Three-Dimensional Electrical Resistivity Characterization of Mountain Pass, California and Surrounding Region

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Abstract The Sulphide Queen carbonatite deposit at Mountain Pass in southeast California is a world class rare earth element (REE) resource. This study images electrical resistivity structure of the REE deposit and surrounding area to characterize resources under cover. An east-west elongated grid (35 × 15 km) of 65 wideband magnetotelluric stations spanning from eastern Shadow Valley to eastern Ivanpah Valley were collected and modeled in three-dimensions (3-D). Gravity, aeromagnetic, and geologic data are used to inform interpretation of structures in the resistivity model, including the following observations. Shadow Valley is filled with conductive sediment that locally dips southward to a depth of 1 km. The Kingston Range-Halloran Hills detachment fault dips westward at ~15 degrees. The REE deposit is a moderate low resistivity zone dipping southwest to a possible depth of ~1 km, and is bounded by the North and South faults and bisected by the Middle fault. Ivanpah Dry Lake is underlain by a north striking southward dipping sedimentary basin. Two possible zones of mineralization are observed in Ivanpah Valley, one along the western edge of Ivanpah Dry Lake and one on the western edge of valley along a now inferred fault. The brittle-ductile transition is imaged at ~10 km below mean sea level. No deep electrically conductive structures are imaged to be related to the REE deposit likely due to the complex geologic history of the Mojave terrane. Future studies should regional target Proterozoic rocks and search within for geophysical signatures similar to Mountain Pass.

Plain Language Summary In southeast California there is a world class rare earth element deposit (REE) at Mountain Pass. The goal of this projects is to understand regional structures that are associated with the deposit and characterize other possible resources. To do that magnetotellurics, a passive electromagnetic geophysical method, is used to develop a 3-D electrical resistivity model of the area. Gravity, magnetics, and geologic data are used to make educated interpretations. The REE deposit appears to dip to the southwest and is fault bounded. Unmapped faults are identified in Ivanpah Valley could control other possible resources. However, no deep structures are identified to be associated with the REE deposit. Future studies should search for Proterozoic rocks and geophysical anomalies within that are similar to signatures observed at Mountain Pass.

1. Introduction

Rare earth elements (REE) have atomic numbers ranging from 57 to 71, commonly referred to as the "lanthanides." These elements have unusual chemical and physical properties that make them useful for a variety of technologies ranging from batteries to magnets to glass polishes (Gosen et al., 2017). REEs are common in crustal abundance, however large concentrations of REE are not, making it important to identify resources as global demand increases (Gosen et al., 2017). Large REE deposits are often associated with carbonatite-alkaline complexes where mineralization occurs during intrusion and associated hydrothermal activity (Wang et al., 2020). Carbonitic melts form from small amounts of partially melted primitive mantle rich in REEs. These melts typically intrude the crustal column in rift or subduction settings commonly forming ring shaped zones of mineralization, where secondary hydrothermal activity can increase REE concentration (Wang et al., 2020).

The eastern Mojave Desert in California is home to one of the world's most concentrated REE resources, the Sulphide Queen carbonatite deposit at Mountain Pass (Castor, 2008b). For over 30 years (1960’s–1990’s) the Mountain Pass mine supplied much of the world's light REE (LREE). The main ore is bastnaesite-rich with...
an average of concentration of 8.9% rare earth oxides (Castor, 2008b). The Sulphide Queen deposit does not have a ring like structure, rather it is part of a local 10 km long ultrapotassic intrusive suite (Hewett, 1956; Olson et al., 1954), which may be part of a regional 130 km long north-northwest trending narrow belt of alkaline rocks (Castor, 2008b; Olson et al., 1954). Along with REE resources other mineral resources occur in the Mountain Pass region including gold, silver, tungsten, uranium, mercury, and lead (Hewett, 1956).

Previous studies of mineral resources in the Mountain Pass region have primarily concentrated on surface geology, geochemistry, and geochronology (Haxel, 2007; Hewett, 1956; Olson et al., 1954; Poletti et al., 2016), and geophysics characterizing upper crustal structures related to mineral deposits (Denton & Ponce, 2018; Denton et al., 2019). However, imaging deeper features can provide a more complete characterization of mineralization throughout the crustal column to help identify resources under cover and deeper sources of mineralization (Heinson et al., 2006, 2018; Thiel & Heinson, 2013; Heinson et al., 2018).

Magnetotellurics (MT) is a common tool for imaging electrically conductive structures associated with mineral deposits (e.g., Cherevatova et al., 2015; Fernandes et al., 2018; Hayward et al., 2016; Hübert et al., 2009; Kalscheuer et al., 2017; Padilha et al., 2013; Thiel et al., 2016; Wannamaker and Doerner, 2002; Lindsay et al., 2017; Wunderman et al., 2018). A demonstrative example is from South Australia where MT has been used to image the subsurface below Olympic Dam, one of the world’s largest iron-oxide copper gold (IOGC) deposits (Heinson et al., 2006, 2018; Thiel & Heinson, 2013). An electrically conductive body at 20 km depth has been imaged to have narrow, finger-like connections towards the surface directly below known mineral deposits like Olympic Dam and possibly undiscovered deposits. These electrically conductive features are interpreted to be remnant fluid pathways responsible for mineral deposition. MT has been employed to image one of the world’s largest carbonatite and alkaline intrusions in Alnö, Sweden (Yan et al., 2016). The intrusion is a Late Precambrian ring structure with a radius of 2.5 km imaged to have electrically resistive (10,000 $\Omega$ m) core interpreted as the solidified magmatic source. This is surrounded by local conductive (100 $\Omega$ m) zones associated with fault zones exploited by carbonitic melts.

The goal of the current study is to build upon previous work by developing a 3-D electrical resistivity model of the Mountain Pass region. This model will help delineate geometry of important structural features related to mineral deposits, water resources, and regional geology. First, a brief geologic and geophysical background are provided to highlight important geological information for interpretation of the resistivity model. Next, the MT method, data, and modeling are described. Finally, interpretation of the preferred 3-D resistivity model will be given with summarized concluding remarks.

2. Geological Setting

In the study region, a northwest trending mountain belt separates Shadow Valley to the west and Ivanpah Valley to the east. These are the Clark Mountain Range and the Mescal Range (Figure 1). The western side of these mountains are composed of Neoproterozoic to early Paleozoic metasediments and carbonates (Burchfiel & Davis, 1971). These are thrust against autochthonous Paleoproterozoic metamorphic crystalline basement rocks to the east, mainly schist and gneiss but also contains plutonic rocks (Burchfiel & Davis, 1971; Hewett, 1956; Wooden & Miller, 1990). Mesozoic plutonic rocks associated with the Teutonia Batholith are exposed to the south and west (Beckerman et al., 1982), one prominent feature being Cima Dome (Figure 1). Southwest of the study area is the Cima Volcanic Field (CVF), which includes multiple basaltic flows from two major pulses of magmatism 7.6–3.0 Ma and 1 Ma to present (Wilshire et al., 1991). The most recent eruption age is 11.5 ka (Phillips, 2003).

2.1. Mountain Pass

Unlike most of the Mojave, the eastern Mojave has not been as widely overprinted by Cenozoic tectonics preserving Proterozoic lithology. The Mountain Pass region is marked by episodic intrusions of alkalic ultrapotassic rocks varying from mafic shonkinite to silicic syenite at 1.425, 1.405, and 1.380 Ga, with carbonatite melts being coeval with the latter two intrusions (Castor, 2008b; Haxel, 2007; Olson et al., 1954; Poletti et al., 2016). The shonkinite, syenite, and carbonatite are all enriched in incompatible elements, including Sr and Ba, and REEs, namely samarium, neodymium, cerium, praseodymium, and lanthanum, suggesting a single mantle-derived source (Castor, 2008b; Gittins, 1989; LeBas, 1989; Olson et al., 1954; Woolley, 2003;
Woyski, 1980; Wyllie, 1989). In particular, the fluoro carbonate bastnäsite is enriched in light REEs, and has been extensively mined from Mountain Pass (Castor, 1991, 2008b; Haxel, 2007; Long et al., 2010). These ultrapotassic and carbonatite rocks outcrop along a 10 km north-northwest trending belt, similar to foliations in the intruded Proterozoic gneiss. The intrusive suite exhibits widespread hydrothermal alteration which may have contributed to elevated concentrations of REE’s (Denton et al., 2019; Poletti et al., 2016; Premo et al., 2013; Stoeser, 2013).
2.2. Faults

Numerous faults are identified in the area, many of which have few offset indicators, but most are assumed to have left-lateral motion (Hewett, 1956, oral commun. D. M. Miller, 2021). The faults are described from west to east (Figure 2). The Kingston Range-Halloran Hills detachment fault (KR-HHF) is of Miocene age and is a shallow-dipping (∼30°) west-rooting fault under Shadow Valley that cuts discordantly across Precambrian and Paleozoic units (Davis et al., 1993). The Keaney-Mollusk Mine thrust fault is a north trending west-dipping fault that thrusts Paleozoic carbonates over Proterozoic gneiss on the eastern end of the Mesecal Range and continues north along the Clark Mountain Range.

Figure 2. (a) Simplified geologic map (same as Figure 1) showing Magnetotellurics stations (blue triangles). (b) Isostatic gravity map (Denton et al., 2019). (c) Regional aeromagnetic and high-resolution magnetic data (Ponce & Denton, 2018b). KR-HHF–Kingston Range-Halloran Hills detachment fault; KTF–Keaney-Mollusk Mine thrust fault; MTF–Mesquite Pass thrust fault; KF–Kokoweef fault; SF–South fault; MF–Middle fault; NF–North fault; WF–Wheaton fault; BF–unnamed basin fault; UNF–unmapped fault; SLF–State Line fault; dashed lines–inferred faults.
The Kokoweef fault, also referred to as the Kokoweef-Slaughterhouse fault (Ramsdell, 1999), is a steeply southwest dipping (~70°) north-northwest striking normal fault with an inferred left-lateral oblique offset of ~300 m (Hewett, 1956; Olson et al., 1954; Ramsdell, 1999; Walker et al., 1995). The Kokoweef fault juxtaposes Paleozoic carbonates and Mesozoic sandstone and volcanic units against Proterozoic gneiss on the northeast side (Ramsdell, 1999). Crosscutting relationships indicate the fault was most active between 100–95 Ma and possibly active during eastward thrust faulting (Ramsdell, 1999). The Kokoweef fault truncates northward at the South fault.

Intersecting at the northwestern extent of the Kokoweef fault is the west-northwestern striking high-angle South fault which bends westward forming the western edge of the Mescal Range (Denton et al., 2019). At the intersection of these two faults geologic units have been down-dropped and both faults truncate post-Jurassic magmatic rocks indicating some of the youngest faulting in the area (Fleck et al., 1994; Walker et al., 1995). The west-northwest striking left-lateral strike-slip North fault extends for at least 8 km just north of the Birthday stock and may extend northwest of Mountain Pass (Miller et al., 2007). The North fault truncates the Birthday stock and other intrusive dikes (Olson et al., 1954). The Middle fault runs 3 km sub-parallel to the North and South faults and is roughly midway between the two (Olson et al., 1954). The Middle fault has had two recorded earthquakes (SCEDC, 2013). Alteration assemblages are observed on the South, Middle, and North faults, where the North and Middle faults also have breccia and gouge fault materials (Denton et al., 2019). The Wheaton fault is a north-northwest trending southwest steeply-dipping fault that merges with the South, Middle, and North faults on the eastern edge of the Mescal Range (Denton et al., 2019).

Ivanpah Valley contains a few north-trending unnamed faults that constrain basin geometry (Denton et al., 2019; Miller et al., 2019). The Stateline fault is a right-lateral strike-slip fault that parallels the Nevada-California border that may have up to 30 km of offset (Guest et al., 2007). The Stateline fault forms a conjugate pair with the east trending left-lateral Nipton strike-slip fault, and at the intersection possibly creates a small basin (Langenheim et al., 2009; Miller et al., 2019).

2.3. Previous Geophysical Studies

Denton et al. (2019) provides a detailed geophysical characterization of the upper crust of Mountain Pass and surrounding area. They collected gravity data over the Mountain Pass Area and used existing aeromagnetic data to develop potential field maps and two-dimensional (2-D) models of the subsurface along three northeast profile lines. They found the ultrapotassic and carbonatite intrusive suite causes a relative gravity high. Magnetic data suggests the intrusive suite is structurally controlled by a northwest trending zone of weakness (Denton et al., 2019; Ponce & Denton, 2018a, 2018b, 2018c). Denton et al. (2019) interpreted collected MT data (Peacock et al., 2019) and developed a 2-D resistivity model. The resistivity model imaged an electrically conductive body (<80 Ω m) under the Mountain Pass mine that extended to about 1 km depth interpreted as rocks related to the Proterozoic intrusive suite. Shadow Valley and Ivanpah Valley are imaged to be electrically conductive (<30 Ω m) and relatively thin (~1 km). A deeper conductor below 10 km was imaged below the Mountain Pass area that may represent the brittle-ductile transition (BDT) zone. However, MT data collected in the eastern Mojave indicate three-dimensional (3-D) structures, thus further studies should include 3-D modeling (Mackie et al., 1996).

3. Methods and Data

Magnetotellurics (MT) is a passive electromagnetic method that measures the Earth’s electrical response to natural time-varying magnetic fields (Cagniard, 1953; Tikhonov, 1950). In the frequency domain, magnetic and electric fields are linearly related by a complex rank 2 transfer function, known as the impedance tensor (Kauffman & Keller, 1981; Vozoff, 1990). The impedance tensor contains information about subsurface resistivity structure as a function of frequency (a proxy for depth) and direction related to the polarity of the electromagnetic fields (Chave & Jones, 2012). The wealth of information stored in the impedance tensor helps inform 3-D inversions.

Between 2015 and 2017, 65 MT stations were collected in the Mountain Pass region (Peacock et al., 2019) (Figure 2a). All data were collected with 32-bit ZEN data loggers from Zonge International, ANT-4 induction...
coils from GeoTell, and a mix of Cu-CuCl CoorsTek porous pots (2015) and Ag-AgCl Stelth-4 Borin electrodes (post 2016). Electric dipoles were 50–100 m in length, oriented with geomagnetic north (N11.5E), and only the horizontal components were collected due to the rocky terrain. Data were recorded for an average of 20 hr, and processed with a robust bounded influence remote reference processing code (BIRRP 5.3.1 (Chave & Thomson, 2004)). Synchronous stations were used as remote references. Data quality was generally good with measurement errors of less than 2%, except near the Mountain Pass Mine due to cultural noise from mining infrastructure, and between at periods between 1–20 s in Ivanpah Valley from an unknown noise source that upward biases the apparent resistivity.

Strike analysis of the 2-D components of the phase tensor, identified by components where skew angles are less than 6 degrees and ellipticity is less than 0.1 (Caldwell et al., 2004), indicates that the electrical current flow is related to known structures in the area. Note that strike angle estimation has a 90 degree ambiguity due to polarization of electromagnetic fields (Caldwell et al., 2004), thus all possible parallel and perpendicular directions are plotted in Figure 3. Partitioning the survey area into three sections (west, middle, and east) based on topography and binning periods by decade indicates geoelectrical strike directions vary across the survey area (Figure 3). At periods between 0.01–0.1 s strike direction is basically random in the western and middle parts of the survey and has a stronger northeast direction in the eastern part of the survey. At periods between 0.1–10 s the predominant geoelectric strike direction is northeast parallel/perpendicular to the strike of mapped faults. In Ivanpah Valley the strike direction between the basin faults rotates to a northerly strike direction possibly related to current channeling along structure causing the magnetic high. At periods greater than 100 s the geoelectric strike direction rotates to parallel/perpendicular to plate motion (Liu et al., 2015) and/or upper mantle flow (Barbot, 2020).

4. Modeling

The parallel inversion code ModEM (Egbert & Kelbert, 2012; Kelbert et al., 2014) was used to invert the data in 3-D. The inversions were run on a distributed memory high-performance computer (USGS Advanced Research Computing, 2015). Prior to inversion, data were edited using an editor in MTpy (Kirkby et al., 2019). Obvious bad data points were removed and suspect data points were down weighted by increasing error bars, specifically in the period range of 1–20 s in the Ivanpah Valley stations. All four components of the impedance tensor were inverted using 23 periods between 0.005 and 1,024 s. The model grid was 71 × 178 × 59 cells (156 × 182 × 173 km) where cell size within the station area was set to 250 × 250 m. Topography was included by interpolating 30 m resolution data from the U.S. Geological Survey National Elevation Database onto the grid, where the first layer was set to 20 m and increased exponentially downwards. The starting resistivity was 100 Ω m.

To obtain a preferred model, the inversion was run in a few steps. First, the inversion was run with an error floor of 10% of the arithmetic mean of the impedance tensor eigenvalues as a function of period. A covariance value of 0.5 was applied once in all directions and the starting lambda value was set to 10,000 to get a relatively smooth model. The inversion converged to a normalized RMS of 1.8 after 144 iterations. The second step used this converged model as a prior model, the error floor on the impedance tensor elements was set to 5%, the covariance was reduced to 0.2 and applied twice, and the starting lambda was set to 100. After 132 iterations the inversion converged to a normalized RMS of 1.6. Phase tensor ellipses representing the input data and model response are displayed in Figure 4, as well as the residual phase tensor displaying the difference between input data and the model response. Random orientation of the residual phase tensors indicates the misfit does not have a directional bias. Misfits are generally larger at longer periods in Ivanpah Valley likely due to the screening effect of upper crustal conductors, and near the Mountain Pass mine due to anthropogenic noise. The preferred model was tested for sensitivity to structures and resolution of features. Depth resolution is around 50 km below the middle of the survey area with shallower depths of around 15 km below Shadow and Ivanpah Valley due to screening effects of the conductive basins.

Major resistivity anomalies in the preferred resistivity model includes R1 a large resistive body (>500 Ω m) under the Clark Mountain Range and Mescal Mountains (Figure 5), R2 a resistive body (150–300 Ω m) about 2 km below Ivanpah Valley, C1 a conductive zone (70–120 Ω m) directly below the Mountain Pass mine, C2 a conductive zone (<50 Ω m) directly under Shadow Valley, C3 a conductive zone (<50 Ω m) directly under...
Figure 3. Estimates of geoelectrical strike direction from the 2-D components of the phase tensor (Caldwell et al., 2004) for three different regions per period decade. North is 0°, east is 90° and rings are incremented at five samples. The number at the top of each rose diagram is the statistical mode of the strike estimate. The base map is a high-resolution aeromagnetic map superimposed on a regional aeromagnetic (Ponce & Denton, 2018b). (a) Periods 0.01–0.1 s: the random direction suggests 1-D geoelectrical structure indicative of sedimentary basins. (b) Periods 0.1–1 s: A coherent strike direction persists through the upper crust sub-parallel to mapped structures. (c) Periods 1–10 s: strike direction rotates northward from west to east in the middle to lower crust. (d) Periods 10–100 s: A different prominent strike is estimated to be northerly in middle to lower crust. (e) Periods 100–1000 s: Estimated strike is parallel/perpendicular to plate motion (Liu et al., 2015) and/or upper mantle flow (Barbot, 2020).
Ivanpah Valley, C4 a conductive zone (1–30 Ω m) that underlies the eastern edge of Ivanpah Valley below 1 km depth between the Stateline fault and a basin fault, C5 a small conductive zone (<10 Ω m) below the western edge of Ivanpah Dry Lake, C6 (5–50 Ω m) a small anomaly on the eastern side of Ivanpah Valley near the western edge of the Clark Mountain Range, and C7 (20–80 Ω m) underlies the entire survey below a depth of 10 km below mean sea level (bmsl).

5. Interpretations

5.1. Sulphide Queen Carbonatite Deposit

Conductive anomaly C1 (<150 Ω m), directly underneath the Mountain Pass mine, is a small (<2 km³) structure that dips southwest to a depth of about 1 km below the surface (Figure 6). C1 is structurally bound between the North and South faults, and bisected into two bodies by a strand of the Middle fault. Anomaly C1 is similar to the conductive anomaly observed in the 2-D resistivity model of Denton et al. (2019), however by using 3-D modeling the geometry and location are better constrained.

The intrusive suite is composed of sill-like stocks that are only a few meters thick that dip towards the southwest at 40 degrees (Olson et al., 1954; Castor, 2008a), which are too small to resolve with current MT data. Thus, the resistivity model is sensitive to the combined bulk resistivity of the intrusive suite and Proterozoic gneiss. Anomaly C1 represents a zone where bulk resistivity of the gneiss is reduced by a factor of about 7 from about 700 Ω m to 100 Ω m caused by intrusion of carbonatite and associated alteration. The western part of C1 is thicker than the portion on the east (Figure 6) suggesting vertical offset of about 200 m on this strand of the Middle fault which has observed fault gouge, breccia and alteration assemblages (Denton et al., 2019).

Figure 4. Phase tensor plots representing the data, model and residual difference between input data and the model response as a function of period (T). The images below the phase tensor ellipses in the data and model plots are the same depth slice from the 3-D resistivity model at the approximate depth (d) below mean sea level for the given period estimate as the skin depth. The data and model ellipses are colored by the minimum phase of the phase tensor and normalized to the overall maximum phase for the all stations at that period. Blue colors represent subsurface variations are resistive, and red colors represent subsurface variations are conductive. Similarly, smaller ellipses represent more resistive variations. The ellipses tend to elongate in the preferred direction of electrical current flow. The residual phase tensors plotted on a digital elevation model for clarity, and are self normalized by the maximum phase for easier visualization. The color represents the Frobenius norm as a percent, which describes how well the model fits the data. Shape and direction describe bias in fitting different components where a circle would indicate all components are fit equally and a line would indicate one component is not fit well. The western part of the survey is fit better than the east, likely due to screening of the conductive Ivanpah Dry Lake, complicated geology, and noisier data.
The eastern part of C1 spatially correlates with the Sulphide Queen REE deposit (Figure 6). The intrusive suite has electrically conducting trace mineral phases such as pyroxene, fluorite, pyrite, and pyrrhotite (Castor, 2008a) that reduces bulk resistivity. Denton et al. (2019) observes that the carbonatite deposit is essentially non-magnetic but relatively dense (3,000 kg/m³). They model the carbonatite deposit terminating...
between the Middle and South faults at a northwest trending magnetic gradient (Figure 6). This magnetic gradient is imaged with new aeromagnetic data (Ponce & Denton, 2018b) as two northwest trending relative magnetic highs separated by a low directly where C1 projects towards the southwest (Figure 6b). New gravity gradiometry data (Ponce & Denton, 2018a) shows the Mountain Pass mine is on the edge of a moderate vertical gravity gradient with the carbonatite deposit represented as a small positive vertical gravity gradient that extends towards the south and west (Figure 6c). The contrast in the aeromagnetic and vertical gravity gradient is not strong which could indicate the source of those anomalies is deeper and lithology does not drastically change in that area. If the potential field sources are deeper, then this could support further extension of the carbonatite deposit to the southwest near the South fault (Figure 6). Alternatively, if minimal contrast in lithology occurs in the western part of C1, reduced electrical resistivity could represent fractured gneiss caused by the South and Middle faults which have measured earthquakes (SCEDC, 2013). This is less likely due to the localization of C1 unless there is a graben or fault like structure that trends east-north east through Mountain Pass.

Figure 6. Top: Zoomed in maps of the Mountain Pass area. Depth of the electrical resistivity anomaly is contoured in purple lines (lighter is deeper). Bottom: cross sections along M–M’ of the resistivity model and the B–B’ potential field model from (Denton et al., 2019). (a) Lidar image of Mountain Pass with MT stations (black triangles). (b) Reduced-to-pole aeromagnetic data (Ponce & Denton, 2018a). (c) Vertical gravity gradient (Ponce & Denton, 2018c). (d) Cross section of the 3-D electrical resistivity model along M–M’. Drawn in are structures identified from potential field modeling (Denton et al., 2019). (e) Potential field model from (Denton et al., 2019) with C1 drawn in. Pink polygons-syenite and shonkanite granites (Olson et al., 1954); dark purple hashed polygon-carbonatite deposit (Olson et al., 1954); solid lines-fault; dashed lines-inferred fault; dashed lines with question marks-ambiguous faults; I-15-interstate 15; MTF-Mesquite Pass thrust fault; KTF, Keaney-Mollusk Mine thrust fault; NF-North Fault; SF-South Fault; MF-Middle Fault; TF-Thrust Fault; dark gray circles-earthquake hypocenters (SCEDC, 2013); Xg-Proterozoic gneiss; Tg-tertiary gravels; ma-possible granitic intrusion; gr-granitic rock; PDI-Permian and Devonian limestone; Cd-Cambrian dolomite.

Figure 5. Depth slices and a cross section of the 3-D electrical resistivity model showing location of robust resistivity anomalies. (a) Depth slice at 350 m above mean sea level showing conductive anomalies C2 in Shadow; C3, C5, and C6 in Ivanpah Valley; and resistive anomaly R1. (b) Depth slice at 10 km below mean sea level showing conductive anomaly C7. (c) Cross section along the profile line shown in a and b displaying the various conductive anomalies and resistive anomalies at depth. Faults are drawn as dashed and dotted lines inferring geometry at depth. Solid black line under Ivanpah Valley is estimated depth of the sedimentary basin (Miller et al., 2019), thick dashed line at 30 km is the Moho with temperature estimates (Schutt et al., 2018), and dot-dashed line is the BDT as estimated from seismic data (Allison et al., 2013; Shive et al., 2018). Brown polygon-Ivanpah Dry Lake; solid black lines-mapped faults (Ludington et al., 2007; Miller et al., 2007; Olson et al., 1954); dotted black lines-concealed faults (Miller et al., 2019; Olson et al., 1954); dashed black lines with question mark-inferred fault from this study; orange star-Mountain Pass mine; white dot-earthquake hypocenters (SCEDC, 2013); KR-HHF–Kingston Range-Halloran Hills detachment fault; KTF-Keaney-Mollusk Mine thrust fault; SF-South fault; MF-Middle fault; NF-North fault; KF-Kokoweef fault; WF-Wheaton fault; BF-unnamed basin fault; SLP-State Line fault.
The granitic intrusion 1.5 km below Mountain Pass introduced by Denton et al. (2019) (ma; Figure 6) was included into their 2-D model to fit magnetic and gravity data. The resistivity model does not show any clear evidence for such a body at those depths nor evidence for a deeper track of magma ascension in the vicinity of the proposed intrusion. This could mean that the intrusion is dry and cool and therefore does not create an observable reduction in bulk resistivity of the Proterozoic gneiss. Alternatively, the western part of C1 may be the source of the relative magnetic increase and relative gravity decrease observed in the potential field data if C1 represents a mineralized fault zone.

5.2. Shadow Valley

Conductive anomaly C2 lies directly below Shadow Valley (Figure 5). C2 follows the Shadow Valley basin structure which is deepest on the down-dropped eastern side (Davis et al., 1993). Moreover, the eastern edge and bottom of C2 correlate with the KR-HHF (Davis et al., 1993). Following the 40 Ω m isosurface of C2, the approximate resistivity upper bound based on approximate location of the KR-HHF and basement depth estimated by Denton et al. (2019), C2 dips to the west at about 15 degrees, has a maximum depth of about 1.1 km, and deepens towards the south. The basin is filled with 4 different rock types including alluvial facies, lacustrine facies, volcaniclastic rocks, carbonate glide blocks, and rock avalanche breccia (Friedmann, 1999). Resistivity of C2 gets as low as 7 Ω m and has a median value of 20 within the basin which could represent fluids and/or clays related to lacustrine deposits or altered tuff layers (Friedmann, 1999). A detailed analysis of Shadow Valley is limited by the spatial coverage of MT stations.

To the east of Shadow Valley are the Mesquite Pass and the Keaney-Mollusk Mine thrust faults that thrust early Paleozoic carbonates and metasedimentary rocks, and Mesozoic silicic volcanic and plutonic rocks on the west over Proterozoic gneiss on the east (Burchfiel & Davis, 1971). The thrusted strata are modeled with potential field data to increase in dip towards the faults (Denton et al., 2019). No strong resistivity contrast relative to the Proterozoic gneiss exists except near the surface where the angle of the thrust faults increase (Figure 5). As the thrust angle increases the strata bends, creating fracture zones which will likely contain some amount of fluids or mineralization that decreases the bulk resistivity. These zones appear to be be small and focused (Figure 5) and have no strong connection to structures in the middle or lower crust. It is enticing to extend the trace of the Keaney-Mollusk Mine fault to depths of 5–10 km to link with an observed earthquake, however that does not agree with potential field models nor the resistivity model. Instead that earthquake is likely related to anomaly C7 discussed below.

5.3. Ivanpah Valley

Ivanpah Valley is composed of multiple resistivity structures that include R2, C3, C4, C5, and C6 (Figure 7). Ivanpah Dry Lake is filled with mainly lacustrine strata with episodic layers of fluvial and aeolian sediment including loamy sand, silt loam, and clays with a large amount of soluble salts (Sims & Spaulding, 2017), which sits on Miocene gravels. Comparing the resistivity model with depth-to-basement estimates (Miller et al., 2019) indicates that C3 represents about 300 m of electrically conductive (<5 Ω m) material, likely combination of a thin layer of lacustrine sediments and saturated Miocene gravels. The geometry of C3 extends west of the modern day playa floor representing lacustrine sediments deposited in larger episodic lakes formed over the past 13 ka (Sims & Spaulding, 2017). MT coverage across the playa is limited therefore detailed analysis of small scale structures in the near surface would be over optimistic.

In the middle of Ivanpah Valley are two basin faults BF1 and BF2 (Figure 7) that trend north-northeast and have an assumed dip towards the east (Miller, 2019). Between these two basin faults resides an asymmetric relative magnetic high with higher magnetic intensity near BF1, the western basin fault (Figure 7). Gravity gradients are observed for these two faults where relative highs are observed to the west and relative lows to the east of each basin fault (Figure 7). Both faults have had measured earthquakes along them (SCEDC, 2013) at around 5 km bmsl a indicating zone of structural weakness. The observed magnetic anomaly has been interpreted as unaltered Proterozoic basement with an estimated depth of around 1.7 km (Carlisle et al., 1980). Denton et al. (2019) interpreted the magnetic high as magnetic plutons and/or dikes within the gneissic basement.
Resistivity anomalies C5 and R2 are collocated with the relative magnetic high, and C4 is proximal (Figure 7). R2 is a resistive zone (150–300 Ω m) approximately 2 km below the surface that extends down to about 7 km depth and is observed on the north side of the magnetic high maxima. Conductive anomaly C5 (<50 Ω m) is at about 400 m depth and collocated with the local magnetic intensity maxima. 10 kilometers to the northwest is the Colosseum gold deposit, which extracts ore from Cretaceous felsite breccia pipes that are about 200 m wide located in a horst block of Proterozoic granitoids (Theodore, 2007). Metal zoning within the Clark Mountain Mining District contains related breccia-pipe mineralization, comprised mainly of sulfide minerals (Theodore, 2007). One interpretation is that C5 is a mineralized zone associated with hydrothermal alteration related to a magnetite rich Mesozoic intrusion R2.

Conductive anomaly C4 is observed east of the magnetic maxima and on the eastern side of a basin fault (BF2 in Figure 7). The right-lateral Stateline fault and left-lateral southwest-striking Nipton fault to the south structurally control the deeper parts of Ivanpah Valley (Langenheim et al., 2009; Mahan et al., 2009; Miller et al., 2019). On the east side of BF2 is a relative gravity low with moderate magnetic intensity that forms a wedge between BF2, the Stateline fault, and the Nipton fault. This wedge was formed in the Plio-Pleistocene when the New York Mountains to the east were uplifted as a result of strike-slip fault interactions of the Stateline and Nipton faults, normal fault BF2 may also provide structural control (Miller et al., 2019). The resulting basin has been interpreted as containing volcanic rock, alluvium and gravels that thicken southward (Miller et al., 1986) to a depth of about 3 km (Miller et al., 2019). C4 mainly lies below the estimated depth-to-basement but could represent electrically conductive lithology that fills this wedge, likely alluvium and gravels, as well as possible fluids in porous units. A local relative magnetic high is observed near the Stateline fault that could indicated fault induced mineralization, but this is speculative at best.

The resistivity model does not image the deeper basin to the south. This could be due to the lack of stations in that area. However, due to the volumetric nature of MT one would expect some type of conductive body to the south even if the geometry is not well controlled. The magnetic high in the southern part would suggest volcanic rocks that would not be electrically conductive therefore the resistivity model would not
be sensitive to a deeper basin. Alternatively, the depth-to-basement modeling is based solely on the gravity data which may not be sensitive to lithologic changes that have no density contrast. Magnetic data and the resistivity model would suggest that a basin is shallower than modeled. More data needs to be collected in this area to educate joint inversions and interpretations.

An unmapped fault in western Ivanpah Valley is inferred from the MT, gravity, and aeromagnetic data (UMF in Figures 5 and 7). Gravity data images a north-northwest trending gradient from a relative high west of north-northwest striking basin fault (BF1) to a relative low west of C6 (Figure 7). Aeromagnetic data images a north-northwest trending relative magnetic low between relative magnetic highs to the east and west of C6 (Figure 7). The resistivity model images a C6 between −0.5 and 3 km depth on the east side of the unmapped fault (Figures 5 and 7). Denton et al. (2019) interpreted the gravity high as mafic amphibolite veins and dikes intruding Proterozoic gneissic rocks. This intrusion could have preferentially followed the unmapped fault and the basin fault to the east. Nearby intrusions are Cretaceous age (Theodore, 2007), suggesting the fault is older but this should be further investigated. Lack of magnetic intensity could suggest hydrothermal alteration. Similarly, enhanced electrical conductivity of C6 could be caused by intrusion related hydrothermal alteration and/or mineralization. A possible deeper connection between C6 and C7 is imaged, which could have been the intrusive fluid pathway often observed in other mineral systems (e.g., Heinson et al., 2018; Thiel et al., 2016). However, this connection is not well constrained by the resistivity model.

5.4. Deep Features

The BDT is imaged as a strong resistivity contrast at 10 km depth between C7 (50–70 Ω m) and the resistive crust above. Seismic data indicates that the BDT is between 12–15 km depth a few kilometers below the seismic-aseismic zone at 10 km depth (Allison et al., 2013; Shivevar et al., 2018). The BDT can be a zone of spatially well connected hydrous phases trapped in the ductile crust enhancing electrical conductivity (Wannamaker et al., 2009). The resistivity model suggests that a breach in the transition occurs under Shadow Valley where fluids permeate vertically, likely along a path related to fractures in folded Paleozoic carbonate rocks modeled by potential field data (Denton et al., 2019). Another potential breach is imaged below C6 between the basin fault BF1 and an inferred fault (UMF in Figure 5). This connection is not well constrained by the resistivity model. BF1 appears to be a possible boundary for the eastern part of C7, suggesting BF1 is a crustal fault that is impermeable at depth due to pressure or temperature. Also, possible is that the conductive playa C3 is shielding electromagnetic energy reducing model resolution on the eastern part of the survey. The resistivity model suggests a conductive zone exists to the southwest below 10 km near the CVF. This body is not well constrained by the existing data coverage and requires further investigation in future studies.

6. Conclusions

Characterization of REE deposits is becoming increasingly important as worldwide demand grows. The world class REE deposit at Mountain Pass, California, provides an important testing area to identify geophysical signatures associated with REE deposits in the Mojave Desert. Carbonatite deposits commonly have a ring of alteration easily identified with geophysical methods, however the Sulphide Queen carbonatite and associated alkalic ultrapotassic intrusive suite does not. The REE appears to be fault controlled, and spatially isolated in areal extent and depth. The REE deposit is geophysically characterized as having a relative gravity high, a relative magnetic low, and a moderate resistivity (70–120 Ω m). These geophysical signatures could be used to identify other carbonatite deposits in the Mojave Desert that may be undercover. Unfortunately, the deposit is relatively small (about 1 km³) and the resistivity model does not image a deep connection as observed in other mineral deposits. This makes identifying other deposits in the Mojave Desert using regional geophysical data difficult. One method could be to target Proterozoic rocks, which tend to be relatively dense, relatively more magnetic than surrounding rocks, and highly resistive. Then, with in these zones search for areas with a relative gravity high, a relative magnetic low, and a moderate resistivity that maybe fault controlled for further investigation.
This study reveals other interesting features in the Mountain Pass region along a narrow east-west zone from eastern Shadow Valley to eastern Ivanpah Valley, California. The 3-D electrical resistivity model jointly interpreted with other geophysical data provides the following observations. Shadow Valley contains a shallow sedimentary basin that locally dips towards the south. The eastern edge of the basin correlates with the Kingston Range-Halloran Hills detachment fault that dips westward at dip at about 15 degrees. At depths of 3 km below Shadow Valley a conductor is imaged that could be related to fluids penetrating a fracture network in the folded Paleozoic carbonates that were thrust over Proterozoic gneiss. The Sulphide Queen REE deposit has moderate resistivity and possibly extends southwest to a depth of about 1 km. Ivanpah Valley includes an electrically conductive basin that dips southward to a depth of about 1 km depth, and two zones of possible mineralization. One zone is just below the basin sediments at a depth of about 200 m on the eastern edge of the Clark Mountain Range near a north-northwest striking inferred fault. The other possible mineralization zone is below 200 m depth between nort striking basin faults. The BDT is imaged to be around 10 km depth as a transition from resistive brittle crust to electrically conductive ductile crust. Future work will include 3-D modeling of potential field data and collecting regional MT data and potential field data to identify Proterozoic targets which may host REE deposits like Mountain Pass.

Data Availability Statement

Data used in this study are available at the following URL's, MT data: https://doi.org/10.5066/P9JN-PLPJ, high-resolution aeromagnetic data: https://doi.org/10.5066/P92XVOOF, gravity data: https://doi.org/10.3133/ofr20161070.

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