of the magnetic data are also similar to that of gravity data, which will be discussed in Section 3.4.

One important aspect of magnetic data interpretation is to constrain the interpretation of other geophysical methods. Making correlations between the various gravity and magnetic maps along with outside constraints is a key to interpretation. There are basic generalizations that can be made between the results of the various maps, but most of the interpretation falls upon the background and experience of the researcher. In

some cases interpretations can be checked against drill-hole samples to see the actual lithological makeups in the subsurface. Unfortunately, most drill holes in the study area do not go much deeper than one kilometer, and generally stop soon after reaching the crystalline basement material as the rock is extremely difficult to cut.

3.3.1 Magnetic Intensity Maps. The magnetic anomaly maps of the study area in the St. Francois region reflect changes in magnetic susceptibility in the Precambrian basement as the overlying sedimentary layers, Paleozoic sandstones and carbonates have little to no magnetically susceptible minerals. The Earth's magnetic field is dipolar which creates a pairing of an asymmetric magnetic high and low over a magnetic body with the effect amplified further away from the Earth's Polar Regions (Lowe, 1999). Reducing the magnetic data to the pole places the magnetic maxima directly above the source of the causative body (Mickus, 2007). Figure 8 shows the reduced to pole magnetic anomaly map of the study area. The magnetic highs throughout the region are largely caused by large iron ore deposits, specifically magnetite at Pea Ridge, and other mafic bodies in the Precambrian basement (Kisvarsanyi, 2007). The effect of reducing to pole can be seen in areas 1 and 2 when comparing Figure 7 to Figure 8. Notice that the small scale lows are minimized or completely removed, and some magnetic highs increase in magnitude.

Figures 7 and 8 show a general northwest-to-southeast trend to the magnetic maxima with a particular high at the Pea Ridge Mine site (Fig. 8), which would be consistent with the large subsurface magnetite body. Other notable magnetic maxima are located at known large iron ore deposits: Kratz Spring, Bourbon, Boss Bixby, Iron Mountain, and Pilot Knob. The reduced-to-pole (RTP) magnetic anomaly map is an unfiltered intensity map, and comparing it to Kisvarsanyi's (1981) basement lithology

map (Fig. 5) the high anomalies generally follow the trend of the igneous ring intrusions (anomalies 3 and 4 in Fig. 8). The intrusions vary widely in mineral and chemical composition, and include trachyte, syenites, trachyandesites, and trachybasalts; additionally their extent is not well known, and it is believed that much of their bulk is yet to be discovered (Kisvarsanyi, 1981). Even with this diverse group of rocks the magnetic attraction in hand samples has been found to be moderate to high, which could be the reason the magnetic maps show a spatially larger area of lower intensity compared to the smaller, but high-intensity-signal iron ore bodies (Kisvarsanyi, 1981).

3.3.2 Residual Magnetic Anomaly Maps. Gravity and magnetic anomaly maps may have long wavelength trends which are called regional anomalies, which are due to the larger scale density and/or magnetic susceptibility variations (e.g., crust/mantle boundary). These trends can be removed to create residual anomalies which are usually anomalies of shorter wavelength and of interest to the interpreter (Burger et al., 2006). There are many methods to remove regional anomalies (polynomial trend surface, upward continuation, and wavelength filtering). Band-pass filtering was used for these maps, which allows the passage of defined wavelengths by removing high and/or low wavelengths from the map. In the filtering process long wavelengths remove regional anomalies, and short wavelengths remove shallow signal sources and/or noise (Burger et al., 2006). This procedure accentuates the actual source of the anomalies, and also removes any effects of small shallow bodies. Applying wavelength filters to the data is partially trial-and-error, making many maps and then choosing which filter best represents the data and possible true sources of the anomalies. For the magnetic anomaly maps of the northwest St. Francois terrane over a dozen different maps were created with

various combinations removing long wavelengths from >250 km down to >75 km, and conversely removing shorter wavelengths <25 km down to <5 km.

Figure 9 is a magnetic band-pass filtered map where wavelengths between 10 and 100 km were passed. This filter removed the smallest and largest anomalies, and thus accentuated the general strong anomalies of the syenite intrusives. The filtering also removed the high intensity magnetic anomaly at Pea Ridge, but still kept the northwest-to-southeast trend seen in the previous non-filtered map.

Another method of enhancing potential field data is applying some type of derivative to the data. There are several kinds of derivatives: horizontal, vertical, analytic signal, and tilt-derivatives, each highlighting a particular aspect of the source body (Lowe, 1999). Horizontal derivatives emphasize the edges of the body, whereas vertical derivatives highlight the width of the body, and the tilt-derivative technique combines the vertical and horizontal derivative to accentuate the middle of the magnetic body, thus effectively equalizing the anomalies and minimizing local trends (Salem et al., 2008). Derivative methods are sensitive to noise and small-scale anomalies, so the magnetic data were upward continued to deemphasize any small-scale anomalies. Figure 10 was upward continued by 2 km and then the tilt-derivative method applied, which kept the high intensity anomalies but decreased the remaining magnetic low anomalies in the area, minimizing the general northwest-to-southeast trend seen in the previous images.

3.4 Gravity

Complete Bouguer gravity anomaly values when contoured and/or modeled can give some insight into the lithology and geometry of the rocks in the subsurface. All

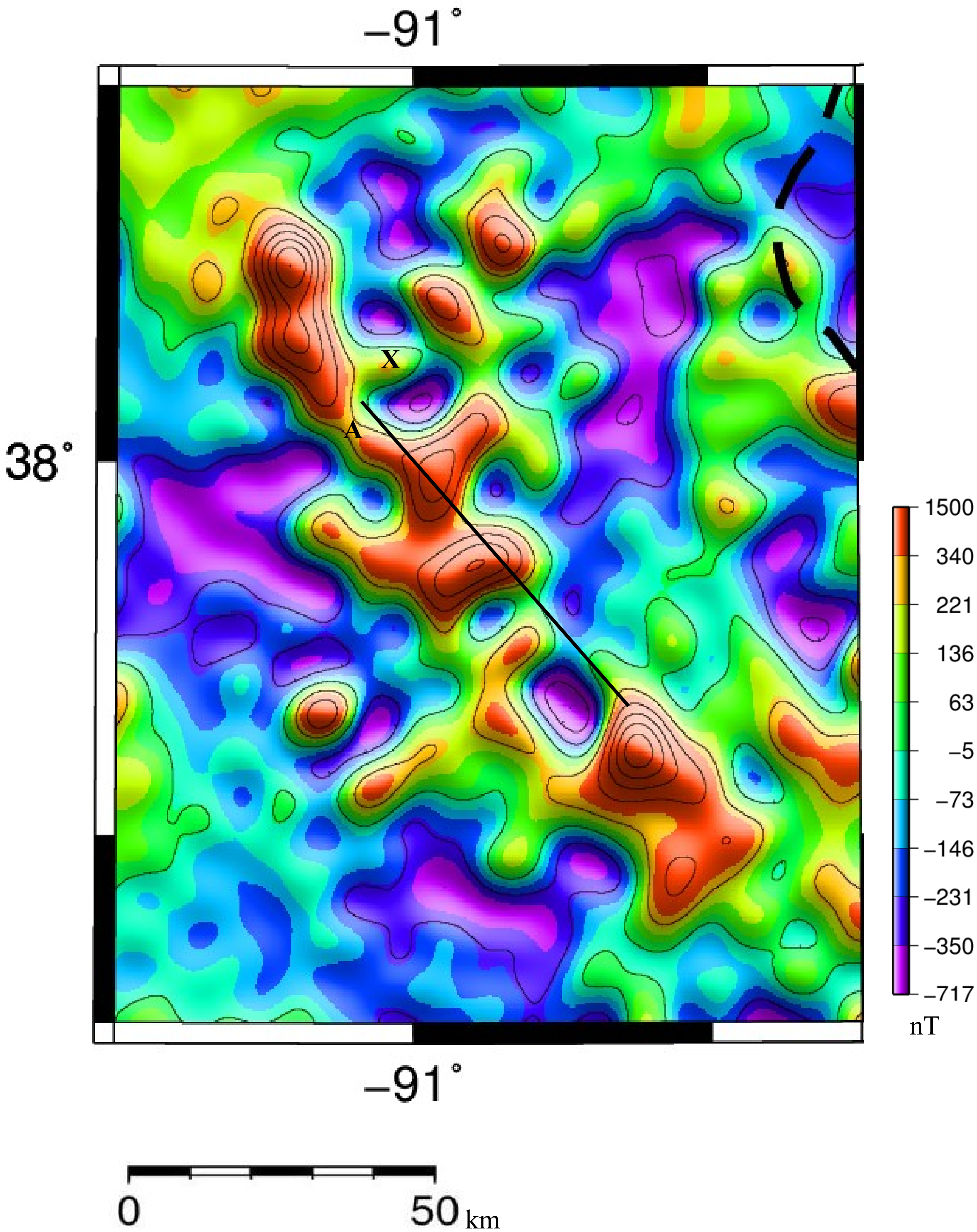

Figure 9. Residual magnetic anomaly map of the study area. The map was band-pass filtered with wavelengths longer than 100 km and shorter than 10 km being passed. Line A shows the general trend discussed in the text. The X represents the location of the Pea Ridge Mine.

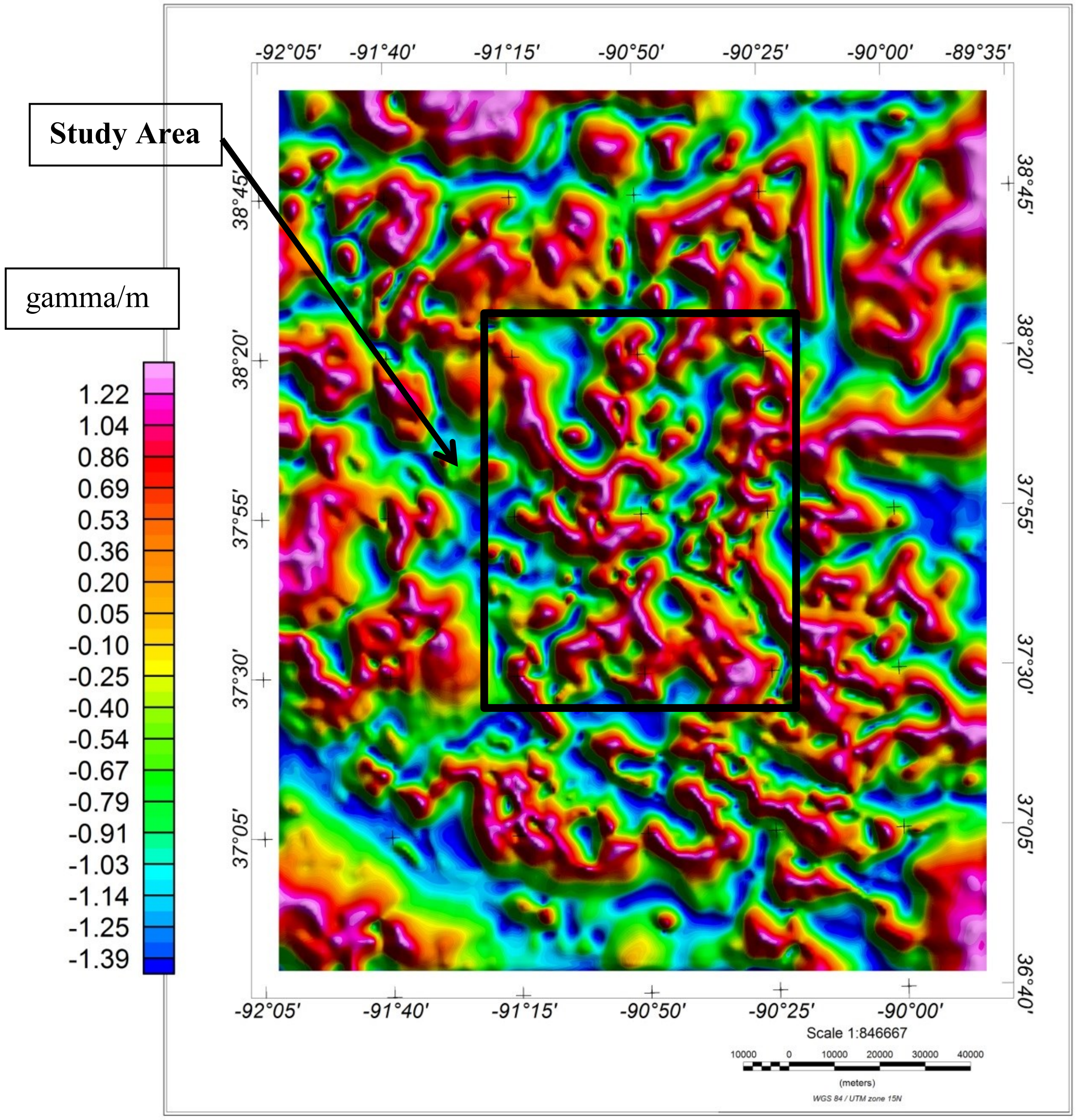

Figure 10. Tilt-derivative magnetic map of the northwest St. Francois region. The black border represents the extent of the magnetic and Bouguer gravity anomaly maps.

interpretations are theoretical and non-unique as multiple density and structural geometries can produce the same gravity reading at the surface (Thomas, 1999). Using permutations of different gridding and contouring of the data can help represent anomalies and structures differently, emphasizing a particular aspect or trend in the data, but there are trade-offs and finding the balance is key to the interpretation. This is also true for the 2- and 3-D models where multiple parameters must be chosen to give the best representation of the data. An object of the same size and density has different effects on the gravity profile depending on its depth, and an object of smaller size can appear to be a much larger body if it is located closer to the surface (Burger et al., 2006). This is why it is a good idea to develop models with some idea of what the subsurface looks like using surface geology, drill cores and other geophysical methods (e.g., seismic, magnetotellurics) as constraints. This research uses a TIN (triangular irregular network), created from drill hole logs that penetrated the basement rocks, and compared this map to Kisvarsanyi's (1979) basement depth map to approximate the thickness of the sedimentary overburden. This Paleozoic thickness map was used to constrain the 2.5-D modeling and to construct a gravity anomaly map where the gravitational effect of the Paleozoic sediments was removed from the complete Bouguer gravity anomaly map.

3.4.1 Bouguer Gravity Anomaly Maps. In Figure 6 the locations of all the gravity stations in the study area are shown and large voids can still be easily seen in the station coverage. One of the goals of this research was to fill in some of the voids to give better local and regional gravity resolution, and ideally to isolate the extent of some of the promising anomalies located with earlier data that were based on few gravity points. The station spacing for this research was one half of a mile. Using a Lacoste and Romberg

Model-G gravity meter and Topcon GB-1000 DGPS each station was recorded using both instruments concurrently.

Looking at the differences between the previous simple Bouguer anomaly map (Fig. 11) and the new complete Bouguer anomaly map (Fig. 12) with the new gravity stations, there are some notable changes that illustrate how more data can improve maps. At anomaly 1 there is greater refinement along the gravity contour on both sides indicating a much higher resolution in the data. Anomaly 4 shows two new and interesting anomalies, a gravitational maximum and minimum. The new gravity low to the north of anomaly 2 may have a number of different causes including an edge effect of the Missouri gravity low, large karst environment, or lower density body in the subsurface. To the south of anomaly 2, there is a noticeable gravity high near the unincorporated town of Huzzah, Missouri. In Figure 11 the gravity anomaly around Huzzah was delineated by one gravity station. The new data adds over 30 new stations around Huzzah (Fig. 6). To the east of Huzzah is a completely new unexplained gravity low. Anomaly 3 is a new gravity high that was delineated by the new gravity data that may be caused by a previously unknown orebody, a part of the basement closer to the surface, or lack of lower density material in the basement.

3.4.2 Filtered Bouguer Gravity Anomaly Maps. Gravity maps can be analyzed in the same manner as the above magnetic maps, so the same process was used with complete Bouguer gravity anomaly data as was done with the magnetic data. Figure 13 is a band-pass filtered map that passed wavelengths between 10 and 100 km. This map shows a smoothed regional high trend northwest-to-southeast similar to the trend seen in the magnetic maps above. The trend may be caused by tectonic uplift during the Ouachita

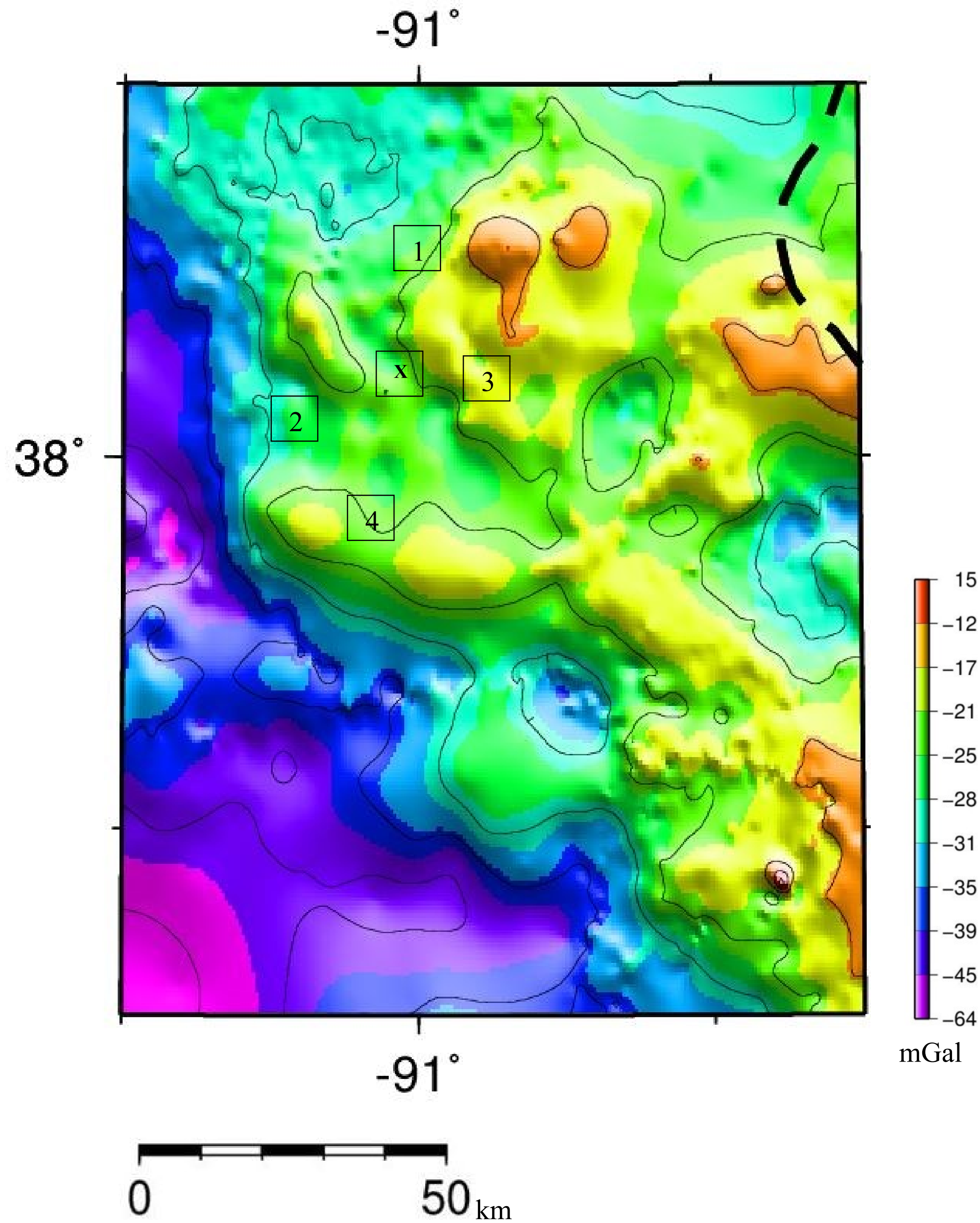

Figure 11. Bouguer gravity anomaly map using the preexisting gravity data. The X represents the location of the Pea Ridge Mine, and 1, 2, 3, and 4 are noticeable changes within the data collection area and are for comparison to Figure 12 and are discussed in the text. Contour interval is 10 mGal.

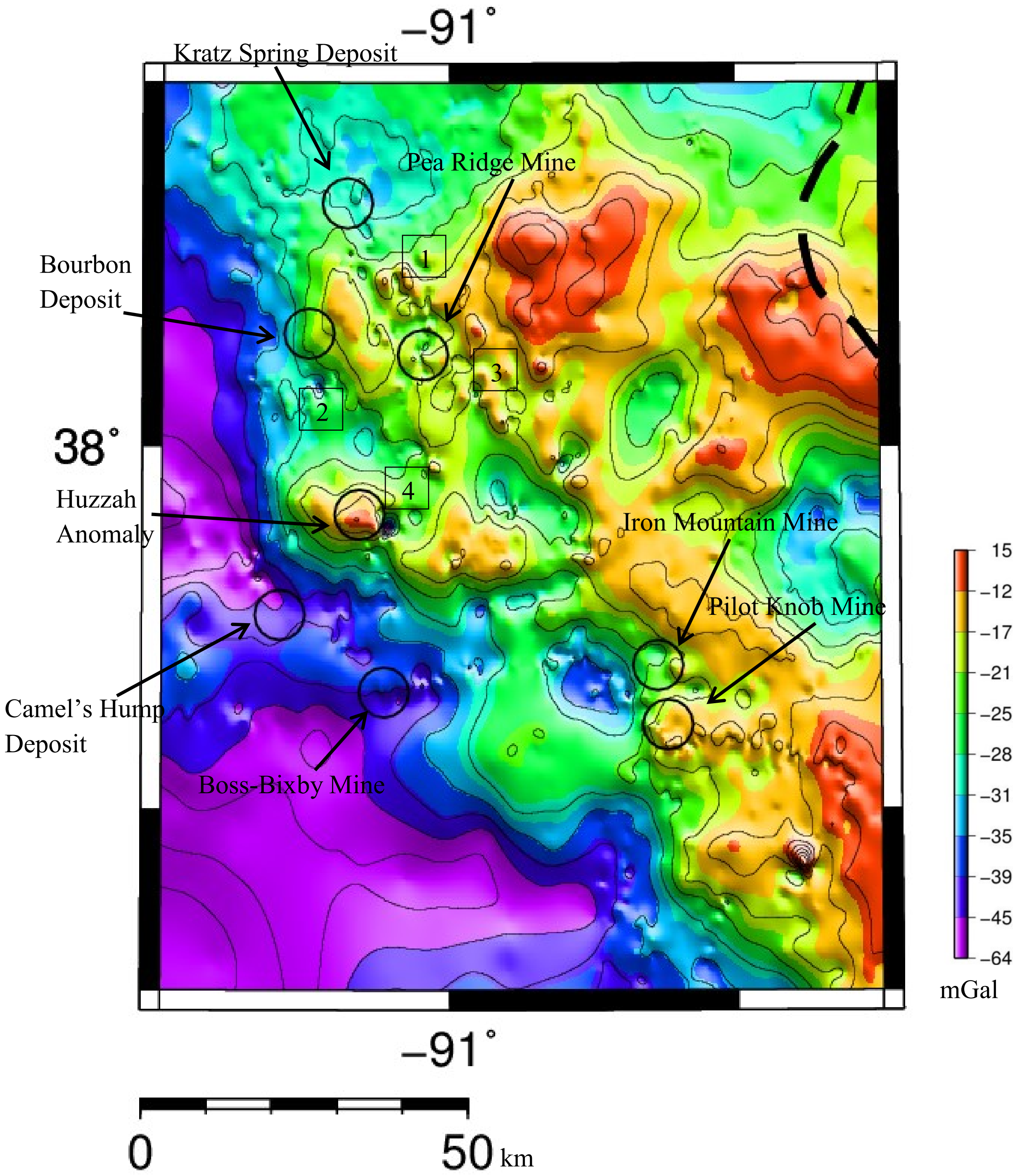

Figure 12. Bouguer gravity anomaly map including the newest data collected in 2013 and 2014. A, B, C, and D are noticeable changes within the data collection area and are for comparison to Figure 11 and are discussed in the text. Contour interval is 5 mGal.

orogeny or region-wide denser crustal bodies. Multiple other filtered maps were created, and all showed the large overall high trend. Figure 14 was band-pass filtered between 50 km and 10 km to remove even more of the high intensity anomalies than the version of Figure 13. Even so, Figure 14 removes most of the overall high trend, but the northwest-to-southeast trend can still be seen.

To delineate trends in the data, a tilt derivative was applied in a similar manner as was done with the magnetic data. The tilt-derivative map incorporates both the vertical and horizontal derivative constraining edge and magnitude of the signal which highlights the middle of the anomaly source. Again, the northwest-to-southeast trend is clearly seen, imitating what has been seen in the magnetic maps (Fig. 8) and other filtered gravity maps (Figs. 15).

3.4.3 Depth to Basement Gravity Map. In the early 1960s Hammer (1963) developed a technique of deep gravity stripping which involves removing the gravitational effect of the sediments overlying basement rocks in order to delineate structures related to the basement rocks alone. Since the study area is mostly covered by Paleozoic sedimentary layers ranging from 0 to over 1500 meters thick, and the surface of the basement is a large nonconformity. Applying Hammer's technique might prove beneficial to highlighting the gravitational anomalies due to the Precambrian lithologies. The thickness of the Paleozoic sediments was determined using depth data from drill core logs that recorded the depth to the basement (Fig. 16). These depth data were gridded using the same parameters as was done for the Bouguer gravity anomaly maps (Figs. 11 and 12). Then, the gridded depth data were entered into a 3-D gravity forward modeling program to determine the gravitational attraction of the sediments. The 3-D program uses

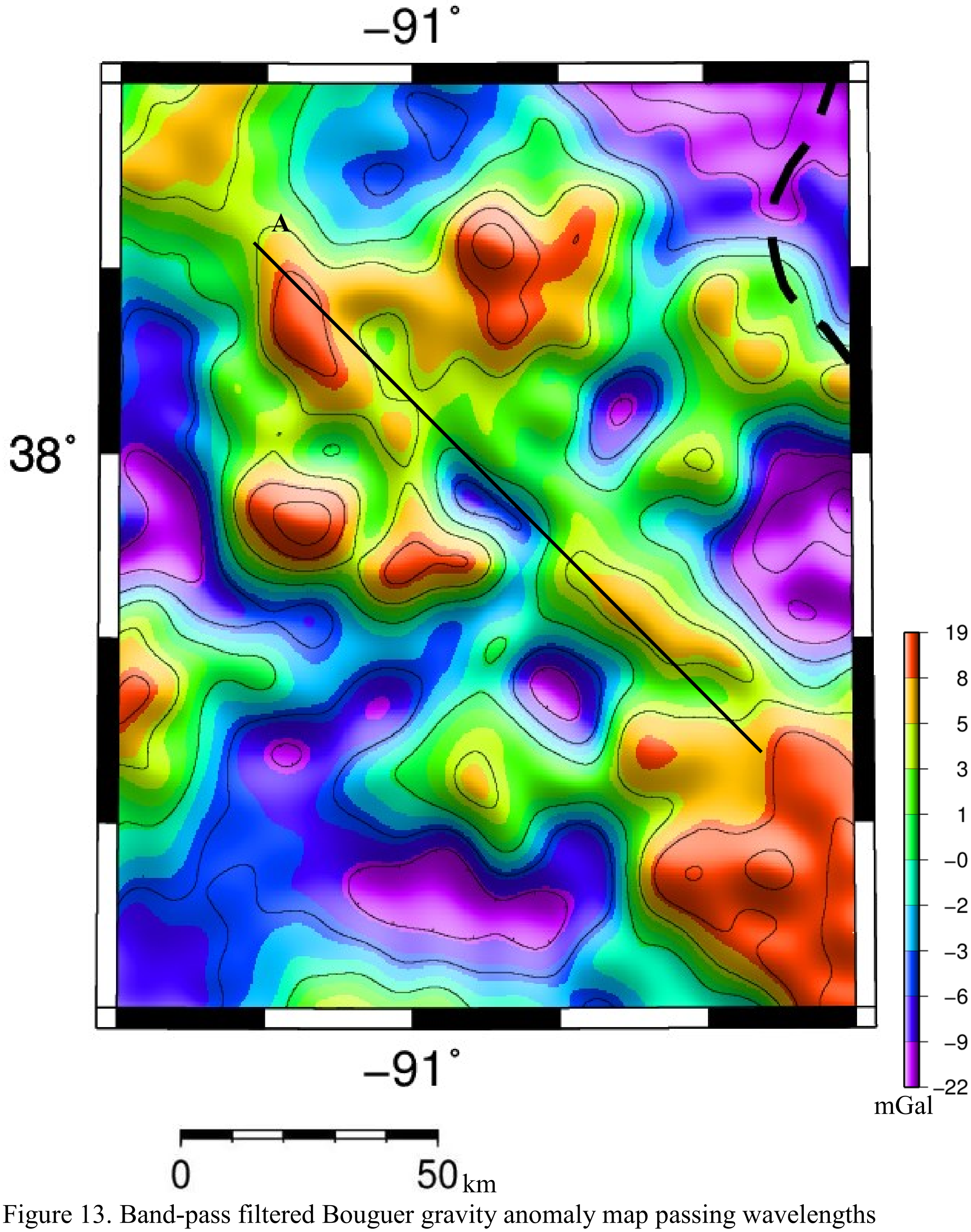

Figure 13. Band-pass filtered Bouguer gravity anomaly map passing wavelengths between 10 and 100 km. The contour interval is 10 mGal. Line A shows the general trend discussed in the text.

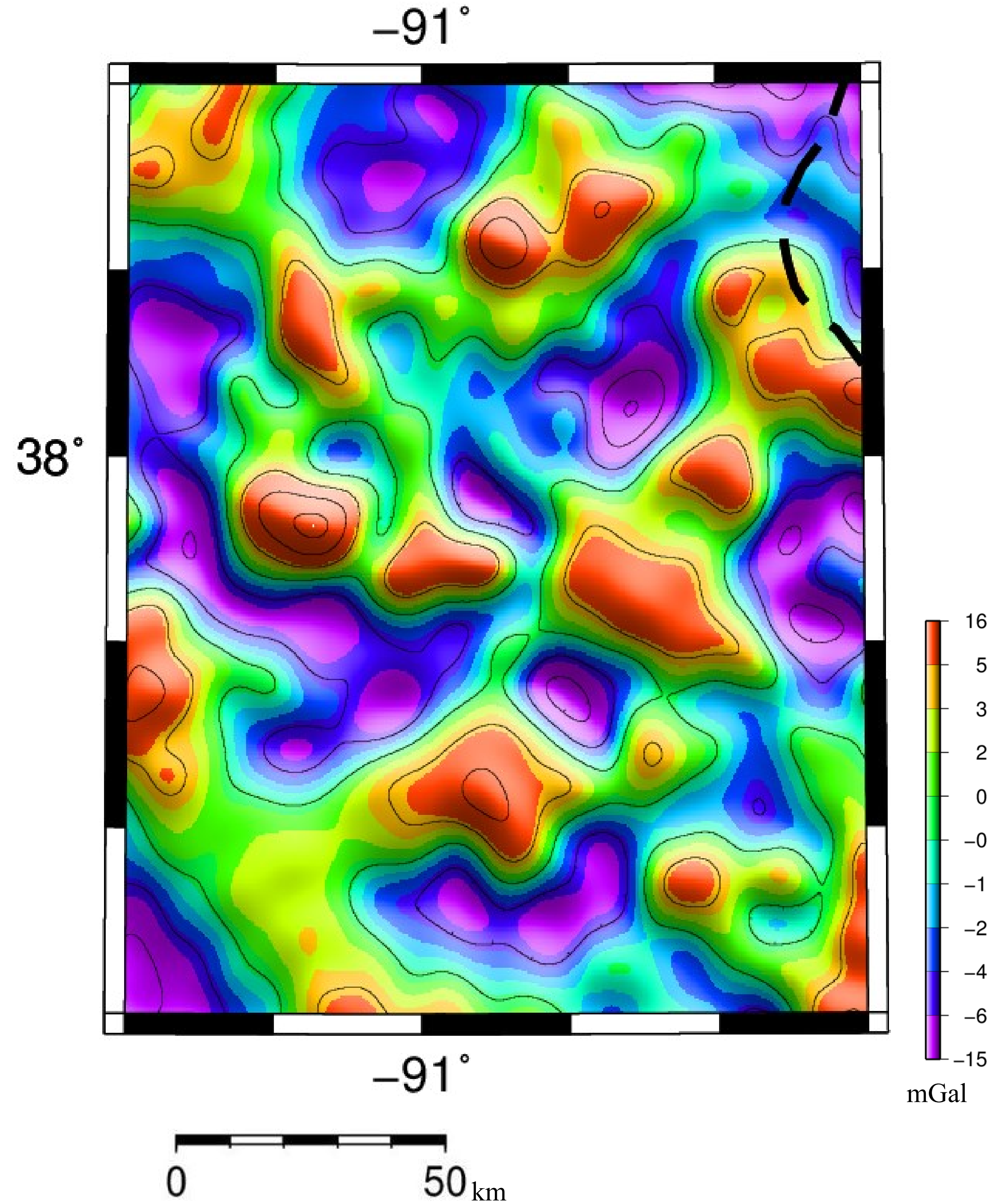

Figure 14. Band-pass filtered Bouguer gravity anomaly map passing wavelengths between 10 and 50 km. The contour interval is 10 mGal.

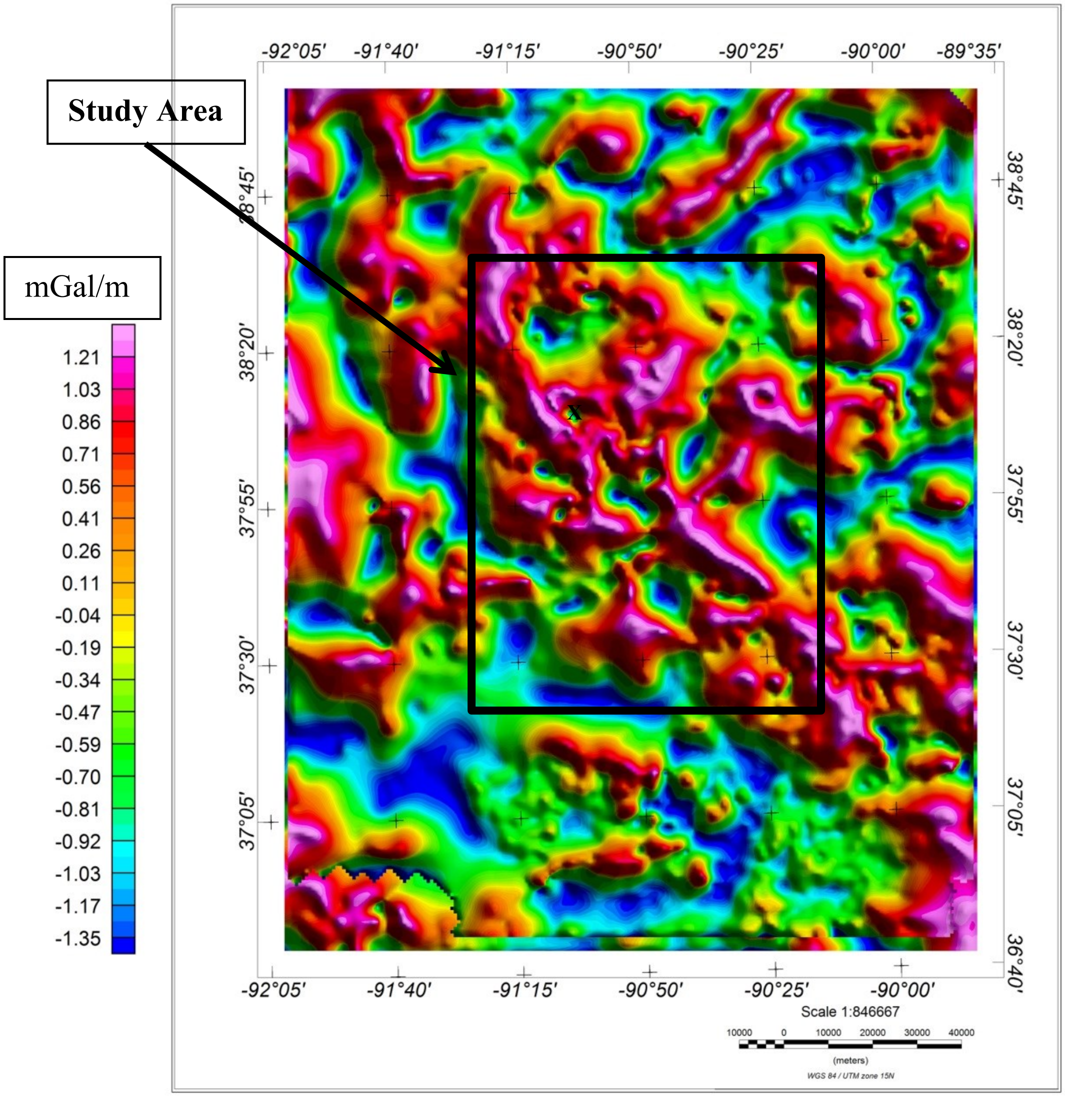

Figure 15. Tilt-derivative of the complete Bouguer gravity data applied to the larger region. The black border represents the extent of the magnetic and Bouguer gravity anomaly maps. The Pea Ridge Mine site is marked by an X.

an ensemble of right regular prisms with each prism having its own density. The top of each prism represents the Earth's surface in meters above mean sea level. To simplify the calculations, each prism was given the same density contrast (density difference between the sediments and basement lithology). Density contrasts from -0.1, -0.2, -0.3, and -0.4 g/cm^3 were tested and the resultant gravity field for each density contrast was subtracted from the complete Bouguer gravity anomaly grid (Fig. 12). Figure 17 shows the deep-seated gravity anomaly map based on the largest contrast -0.4 g/cm^3. All the deep-seated gravity anomaly maps showed the same anomalies and the largest contrast, -0.4 g/cm^3, was chosen to best represent the average density contrast based on lithology types. Although Figure 17 shows all the same trends seen in the complete Bouguer anomaly maps (Fig. 12) there is an increase in the extent of the high gravity anomalies. The outcome of this process is not as substantial as hoped, but it does show that there is some effect on the basement gravity based on the thickness of the sediments as Hammer (1963) showed. For much deeper basements (5+ km) this technique should offer a greater understanding of the gravity in the basement.

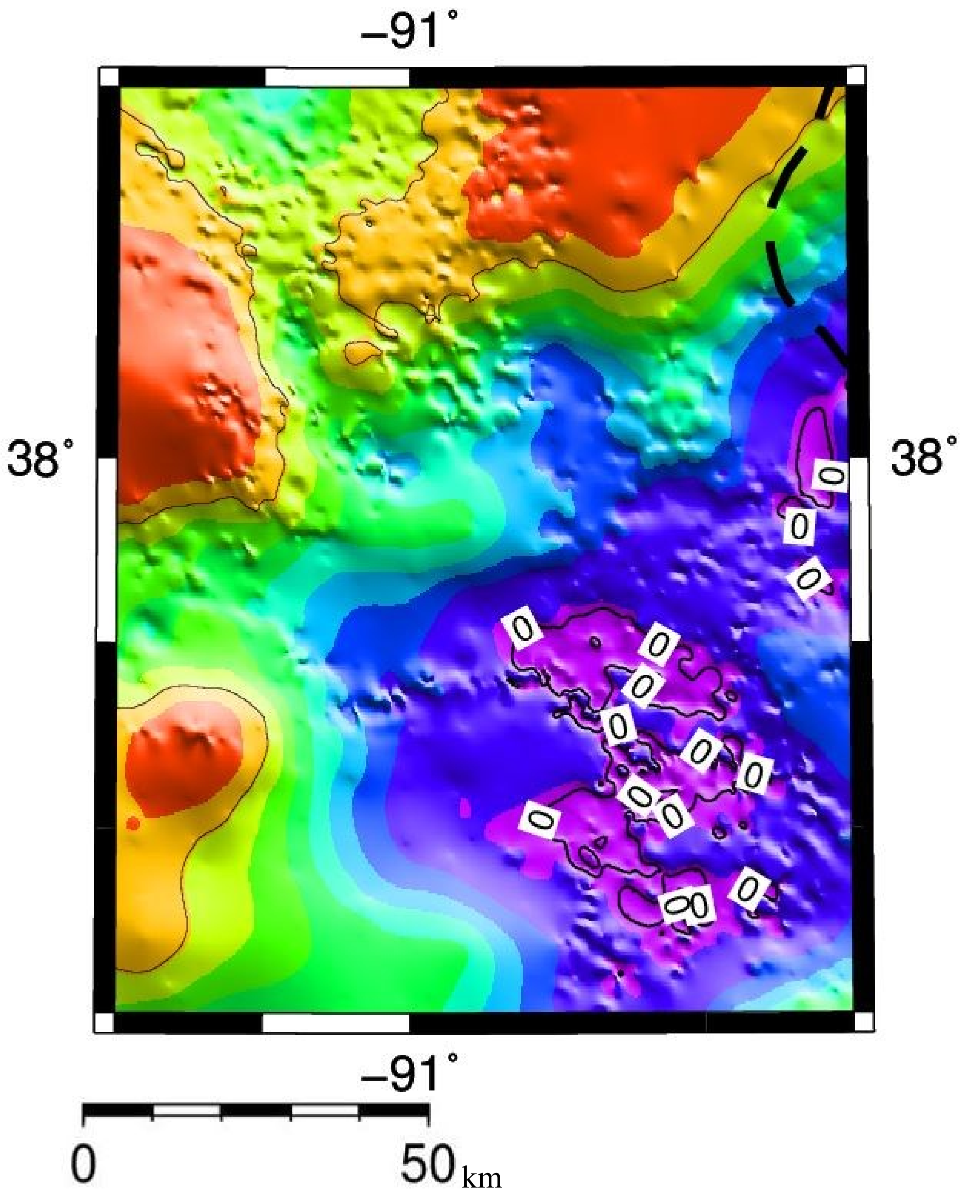

Figure 16. Thickness of the Paleozoic sediments as determined from drill core data (DNR). Surface exposures of the St. Francois Mountains are light purple and represented by the 0 contour line. The outcrops can also be seen in Figure 6. The deepest parts of the basement are bright orange and are over 1500 meters deep.

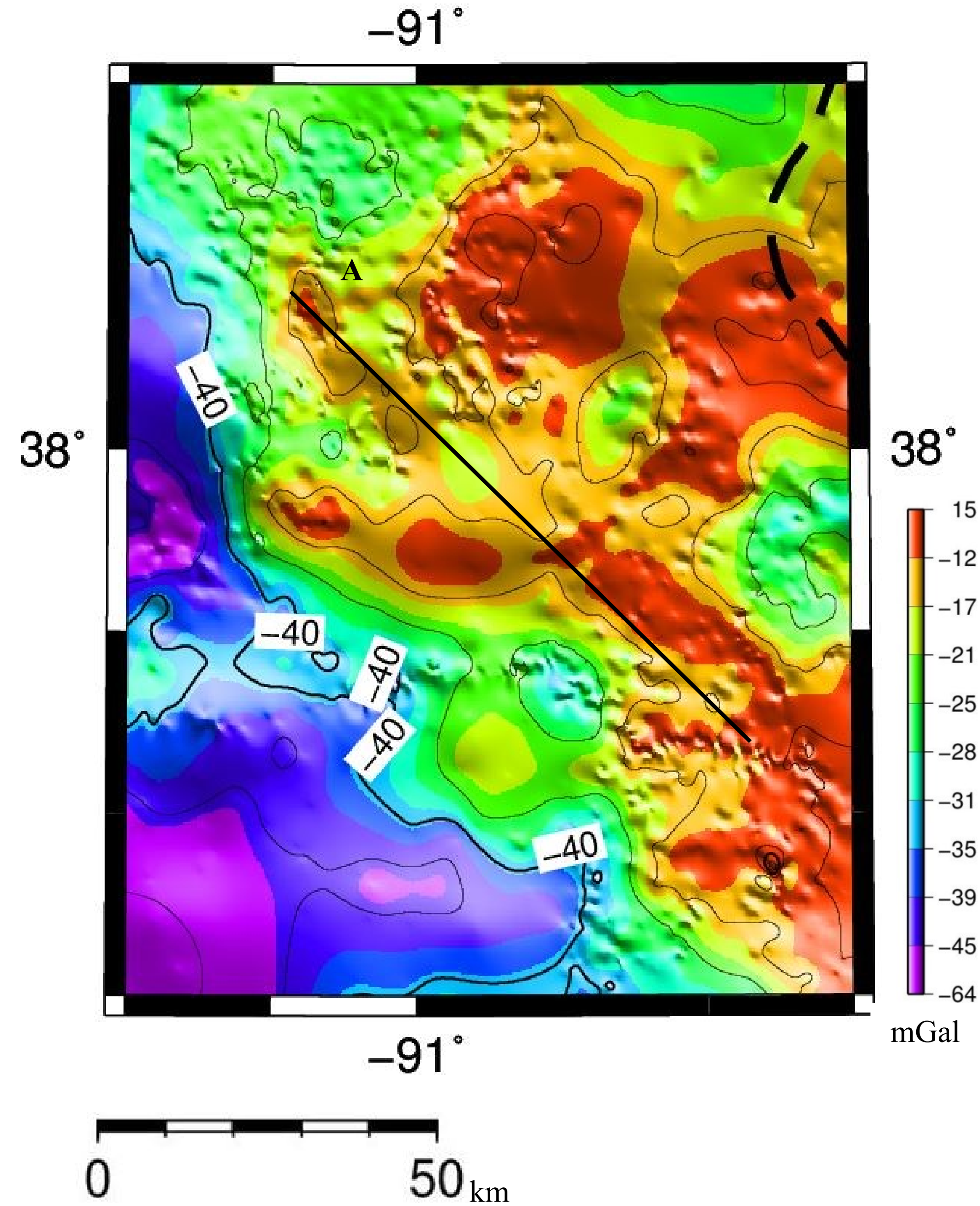

Figure 17. Deep gravity anomaly map reflecting gravity anomalies due to basement features where the effects of the sediments were removed using Hammer’s (1963) stripping method. Line A shows the general trend discussed in the text. Contour interval is 10 mGal.

3.4.4 Two and One-Half Dimensional Models. Using a regional map with all the gravity stations listed as a guide (Fig. 18) three models were developed using a 2.5-D forward modeling program where each of the n-sided polygons have their own density. The observed gravity data were chosen along profiles based on areas of interest and those profiles which have a sufficient number of readings near the chosen traverse. The subsurface geology under each profile (e.g., sedimentary units, Precambrian basement lithology, and upper crust lithology) is entered with each body having its own density. The bodies' geometries, depth and densities are varied until the calculated gravity value due to these bodies matches the observed gravity anomalies. The modeling process is a trial-and-error exercise and as much experimentation as it is scientific insight and experience.

The final step in the representation portion of the research is developing 2.5-D models of the study area to better illustrate the possible subsurface lithologies. The first step in the process is to choose the profiles. Since the Pea Ridge Mine is a focal point of this work having A-A' and B-B' atop this region was important. The other major gravity maximum developed from the new data was the high anomaly at Huzzah (Fig. 18), so having another intersection near there was also important. The C-C' model was chosen to have as many data points near the line along the region as possible. Once the profiles were chosen whatever information was known about the area was added.

First the sedimentary layer and two igneous layers were added and the depth of the model was chosen to be 10 km. The sedimentary layer was given a density of 2.60 g/cm^3 based on an average of measured specific gravity from core samples in the

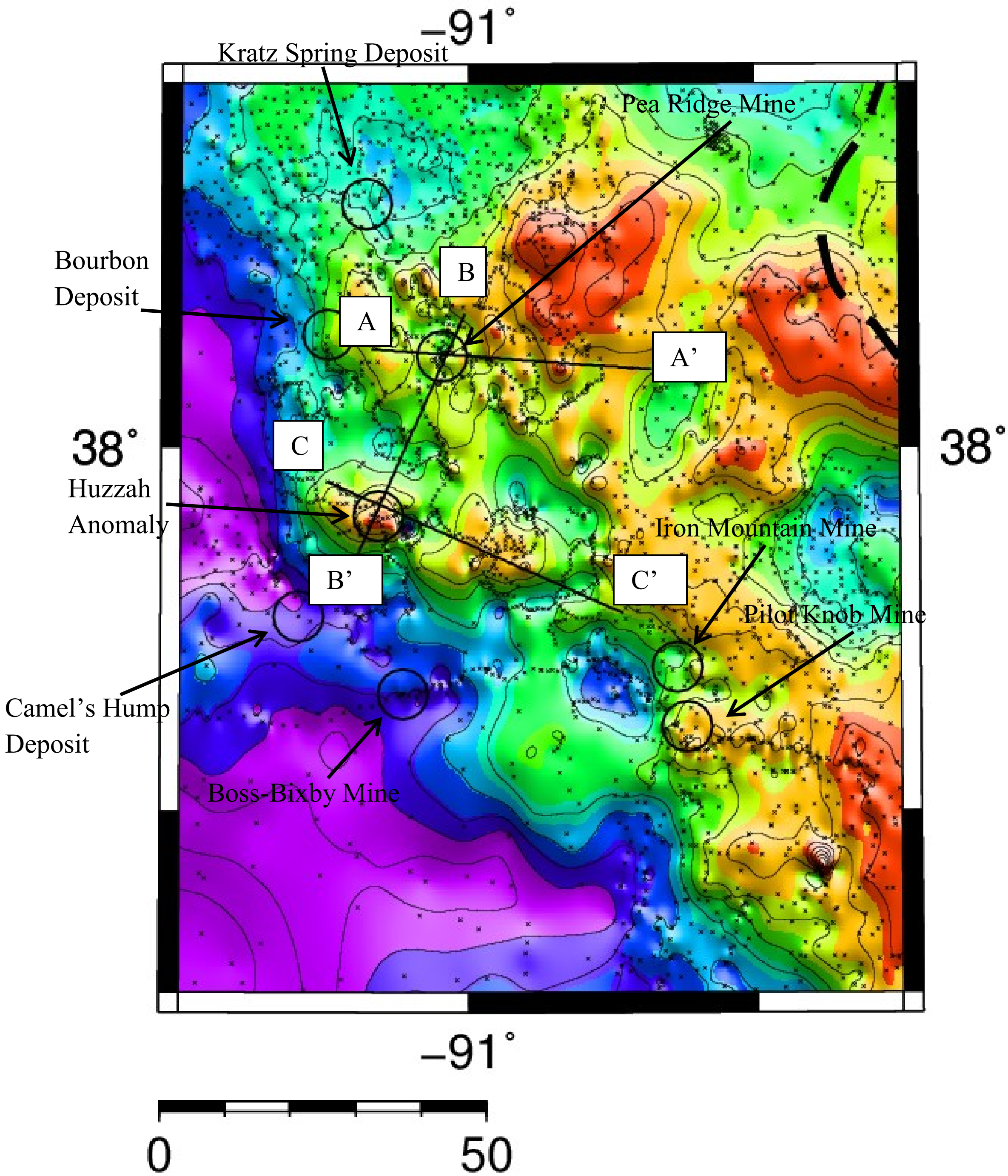

Figure 18. Complete Bouguer gravity anomaly map showing all gravity stations, major deposit locations, and the location of gravity profiles A-A', B-B', and C-C'.

McCracken Core Library Rolla, Missouri. The geometry of the sediments was based on the TIN of depth to the basement and Kisvarsanyi's (1979) basement depth map. The igneous layers were given densities of 2.74 g/cm^3 for the lower, and 2.67 g/cm^3 for the upper igneous based on values used by Hildenbrand et al. (1996) model Z-Z' and some experimentation. The west-east models, A-A' and C-C', were given some westward dip on the upper and lower igneous boundary based on the possible geometry of the Ozark Dome, and a similar dip identified by Stewart (1968) on a seismic refraction model near the study area. With the simple initial model of profile A-A' the need for lower density bodies below becomes clear as the calculated gravity in the models is much higher than the actual recorded gravity as seen in the upper window of Figure 19a.

The next step was to add bodies based on the known lithologies from Kisvarsanyi's (1982) basement lithology map, and Seeger et al.'s (2001) map of the Pea Ridge Mine. The density of 3.00 g/cm^3 for the Pea Ridge body was chosen based on experimentation and an average of assumed lithologies around the main magnetite body. The Huzzah body was modeled in a similar manner as the Pea Ridge body since its lithology is unknown. A similar method of experimentation within reasonable boundaries was also done for the ring intrusive bodies and a density of 2.90 g/cm^3 was used.

Once the known lithologies were established within the models the final step of matching the observed and calculated gravity curve begins. The general trend of the model is a higher gravity gradient across the models before adding the lower density bodies in the upper igneous layer. The lower density bodies were given a 2.40 g/cm^3 specific gravity based on experimentation with the size and shape of the bodies. Using

lower density bodies within the upper igneous also allowed for the Pea Ridge gravity minimum to be explained.

The experimentation step is several iterations of adjusting the densities and geometries to make a “best fit” between the calculated and observed Bouguer gravity anomalies before the final model is decided upon. Iterations will have smaller and larger changes as can be seen between Figures 19b and 19c. Figure 19b has a higher density for the low density bodies and two igneous layers, but the bodies are unrealistically large and the density change between the igneous layers is much lower than seen in previous geophysical models. In Figure 19c the sedimentary layer and both igneous layers densities are lowered, and though the low density bodies are now realistic in size and the igneous interface is close to previous models the fit between the calculated and observed Bouguer gravity anomaly is not a very good fit. This process is repeated with each model as can be seen in Figures 19d, e, f, g.

The final models (Figs. 20a, 20b, and 20c) must be consistent and logical spatially and lithologically, so the same density and relative size of bodies must agree between modes connected in space. Since the models are non-unique representations of what the lithologies might be in the basement, these are only three of many different possible constructions. In reality the lower density bodies are most likely smaller in size, but greater in number representing clusters of rock instead of singular rock masses. Also, the densities given for any of the model objects will vary from the given number and across the terrane. These models help to refine possible combinations of lithologies and geometries in the St. Francois Precambrian basement.

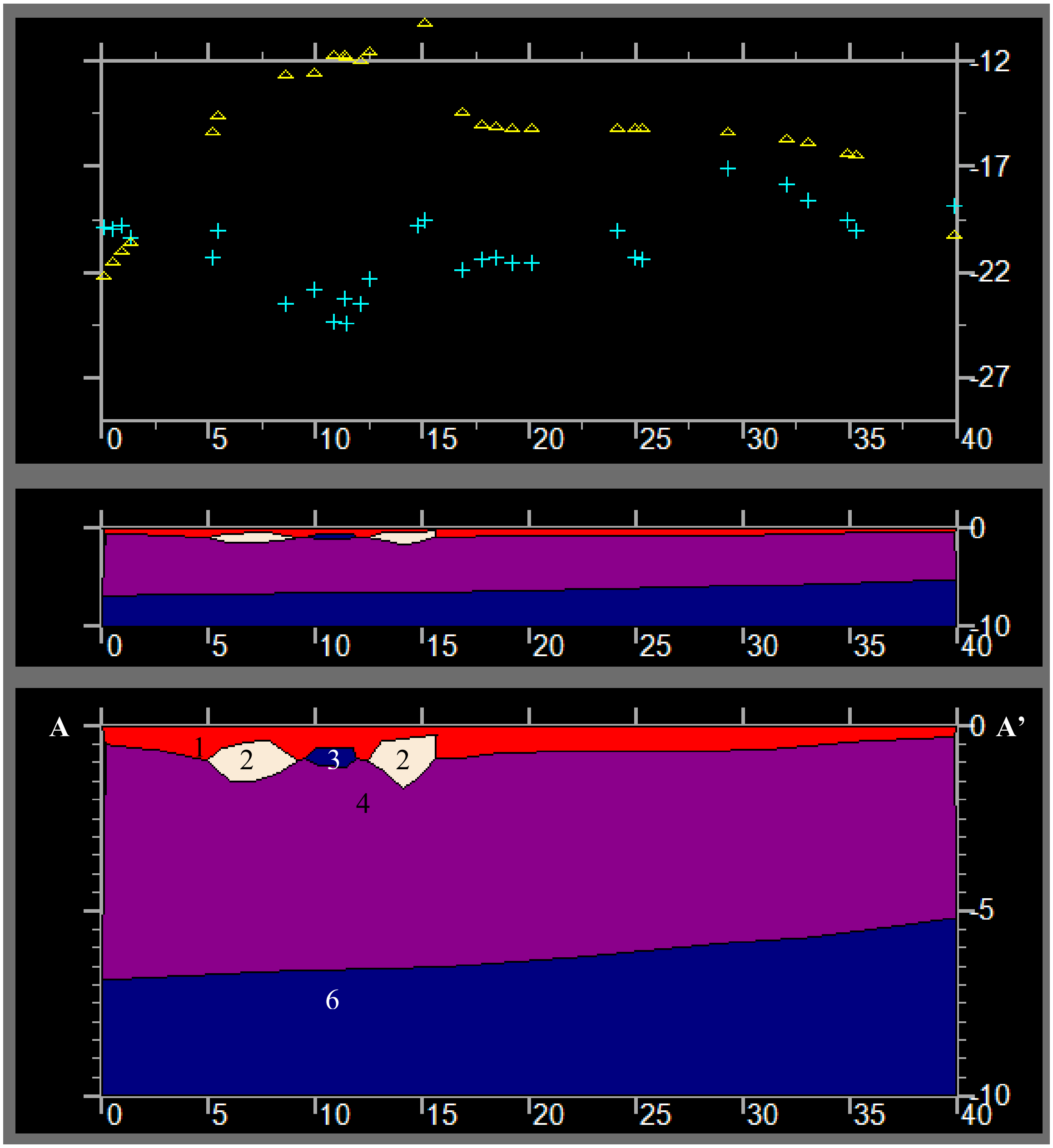

Figure 19a. Initial 2.5-dimensional gravity model of profile A-A' from Figure 18 through the Pea Ridge Mine area. 1. Paleozoic sediments – 2.60 g/cm^3, 2. Ring intrusions - 2.90 g/cm^3, 3. Pea Ridge Mine body – 3.00 g/cm^3, 4. Upper igneous layer - 2.67 g/cm^3, 6. Lower igneous layer - 2.74 g/cm^3.

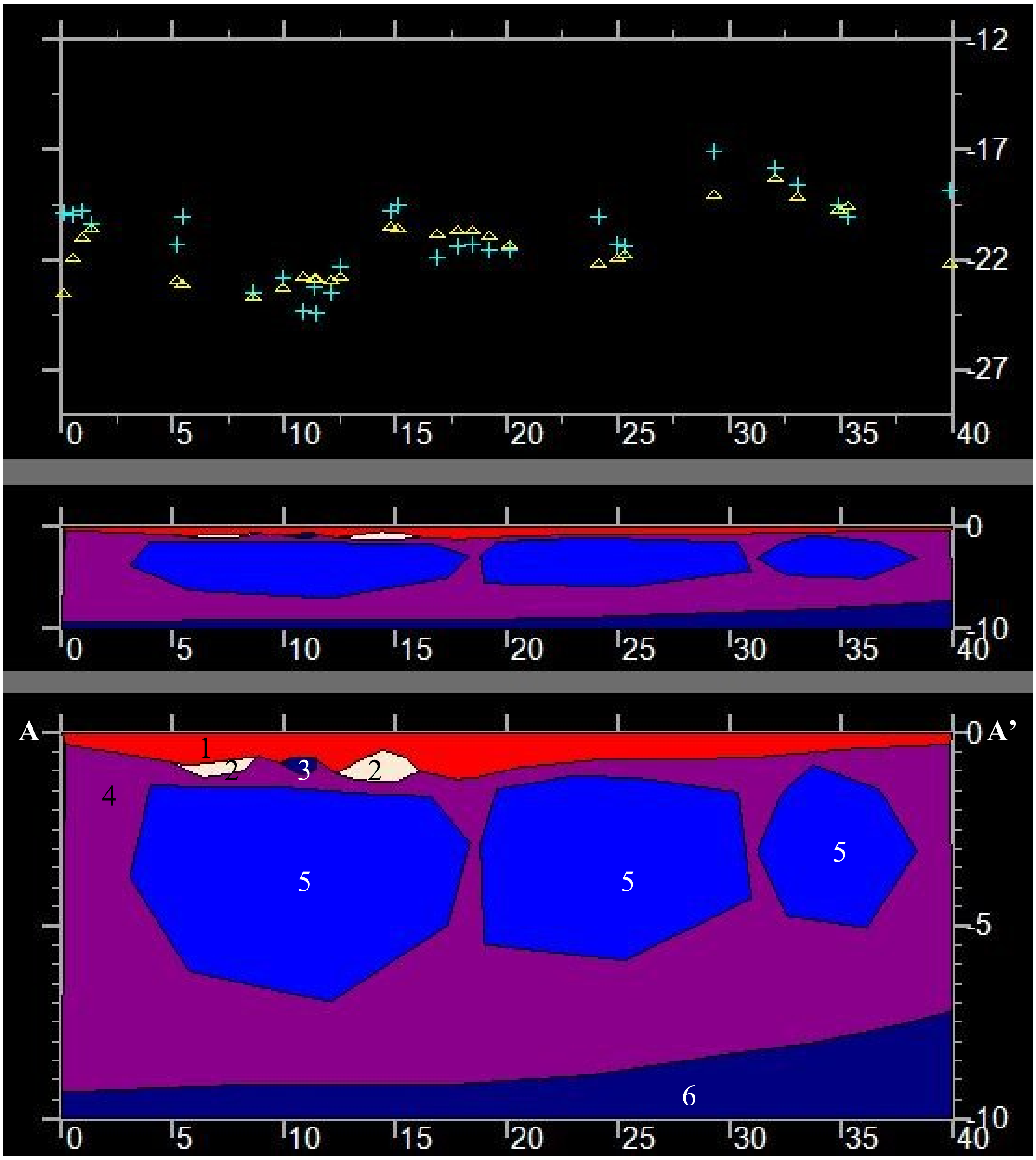

Figure 19b. Iteration gravity model of profile A-A' from Figure 18 through the Pea Ridge Mine area. 1. Paleozoic sediments – 2.65 g/cm^3, 2. Ring intrusions - 2.85 g/cm^3, 3. Pea Ridge Mine body – 3.00 g/cm^3, 4. Upper igneous layer - 2.76 g/cm^3, 5. Low density bodies – 2.55 g/cm^3,6. Lower igneous layer - 2.81 g/cm^3.

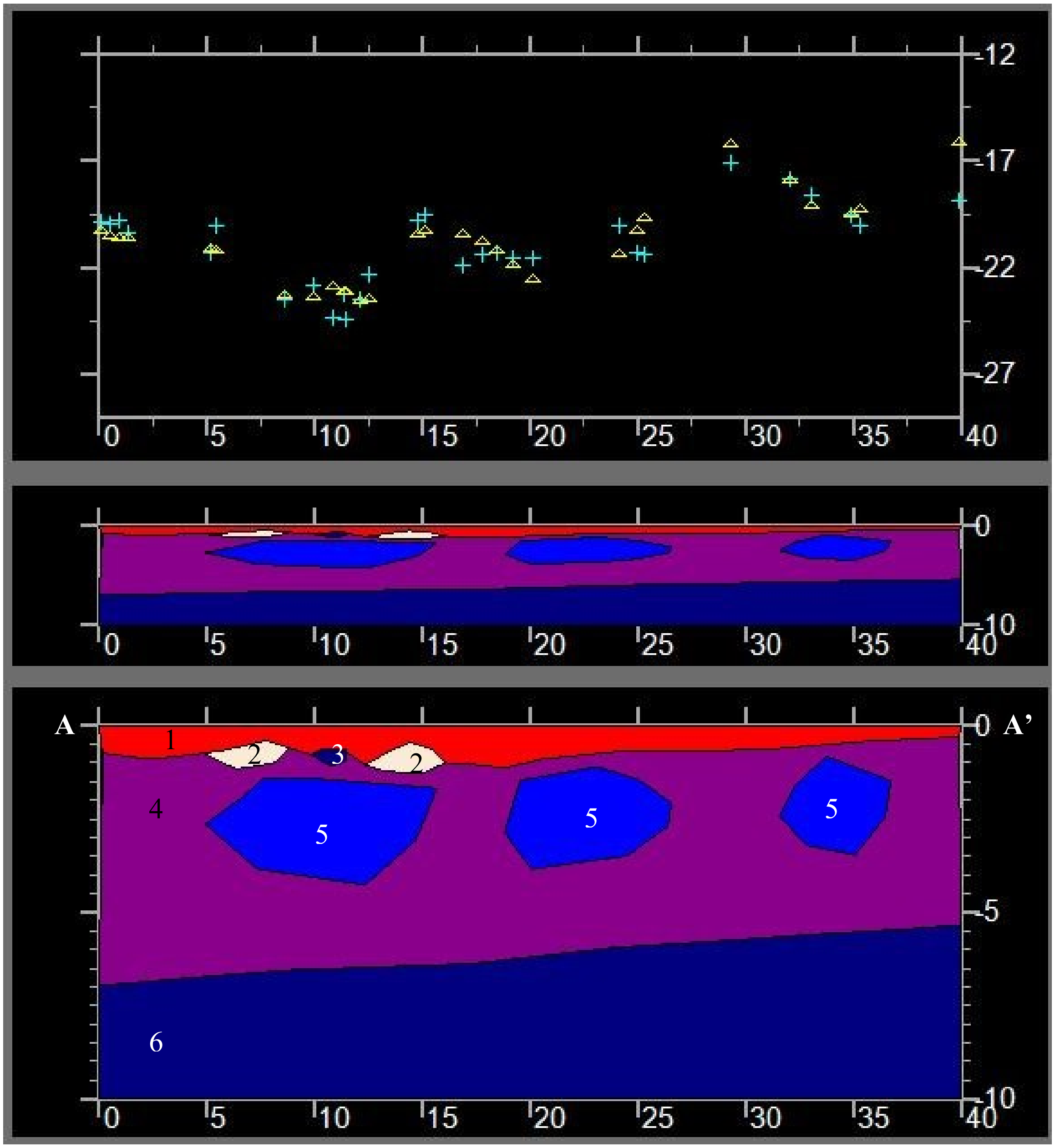

Figure 19c. Iteration of gravity model profile A-A' from Figure 18 through the Pea Ridge Mine area. 1. Paleozoic sediments – 2.50 g/cm^3, 2. Ring intrusions - 2.70 g/cm^3, 3. Pea Ridge Mine body – 3.00 g/cm^3, 4. Upper igneous layer - 2.65 g/cm^3, 5. Low density bodies – 2.55 g/cm^3, 6. Lower igneous layer - 2.75 g/cm^3.

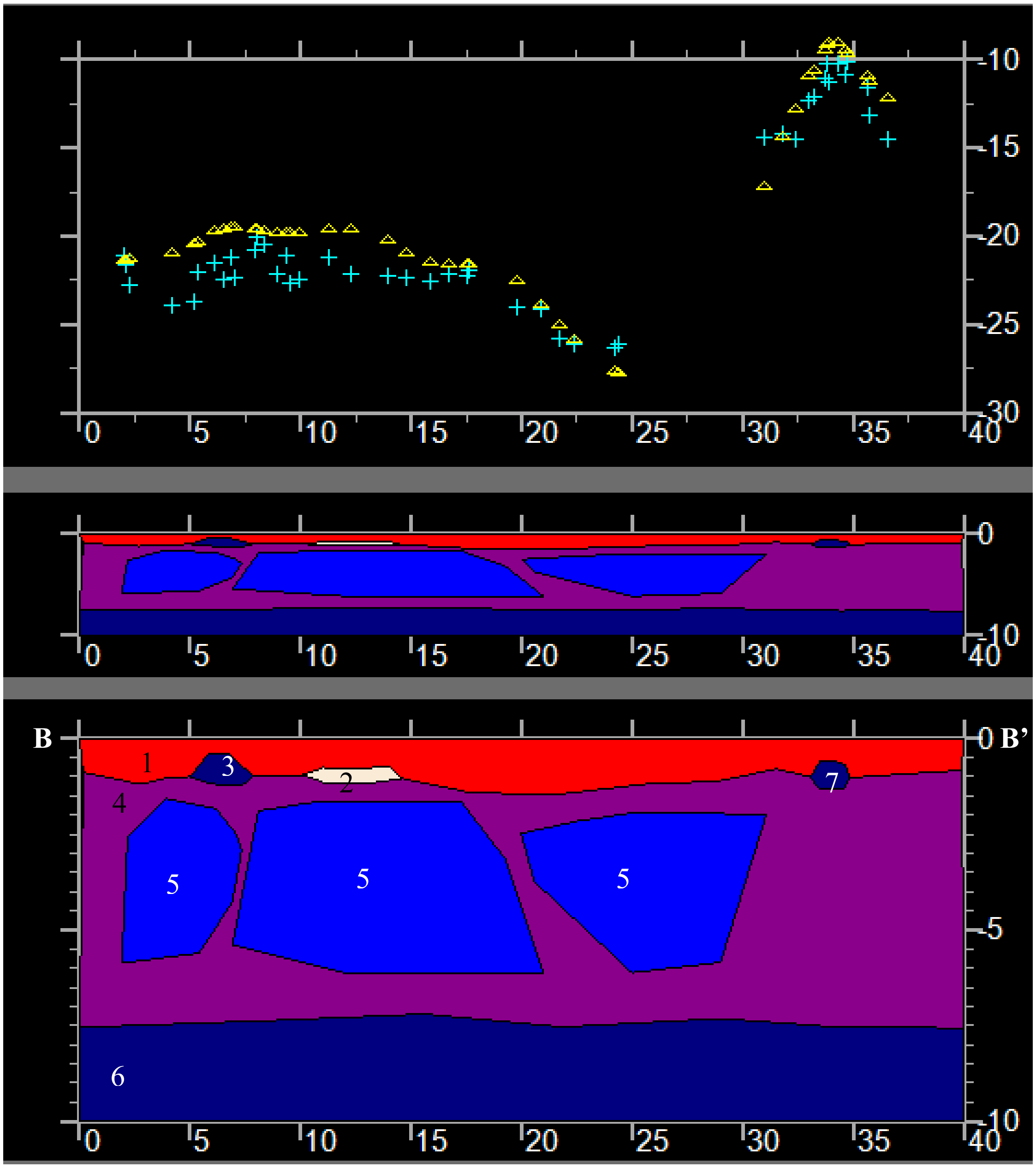

Figure 19d. Iteration of gravity model profile B-B' from Figure 18 through the Pea Ridge Mine and Huzzah anomaly. 1. Paleozoic sediments – 2.65 g/cm^3, 2. Ring intrusion - 2.85 g/cm^3, 3. Pea Ridge Mine body – 3.00 g/cm^3, 4. Upper igneous layer - 2.76 g/cm^3, 5. Low density bodies – 2.55 g/cm^3,6. Lower igneous layer - 2.81 g/cm^3, 3. Huzzah anomaly – 3.00 g/cm^3.

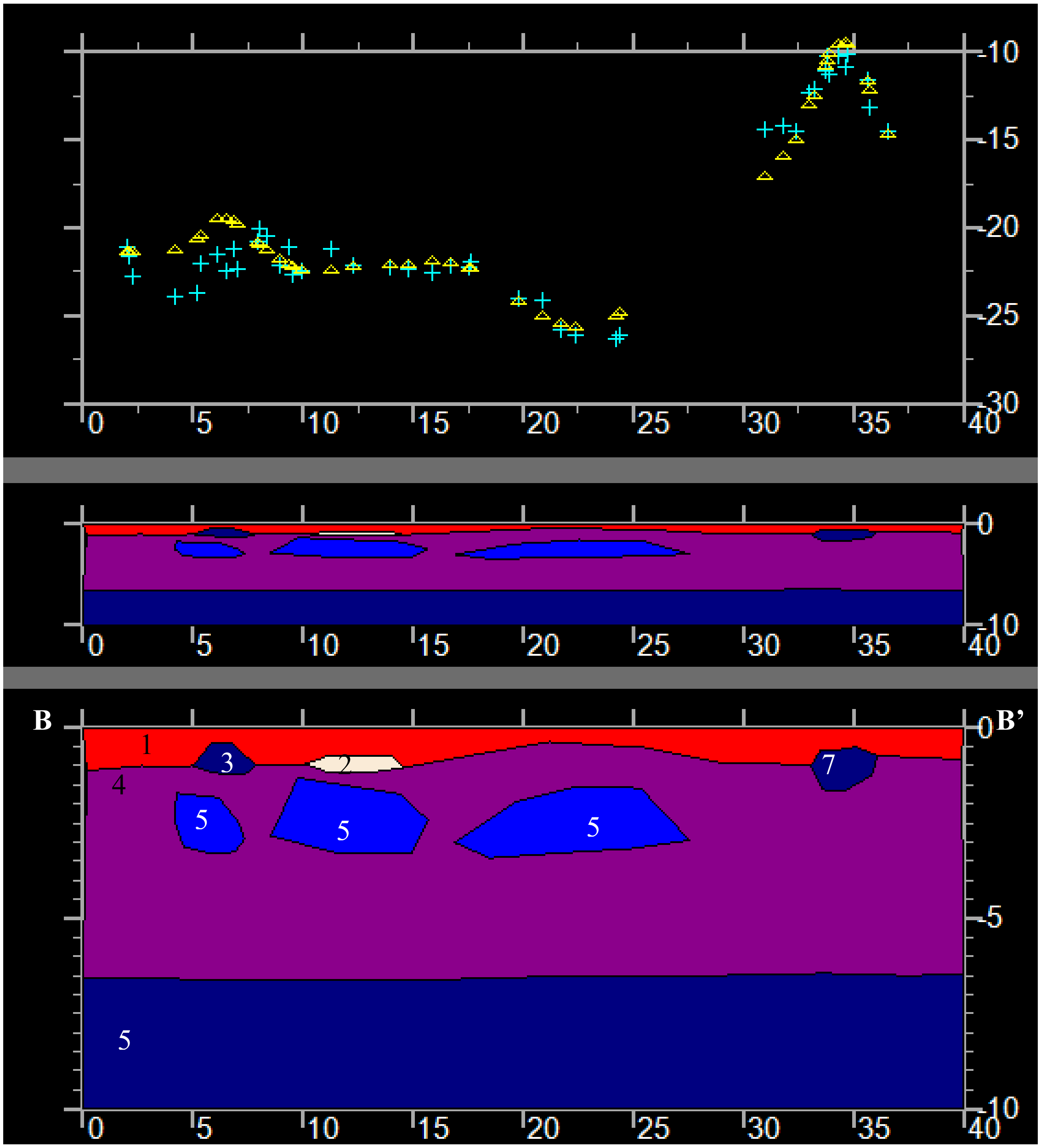

Figure 19e. Iteration of gravity model profile B-B' from Figure 18 through the Pea Ridge Mine and Huzzah anomaly. 1. Paleozoic sediments – 2.50 g/cm^3, 2. Ring intrusion - 2.70 g/cm^3, 3. Pea Ridge Mine body – 3.00 g/cm^3, 4. Upper igneous layer - 2.65 g/cm^3, 5. Low density bodies – 2.55 g/cm^3,6. Lower igneous layer - 2.75 g/cm^3, 7. Huzzah anomaly – 3.00 g/cm^3.

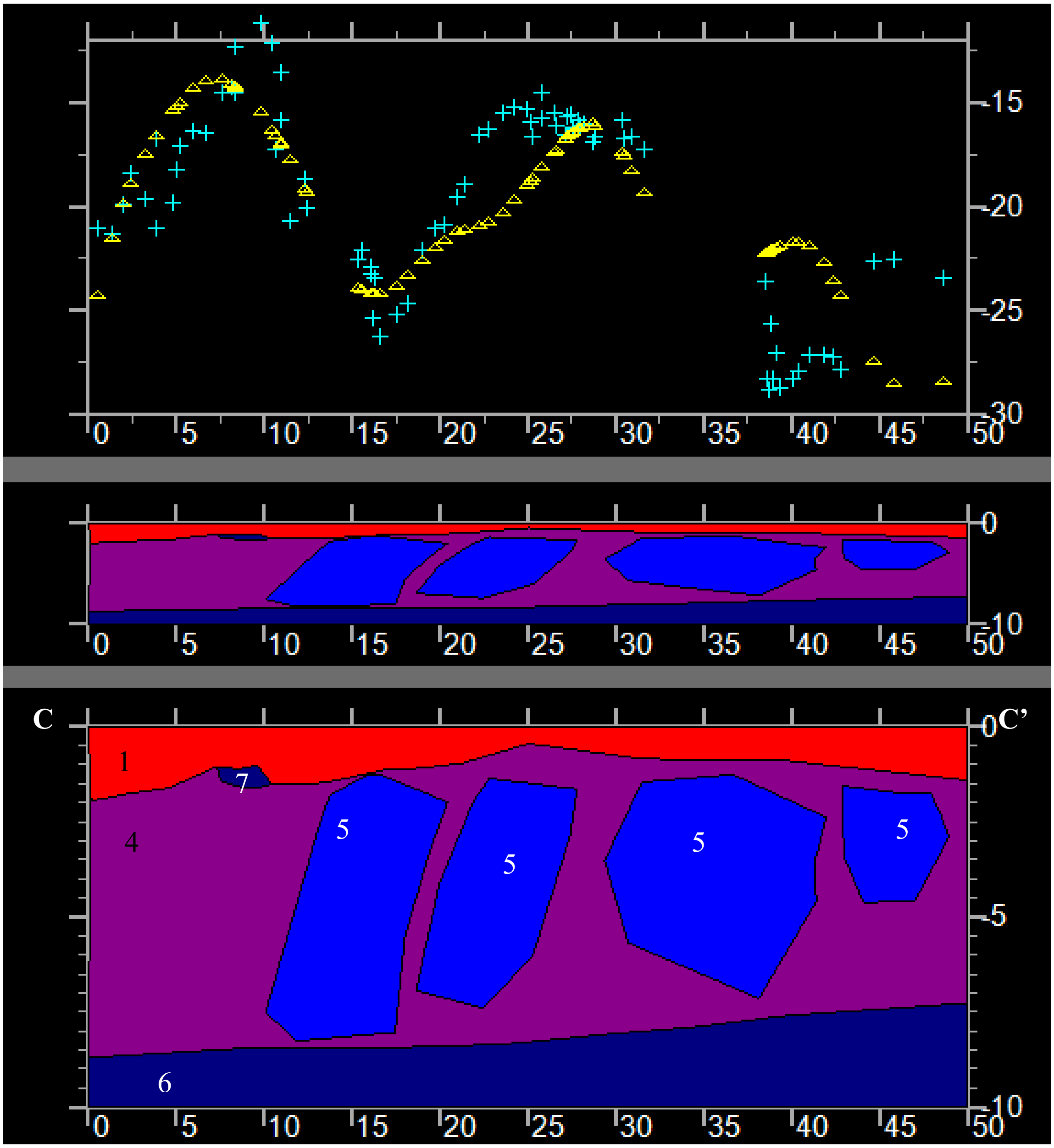

Figure 19f. Iteration of gravity model profile C-C' from Figure 18 through the Huzzah anomaly. 1. Paleozoic sediments – 2.65 g/cm^3, 4. Upper igneous layer - 2.76 g/cm^3, 5. Low density bodies – 2.55 g/cm^3,6. Lower igneous layer - 2.81 g/cm^3, 7. Huzzah anomaly – 3.00 g/cm^3.

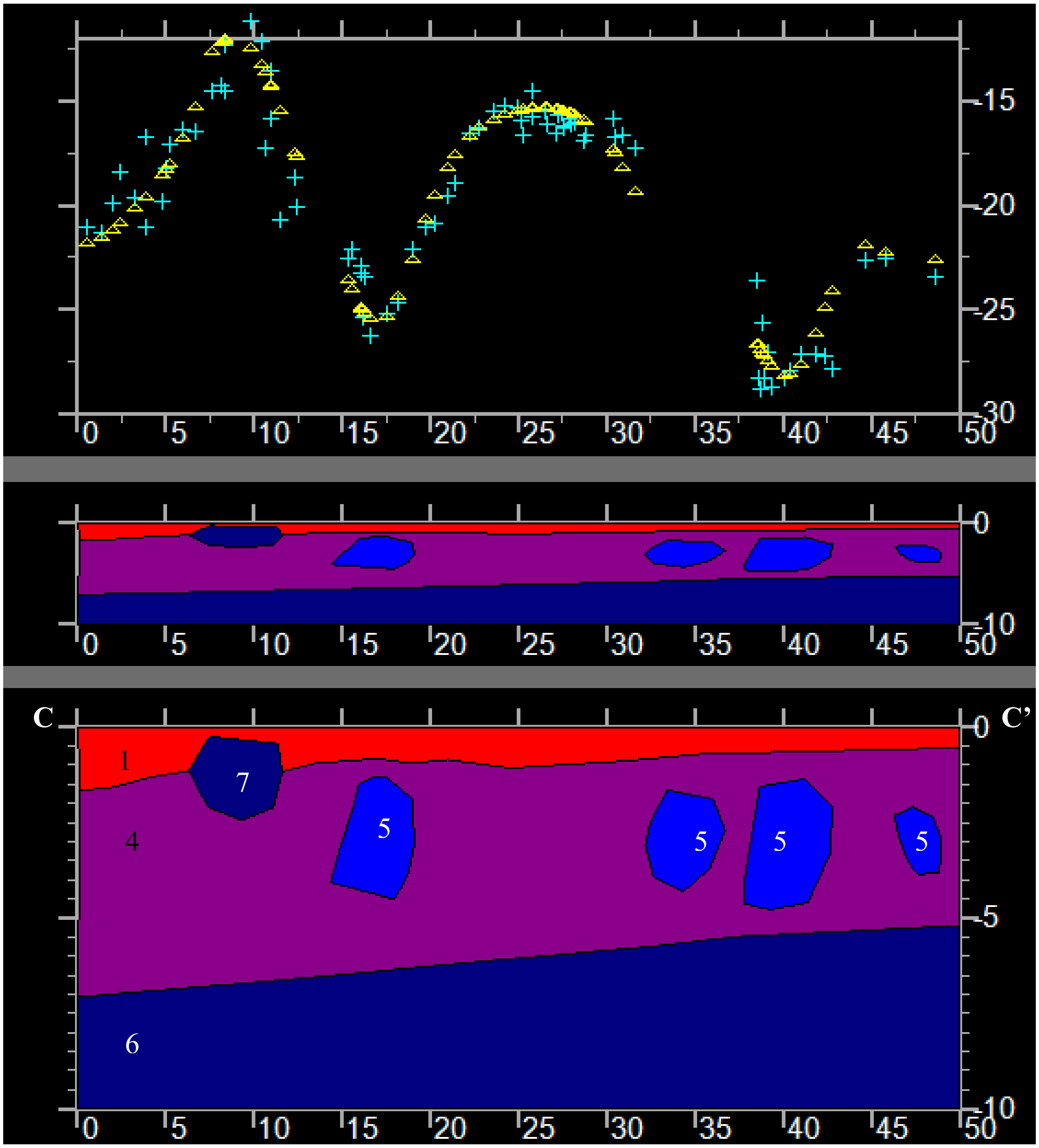

Figure 19g. Iteration of gravity model profile B-B' from Figure 18 through the Huzzah anomaly. 1. Paleozoic sediments – 2.50 g/cm^3, 4. Upper igneous layer - 2.65 g/cm^3, 5. Low density bodies – 2.55 g/cm^3,6. Lower igneous layer - 2.75 g/cm^3, 7. Huzzah anomaly – 3.00 g/cm^3.

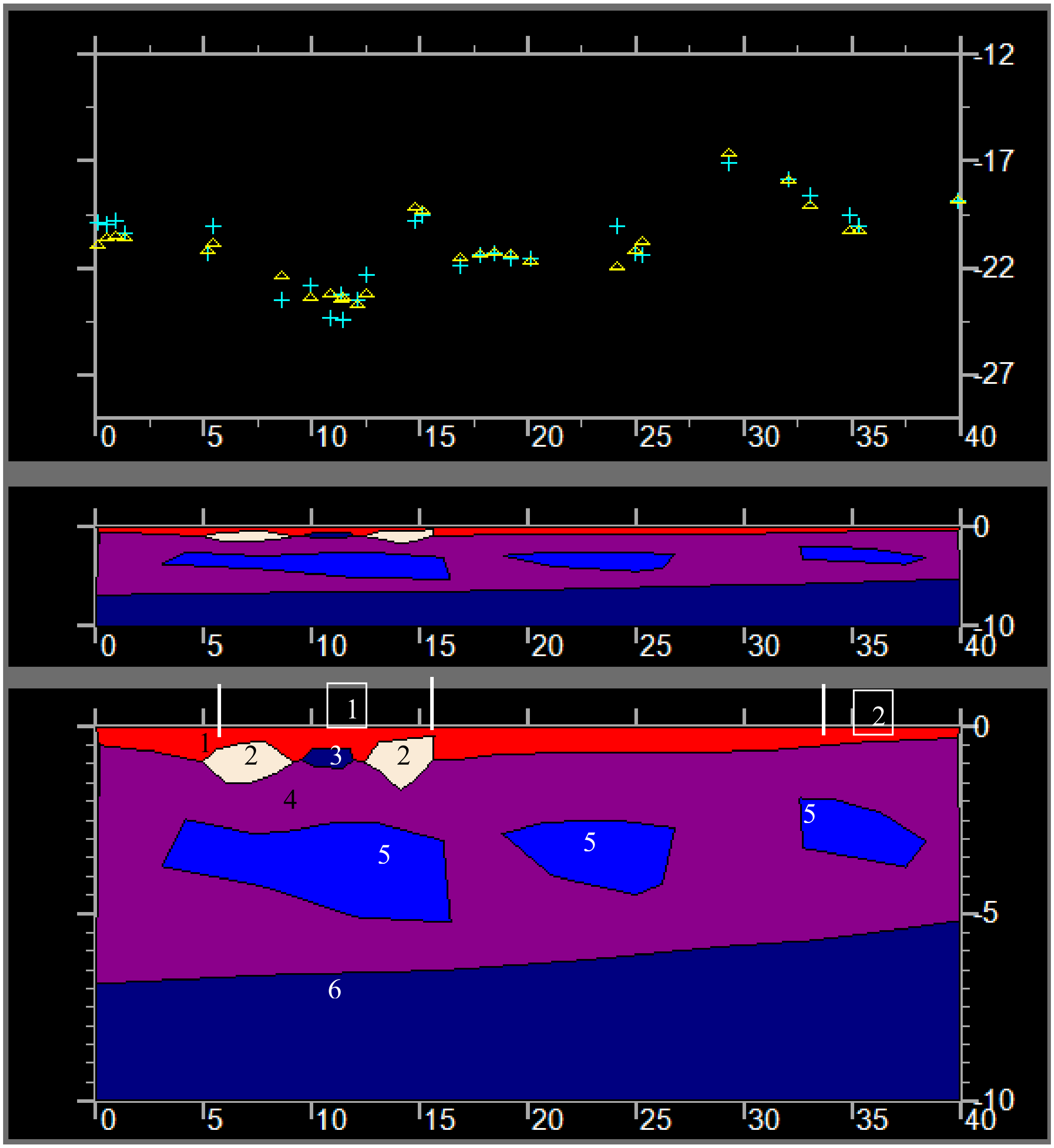

Figure 20a. Final gravity model of profile A-A' from Figure 18 through the Pea Ridge Mine area. Green lines refer to the probable boarders of the old caldera, and the numbers refer to the calderas pictured in Figure 5. 1. Paleozoic sediments – 2.60 g/cm^3, 2. Ring intrusions - 2.90 g/cm^3, 3. Pea Ridge Mine body – 3.00 g/cm^3, 4. Upper igneous layer - 2.67 g/cm^3, 5. Low density bodies – 2.40 g/cm^3, 6. Lower igneous layer - 2.74 g/cm^3.

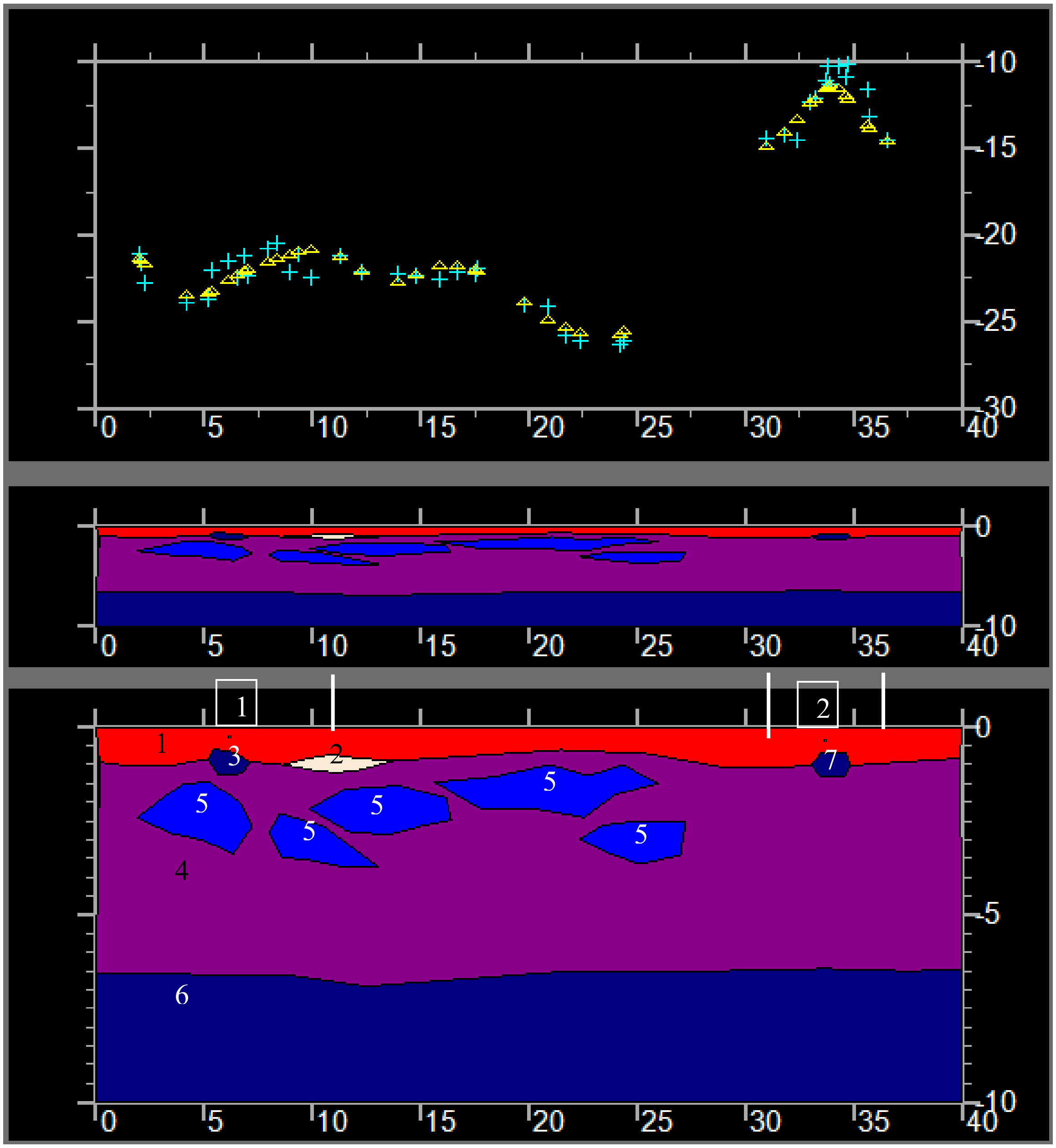

Figure 20b. Final gravity model of profile B-B' from Figure 18 intersecting both the Pea Ridge Mine site and the Huzzah gravity anomaly. White lines refer to the probable boarders of the old caldera, and the numbers refer to the calderas pictured in Figure 5. 1. Paleozoic sediments – 2.60 g/cm^3, 2. Ring intrusions - 2.90 g/cm^3, 3. Pea Ridge Mine body – 3.00 g/cm^3, 4. Upper igneous layer - 2.67 g/cm^3, 5. Low density bodies – 2.40 g/cm^3, 6. Lower igneous layer - 2.74 g/cm^3, 7. Huzzah anomaly – 3.00 g/cm^3.

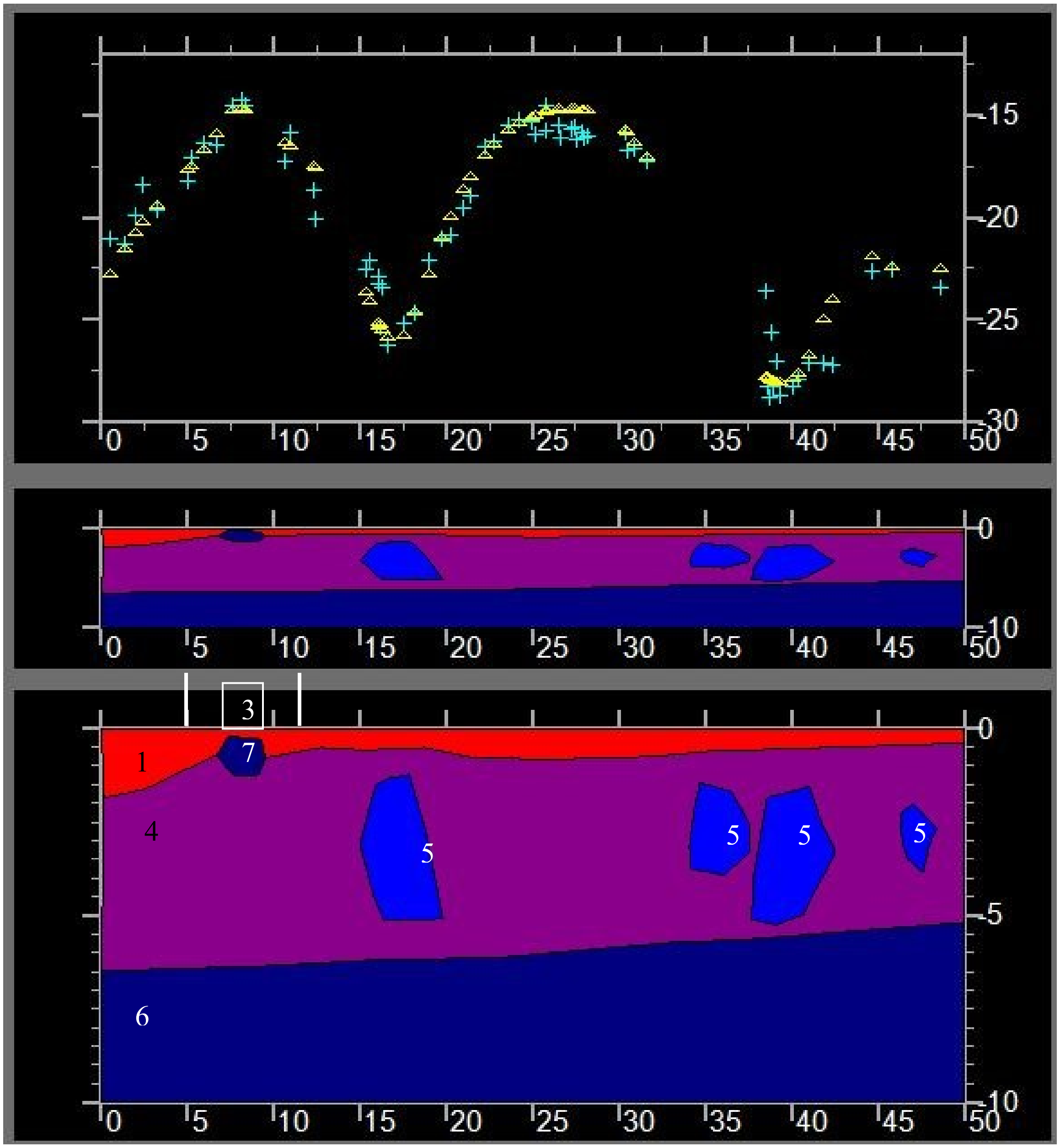

Figure 20c. Final gravity model of profile C-C' from Figure 18 through the Huzzah gravity anomaly. White lines refer to the probable boarders of the old caldera, and the numbers refer to the calderas pictured in Figure 5. 1. Paleozoic sediments – 2.60 g/cm^3, 4. Upper igneous layer - 2.67 g/cm^3, 5. Low density bodies – 2.40 g/cm^3, 6. Lower igneous layer - 2.74 g/cm3, 7. Huzzah anomaly – 3.00 g/cm^3.

CHAPTER 4

4.1 Discussion

The two goals for this research were simple: 1) to collect enough new gravity stations to better define the gravity anomalies related to subsurface bodies within the Precambrian basement of the St. Francois Mountains, and 2) to model and interpret the gravity and magnetic data to delineate the Precambrian geology and the related REE and other economic ore deposits. These two goals offer future researchers a much greater understanding of what is contained in the Precambrian lithologies of southeast Missouri. There is a great amount of information to be gleaned from the St. Francois Mountains terrane that has the possibility to rejuvenate this once prosperous mineral resource region.

Federal and state government research has made up the bulk of research performed on the northwest St. Francois terrane, with most of the results published in various government reports from the USGS, Missouri Geological Survey, Missouri Department of Natural Resources, and U.S. Department of Mines (e.g., Kisvarsanyi, 1981; Whitten and Yancey, 1990; Cordell and Knepper, 1987; Sidder et al., 1993; Seeger et al., 2001; Grauch et al., 2010). Most academic geophysical studies on the western side of the St. Francois Mountains have been large-scale, regionally focused, and based on the decades-old aeromagnetic, gravity, and seismic surveys (Stewart, 1968; Cordell, 1979; Guinness et al., 1983; Hildenbrand, 1985). Historically, there has been some academic interest in economic minerals developed in and around the Viburnum Trend, and also with the REE deposits in Pea Ridge as an exemple of hydrothermal development of REEs associated with iron ore bodies (Erickson et al., 1981; Horrall et al., 1993; Gleason et al.,

2000; Castor and Hendrik, 2006; and Nold et al., 2013). The bulk of the research around the St. Francois Mountains has focused on the eastern side, in efforts to better understand the Reelfoot Rift and Mississippi River Embayment (e.g., Braile et al., 1986; Langenheim and Hildenbrand, 1997; and Csontos et al., 2008). What the relative lack of studies in the western St. Francois Mountains shows overall is that there is room for improvement in the data, and that there are still large areas yet to be explored. This research expands on the breadth and depth of the current body of knowledge of the area by using information gathered on a local level and extrapolating that new knowledge out to the region as a whole. The interpretation in this research makes a contribution toward achieving the goal of delineating the subsurface lithology and geometry with the possibility of locating other REE deposits in the St. Francois terrane. This research will aid exploration geologists searching for new REE deposits in southeast Missouri. The new interpretation provides insights into future research possibilities in southeast Missouri, and adds to the current body of knowledge. Additionally, this research adds new possibilities into what was happening during the Precambrian after the collapse of the central caldera and the possible origins for mineral deposits of the St Francois Mountains.

4.2 Regional Analysis

In considering the gravity station coverage map (Fig. 9), large voids were quite noticeable in the central-western section of the map. Filling in some of these sparse areas and improving the spatial resolution of the data has been important to this research. The gravity data collection was initiated by the USGS in the spring of 2013 with most of the data recorded on or near the Pea Ridge Mine. The additional new data was collected with

an emphasis on refining known gravity anomalies using magnetic high anomalies as a guide in the sparsely sampled areas. The known REEs at Pea Ridge are associated with a high magnitude magnetic maximum, and theoretically should also be gravity maximum, as the magnetite body adjacent to the REE-containing breccia pipes is a known dense body.

The Pea Ridge Mine is located in an area of lower gravity than the surrounding region. From samples taken from within the mine, it is known that there is a large magnetite body with a density almost twice that of the surrounding lithologies (Seeger et al., 2001). The plutonic intrusive ring around the Pea Ridge Mine region does have the higher gravity values (Fig. 15) and can be seen in the gravity models (Figs. 20a and 20b). The gravity anomaly pattern over Pea Ridge Mine should appear similar to the anomaly shown at the Huzzah high gravity anomaly (Fig. 15) according to gravity model Figure 20a. There are several ways that this may have happened, but most are problematic. One way to explain the discrepancy between Pea Ridge Mine and Huzzah in the models (Fig. 20a) could be a large magmatic pluton under the area, but the St. Francois Mountains has been dormant for 500 million years. Another explanation would be the Pea Ridge ore body may be smaller and less dense than believed, but it has been well characterized and mapped (Seeger et al., 2001). There could also be a large lower density body below the denser magnetic body, but if this is the case it is unclear how the less dense body would have formed under the denser body.

To address aspects of the research that was undertaken but did not aid in the creation or interpretation of the models, Hammer’s (1963) gravity stripping technique does generally work to give a better understanding of the deep source gravity anomalies,

but in this case the sedimentary overburden had little effect on the deep gravity anomaly. The deep gravity anomaly map (Fig. 17) has the same general pattern as the complete Bouguer gravity anomaly map (Fig. 12). There are two main explanations for this: 1) the density difference between the sediments and the basement is not as great as believed, or 2) the sediments are not thick enough to have much effect. However, the densities are well known and fit well in the models. The sediments are 0 meters at the outcrops and at their deepest over 1500 meters (Fig. 16), so at most the sediments represent 15% of the depth of the models. This would suggest that whatever is affecting the gravity readings at the surface lies within or below the Precambrian basement. The gravity stripping did help confirm the general northwest-to-southeast regional trend (Line A, Fig. 17) seen in the other maps (Figs. 11 and 15).

4.2.1 Magnetic Maps. The magnetic anomaly RTP map of the study area in Figure 8 shows much better resolution of the magnetic bodies than the total-field map (Fig. 7) demonstrating the reason to perform the reduction to the pole. Comparing the RTP map (Fig. 8) with the tilt-derivative of the RTP data (Fig. 10), the tilt-derivative enhanced the central source and better defined the edges of the lower intensity anomalies creating magnetic highs in places that had not appeared to be highs in the unfiltered maps (Figs. 7 and 8). The tilt-derivative map deemphasized the overall northwest-to-southeast trend seen in the RTP map (Fig. 8), and though it is still partially visible, much of it is lost in the small wavelength anomalies. This suggests that the region has a more spatially diverse distribution of magnetically susceptible material throughout the region than the other mapping techniques have shown (Figs. 7, 8, and 9). Since the goal of the magnetic

maps was to help refine and limit the boundaries of the magnetic bodies for comparison to the gravity maps, the tilt-derivative was not very useful.

The band-pass filters passing wavelengths between 10 and 100 km (Fig. 9) did confirm the regional northwest-to-southeast trend of the magnetic data. By removing the higher frequency anomalies, the resultant map has a smoother trend over the entire region that does not help in delineating lithological changes, but does show some large moderate intensity areas. Using this process, the anomaly over the Pea Ridge Mine has disappeared almost entirely, as have other high intensity anomalies throughout the region. Kisvarsanyi (1981) noted that the locations of syenite intrusions are not well known, so it may be that some of these moderate intensity anomalies are unmapped syenite. Using the RTP magnetic map and band-pass filtered map together the areas of highest intensity and longest wavelength can be identified and gives one good starting parameter to find areas similar to Pea Ridge elsewhere in the region. Using just the magnetic data alone will not allow the desired refinement of areas of possible economic mineralization, but it does isolate areas to further study using the Bouguer gravity anomaly maps.

4.2.2 Gravity Maps. Comparing the complete Bouguer gravity anomaly maps (Figs. 11 and 12), the increase in data resolution and the refinement of the boundaries of anomalies within the new collection area is obvious, and does show how new anomalies, both high and low, can appear (near anomalies 3 and 4 in Figure 12). The band-pass filtered maps (Figs. 13 and 14) were similar to the magnetic band-pass filtered map (Fig. 9) in creating a larger regional gravity maximum gradient over the entire area and showing the recurring northwest-to-southeast trend seen in the other geophysical maps. Figure 13, which passed wavelengths between 10 and 100 km, is marked with line A for

the directional trend. In Figure 14, which passed wavelengths between 10 and 50 km, many large regional gravity anomalies still remain. This illustrates that the overall gravity field of the study area falls within a narrow window of variation in the total gravity field.

4.2.3 Gravity Models. The locations of the profile lines (Fig. 18) for the development of the models were selected based on: 1) the models needing to include the lithologies at the Pea Ridge Mine as the Pea Ridge Mine contains the known REE deposits that will be used as the known factor to be compared with the rest of the study area, 2) to develop profiles of other areas of interest that may contain REE deposits, and 3) the profiles were selected where there was sufficient data to create the models. This third criterion is why none of the profiles pass through other well-known iron deposits in the area. The Boss-Bixby Mine may be another area of interest, but the amount of data near the mine and the deposits at Boss-Bixby are not enough to create useful models. The known, but not developed, Bourbon deposit (Fig. 18) does have a significant magnetic anomaly, but the western extent of line A-A' does come near to this region.

The Huzzah region (Fig. 18) was chosen for the modeling for multiple reasons. First, it is unexplored and is associated with both a gravity and magnetic maximum. The other factor was the large clustering of gravity stations defining the gravity anomaly (Fig. 18). The second line B-B' chosen was to connect the Pea Ridge Mine and the Huzzah region into one profile for a direct comparison. Within the study area, the Huzzah gravity maximum is a gravity anomaly with no historic efforts to investigate the area for ore deposits. On historic magnetic anomaly maps there is a noticeable magnetic maximum anomaly in the Huzzah region, and while not as high a magnitude as some of the other regional deposits it is still significant (Cordell and Knepper, 1987; and Fig. 8). The

complete Bouguer gravity anomaly map created before the new stations were added (Fig. 11) does show a small wavelength gravity maximum, but the anomaly is based on a single gravity station. With the new gravity stations within the Huzzah area (Fig. 12) the anomaly increased significantly in magnitude and wavelength.

All three models were developed using known lithologies and densities as discussed in Section 3.4.4. Figure 20a represents the model of profile A-A' (Fig. 18) passing roughly west-to-east through the Pea Ridge Mine. As discussed earlier, the Pea Ridge Mine anomaly should be a gravity maximum caused by the large magnetite ore body contained within the structure. Before the low density bodies were added in the Precambrian section, the calculated Bouguer gravity anomalies reflected the gravity maximum. The geometries and depths of the sedimentary and igneous bodies' are known, and variations in density can only be within a narrow range. Within those constraints the observed gravity minimum seen over the Pea Ridge Mine cannot be explained. Also, lowering the density of the Pea Ridge deposit below 3.0 g/cm^3 would not produce the observed anomaly, particularly since the trend throughout the region is a higher calculated gravity than the observed gravity values. One possible model is low density bodies within the Precambrian upper crust. The decision that the addition was the correct choice is reinforced by what appears as a gravity maximum 30 km along the A-A' profile (Fig. 18). Within the model (Fig. 19a) this area shows the calculated and observed gravity as close and is only influenced by the sedimentary cover and two Precambrian igneous layers.

The same addition of lower density bodies in models B-B' (Fig. 20b) and C-C' (Fig. 20c) solved similar discrepancies between the calculated and observed gravity

readings observed in model A-A' (Fig. 20a). The low density bodies are most likely a cluster of similar extrusive igneous rocks that were once the roof of a caldera that collapsed and were then reincorporated into the igneous terrane during later volcanic events. This interpretation is strictly speculative as there are no drill cores that penetrate far enough into the crystalline basement to confirm the existence of the low density bodies, but it does fit the models and known history of the area (Kisvarsanyi, 1980 and 2007). Model A-A' (Fig. 20a) is the keystone model to understanding the region as the lithology of the Pea Ridge deposit is known, and though the extent of the breccia pipes containing the REEs adjacent to the main ore body may not be completely uncovered their location and orientation are known (Seeger et al., 2001).

Model B-B' (Fig. 20b) passes through the Pea Ridge Mine and also passes though the Huzzah high gravity anomaly. In Figure 20b, the Huzzah high gravity anomaly appears at least 10 mGals higher than Pea Ridge Mine region. A high density body of similar size and density to Pea Ridge was added to represent the high anomaly and fitted the observed gravity, and without a lower density body below it. It follows that when the roof of the caldera collapsed not all the material would be distributed evenly throughout the area. It is possible that the Huzzah source is also smaller, but denser, than the Pea Ridge deposit, but it is not likely that it is a larger, but lower density deposit. It may also be that the body itself is closer to the surface which would cause the anomaly to appear larger. This can only be confirmed by drilling in the area. The RTP magnetic anomaly map (Fig. 8) shows three long thin lobes which may represent diking or fractures in the basement from which the body was formed.

Model C-C’ (Fig. 20c) offers another view of the Huzzah anomaly and the adjacent low represented by a large cluster of low density bodies. In this view, the Huzzah anomaly is larger in volume, but the RTP magnetic anomaly map (Fig. 8) indicates that the profile crosses more of the magnetic high, and thus may be representative of a more complex geometry of the Huzzah anomaly body in comparison with the Pea Ridge anomaly. On profile C-C’ there are other large clusters of low density bodies that may give some insight into the topography of the surface of the Precambrian pre-collapse caldera.

The low density bodies modeled above based on gravity and magnetic analysis, and regional geological setting could be the remains of the original volcanic roof consisting of rhyolites and ash-flow tuffs that were incorporated into later igneous activity. The level of alteration to the low density bodies is unknown, but the Pea Ridge magnetite and REE deposits are hydrothermal in origin (Gow et al., 1994, Seeger, et al., 2001, and Nold et al, 2013). It is possible that the low density bodies are the origin of the material that developed the Fe-oxide ore deposits in the region, but this would need to be confirmed by drill core samples. If the low density bodies are the origin of the material that created the Fe-oxide ore deposits the density would be lower than the same early rhyolite and ash-flow tuff deposits. In addition, if these low density bodies are the result of leaching during hydrothermal alteration, then any Fe-oxides in the bodies would have been removed and thus have a lower magnetic susceptibility. This could be important for understanding the origin of the REE deposits at the Pea Ridge Mine and the extrapolation of that information throughout the region.

4.3 Conclusions

The gravity analysis, especially with the addition of 700 new stations, allowed for greater definition of the boundaries and geometries of the Precambrian lithological changes. What these lithologies actually are is still unknown, but this new understanding of the geometry of the basement shows that it is more complicated than previously shown. The gravity and magnetic analysis also allowed for the speculation of the occurrences of possible economic ore deposits similar to the Pea Ridge REE containing breccia pipes. The most promising of the anomalies occurred over the Huzzah region where the gravity and magnetic maxima suggest the occurrence of subsurface iron deposits. Using existing Precambrian basement maps as a guide, both the Pea Ridge and Huzzah regions are located in silicic granite and rhyolite terranes near the mapped syenite intrusions. The currently active Boss-Bixby Mine also shares a similar lithology, and may also contain undiscovered REEs and other economic minerals.

4.4 Future Work

As stated above, drill core sampling is key to understanding what actually exists in the crystalline basement of the northwest St. Francois terrane. The lower density bodies developed from the material of the collapsed caldera should be easy to confirm with deeper drill core samples. A better characterization of the Pea Ridge deposit would also be a great boon to understanding how to identify REEs using geophysical methods. A magnetotelluric survey over the main body, and especially around the northeast corner where the REE bearing breccia pipes are located, would allow a much needed refinement to the makeup of the key location in the study if the deposit has a different electrical

resistivity than the surrounding material. Additionally, at least two crossing profiles of gravity stations with a spacing of no more than 100 meters over the main ore body would help in establishing the geophysical signature needed to extrapolate to the rest of the region.

There are many avenues of research left in the study area, using both field geology and geophysical methods. This project is just another step built atop earlier research that provides a base for future studies. Future investigations are paramount to verify the theories put forth in this research that will allow a greater understanding of what southeast Missouri and the St. Francois Mountains looked like 1.5 billion years ago, and what economic minerals may still exist in the region.

REFERENCES CITED

Bankey, V., Cuevas, A., Daniels, D., Finn, C., Hernandez, I., Hill, P., Kucks, P., Kucks, R., Miles, W., Pilkington, M., Roberts, C., Roest, W., Rystrom, V., Sherer, S., Snyder, S., Sweeny, R., Velez, J., Phillips, J., and Ravat, D.,2002, Digital data grids for the magnetic anomaly map of North America: United States Geological Survey Open File Report 02-0414.

Bradley, D.C., and Leach, D.L, 2003, Tectonic controls of Mississippi Valley-type lead-zinc mineralization in orogenic forelands: Mineralium Deposita, vol. 38, p. 652-667.

Braile, L.W., Hienze, W.J., Keller, G.R., Lidiak, E.G., and Sexton, J.L., 1986, Tectonic development of the New Madrid rift complex, Mississippi Embayment, North America: Tectonophysics, v. 131, p. 1-21.

Brown, S., 2005, Ozark Plateau, midcontinental North America: insights into thermochronology using apatite fission track analysis [masters thesis]: University of Illinois at Urbana-Champaign, p. 137.

Burger, H.R., Sheehan, A.F., and Jones, C.H., 2006, Introduction to applied geophysics: exploring the shallow subsurface: New York, W. W. Norton & Company, 554 p.

Castor, S.B., and Hendrik, J.B., 2006, Rare earth elements, *in* Kogel, J.E., Trivedi, N.C., Barker, J.M., and Krukowski, S.T., eds., Industrial minerals and rocks: commodities, markets, and uses: United States, Society for Mining Mineralogy, ed. 7, p. 769-792.

Csontos, R., Van Arsdale, R., and Waldron, B., 2008, Reelfoot Rift and its impact on Quaternary deformation in the central Mississippi River Valley: Geosphere, v. 4, no. 1, p. 145-158.

Cordell, L., and Knepper, D.H., 1987, Aeromagnetic images: Fresh insight to the buried basement, Rolla quadrangle, southeast Missouri: Geophysics, v. 52, no. 2, p. 218-231.

Cordell, L., 1979, Gravity and aeromagnetic anomalies over basement structure in Rolla quadrangle and southeast Missouri lead district: Economic Geology, v. 74, p. 1383-1394.

Erickson, R.L., Mosier, E.L., Odland, S.K., and Erickson, M.S., 1981, A favorable belt for possible mineral discovery in subsurface Cambrian rocks in southern Missouri: Economic Geology, v. 76, p. 921-973

Garven, G., Appold, M.S., Toptygina, V.I., and Hazlett, T.Z., 1999, Hydrogeologic modeling of the genesis of carbonate-hosted lead-zinc ores; Hydrogeology Journal, vol. 7, p. 108-126.

Gerdemann, P.E., and Myers, H.E., 1972, Relationships of carbonate facies patterns in the Southeast Missouri lead district: Economic Geology, v. 67, p.426-433.

Gleason J.D., Marikos, M.A., Barton, M.D., and Johnson, D.A., 2000, Neodymium isotopic study of rare-earth element sources and mobility in hydrothermal Fe oxide (Fe-P-REE) systems; Geochemica et Cosmochimica Acta, vol. 64, no. 6, p. 1059-1068

Gow, P.A., Wall, V.J., Oliver, N.H.S., and Valenta, R.K., 1994, Proterozoic iron oxide (Cu-U-Au-REE) deposits: Further evidence of hydrothermal origins: Geology, v. 22, p. 633-636.

Graf, J.L., 1984, Effects of Mississippi Valley-type mineralization on REE carbonate rocks and minerals, Viburnum Trend, southeast Missouri: The Journal of Geology, v. 92. no. 3, p. 307-324.

Grauch, R.I., Verplanck, P.L., Seeger, C.M., Budahn, J.R., and Van Gosen, B.S., 2010, Chemistry of selected core samples, concentrate, tailings, and tailings pond waters: Pea Ridge iron (-lanthanide-gold) deposit, Washington County, Missouri: U.S. Geological Survey Open-File Report 2010-1080, 15 p.

Groves. D.I., Bierlein, F.P., Meinert, L.D., and Hitzman, M.W., 2010, Iron oxide copper-gold (IOCG) deposits through Earth history: Implications for origin, lithospheric setting, and distinction from other epigenetic iron oxide deposits: Economic Geology, v. 105, p. 641-654.

Guinness, E.A., Arvidson, R.E., Leff, C.E., Edwards, M.H., and Bindschadler, D.L., 1983, Digital image processing applied to analysis of geophysical and geochemical data for southern Missouri: Economic Geology, v. 78, p. 654-663.

Hammer, S., 1963, Deep gravity interpretation by stripping: Geophysics, v. 28, p. 369-378.

Hildenbrand, T.G., 1985, Rift structure of the northern Mississippi embayment from the analysis of gravity and magnetic data: Journal of Geophysical Research: Solid Earth, v. 90, is. B14, p. 12607-12622.

Hildenbrand, T.G., Griscom, A., Van Schmus, W.R., and Stuart, 1996, Quantitative investigations of the Missouri Gravity Low: A possible expression of a large, large Precambrian batholith intersection the New Madrid seismic zone: Journal of Geophysical research: Solid Earth, vol. 101, is. B10, p. 21921-21942.

Horrall, K.B., Hagni, R D., and Kisvarsanyi, G., 1993, Mafic and ultramafic plutons associated with the New Madrid Rift complex – A possible major source of the copper-cobalt-nickel mineralization of Southeast Missouri: Economic Geology, v. 88, p. 328-343.

Kisvarsanyi, E.B, 1979, Structure contour map of buried Precambrian basement-rock surface, Rolla 1 degrees by 2 degrees quadrangle and adjacent areas, Missouri; Miscellaneous Field Studies Map: U. S. Geological Survey Report MF-1001-B.

Kisvarsanyi, E.B., 1980, Granitic ring complexes and Precambrian hot-spot activity in the St. Francois terrane, Midcontinent region, United States: Geology, v. 8, p. 43-47.

Kisvarsanyi, E.B., 1981, Geology of the Precambrian St. Francois Terrane, Southeastern Missouri: Missouri Department of Natural Resources Report of Investigations Number 64, p. 58.

Kisvarsanyi, E.B, 2007, The Precambrian framework of Missouri as interpreted from the magnetic anomaly map: ACTA GGM DEBRECINA, v. 2, p. 143-150.

Langenheim, V.E. and Hildenbrand, T.G., 1997, Commerce geophysical lineament – its source, geometry and relation to the Reelfoot Rift and New Madrid Seismic Zone: Geological Society of America Bulletin, v. 109, p. 580-595.

Leach, D.L. and Rowan, E.L., 1986, Genetic link between Ouachita foldbelt tectonism and the Mississippi Valley-type lead-zinc deposits of the Ozarks; Geology, v. 14, p. 931-935.

Long, K.R., Van Gosen, B.S., Foley, N.K., and Cordier, D., 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, 96 p

Lowe, C., 1999, Application of the magnetic method in mineral exploration: fundamentals and recent developments, in Lowe, C., Thomas, M.D., and Morris, W.A., eds., Geophysics in Mineral Exploration: Fundamentals and Case Histories: Geological Association of Canada, Short Course Notes, v. 14, p. 131-162.

Lowell, G.R., 2000, Eruptive style of Mesoproterozoic A-type calderas in southeastern Missouri, USA: Revista Brasilerira de Geociencias, v. 30, is. 4, p. 745-748

Meert, J.G., and Stuckey, W., 2002, Revisiting the paleomagnetism of the 1.476 Ga St. Francois Mountains igneous province, Missouri: Tectonics, v.21, no. 2, p. 1-1--1-19

Menuge, J.F., Brewer, T.S., and Seeger, C.M., 2002, Petrogenesis of metaluminous A-type rhyolites from the St. Francois Mountains, Missouri and the Mesoproterozoic evolution of the southern Laurentian margin; Precambrian Research, vol. 113, p. 269-291.

Mickus, K., 2007, Precambrian blocks and orogeny boundaries in the north-central United States determined from gravity and magnetic data, *in* Hatcher, R. D., Jr., Carlson, M. P., McBride, J. H., and Martínez Catalán, J. R., eds., 4-D Framework of Continental Crust: Geological Society of America Memoir 200, p. 327-340.

Mickus, K.L., and Keller, G.R., 1992, Lithospheric structure of the south-central United States: Geology, v. 20, p. 335-338.

Morelli, C., 1976, Modern standards for gravity surveys; Geophysics, v. 41, p.1051.

Nold, J.L., Davidson, P., and Dudley, M.A., 2013, The Pilot Knob magnetite deposit in the Proterozoic St. Francois Mountains terrene, southeast Missouri, USA: A magmatic and hydrothermal replacement iron deposit: Ore Geology Reviews, v. 53, p. 446-469.

Nuelle, L.M., 1998, Minerals of the Pea Ridge Mine, Washington County, Missouri: Rocks and Minerals, v. 73, is. 2, p. 90-97.

Pratt, T.L., Hauser, E.C., and Nelson, D., 1992, Widespread buried Precambrian layered sequences in the U.S. mid-continent: Evidence for large Proterozoic depositional basins: The American Association of Petroleum Geologists bulletin, v. 76, no. 9, p. 1384-1401.

Rohs, C.R., and Van Schmus, W.R., 2007, Isotopic connections between basement rocks exposed in the St. Francois Mountains and the Arbuckle Mountains, southern mid-continent, North America: International Journal of Earth Sciences, v. 96, p. 599-611.

Rohs, C.R., 2013, Timing of thermal overprints in the Silvermines Granite and associate diabase intrusions, St. Francois Mountains, Missouri: The Compass: Earth Science Journal of Sigma Gamma Epsilon, v. 85, is. 3, p. 78-97.

Salem, A., Williams, S., Fairhead, D., Smith, R., and Ravat, D., 2008, Interpretation of magnetic data using tilt-angle derivatives: Geophysics, vol. 73, no. 1, p. L1-L10.

Seeger, C.M., 2013, Rare earth minerals in the world and in Missouri: http://kcengineers.org/geotech/wordpress-content/uploads/2013/03/Rare-Earth-Minrerals-and-the-Geology-of-Pea-Ridge-Fe-REE-Au-Deposit-Seeger.pdf, (accessed November 2013).

Seeger, C.M., Nuelle, L.M., Day, W.C., Sidder, G.B., Marikos, M.A., and Smith, D.C., 2001, Geologic maps and cross sections of the mine levels at the Pea Ridge iron mine, Washington County, Missouri, U.S. Department of Interior miscellaneous field studies map MF-2353, 6 p.

Shah, A.K., Bedrosian, P.A., Anderson, E.D., Kelley, K.D., and Lang, J., 2013, Integrated geophysical imaging of a concealed mineral deposit: A case study of the world-class pebble porphyry deposit in southwestern Alaska: Geophysics, v. 78, no. 5, p. B317-B328.

Shoberg, T., and Stoddard, P.R., 2013, Integrating stations from the north America gravity database into a local GPS-based land gravity survey: Journal of Applied Geophysics, v. 89, p. 76-83.

Sidder, G.B., Day, W.C., Nulle, L.M., Seeger, C.M., and Kisvarsányi, E.B., 1993, Mineralogic and fluid-inclusion studies of the Pea Ridge iron-rare-earth-element deposit, Southeast Missouri: U.S. Geological Survey bulletin 2039, p. 205-216.

Sides, J.R., Bickford, M.E., Shuster, R.D., and Nusbaum, R.L., 1981, Calderas in the Precambrian of the St. Francois Mountains, Southeastern Missouri: Journal of Geophysical Research, vol. 86, no. B11, p. 10349-10364.

Sims, P.K., Kisvarsányi, E.B., and Morey, G.B., 1987, Geologic and metallogeny of Archean and Proterozoic basement terranes in northern midcontinent, U.S.A. - An overview: U.S. Geological Survey bulletin 1815, 51 p.

Sims, P.K., and Petermar, Z.E., 1986, Early Proterozoic Central Plains Orogen: A major buried structure in the north-central United States: Geology, v. 14, p. 488-491.

Stewart, S.W., 1968, Crustal structure in Missouri by seismic-refraction methods: Bulletin of the Seismological Society of America, vol. 58, no. 1, p. 291-323.

Thomas, M.D., 1999, Application of the gravity method in mineral exploration: fundamentals and recent developments, in Lowe, C., Thomas, M.D., and Morris, W.A., eds., Geophysics in Mineral Exploration: Fundamentals and Case Histories: Geological Association of Canada, Short Course Notes, v. 14, p. 73-100.

United States Geological Survey (USGS), 2013, Setting and origin of iron oxide-copper-cobalt-gold-rare earth element deposits of southeast Missouri: http://minerals.usgs.gov/east/semissouri/index.html, (accessed November 2013).

Unklesbay, A.G., and Vineyard, J.D., 1992, Missouri geology: three billion years of volcanoes, seas, sediments, and erosion, The University of Missouri Press, 189 p.

Van Schmus, W.R., Bickford, M.E., and Turek, A., 1996, Proterozoic geology of the western midcontinent basement, *in* van der Pluijm, B.A. and Catacosinos, P.A., eds., Basement and Basins of Eastern North America, Geological Society of America, Special Paper 308, p. 7-23.

Whitten, C.W., and Yancey, R.J., 1990, Characterization of the rare-earth mineralogy at the Pea Ridge deposit, Missouri: U.S. Department of Interior report of investigations 9331, 9 p.