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GEOPHYSICAL CHARACTERIZATION OF A RARE EARTH ELEMENT
ENRICHED CARBONATITE TERRANE AT MOUNTAIN PASS, CALIFORNIA
EASTERN MOJAVE DESERT

A Thesis

Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Kevin M. Denton

December 2017

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ABSTRACT

Mountain Pass, California, located in the eastern Mojave Desert, hosts one of the world's richest rare earth element (REE) deposits. The REE-rich rocks occur in a 2.5 km-wide, north-northwest trending zone of Mesoproterozoic (1.4–1.42 Ga) stocks and dikes, which intrude a larger Paleoproterozoic (1.7 Ga) schist-gneiss terrane that extends ~10 km southward from Clark Mountain to the Mescal Range. Several REE-enriched bodies make up the Mountain Pass intrusive suite including shonkinite, syenite, and granite comprising an ultrapotassic intrusive suite and the Sulphide Queen carbonatite body.

Two-dimensional modeling of gravity, magnetic, and electrical resistivity data reveals that the Mountain Pass intrusive suite is associated with a local gravity high that is superimposed on a ~4-km wide gravity terrace. Rock property data indicate that the Mountain Pass intrusive suite is unusually nonmagnetic at the surface (2.0×10^{-3} SI, $n=67$). However, aeromagnetic data indicate that these rocks occur along the eastern edge of a prominent north-northwest trending aeromagnetic high of unknown origin. The source of this unknown magnetic anomaly is ~2–3 km below the surface and coincides with a body of rock having high electrical conductivity. Electrical resistivity models indicate that this unknown magnetic anomaly is several orders of magnitude more conductive ($10^3 \Omega \cdot \text{m}$) than the surrounding rock. Combined geophysical data suggest that the carbonatite and its associated ultrapotassic intrusive suite were preferentially emplaced along a northwest zone of weakness and/or a fault.

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INTRODUCTION

Carbonatite ore deposits are the primary natural source of rare earth elements (REEs), which are essential in modern military defense applications, healthcare and medical devices, “green” technologies, and civilian electronics. REEs have crustal abundances similar to common industrial grade metals (for example, chromium, nickel, copper, zinc, tin, and lead); however, large economically viable REE ore deposits are uncommon (Haxel, 2005; Long et al., 2010; Verplanck and Van Gosen, 2011). Since the late 1990s, China has been the global leader in REE production with the world’s largest known REE deposit, Bayan Obo, currently producing ~95% of global demands (Haxel et al., 2002; Long et al., 2010; Hatch, 2012; Massari, 2013; USGS, 2016). Recent initiatives by China to limit exports caused dramatic fluctuations in REE value (Tse, 2011; Chakhmouradian and Wall, 2012; Ding, 2014). International concerns about increasing demand and economic and global supply vulnerability by China’s REE monopoly have prompted actions by many countries, including the United States, to explore and assess domestic sources (Alonso et al., 2012; Bleiwas et al., 2013).

Increased efforts to revive the United States REE industry have focused attention on the Mountain Pass mine in eastern California (Fig. 1), a small REE mining district in the eastern Mojave Desert located just outside the boundaries of the Mojave National Preserve. A Proterozoic carbonatite terrane at Mountain Pass hosts the largest single reserves of light-REEs (LREEs) in North America, with proven reserves of 16.7 million metric tonnes at an average ore grade of ~8 wt% rare earth oxide (Castor, 2008; Mariano

Figure 1. Regional tectonic map showing major regional terranes adjacent to the eastern Mojave Desert region (modified from Theodore et al., 2007; Burchfiel and Davis, 1981, 1988). Red box, study area; red line, eastern limit of late Proterozoic sedimentary rocks; dashed yellow line, border, eastern limit of Paleozoic miogeocline; blue line, eastern limit of Jurassic magmatic arc; green line, eastern limit of large Cretaceous plutons; orange polygons, metamorphic core complexes.

and Mariano, 2012). Accordingly, studies focused on geologic and geophysical characterization of the Mountain Pass carbonatite terrane are essential to understanding the occurrence, extent, and genesis of local REE resources.

Although many studies of the eastern Mojave Desert crustal province have focused on its regional surface geology and geochronology (Olson et al., 1954; Hewett, 1956; Burchfiel and Davis 1971, 1988; Miller et al., 1986; DeWitt et al., 1987), none have provided detailed subsurface geophysical interpretations directly related to the geologic framework and structures associated with the eight REE enriched stocks of the Mountain Pass REE intrusive suite (MPRIS). This geophysical study aims to provide much needed insight into the overall framework for identifying and characterizing the structural setting for this spatially and chemically similar, northwest-trending REE suite at Mountain Pass, California.

Geophysical studies are useful in identifying and characterizing geologic structures and their subsurface extent. Geologic structures typically produce geophysical signatures, such as gravity, magnetic, and resistivity anomalies that can be detected using surface gravity, magnetic, and electrical techniques. In general, carbonatites and associated alkaline rocks have distinct regional and local gravity and magnetic signatures because they contain relatively dense mineral assemblages with primary or secondary magnetite.

Appreciable variations in gravity and magnetic responses are produced as a result of lateral changes in mass and magnetic distribution of geologic sources at depth. Geologic offsets for any structure (e.g., faults, dikes, etc.) cutting through a dense or magnetic body

produce quantifiable offsets in gravity and magnetic anomalies. For example, sedimentary rocks and basin fill are generally less dense and weakly magnetized and produce smaller density and magnetic effects relative to underlying dense and often magnetic crystalline rocks, which makes it possible to resolve the structural extent of an underlying crystalline basement using gravity and magnetic methods (Blakely, 1995). Variations in electrical conductivity could also result from variations in rock properties of geologic sources at depth.

Conductive and resistive imaging of the subsurface can provide important constraints on the crustal fluid distribution and hence on the mechanical and dynamic state of structures related to the MPRIS (Peacock et al., 2015). The magnetotelluric (MT) method, is an electrical technique that is especially sensitive to any fluids or hydrothermal mineralization associated with geologic structure, such as faults, that are often highly conductive. Enhanced conductivity is commonly attributed to deformation-enhanced porosity and permeability that creates high fluid connectivity that contains pore space, sufficient to produce significant conductive anomalies.

Fluid-filled interconnected pore spaces can increase the overall bulk rock conductivity of the subsurface features (Olhoeft, 1985; Peacock et al., 2016). Electrically conductive features are especially pronounced when compared to competent resistive basement rocks, which can differ by several orders of magnitude. Combining data from diverse geophysical techniques can thus provide better characterization of the subsurface structures related to the Mountain Pass rare earth element intrusive suite.

Gravity, magnetic, and electrical resistivity data are used in this study to constrain the subsurface geology and extent of the Proterozoic Mountain Pass REE intrusive suite at Mountain Pass, California. The primary goals of this study are to: (1) construct new isostatic gravity and magnetic anomaly maps of the area; (2) develop and interpret structural geologic models using two-dimensional (2D) potential field modeling of the geophysical data as constrained by rock physical properties, geologic mapping, and other subsurface data where available. Results of this work will serve as a foundation to future studies in the eastern Mojave Desert region and contribute to the overall understanding of the REE deposits.

GEOLOGIC BACKGROUND

Mountain Pass is a small mining district located in the eastern part of the Mojave Desert at the complex transition between the Mojave Desert and the Basin and Range physiographic province (Fig. 1). This district lies east of the termination of the sinistral Garlock fault and in close proximity to other regional Cenozoic and Mesozoic fault systems (Hewett, 1956; Jennings et al., 1977). Mountain Pass lies along the central portion of a northwest-trending mountain belt, which is bound by Shadow Valley to the west and Ivanpah Valley to the east (Fig. 2; Olson et al., 1954; Hewett, 1956; Wooden and Miller, 1990). This northwest-trending mountain belt that forms the topographic high of the region includes, from south to north, the Ivanpah Mountains, Mescal Range, Mohawk Hill, and Clark Mountain Range (Fig. 2).

Proterozoic autochthonous metamorphic basement rocks are among the oldest rocks found in the Mountain Pass region and demonstrate its early geologic history (Fig. 2). Gneissic basement exposures that make up the eastern section of these ranges are part of the Mojave crustal province, an area of regional magmatism, high-grade metamorphism and deformation related to the 1.7 Ga Ivanpah Orogeny (Wooden and Miller, 1990).

Orogenic processes transformed older crustal rocks from the early arc setting of the region to upper amphibolite- to lower granulite-facies metamorphic rocks that comprise the 1.7 Ga Ivanpah gneissic basement complex (Hewett, 1956; Wooden and Miller, 1990; Strickland et al., 2012). This metamorphic basement block consists primarily of gneiss and schist, with abundant leucocratic granitoid plutons, pegmatites, and alkali granite

Figure 2. Simplified geologic map of the eastern Mojave Desert region, California and Nevada (modified from Jennings et al., 1977; Stewart and Carlson, 1978). Red box denotes study area. Bold gray line enotes the Mojave National Preserve boundary; KP, Kokoweef Peak.

dikes formed by regional magmatism associated with orogenesis. Many of the foliated rocks within this basement block are characterized by north- northwest trending foliations with near vertical dips and steeply plunging, small isoclinal folds (Hewett, 1956; Wooden and Miller, 1990; Miller and Wooden, 1994; Miller et al., 2007a; 2007b).

Regional Cordilleran thrusting in the Mountain Pass locality formed the Clark Mountain thrust complex at the intersection of the Mesozoic magmatic arc and the East Sierran and Sevier thrust belts (Fig. 3). Deformation likely started in the Late Jurassic and continued through the middle Cretaceous consisting of multiple east-vergent low-angle faults (Burchfiel and Davis, 1988; Fleck et al., 1994). The Mountain Pass REE intrusive suite and minor mafic to ultramafic rocks are hosted in the basement footwall of the west-dipping Clark Mountain thrust complex. The thrust complex is comprised of a competent succession of very resistive Paleozoic to Mesozoic metasedimentary thrust sheets (~4 km-thick) that are thrust and truncated against Precambrian crystalline gneissic basement (Burchfiel and Davis, 1971, 1988). Thrust sheets of largely cratonic sequences that originated near the margin of the North American craton ~60–80 km west of their current location represent the southeastern-most expression of foreland thrusting (Fig. 3; Hewett, 1956; Burchfiel and Davis, 1971, 1988; Fleck, 1994).

Faults that trace through the eastern part of Clark Mountain and Mescal Ranges consist of at least two major north-northwest striking, sub-parallel, and west dipping (30° - 55°) thrust faults ~2 km apart (Fig. 3; Hewett, 1956; Burchfiel and Davis, 1988). The westernmost fault is the Mesquite Pass thrust, which juxtaposes Cambrian carbonates and siliciclastic units over Permian–Devonian carbonates with eastward lateral

Figure 3. Detailed geologic map of the Mountain Pass study area. Red lines, show locations of geologic and geophysical model profiles (modified from Olson et al., 1954; Burchfiel and Davis, 1971; Miller et al., 2007). Bold gray line denotes, Mojave National Preserve. Red box indicates location of Figure 4.

displacement along its upper block of at least 13 km (Fleck et al., 1994; Walker et al., 1995). The Mesquite Pass thrust is correlated to its type section in the Spring Mountains farther north and is considered to be ductile, as it carries crystalline basement and plutonic rocks in its hanging wall (Burchfiel and Davis, 1988).

The Keaney-Mollusk Mine fault is the easternmost thrust fault of the Clark Mountain thrust system and the easternmost extent of the Mesozoic Sevier foreland thrust belt in the Mountain Pass region. Sections of the thrust have been described as a brittle décollement that connects the Keaney fault in the Clark Mountain Range to its corresponding southern segment near the Mollusk Mine in the Mescal Range (Fig. 3; Burchfiel and Davis, 1988; Fleck et al., 1994). The Keaney-Mollusk Mine thrust fault is likely the youngest thrust in the Clark Mountain thrust complex that juxtaposes Paleozoic carbonates and clastic continental shelf deposits with Proterozoic metamorphic basement rocks, with an apparent total displacement of ~1.6 km (Burchfiel and Davis, 1988; Fleck et al., 1994). The Mesozoic thrust complex is truncated to the east by range-bounding Cenozoic faults discussed in more detail below.

Jurassic and Cretaceous plutons intruding the Clark Mountain thrust complex in the Mescal Range and Ivanpah Mountains are contemporaneous with plutonic activity farther south in the Mesozoic Cima Dome (Fig. 2; Hewett, 1957; Strickland et al., 2012). The region underwent Cretaceous to Paleogene large-magnitude extensional deformation that formed metamorphic core complexes along the lower Colorado River to the east and in the central Mojave Desert to the southwest (Fig. 1; Tosdal, 2007). This deformation event is characterized in the nearby Clark Mountain Range as shallow-dipping

extensional detachment faults with an intensely faulted upper crustal plate and a lower plate of mylonitized mid-crustal rocks, extending south into the Mescal Range (Burchfiel and Davis, 1988; Davis et al., 1993; Davis and Friedman, 2005).

MOUNTAIN PASS REE INTRUSIVE SUITE

The Mountain Pass REE intrusive suite (MPRIS) is one of the largest LREE deposits in the world, second only to the Bayan Obo mining district in northern China. The Sulphide Queen carbonatite body of the MPRIS is considered to be the most concentrated, single LREE ore body known (DeWitt et al., 1987; Castor and Hedrick, 2006; Haxel, 2005; Castor, 2008; Long et al., 2010). Surface exposures of the Mesoproterozoic (Statherian) MPRIS occupy a 3-km wide zone that extends ~8–10 km from the Ivanpah Mountains to the southern base of the Clark Mountain Range (Fig. 4; Olson et al., 1954). The MPRIS intrudes Paleoproterozoic (Orosirian) gneissic basement along a discontinuous northwest trend (Fig. 4). There are eight identified tabular to oblate, sill-like alkaline stocks that typically contain numerous dikes radiating away from a larger central body (Fig. 4; Olson et al., 1954; Haxel, 2005).

The Mountain Pass REE intrusive suite is composed of an ultrapotassic suite of mafic to silicic rocks (Castor, 2008; Castor and Nason, 2004; Haxel, 2005) and an ore-bearing carbonatite body. Previous workers have characterized the ultrapotassic suite by differences in mineralogy: shonkinite (<60% mafic minerals), syenite (<30% mafic minerals), and granite (<5% mafic minerals). These rocks are considered to be associated with the ~1.4 Ga carbonatite (>50% carbonate minerals) ore body at Mountain Pass (Olson et al., 1954; Dewitt et al., 1987; Haxel, 2005). Field relationships, isotope dating, and mineral studies have suggested complex spatial, temporal, and genetic relationships between the ultrapotassic suite and the carbonatite body (Olson et al., 1954; Dewitt et al., 1987; Mariano, 1989; Haxel, 2005). The ~1.42 Ga shonkinitic rocks are among the

Figure 4. Detailed geologic map of the Mountain Pass area. Related faults are black and dashed where concealed. Geophysical 2D profiles shown in red (modified from Olson et al., 1954; Burchfiel and Davis, 1971, 1988; Fleck et al., 1994). Refer to Figure 3 for map legend.

oldest rocks and make up ~60% of the MPRIS exposures (Olsen et al., 1954; Dewitt et al., 1987; Premo, 2015). Cross cutting of shonkinite by syenite and granite, back-intruding of shonkinite into itself, as well as co-magmatic mingling and mixing of shonkinite and syenite have also been documented (Olsen et al., 1954; Haxel, 2005). Shonkinite dikes are also observed cutting older sills within the Sulphide Queen carbonatite stock, possibly indicating that carbonatite emplacement occurred during multiple episodes (Olsen et al., 1954; Castor, 2008).

The ~1.42 Ga ultrapotassic suite and the ~1.4 Ga carbonatite share a similar northwest trend that is approximately parallel to the regional foliation of the basement rocks. The MPRIS rocks also have similar enrichments of incompatible elements such as Sr and Ba, but are mostly enriched in light rare-earth elements (lanthanum, cerium, praseodymium, neodymium, samarium) that are primarily hosted in the ore mineral bastnasite (Fig. 5). Bastnasite is a fluocarbonate and has been the principal focus of mining activity at the Mountain Pass mine for decades (Fig. 5; Castor, 1991; Castor and Nason, 2004; Haxel, 2005; Long et al., 2010).

Although rare earth oxide (REO) enrichment is present in highly variable amounts in mafic shonkinites (2% REO; Roeder et al., 1987), and to a lesser degree throughout the other ultrapotassic rocks, only the Sulphide Queen carbonatite has been proven economical (8–15% REO; Castor and Hedrick, 2006; Haxel, 2005; Theodore et al., 2007; Castor, 2008). Enrichments in incompatible elements have prompted previous workers to suggest that the heterogeneous rocks of the MPRIS may have been cogenetic and have

Figure 5. Generalized REE spectra of igneous rocks. Concentrations normalized to chondrite for several common suites of ultramafic to intermediate tholeiitic and calcalkaline igneous rocks; several varieties of continental alkaline igneous rocks, shonkinite, and carbonatites from Mountain Pass and Bayan Obo. Bracketed numbers indicate chondrite-normalized La/Yb, indicating the degree of REE fractionation (modified from Haxel, 2005).

evolved from a single, mantle-derived magmatic source (Woyski, 1980; Woolley, 2003; Castor, 2008), as supported by experimental petrologic studies (Gittins, 1989; LeBas, 1989; Wyllie, 1989).

Several subparallel high-angle faults span the study area in close proximity to outcrops of the MPRIS. High-angle faults include, from southwest to northeast, the Kokoweef, South, Middle, and North faults (Fig. 4; Olson et al., 1954; Walker et al., 1995). These faults generally trend north-northwest and dip steeply ($\sim 70^\circ$) to the southwest (Burchfiel and Davis, 1988; Davis et al., 1993; Walker et al., 1995). Motion indicators along many of these faults are rare but are generally thought to be mostly left-lateral (Hewett, 1954; D. Miller, personal communication, 2016).

The Kokoweef fault, also known as the southern extent of the Clark Mountain fault, is recognized as a normal north-northwest trending fault that extends at least 9.5 km from its southern exposure in the northeastern Ivanpah Mountains and cuts Kokoweef Peak before terminating in the eastern Mescal Range (Fig. 4). Across this fault, Mesoproterozoic crystalline basement gneiss (Xg) to the east is juxtaposed against Paleozoic carbonates (CSz, Cd, PDI) and Mesozoic sandstones (Ja) and volcanics (Kv) to west (Hewett, 1956; Walker et al., 1995). Vertical displacements of Triassic Moenkopi formation marker beds along the Kokoweef fault trace are estimated to be offset ~ 300 m (Hewett, 1956).

At its northwestern-most extent, the Kokoweef fault is intersected by the west-northwest trending South fault that bends prominently to the west and constitutes a bounding structure of the Mescal Range (Fig. 4). Units are truncated and down-dropped

where the two faults converge, although it is not entirely clear which fault segment continues north to eventually cut the eastern Mohawk Hill, just west of the Sulphide Queen carbonatite body (Fig. 4). This report follows the interpretations and nomenclature of Walker et al. (1995) who trace the continuation of the South fault northward, west of the MPRIS. Both the Kokoweef and South fault are thought to be some of the youngest faults in the area, as they truncate all post-Jurassic magmatic rocks, including the Late Jurassic Ivanpah pluton and late Early Cretaceous Delfonte volcanics (Fleck et al., 1994; Walker et al., 1995).

The Middle fault is a north-northwest trending fault adjacent to and subparallel to the South fault (Fig. 4). The Middle fault was mapped by Olson et al. (1954) as a ~3-km-long linear trace that begins west of Mineral Hill (a syenite body), through the western edge of “Pop’s Pluton” (a large shonkinite body intruded by syenite), and extending northwestwards before it is concealed beneath alluvial deposits north of Interstate 15, near Mexican Well (Fig. 4). It is unclear if the Middle fault continues northwest along this trend and joins the Celebration fault, a northwest-striking fault with apparent left-lateral offset that cuts the Sulphide Queen ore body at Mountain Pass (Fig. 4).

The North fault is a northwest-trending left-lateral fault that extends for at least 8 km and is thought to continue an unknown distance northwest of Mountain Pass (Fig. 4). The fault cuts metamorphic rocks just north of Wheaton Springs and traverses discontinuously until passing only a few meters north of the REE-enriched Birthday shonkinite-syenite body at Mountain Pass. Olson (1954) reports “considerable” displacement and an abrupt truncation of the Birthday body and associated dikes related

to the North fault contact. The North fault continues northeast ~0.5 km beyond Mountain Pass where it is concealed beneath shallow alluvium before surfacing north of the Mohawk Hill summit. Here, the fault displaces at least 350 m of Precambrian metamorphic rocks from the Paleozoic and Mesozoic geologic units (Olson et al., 1954).

GEOPHYSICAL STUDIES

Geophysical studies are useful in identifying and characterizing geologic structures and their subsurface extent. Geologic structures typically produce gravity, magnetic, and electrical anomalies that can be detected using gravity, magnetic, and magnetotelluric (MT) techniques. In general, carbonatites have distinctive gravity, magnetic, and radiometric signatures because these deposits are relatively dense, are often magnetic, and contain thorium and/or uranium.

Discernable density contrasts associated with different rock masses produce variations in the Earth's gravity field that are consistent with the distribution of mass in the subsurface. Lateral changes can be indirectly measured and interpreted from calculated densities of local rocks to determine geologic sources. Known mineral compositions that make up the MPRIS rocks at Mountain Pass are very dense when compared to crustal averages ($\sim 2.7 \text{ g/cm}^3$). For example, the Sulphide Queen carbonatite contains $\sim 25\%$ barite (4.50 g/cm^3), $\sim 15\%$ Ce-bastnasite (4.90 g/cm^3), and $\sim 60\%$ dolomite (2.87 g/cm^3), resulting in specific gravity values high enough to produce discernable gravity anomalies that are used to approximately determine the underlying bodies related to the MPRIS.

Unaltered crystalline rocks typically contain variable amounts of magnetic minerals, most commonly magnetite, enough to produce discernible changes in the Earth's magnetic field that can be measured using magnetic techniques (Blakely, 1995). Sedimentary rocks and basin fill are generally weakly magnetized and produce smaller magnetic effects, which makes it possible to resolve the structural extent of an underlying

crystalline basement using magnetic anomalies (see Blakely, 1995). Any faults cutting through a magnetic body can produce measurable offsets in magnetic anomalies across the fault.

Electrical resistivity changes due to lithology and/or the presence of subsurface fluids (for example, anisotropy of mineral phase changes, partial melts, hydrothermal and metamorphic fluids) can vary by orders of magnitude (e.g., Olhoeft, 1985). Electrical methods are highly sensitive to resistivity changes within the subsurface, and one distinct advantage is that MT methods can ascertain both directional and depth information related to subsurface resistivity structures (Peacock, 2015). Thus, coupled with gravity and magnetic results, MT data can provide additional constraints on the geophysical framework of the Mountain Pass carbonatite terrane.

Although many regional geologic studies have been focused on the eastern Mojave Desert crustal province (Olson et al., 1954; Hewett, 1956; Burchfiel and Davis, 1971, 1988; Miller et al., 1986; DeWitt et al., 1987; Miller et al., 1991; Miller and Wooden, 1993), few have included geophysical interpretations. Previous geophysical studies in this area have primarily been conducted on a regional scale or focused on localities adjacent or outside the Mountain Pass area (Fig. 6; Carlisle, 1982; Hendricks, 2007; Langenheim et al., 2009).

Previous gravity and magnetic studies of the Mojave National Preserve (MNP) region focused on groundwater resource assessments. Langenheim et al. (2009) suggested that the basins within the MNP are shallow, with <1 km of Cenozoic fill. The deepest basins of the region are greater than 1 km deep and occur ~100 km south of Mountain Pass near

Figure 6. Regional topographic map showing locations of previously collected gravity measurements in the Mojave National Preserve and vicinity (modified from Langenheim et al., 2009). Blue bold line, Mojave National Preserve; red box, Mountain Pass study area.

the southernmost extent of the MNP (Langenheim et al., 2009). In addition, regional aeromagnetic data have been used to help identify Cenozoic faulting in the region (Langenheim et al., 2009). Previous regional geophysical studies of areas adjacent to Mountain Pass conducted by the U.S. Geological Survey are summarized in Langenheim et al. (2009).

However, these earlier studies lack the resolution (station density) and location accuracy that is easily achievable with modern high-resolution GPS (sub-meter resolution), which limits interpretations of subsurface geology. In addition, recent advances in statistical analysis associated with data reduction that include filtering and forward modeling (2D gravity modeling) have greatly improved measurement accuracy and resolution of geophysical anomalies (Blakely, 1995; Phillips, 2007; Phillips et al., 2007). Furthermore, gravity and MT coverage near Mountain Pass is either sparse or nonexistent, as very few constraints have been placed on the subsurface geology and structure of the REE intrusive suite. Using high-resolution gravity and MT techniques with regional magnetic data, this study will contribute to the overall geophysical database and provide new insights and interpretations on the subsurface geologic structures associated with the Mountain Pass carbonatite terrane.

GEOPHYSICAL METHODS

To improve the overall understanding of the geophysical and structural framework of the Mountain Pass carbonatite terrane, this study uses a complement of geophysical methods, including gravity, magnetic, and MT methods that are constrained by geologic observations and rock physical property measurements. GPS data were collected at each station to ensure location accuracy. From May 2011 to August 2014, >2,300 gravity stations, ~640 rock specimens, and 19 MT stations were collected in the Mountain Pass study area.

The SI system of units is used throughout the report. Density is measured in kg/m^3 , susceptibility is a dimensionless unit that measures the degree to which a rock may be magnetized, gravity units are in milligals (mGal), magnetic field is measured in nanoteslas (nT), and electrical resistivity is reported in Ohm-meter ($\Omega\cdot\text{m}$).

Rock Physical Properties

In addition to field surveys, geophysical techniques rely heavily on the physical properties of the rock units themselves, as they often correlate directly to the observed geophysical anomalies. Typically, physical property measurements such as density and magnetic susceptibility are performed on whole rock samples to adequately characterize the geologic units or structures unique to a given study area (Table 1). Density and magnetic susceptibilities were determined on >600 rock samples collected throughout the field area at key geologic locations (Fig. 7). Combined, these new data were used to constrain the 2D geophysical models presented in this study.

Table 1. Physical Properties of Selected Rock Samples from the Study Area.

Label	N (# of samples)	Average density (kg/m³)	Average susceptibility (10⁻³ SI)	% magnetite
Kt	21	2610	0.33	0.01
Kv	2	2613	3.47	0.09
Ja	2	2523	0.04	0.00
CZs	3	2645	1.36	0.03
PDI	11	2712	0.02	0.00
Cd	49	2730	0.01	0.00
AM	27	2974	16.29	0.41
MO	157	2670	1.92	0.05
GT	54	2612	0.80	0.02
Yc	76	3009	0.80	0.02
Ysy	50	2671	5.66	0.14
Ysh	51	2794	2.03	0.05
Xg	142	2729	7.38	0.18

Kt, Cretaceous Teutonia adamellite; Kv, Cretaceous Delfonte volcanics; Ja, Jurassic Aztec Sandstone; CZs, Cambrian quartzite; PDI, Paleozoic carbonates; Cd, Cambrian Dolomite; AM, amphibolite; MO, monzogranite; GT, Paleozoic and Precambrian granite to granitic gneiss; Yc, Precambrian carbonatite; Ysy, Precambrian syenite; Ysh, Precambrian shonkinite; Xg, Precambrian gneiss (refer to detailed geologic map and models for comparison).

Figure 7. Simplified geologic map of the eastern Mojave Desert region showing rock sample locations (black triangle). Precambrian basement rocks, brown; Paleozoic rocks, purple and blue; plutons in pink and blush.

Densities were determined using a high-precision Sartorius electronic balance (Table 1). All rock samples were weighed dry in air, saturated in water, and saturated with water in air, to determine grain density, dry bulk density, and saturated bulk density, respectively. Magnetic susceptibilities were measured using GF Instruments SM-20 or Terraplug KT10 magnetic susceptibility meters. These instruments calculate volume susceptibility by assuming the sample is an infinite half-space. The instrument's ability to measure magnetic susceptibility is affected by surface roughness, weathering, and sample size, all of which can result in an underestimation of a sample's true susceptibility. The magnetic-susceptibility values reported here represent an average of multiple readings on each sample (Table 1).

Gravity

Detailed gravity surveys were collected throughout the study area between May 2011 and September 2014 at 2,321 stations concentrated in areas of poor control, as well as along traverses of interest, using LaCoste and Romberg and/or Scintrex CG-5 gravity meters (Fig. 8). Station spacing varied from ~100–400 m, with denser spacing near geophysical or geologic targets of interest. Data were collected across parts of Shadow Valley, Clark Mountain Range, Mescal Range, Ivanpah Mountains, Cima Dome, Spring Mountains, Ivanpah Valley, Lucy Grey Mountains, and New York Mountains (Fig. 8). Individual surveys consist of a number of “survey loops”, beginning and ending each day at the same established “base station” (e.g., Denton and Ponce, 2016). All gravity data were tied to primary base stations (PRIMM and PVR-A) in Primm, Nevada and/or a secondary field base station (MTN PASS). These stations were ultimately tied to a high-

Figure 8. Simplified geologic map showing gravity station locations in the eastern Mojave Desert, region. Red circle, new gravity station collected as part of this study; gray circle, pre-existing gravity station (Ponce, 1997; Langenheim et al., 2009); black triangle, physical-property site location; black square, Thor REE deposit site; bold gray line, Mojave National Preserve boundary. See Figure 2 for additional explanation.

precision gravity base station (PB1021) near Baker, California described by Robert and Jachens (1986) as part of their southern California high-precision gravity base station network, and to a World Relative Gravity Reference Network of North America gravity base station at Nipton, California (Jablonski, 1974).

Gravity data were processed using standard methods (Blakely, 1995) and included the following corrections: (1) an earth-tide correction, which corrects for tidal effects of the Moon and Sun; (2) an instrument-drift correction, which compensates for drift in the instrument's spring; (3) a latitude correction, which accounts for variation in the Earth's gravity with latitude; (4) free-air correction, which accounts for the variation in gravity due to elevation relative to sea level; (5) a Bouguer correction, which corrects for the attraction of material between the station and sea level; (6) a curvature correction, which corrects the Bouguer correction for the effect of the Earth's curvature; (7) a terrain correction, which removes the effect of topography to a radial distance of 167 km from attraction of material between the station and sea level; and (8) an isostatic correction, which removes long-wavelength variations in the gravity field related to the compensation of topographic loads.

LaCoste and Romberg and Scintrex CG-5 gravity meters were used in this study. Gravity meter readings were converted to gravity units for LaCoste and Romberg gravity meters by using factory calibration constants, as well as secondary calibration factors determined by multiple gravity readings over the Mount Hamilton calibration loop east of San Jose, California (Barnes et al., 1969). For the Scintrex CG-5 gravity meters, the factory meter calibration was checked and a secondary calibration factor was determined

over the Mount Hamilton calibration loop. Observed gravity values were based on a time-dependent linear drift between successive base readings and referenced to the International Gravity Standardization Net 1971 (IGSN 71) gravity datum (Morelli, et al., 1971). Free-air gravity anomalies were calculated using the Geodetic Reference System 1967 formula for theoretical gravity on the ellipsoid (International Union of Geodesy and Geophysics, 1971, p. 60) and Swick's (1942, p. 65) formula for the free-air correction. Bouguer, curvature, and terrain corrections were added to the free-air anomaly to determine the complete Bouguer anomaly at a standard reduction density of $2,670 \text{ kg/m}^3$. Finally, a regional isostatic gravity field was removed from the Bouguer field by assuming an Airy-Heiskanen model for isostatic compensation of topographic load (Roberts and Jachens, 1999), with an assumed nominal sea-level crustal thickness of 25 km, a crustal density of $2,670 \text{ kg/m}^3$, and a density contrast across the base of the crust of 400 kg/m^3 .

All geophysical data and sample collection are spatially located using high- resolution Trimble GeoXH and/or Trimble Geo 7 handheld units. Dual-frequency and carrier-phase receivers are capable of accessing multiple global satellite networks for triangulation. This technology reports preprocessed positional accuracies that are often less than 15 cm in the horizontal direction and 20 cm in the vertical direction after post- processed differential corrections are applied. Data were post-processed and differentially corrected for better accuracy by using time-varying factors established at known GPS reference stations (for example, Continuously Operating Station receivers or CORS).

Established by the International GPS Service, CORS station P621 located at Mountain Pass, California was utilized to post-process all GPS data using Trimble Pathfinder™ software.

Aeromagnetism

Aeromagnetic data were derived from statewide compilations of surveys flown over California (Roberts and Jachens, 1999) and Nevada (Kucks et al., 2006). The aeromagnetic anomaly map presented in this study reflects a compilation of numerous individual aeromagnetic surveys that span several decades and range in scale and resolution (Fig. 9). These surveys were flown at various flight-line elevations and spacings and were mosaicked together by Roberts and Jachens (1999) and Kucks et al. (2006). Individual surveys were either mathematically upward- or downward-continued to a constant elevation of 305 m above the ground, adjusted to a common datum, and merged to produce a uniform map with a grid spacing of 500 m (Roberts and Jachens, 1999; Kucks et al., 2006). Although composed of multiple surveys acquired with different specifications, this compilation allows for seamless interpretation of magnetic anomalies across survey boundaries.

The regional aeromagnetic survey that was flown in 1975 (survey #53, Fig. 9) lacks the resolution typical of the other surveys (for example, #18, Fig. 9), with a flight-line spacing of 1.6–3.2 km and a flight-line elevation of 2.7 km. A typical high-precision aeromagnetic survey would now be flown “draped” at a constant ~150-m elevation above topography, a 200-m flight-line spacing, and utilize GPS navigation. Widely-spaced surveys or those flown at higher flight-line elevations lack the resolution needed to

Figure 9. Shaded-relief topographic map showing the extent of individual aeromagnetic surveys and their specifications in the eastern Mojave Desert region (Roberts and Jachens, 1999; Kucks et al., 2006). Specifications include survey identifier, flightline spacing, flightline elevation, flightline direction, and year flown. Warm colors (pink), high-resolution survey; Cold colors (blue), low-resolution survey; AG, constant terrain clearance above ground; B, barometric.

resolve shallow magnetic sources in some parts of the aeromagnetic map. However, these issues are not significant for the generalized and regional-scale magnetic interpretations presented in this study.

Magnetotellurics

Electrical resistivity stations were collected along a single, ~40-km-long, east- west profile (Fig. 10) using MT equipment developed by Zonge International during an October 2016 field session. Station spacing varied from ~1–5 km, with closer spacing near the MPRIS (Fig. 10). The MT system consists of a ZEN 32-bit data logger, four ANT-4 induction coils (1000-0.001 Hz), and Borin Ag-AgCl electrodes. Individual MT stations were deployed along Interstate 15, perpendicular to the regional strike of the mountain ranges. At each station, instrumentation was set up in a cross pattern with four electrodes spaced 50 m apart from the data logger and recorded for a ~20-hr durations.

All MT data processing and modeling were performed by Dr. Jared Peacock of the U.S. Geological Survey. MT transfer functions were estimated using Zonge International processing software using synchronous stations as remote references. All collected time series of electrical and magnetic data were processed in the frequency domain using Fourier transforms to estimate the impedance tensor, which contains frequency and directional information related to the regional resistivity structure and electrical response of the subsurface for modeling (Kunetz, 1972).

Figure 10. Simplified geologic map of the eastern Mojave Desert region showing the locations of MT stations (magenta triangles). See Figure 2 for additional explanation.

DATA PROCESSING

Gravity and Magnetic Processing

In general, geophysical methods utilize the inherent variations of rock properties to characterize the Earth's subsurface. Indirect measurements conducted by geophysical instrumentation (gravimeter, magnetometer, MT systems) measure spatial changes at the surface that correspond to geologic sources at depth. When these observed variations are corrected and processed for non-geologic effects, discernable geologic structure can be interpreted. In the case of gravity and magnetic data, colored anomaly maps were constructed to illustrate gradients in density and magnetization (Figs. 11–14).

In addition, 2D forward gravity and magnetic models and a 2D resistivity model were developed to image subsurface geology. To investigate gravity and magnetic anomalies caused by intrusive rocks in the Mountain Pass area, computer-driven filtering techniques in the Fourier transform domain were used to enhance embedded signals. For example, geophysical gradients often define abrupt changes in density and magnetic signatures and can be filtered to reflect more discrete boundaries related to subsurface geology. Characterizing lateral gradients can constrain and delineate fault boundaries or geologic contacts across which density and magnetization change.

In general, gravity data require far less filtering than magnetic data to produce meaningful results (such as anomaly maps) because of the ability to treat data as single point source values. In gravity modeling, the dominant vector force direction is always “down” or vertical. Therefore, the “single point” approach to processing gravity data

Figure 11. Isostatic gravity anomaly map of the eastern Mojave Desert region. Black dots, gravity station locations; red lines, location of geophysical models; warm colors (pink to red) gravity highs; cool colors (green to blue) gravity lows.

Figure 12. Aeromagnetic map of the eastern Mojave Desert region. Red lines, location of geophysical models; warm colors (pink to red) magnetic highs; cool colors (green to blue) magnetic lows. Broad, circular to elongate, and long-wavelength magnetic anomalies reflect exposed or concealed plutons. High-amplitude short-wavelength anomalies reflect volcanic rocks. A local magnetic high near the Mountain Pass area probably reflects a magnetic intrusive body rather than the carbonatite because the carbonatite is essentially non-magnetic.

Figure 13. Detailed gravity map of the Mountain Pass REE intrusive suite that includes carbonatite (red), syenite (pink), and shonkinite (blue). Warm colors (orange to yellow) denote gravity highs, whereas cool colors (blue to purple) denote gravity lows. Colors of REE-enriched bodies do not reflect density but rather symbology. Fine black lines denote gravity gradient contours, whereas bold black lines denote high-angle faults. Red lines indicate modeled geophysical profiles. Note that the REE intrusive suite occurs within a ~3.5-km-wide gravity terrace (green) roughly defined by the Kokoweef/South fault to the west and Wheaton Wash fault to the east.

Figure 14. Detailed aeromagnetic map of the Mountain Pass REE intrusive suite that includes carbonatite (red), syenite (pink), and shonkinite (blue). Note, colors of REE bodies do not reflect magnetization but rather symbology. Warm colors (orange to yellow) denote magnetic highs, whereas cool colors (blue to purple) denote magnetic lows. Bold black lines denote high-angle faults. Open black circles indicate maximum horizontal gradients of magnetic data. Straight red lines indicate modeled geophysical profiles gravity/magnetic profiles (BB', CC') and magnetotelluric profile (MT'). Note, REE suite occurs along the eastern edge of a northwesttrending, prominent magnetic high that is well defined by strong horizontal gradients.

used to produce isostatic anomaly data is simplified. However, magnetic data are more complex and filtering usually consists of several stages that account for complexities that range in scope from dipole effects, shapes of producible anomalies that can vary dramatically with respect to the orientation of the Earth's magnetic field, as well as the variations that arise in the geometries and individual magnetization directions of the source bodies themselves (Fig. 15).

Reduction to the pole

Unlike gravity anomalies, which are centered over their sources, magnetic anomalies experience phase distortions that produce an asymmetrical offset over their respective magnetic sources (Figs. 16 and 17; Blakely and Simpson, 1986; Blakely, 1995). The shape and phase of the anomaly produced depends in part on the magnetic inclination and the presence of any remnant magnetization that produces dipolar effects (Fig. 15). Unless the magnetization and ambient field associated with an anomaly are directly vertical in inclination (for example, a monopole, north magnetic pole= 90°), a phase shift may produce horizontal distortion, offsetting the anomaly laterally away from its corresponding geologic source (Fig. 16; Baranov and Naudy, 1964).

Reduction-to-pole filtering transforms phase effects resulting from the influence of the Earth's magnetic field and the magnetization direction of the source by area. This filtering process changes the inclination of magnetic anomalies from $\sim 61^\circ\text{N}$ to directly vertical ($= 90^\circ$). Ultimately, reduction-to-pole filtering improves the alignment of magnetic anomalies' positions with their respective contributing sources by transforming the data to a vertically-oriented magnetic monopole and reducing asymmetry.

Figure 15. Magnetic dipole effect for two different inclinations before and after reduced to the pole (Sherrif, 2013; reprinted with the permission of Steve Sherrif).

Figure 16. Magnetic anomaly profile before and after being reduced to the pole (Blakely1996; reprinted with the permission of Rick Blakely)

Figure 17. A magnetic anomaly and its pseudogravity transformation (Blakely 1996; reprinted with the permission of Rick Blakely)

Magnetic potential (or pseudogravity) map

To emphasize magnetic sources, the reduced to the pole aeromagnetic anomalies are transformed into pseudogravity (or “magnetic potential anomalies; Baranov, 1957). The magnetic potential filtering procedure allows magnetic anomalies to be directly compared to their corresponding gravity fields, by converting the magnetic field to the “gravity” field that would be produced if all magnetic material was replaced by proportionately dense material. Because the magnetic and gravity potentials are related by a directional derivative, the measured total magnetic field can be transformed into an equivalent gravity potential field that assumes a density distribution proportional to the magnetization distribution (Baranov, 1957; Blakely, 1995).

The magnetic potential transformation amplifies long wavelengths likely caused by deep sources and attenuates short wavelengths usually caused by shallow sources (Fig. 17; Blakely and Simpson, 1986; Blakely, 1995). The magnetic potential transformation is a useful strategy in geophysical interpretations because magnetic maps are often more complex than gravity maps. In addition, “noise” or “chatter” related to regional sources or geologic bodies other than those of interest can interfere with the interpretation of deeper magnetic sources.

Maximum horizontal gradients

As described by Blakely and Simpson (1986), maximum horizontal gradients were calculated from both the isostatic gravity and magnetic potential data to approximate the edges of geophysical sources (Fig. 18). Using these derivative methods, maximum horizontal gradient filtering emphasizes edges of gravity and magnetic anomalies

Figure 18. A magnetic anomaly, pseudogravity anomaly, and magnitude of the horizontal gradient over a tabular body (Blakely 1996; reprinted with the permission of Rick Blakely)

associated with the steep margins that separate contrasting densities or magnetizations (Cordell and Grauch, 1985). Estimating magnetic horizontal gradients is especially effective for resolving shallow sources related to lineaments, faults, and subsurface geologic features (Blakely and Simpson, 1986; Grauch and Cordell, 1987; Blakely, 1995).

Matched filtering

Matched filtering techniques were applied to both Fourier-transformed isostatic gravity and magnetic data using wavelength sensitive band-pass separation to identify horizontal subsurface depths. This technique relies on the assumption that the crust is comprised of horizontal layers and that density and magnetic anomalies are a function of depth (Syberg, 1972b). Using an algorithm described by Phillips (2007), horizontal surfaces were calculated by matching the average radially symmetric wavelength from the power spectrum to approximate maximum average depth to the top of the sources within each layer (Phillips et al., 2007).

Gravity or magnetic data were matched filtered using a three-layer equivalent model that consisted of shallow, intermediate, and deep half-space layers (e.g., Syberg, 1972a; Phillips, 2007; Phillips et al., 2007). The matched filters were then applied to the isostatic gravity and magnetic anomaly fields to separate anomalies originating at different depths. Note that the long-wavelength components of the gravity and magnetic field from deep sources are difficult to separate from the long-wavelength components of shallow sources, thus artifacts or noise related to relatively high-amplitude shallow features may be present (e.g., Hildenbrand et al., 2000; Phillips, 2007; Phillips, et al., 2007).

Magnetotelluric Processing

Passive electromagnetic techniques, such as MT, measure the Earth's electrical response to natural time-varying magnetic fields, resulting in an estimation of subsurface resistivity structure (Cagniard, 1953; Chave and Jones, 2012). The source for the electrical currents that the MT technique relies on is twofold. The primary source for periods greater than 1 s is time-varying distortions of the magnetosphere caused by solar winds. For periods smaller than 1 s, the source is global lightning strikes that propagate within the waveguide between the Earth's surface and the ionosphere (Chave and Jones, 2012). This electromagnetic energy continually bombards the Earth's surface, and a portion of the non-reflected energy diffuses into the electrically conductive Earth, inducing telluric currents. Depth of penetration depends on the frequency of the down-going magnetic wave and the electrical resistivity of the subsurface.

MT is based on the concurrent observations of both the magnetic field and induced electric field (Cagniard, 1953; Berdichevsky and Dmitriev, 2008; Chave and Jones, 2012). Using Maxwell's equations and Lorentz transformations (see Chave and Jones, 2012), the MT process is shown to be a linear relationship in the frequency domain. Moreover, conductive properties of the subsurface can be calculated from the relationship between components of the measured electric and magnetic field variations, using transfer functions (Cagniard, 1953; Berdichevsky and Dmitriev, 2008; Chave and Jones, 2012; Peacock, 2016).

2-D GEOPHYSICAL MODELS

A fundamental component of the project is the development of multiple 2-D forward models of the subsurface Mountain Pass geology for structural interpretation.

Geophysical models yield mathematically non-unique solutions because many theoretical results are possible. As explained by Saltus and Blakely (2011), non-uniqueness in geophysical modeling is intimately linked to scientific uncertainty. Although non-uniqueness is inherent to modeling, combining geologic mapping and rock physical properties with gravity, magnetic, and MT data greatly reduces uncertainty in geologic interpretations. Geologic maps (Olson et al., 1954; Hewett, 1956; Wooden and Miller, 1990), depth to basement estimates (Langenheim et al., 2009), and geologic cross-sections of the Ivanpah quadrangle (Olson et al., 1954; Hewett, 1931, 1956; Burchfiel and Davis, 1988) were used with the rock physical property data to develop 2-D gravity, magnetic, and MT models of subsurface structures associated with the Mountain Pass REE intrusive suite.

Gravity and magnetic 2D forward modeling were accomplished using the GM- SYS module in the Geosoft Oasis Montaj software package. Data were modeled along three parallel southwest-northeast trending profiles (AA', BB', and CC') across the Clark Mountain Range, Mescal Range, and Ivanpah Mountains (Figs. 3 and 4). Surface geology, geologic cross sections, rock properties, drill hole, and structural information were used to independently constrain the inherent non-uniqueness of the potential-field models. The resulting models have a typical northeast-southwest orientation and are ~40 km in length and ~4 km in depth.

Density variations contribute to the spectrum of gravity anomalies shown in isostatic gravity maps (Figs. 11 and 13). Density varies as a function of rock mineralogy and porosity, ranging from about 1800 to 3000 kg/cm³ in the study area. The modeling assumes consistent density and magnetic susceptibility values along the three model profiles (Figs. 3 and 4). The rock properties for the study area were based on the work of Denton and Ponce (2016). Geophysical models (Figs. 19–21) have crystalline basement densities of 2660–2710 kg/m³, based on average physical property measurements (Table 1). Basement rock densities in the model vary slightly from west to east and stratigraphic layers were derived from published geologic maps and cross sections (Olson et al., 1954; Hewett, 1956; Burchfiel and Davis, 1988; Wooden and Miller, 1990; Walker et al., 1995).

Approximately twenty-six mapped geologic units were simplified into 13 layers with different densities and magnetizations (Table 1). All gravity and magnetic models produced from the three profiles (AA'–CC'; Figs. 19–21) include crystalline Cretaceous Teutonia adamellite basement (Beckerman et al., 1982) throughout the western margin beneath the Clark Mountain and Mescal Ranges, as it is the exposed pluton at Cima Dome in parts of the southern Shadow Valley. Models indicate that the Late Paleoproterozoic augen gneiss basement (Olson et al., 1954; Hewett, 1956; Burchfiel and Davis, 1988; Wooden and Miller, 1990) underlies most of the Ivanpah Valley (Figs. 19–21). Density and magnetic susceptibility values of modeled units vary and are based on physical rock property measurements (Table 1; Denton and Ponce, 2016).

Figure 19. Two-dimensional forward gravity and magnetic model along profile A-A' across the northern Mountain Pass study area. Mtf denotes the approximate location and orientation of the Mesquite Pass thrust fault. Ktf denotes the approximate location and orientation of the Keaney-Mollusk Mine thrust fault. Model attributes are as follows: d, density in g/cm³; s, susceptibility in SI units. Refer to Figure 3 for geologic explanation.

Figure 20. Two-dimensional forward gravity and magnetic model along profile B-B' across the central Mountain Pass study area. Mtf denotes the approximate location and orientation of the Mesquite Pass thrust fault. Ktf denotes the approximate location and orientation of the Keaney-Mollusk Mine thrust fault. Sf denotes the approximate location of the South fault. Cf denotes the approximate location of the Celebration fault. Nf denotes the approximate location of the North fault. Wwf denotes the approximate location of the Wheaton wash fault. Black lines denote faults in the region, dashed where inferred. Geophysical bodies are as follows: uga, unknown gravity anomaly; uma, unknown magnetic anomaly; up, unknown pluton. Model attributes are as follows: d, density in g/cm³; s, susceptibility in SI units. Refer to Figure 3 for geologic explanation.

Figure 21. Two-dimensional forward gravity and magnetic model along profile C-C' across the southern Mountain Pass study area. Mtf denotes the approximate location and orientation of the Mesquite Pass thrust fault. Ktf denotes the approximate location and orientation of the Keaney-Mollusk Mine thrust fault. Sf denotes the approximate location of the South fault. Mf denotes the approximate location of the Middle fault. Wwf denotes the approximate location of the Wheaton wash fault. Black lines denote faults in the region, dashed where inferred. Geophysical bodies are as follows: uma, unknown magnetic anomaly; up, unknown pluton. Model attributes are as follows: d, density in g/cm³; s, susceptibility in SI units. Refer to Figure 3 for geologic explanation.

MT model inversions were used to estimate regional resistivity structures using a 2D Occam inversion code (deGroot-Hedlin, 1991). The modeling grid consisted of 144 x 100 mesh cells, where cell width was 250 m and cell depth increased logarithmically downward, such that the total model size was 100 km x 300 km to avoid edge effects (Fig. 22). Multiple starting models and resistivity structures were tested to insure model robustness. A preferred model has a normalized root-mean-square error of 1.73 using only the transverse magnetic model with an error floor of ~20% for the apparent resistivity and an error floor of 1.4 degrees for the impedance phase (Peacock, 2016).

A number of ambiguities associated with 2D geophysical models need to be addressed. As mentioned above, all geophysical models are non-unique in that a number of geometries of bodies and physical properties could fit the models. Great effort has been made to limit this uncertainty by incorporating regional and local geologic information, as well as drill hole data when available. Thus, 2D models are best constrained where such data are available (e.g., Olson et al., 1954; Hewett, 1956; Burchfiel and Davis, 1988; Castor and Nason, 2004). Otherwise, interpretations are based on geophysical data only. The extent of the Mountain Pass carbonatite terrane related to exposed units was extrapolated into the subsurface using outcrop locations and lateral extents of these units based on interpretations of regional gravity, aeromagnetic, and MT data.

Figure 22. Two-dimensional resistivity model along profile MT', indicates that gradients at depth correspond well with geologic features in gravity and magnetic models. Conductive feature coincides with unknown magnetic anomaly (uma), constrained by convergent high angle faults (Kokoweef/South fault system).

DISCUSSION OF MODELS

In general, carbonatites and their associated alkaline terranes typically have distinct gravity, magnetic, and radioactive signatures because they are relatively dense, often contain magnetite, and are commonly enriched in thorium and/or uranium. Interestingly, the Mountain Pass carbonatite and associated intrusive suite are weakly to essentially nonmagnetic (Table 1). The surrounding Proterozoic host rocks and younger Paleozoic rocks in the region are also essentially nonmagnetic at the surface, with a few exceptions that include amphibolite rocks and small veins and dikes of fine-grained shonkinitite (Table 1).

The MPRIS is located within a “terrace” in the gravity data (Fig. 13) and coincides with the eastern edge of a prominent magnetic (Fig. 14) and conductive anomaly (Fig. 20). This magnetic anomaly is sharply defined and probably occurs at a depth of about 2 to 4 km based on matched filtering of the magnetic data (Figs. 18 and 20). Potential sources of the gravity terrace and the magnetic and conductive anomalies are discussed below.

The gravity anomaly values or gradients associated with terracing are flattened. This gravity terrace is bounded by steep, northwest gravity gradients on its western- and eastern-most edges that correlate well with the convergence of the Kokoweef and South faults to the west and a previously unreported “Wheaton Wash” fault to the east (Fig. 13). The gravity terrace is either the relatively lower density basement granitic gneiss (e.g., Xg) or other granitic intrusive rocks (e.g., Kt) and is present in model AA’–CC’ (Figs. 19–21). The source of the magnetic anomaly (“uma”) shown in models BB’ (Fig. 20)

and CC' (Fig. 21) is likely a moderately magnetic intrusive body that is not exposed at the surface but is likely associated with the MPRIS terrane. If the source of the magnetic anomaly is older than the MPRIS, then the Mountain Pass suite may have been preferentially emplaced along a pre-existing feature, and if the anomaly is younger, then vice versa.

Broad, circular to elongate, and long-wavelength magnetic anomalies reflect unexposed or concealed, unaltered plutons (Figs. 12 and 14). High-amplitude short-wavelength anomalies reflect thin volcanic rocks at the surface. A local magnetic high near the western edge of the Mountain Pass mine probably reflects a magnetic intrusive body rather than the carbonatite body because the carbonatite is essentially non-magnetic. Alternatively, MPRIS could be considered to lie entirely within a magnetic low. This raises the possibility that a hydrothermal or magmatic alteration event(s) has altered the magnetic minerals within the rocks comprising the magnetic low.

Geologic mapping and Landsat imagery suggest that the central part of the MPRIS terrane resides in a zone of alteration (David Miller, personal communication, 2016). Outside this zone is moderately to strongly magnetic (~0.5% magnetite) 1.7 Ga Proterozoic amphibolite rocks that are also very dense (Table 1). Geochronological (Premo et al., 2013) and geochemical (Stoeser, 2013) data suggest that the alkaline intrusive suite exhibits widespread hydrothermal alteration and/or multiple stages of alteration or magmatism (Stoeser, 2013; Polletti et al., 2016).

Combined alteration and magmatic events could explain some of the unusual geochemical features of the MPRIS, including extremely elevated enrichment of incompatible elements and the apparent age gap between the carbonatite (~1.4 Ga, DeWitt et al., 1987) and the ultrapotassic rocks of the MPRIS (~1.42 Ga, Premo et al., 2015). Multiple alteration events may not only have affected the Mountain Pass area but also the nearby Thor (New York Mountains) and Music Valley (near Joshua Tree National Park) REE terranes, the latter of which experienced three distinct alteration events, with the oldest event dated at ~1.4 Ga (McKinney et al., 2015).

The 2-D gravity, magnetic, and resistivity models of the study area indicate shallowing of basin fill from south to north for both Shadow and Ivanpah Valleys, with basin depths at <2 km (Figs. 19–21). Shadow Valley extends to a depth of 1–2 km west of the Clark Mountain Range and may be filled with conductive carbonaceous and clay-rich sediments derived from nearby Paleozoic outcrops (Fig. 22). The Kokoweef fault bounds the eastern edge of the Mescal Range before it is truncated by the South fault and may extend at least 4 km into the crust (Figs. 19–21). Similarly, east of the Clark Mountain Range, Ivanpah Valley is an asymmetric basin that reaches a depth of 1–2 km along its eastern margin. The western edge of Ivanpah Valley is less defined in gravity and magnetic models, although MT modeling suggests that the valley is fault-bounded with a steeply dipping component to the east (Fig. 22). The electrical resistivity model (Fig. 22) shows that the central part of Ivanpah Valley is very conductive to depths of ~10 km, which may be related to fluids or mineralization. In the section below, each profile (AA'–CC') is described in detail, including discussion of relevant features.

Model AA'

The northernmost profile AA' (Fig. 3) is a ~40-km long northeast-trend profile that crosses exposures of the southern Clark Mountain Range and clips the southernmost part of the Spring Mountains before crossing the state line and ending in northern Ivanpah Valley near Primm, Nevada. The geophysical model in Figure 19 highlights the low-angle, west-dipping structures of the Mesozoic Clark Mountain thrust complex that consists of Paleozoic carbonates (CZs, PDI, Cd) of similar density ($\sim 2700 \text{ kg/m}^3$) underlain by Cretaceous Teutonia adamellite pluton (Kt).

Based on the model, the Teutonia pluton occurs throughout the western part of the Clark Mountain Range, terminating to the east at the gneissic footwall of the Clark Mountain Range thrust complex (Fig. 19). The depth to the top of the Teutonia pluton is not well constrained beneath Shadow Valley and Clark Mountain Range. However, Teutonia pluton exposures are found throughout much of the Cima Dome area to the south and are mapped to the northwest in the Halloran Hills (outside of the study area), as well as one small exposure that outcrops through alluvial sediments ~20 km north of Cima Dome (Fig. 2). Mapped geologic surface exposures and geophysical data suggest that the Teutonia pluton is an extensive underlying basement unit for much of Shadow Valley and was thus modeled east of the Kokoweef/Keeney-Mollusk Mine faults. Shadow Valley is characterized by a low amplitude gravity and magnetic anomaly whose source is shallow and lies beneath ~1 km of basin fill. This is consistent with the low density and essentially nonmagnetic nature of the pluton (Table 1).

The eastern flank of Clark Mountain Range is composed primarily of variably magnetic gneiss (0.5–1% magnetite) and is also likely the source of the prominent gravity high that makes up the eastern half of the range. Lower density Teutonia granite not exposed at the surface is modeled beneath the Clark Mountain Range thrust complex (Fig. 19). The gneissic basement to the east, beneath Ivanpah Valley, increases in magnitude in both density and magnetic physical properties. The western half of model AA' is generally characterized by magnetic lows that span much of Shadow Valley and continue across Clark Mountain Range (Fig. 19). In contrast, east of Clark Mountain Range, Ivanpah Valley is characterized by a high-amplitude magnetic source beneath the basin. A broad gravity high characterizes most of the Clark Mountain Range and continues to the western margin of Ivanpah Valley basin (Figs. 11 and 19).

Model BB'

Model profile BB' begins just south of Interstate 15 at the eastern edge of Shadow Valley and trends northwest across basin fill before traversing the Mescal Range, continuing across the MPRIS, and terminating in Ivanpah Valley (Fig. 3). Profile BB' crosses the Sulphide Queen carbonatite (Yc; Fig. 3). Geophysical modeling results shown in Figure 20 suggest that the carbonatite is very dense ($\sim 3,000 \text{ kg/km}^3$) and essentially nonmagnetic ($\sim 0.2 \times 10^{-3} \text{ SI}$), and is a shallow-dipping ($\sim 10\text{--}15^\circ$) body that terminates along the eastern edge of a prominent northwest trending aeromagnetic high (Fig. 12).

To satisfy the calculated gravity anomaly profile, an “unknown” gravity anomaly (“uga”), an intrusive body matching the physical properties of the carbonatite Yc, must continue westward to the Kokoweef fault (Fig. 20). It should be noted that the model is non-unique and perhaps could be achieved with a thicker-bodied Yc geometry and lower attributed mass. However, the gravity and magnetic contours associated with portions of the model are well constrained and the calculated and observed responses correlate well (Fig. 20). Furthermore, geophysical data indicate that carbonatite orebody Yc and its associated ultrapotassic intrusive suite formed along the eastern margin of a prominent magnetic high (uma) in the southeastern Clark Mountain Range (Figs. 14 and 20). The source of the magnetic feature is located at 2–3 km depths below the western edge of the MPRIS and is defined by steep gradients (Fig. 14 and 20). Most notably, the eastern edge of the inferred body likely indicates a contact zone of weakness or a fault that potentially controlled the emplacement location of the MPRIS.

Model CC’

The southern-most model CC’ begins at the western edge of Shadow Valley and crosses the southern Mescal Range and the northern Ivanpah Mountains before terminating in Ivanpah Valley, just west of the California-Nevada border (Fig. 3). Model profile CC’ in Figure 21 reveals an overall thickening of the wide alluvial valley basin fill (Qa) southward for both Shadow and Ivanpah Valleys, with basin depths of ~1–2 km, which are consistent with depth to basement studies reported by Langenheim et al.

(2009). Most importantly, model CC' illustrates the southern extent of the prominent aeromagnetic anomaly (uma) that plays a key role in understanding the spatial and structural relationship between the carbonatite and associated syenite and shonkinite trend (Fig. 4).

The magnetic anomaly begins adjacent to the western edge of Sulphide Queen ore body (Yc) and extends southeast at least 5 km, closely following the westernmost margin of four syenite and one shonkinite stocks about 500 meters from the Kokoweef/South fault intersection, just west of Mineral Hill (Figs. 4 and 14). This suggests that the carbonatite and alkaline intrusive suite were preferentially emplaced along a northwest zone of weakness or fault. The source of the magnetic high is ~2–3 km below the surface and coincides with a strongly electrically conductive feature (~3 orders of magnitude higher than surrounding rock).

Model MTMT'

Magnetotelluric model profile MTMT' shown in Figure 22 is ~45 km long and trends east-northeast, from the central part of Shadow Valley, across the Mountain Pass district, and towards Nipton, California (Figs. 2 and 3). In general, basement rocks (e.g., Kt and Xg) in the study area are electrically resistive, as their crystalline structures make them less porous, reducing the ability for ions to move. In contrast, basin fill sediments shed from nearby ranges are composed of calcareous sediment, quartz grains, and clay-rich sands and gravels that are more porous and are probably fluid filled, which could explain their high conductivities. The conductive character of these sedimentary deposits can be used as an aid to approximate basin geometry. For example, Shadow Valley appears as a wedge-shaped conductive feature that tapers to the east near the base of the

Clark Mountain Range, which is consistent with the 2-D gravity and magnetic profiles (Figs. 19–21). The MT model in Figure 22 indicates that the depth of conductive basin fill for Shadow Valley is ~2 km at its deepest western extent and shallows towards the range front. Ivanpah Valley is also very conductive along its strongly defined western edge, however its depth is less clear. A highly conductive zone beneath Ivanpah Valley probably reflects connections to much deeper geologic structures.

Ivanpah Valley is ~150–300 m lower in elevation than Shadow Valley and could serve as a drain for the regional watershed, with increased hydrologic interaction between surface and groundwater fluids that likely contribute to its conductivity. However, this conductive feature continues to great depths (up to 15 km), which is unlikely to be solely attributable to enhanced penetration of meteoric waters. Possibly, this conductive anomaly along Ivanpah Valley could reflect a more complex, conductive network associated with plutons, concealed faulting, mineralization, or hydrothermal fluids.

Perhaps the most prominent feature in the MT model is a shallow (~2–3 km) conductive feature ($\sim 10^1 \Omega\text{-m}$) adjacent to the Sulphide Queen carbonatite ore body (REE mine in Fig. 22). Constrained beneath MT stations 7–10, this conductive feature is ~3-km wide and is cut by the concealed and inferred trace of the Kokoweef fault. While its spatial extent is not well constrained beyond this profile, it is well constrained just west of the Sulphide Queen ore body and correlates well with a prominent magnetic high (uma). Finally, MT stations 14–15 cross near-surface exposures of syenite and shonkinite, which indicate that portions of the intrusive suite could be conductive and that the MPRIS may occupy a larger spatial extent than previously reported (Fig. 22).

SUMMARY AND CONCLUSIONS

Geophysical investigations of the eastern Mojave Desert carbonatite terrane have improved the understanding of its subsurface geologic structures and features related to the REE suite at Mountain Pass, California. Geophysical modeling indicates that the Mountain Pass REE intrusive suite is spatially associated with the eastern margin of a prominent magnetic and conductive feature beneath the southeastern Clark Mountain Range and northeastern Mescal Range. The width of the magnetic high is about 3 km, as defined by its steepest gradient. The source of the magnetic high is located along the western edge of the MPRIS at a depth of about 2–3 km (Figs. 14 and 19–21). Most notably, the eastern edge of the magnetic body likely indicates a preferential zone of weakness or possibly a fault that accommodated the emplacement of the MPRIS.

The moderately magnetic and conductive feature is also relatively low density and probably reflects a granitic pluton or zone of alteration that occurs along the western edge of the carbonatite ore body. This magnetic and conductive feature could have structurally controlled the location of the carbonatite deposit. East of this inferred pluton, a broad magnetic low may indicate hydrothermal alteration, which could be responsible for remobilization and enrichment of the deposit. To the west of the Clark Mountain Range, Shadow Valley is a 1- to 2-km deep basin filled with clay-rich sediments and its eastern edge is bounded by the near-vertical Kokoweef fault that extends to a depth of at least 3 km (Figs. 19–21). On the east side of the Clark Mountain Range, Ivanpah Valley is composed of a 1- to 2.5-km deep basin probably filled with conductive clay-rich sediments. The west side of Ivanpah Valley is bounded by the high-angle, east-dipping

Ivanpah Fault, which could extend to a depth of at least 10 km (Figs. 19–21). Magnetic and conductive anomalies in the central part of Ivanpah Valley could reflect a zone of hydrothermal alteration or mineralization (Figs. 19–22). Combined geophysical and geologic investigations of the eastern Mojave Desert carbonate terrane provide new insights into the structural framework of the Mountain Pass REE deposit.

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