Magnetotelluric Imaging of a Carbonatite Terrane in the Southeast Mojave Desert, California and Nevada

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SUMMARY

The southeast Mojave Desert hosts one of the world's largest rare earth element (REE) deposits at Mountain Pass, California. Although surface geology has been studied, a full understanding of the carbonatite and associated intrusive suite complex requires subsurface geophysical characterization. In this study, a combination of geophysical methods, including magnetotelluric (MT), magnetics, and gravity are used to create a two-dimensional (2D) geophysical model to a depth of about 10 km. An electrically conductive body is found 2-3 km below and west of the deposit that is associated with a magnetic high that could be connected to a deeper (10 km) conductive body related to possible intrusions or hydrothermal systems. The carbonatite body coincides with a steep magnetic gradient and a bench or terrace in the gravity data that may reflect relative lower-density intrusive rocks. Although carbonatite rocks are typically magnetic, the carbonatite rocks, associated intrusive suite, and host rocks in this area are essentially non-magnetic. Combined geophysical data indicate that the enriched REE deposit may be related to a regional extensive hydrothermal alteration event.

Key words: Carbonatite deposits, Magnetotellurics, Potential Fields, Rare Earth Element.

INTRODUCTION

One of the world's largest rare earth element (REE) carbonatite deposits is located in the southeast Mojave Desert at Mountain Pass, California (fig. 1). The carbonatite terrane consists of ~1.7 Ga gneiss and schist that host a ~1.417 Ga ultrapotassic intrusive suite (Premo, 2013) that consists of a series of granitoids including shonkinite, syenite, granite, and late shonkinite dikes (Olsen et al., 1954) and a ~1.375 Ga carbonatite body (DeWitt et al., 1987). The isotopic age of the carbonatite is ~40 Myr younger than the associated and likely contemporaneous, ultrapotassic intrusive suite. We use geophysical methods, specifically magnetotellurics (MT), magnetics, and gravity to characterize and image the subsurface geology near the REE deposit and to generate a geologic model of Mountain Pass. This will aid in understanding the structural controls of the REE deposit and the cause of REE enrichment.

METHODS

To improve understanding of the geophysical and structural framework of the carbonatite terrane, 19 MT stations, more than 2,300 gravity stations, and more than 640 physical rock property samples were collected across the eastern Mojave Desert region (Denton and Ponce, 2016). A regional aeromagnetic survey of parts of California was also used in this study (Roberts and Jachens, 1999).

MT stations were collected along a ~40-km-long east-west profile using ZEN 32-bit data loggers developed by Zonge International, ANT-4 induction coils (1000-0.001 Hz), and Borin Ag-AgCl electrodes. Stations were set in a cross pattern with 100-dipoles and recorded for 20 hours. Station spacing varied from 1-5 km, with closer spacing near the deposit (fig. 1). MT transfer functions were estimated using Zonge International processing codes, with synchronous stations were used as remote references. MT data were inverted for resistivity 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 with depth, such that the total model size was 100 km x 300 km to avoid edge effects. Multiple starting models and resistivity structures were tested to insure model robustness. A preferred model (fig. 2) has a normalized root-mean-square error of 1.73 using only the transverse magnetic mode with an error floor of 20% for the apparent resistivity and an error floor of 1.4 degrees for the impedance phase.

The aeromagnetic map of the study area (fig. 3a) was derived from a statewide compilation of California by Roberts and Jachens (1999). Aeromagnetic data were corrected by Roberts and Jachens (1999) for diurnal variations of the Earth's magnetic field, 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 1 km. This compilation, although composed of multiple surveys acquired with different specifications, allows seamless interpretation of magnetic anomalies across survey boundaries.

Gravity stations were collected throughout the study area (figs. 1 and 3B) using Scintrex CG-5 and LaCoste and Romberg gravity meters. Gravity data were processed using standard methods (e.g., Blakely, 1995) including free-air, Bouguer, Earth's curvature, terrain, and isostatic corrections. Isostatic corrections were computed to remove long-wavelength variations in the Earth's gravity field related to the local compensation of topographic loads to enhance features in the mid to upper crust. The isostatic gravity field was removed assuming an Airy-Heiskanen model for isostatic compensation of topographic loads with an assumed nominal sea-level crustal thickness of 25 km, a crustal density of 2,670 kg/m^3, and a density contrast across the base of the crust of 400 kg/m^3. Rock samples were collected throughout the study area and their density and magnetic susceptibility were measured in the laboratory. Gravity and magnetic 2D forward modeling was accomplished using GMSYS developed by Geosoft. Data were modeled along H-H', a southwest-northeast trending profile (perpendicular to geologic structure) across Clark Mountain Range (figs. 1 and 4a). Surface geology, geologic cross sections, rock properties, drill hole, and structural information were used to help constrain the inherent non-uniqueness of the potential field model.

RESULTS

The carbonatite and associated ultrapotassic intrusive suite occurs east of a conductive (fig. 2) and magnetic body (fig. 3a), along a steep magnetic gradient, and along the west margin of a bench or terrace in the gravity data (fig. 3b). Carbonatite rocks 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. However, rock property measurements reveal that the carbonatite deposit is essentially nonmagnetic with an average susceptibility of 0.18 x 10^{-3} SI (n=31). Similarly, the ultrapotassic intrusive suite is essentially nonmagnetic with an average susceptibility of 2.0 x 10^{-3} SI (n=36). A magnetic and gravity model (fig. 4a) reveals that the electrically conductive body directly below the magnetic anomaly occurs at a depth of about 2-4 km and because of its relatively low density could be caused by a granitic intrusion. If so, the upper parts of the causative source could be fractured and filled with conductive fluids. Alternatively, this feature could be mineralized, where high conductivity arises from hydrothermally altered clays or hydrothermal fluids.

Because the carbonatite and intrusive suite are essentially nonmagnetic, this may indicate that magnetic minerals were altered by hydrothermal activity after emplacement (Denton et al., 2015). Moreover, the intrusive suite appears to occur within a broad alteration zone that is characterized by a shallow conductive anomaly adjacent to the western edge of the deposit, a deeper conductive anomaly below Ivanpah Valley (fig. 4), a magnetic low, and essentially nonmagnetic rocks at the surface. We speculate that such an alteration event likely remobilized REE from the surrounding Paleoproterozoic rocks and may have enriched the deposit in REEs. Furthermore, an alteration event is consistent with geology, elevated light REE concentrations, mineralogy (Stoesser et al., 2013) and unusual geochemistry (Haxel, 2005) of the carbonatite deposit. Temporal constraints (DeWitt et al., 1987; Premo, 2013) also suggest alteration of the carbonatite, as the apparent age of the carbonatite deposit is ~40 Myr younger than the associated, and likely contemporaneous, ultrapotassic intrusive suite.

Resistivity, magnetic, and gravity models (fig. 4) also show that Shadow Valley extends to a depth of 1-2 km west of the Clark Mountain Range that may be filled with conductive carbonaceous and clay-rich sediments derived from nearby Paleozoic outcrops. The Kokoweef fault (fig. 4) bounds the eastern edge of Shadow Valley and may extend deep into the crust to at least 10 km. Similarly on the eastern side of the Clark Mountain Range, Ivanpah Valley is an asymmetric basin that reaches a depth of 1-2 km to the east. The western edge of Ivanpah Valley is bound by the Ivanpah fault (fig. 4b) which dips steeply to the east. The resistivity model shows that the central part of Ivanpah Valley is very conductive to depths of 10 km, which may be related to the aforementioned hydrothermal alteration event, a subsequent alteration event related to Mesozoic tectonism, or mineralization.

CONCLUSIONS

Geophysical investigations of the eastern Mojave carbonatite terrane have improved understanding of its subsurface geologic structures and features. An electrically conductive, moderately magnetic, and relatively low-density granitic pluton 2-4 km deep along the western edge of the carbonatite deposit could have structurally controlled the location of the deposit or vice versa. East of this pluton, a magnetic low and a thin near-surface conductor 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 1-2 km deep basin filled with clay-rich sediments and its eastern edge is bound by the near-vertical Kokoweef fault that extends to a depth of at least 10 km. On the east side of the Clark Mountain Range, Ivanpah Valley is a 1-2 km deep basin probably filled with clay-rich sediments. The west side of Ivanpah Valley is bound by the east-dipping Ivanpah Fault that extends to at least 10 km. Resistivity and magnetic anomalies in the central part of Ivanpah Valley could reflect a zone of hydrothermal alteration or mineralization.

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REFERENCES

Blakely, R.J., 1995, Potential theory in gravity and applications: New York, Cambridge University Press, 441 p.

deGroot-Hedlin, C.D, 1991, Removal of static shift in two dimensions by regularized inversion, Geophysics, v. 56, 2102-2106.

Denton, K.M., and Ponce, D.A., 2016, Gravity and magnetic studies of the eastern Mojave Desert, California and Nevada: U.S. Geological Survey Open-File Report, 21 p.

Denton, K.M., Ponce, D.A., and Miller, D.M., Peacock, J., and Miller, J.T., 2015, Geophysical Investigations of a Proterozoic Carbonatite Terrane, southeast Mojave Desert, California [abs.]: Eos (Transactions, American Geophysical Union), 95, no. 53.

DeWitt, E., Kwak, L.M., and Zartman, R.E., 1987, U-Th-Pb and $^{40}Ar/^{39}Ar$ dating of the Mountain Pass carbonatite and alkalic igneous rocks, southeastern California: Geological Society of America Abstracts with Programs, 19, no. 7, 642.

Haxel, G.B., 2005, Ultrapotassic mafic dikes and rare earth element- and barium-rich carbonatite at Mountain Pass, Mojave Desert, southern California: summary and field trip locations: U.S. Geological Survey Open-File Report 2005-1219, 55 p.

Olson, J.C., Shawe, D.R., Pray, L.C., and Sharp, W.N., 1954, Rare-earth mineral deposits of the Mountain Pass District, San Bernardino County, California—Rare earth deposits, San Bernardino County, California: U.S. Geological Survey Professional Paper 261, 75 p.

Premo, W.R., DeWitt, E.H., Moscati, R.J., Stoeser, D., and Premo, V.L., 2013, Ages and Pb-Sr-Nd isotopes of silicate rocks at Mountain Pass, southern California: Geological Society of America Abstracts with Programs, 45, no. 7, 113.

Roberts, C.W., and Jachens, R.C., 1999, Preliminary aeromagnetic anomaly map of California: U.S. Geological Survey Open-File Report 99-440, 14 p.

Stoeser, D.B., 2013, Mineralogy and late stage alteration of the Mountain Pass, California, ultrapotassic silicate intrusive rocks-preliminary report: Geological Society of America Abstracts with Programs, 45, no. 7, 500.

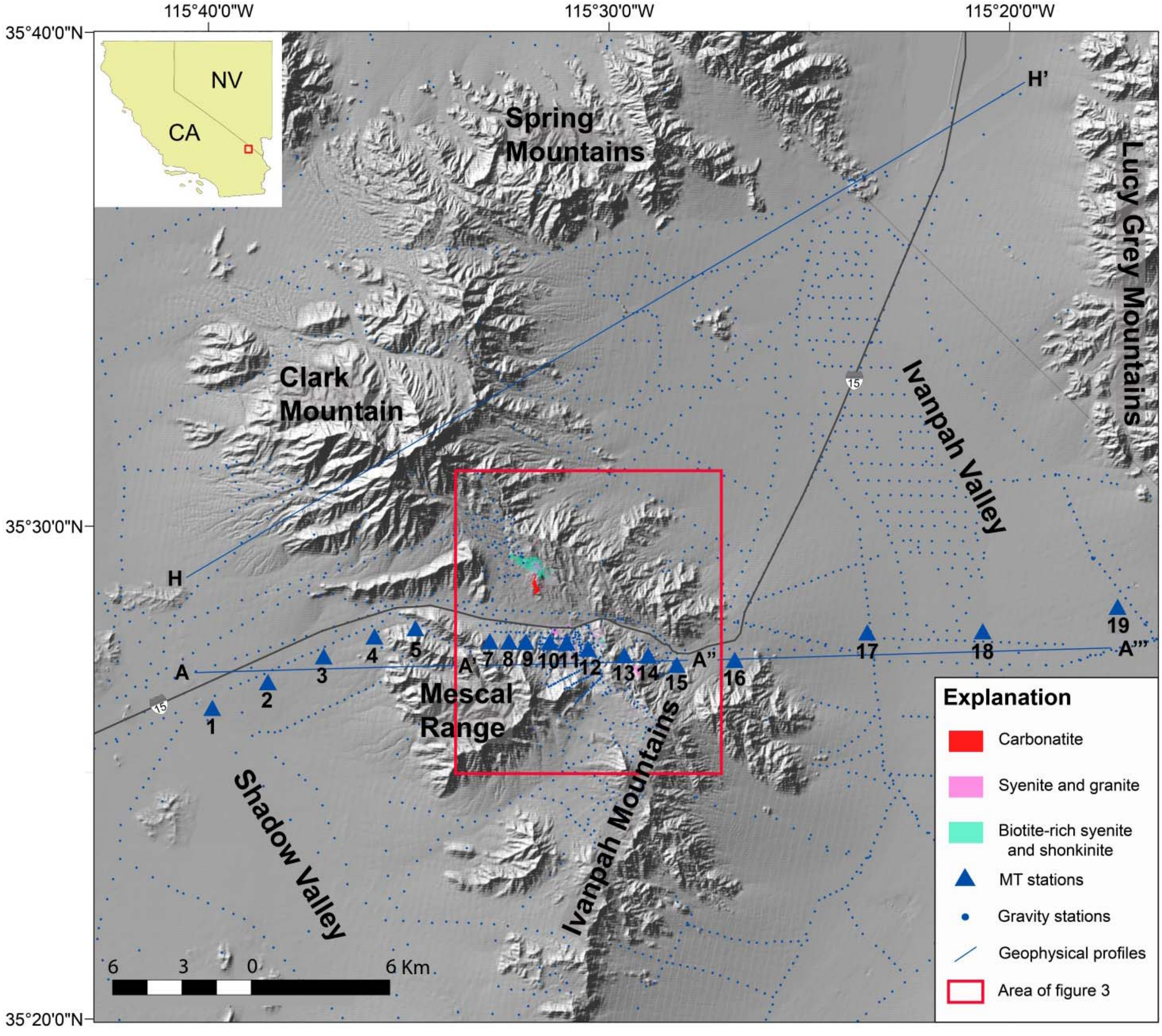

Figure 1: Shaded-relief topographic map showing locations of MT and gravity stations.

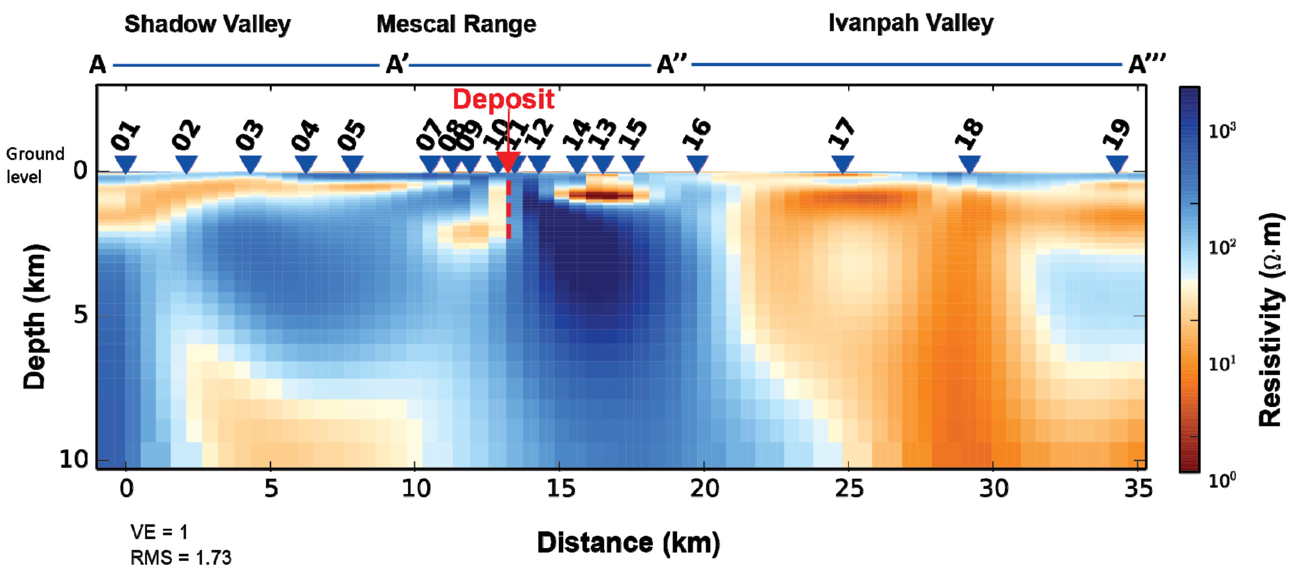

Figure 2: Electrical resistivity model showing location of carbonatite deposit.

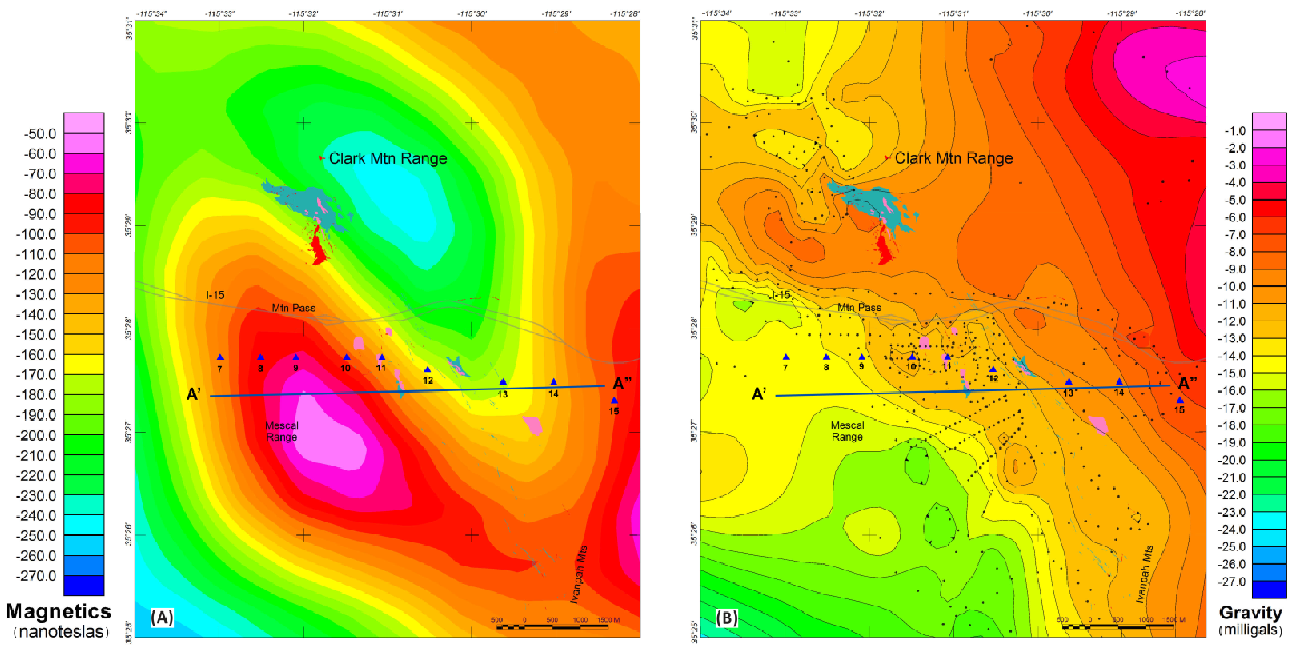

Figure 3: (A) Aeromagnetic map and (B) isostatic gravity map. Green polygon, shonkinite stock; pink polygon, syenite or granite stock; red polygon, carbonatite stock; blue triangle, MT station; gray circle, gravity station.

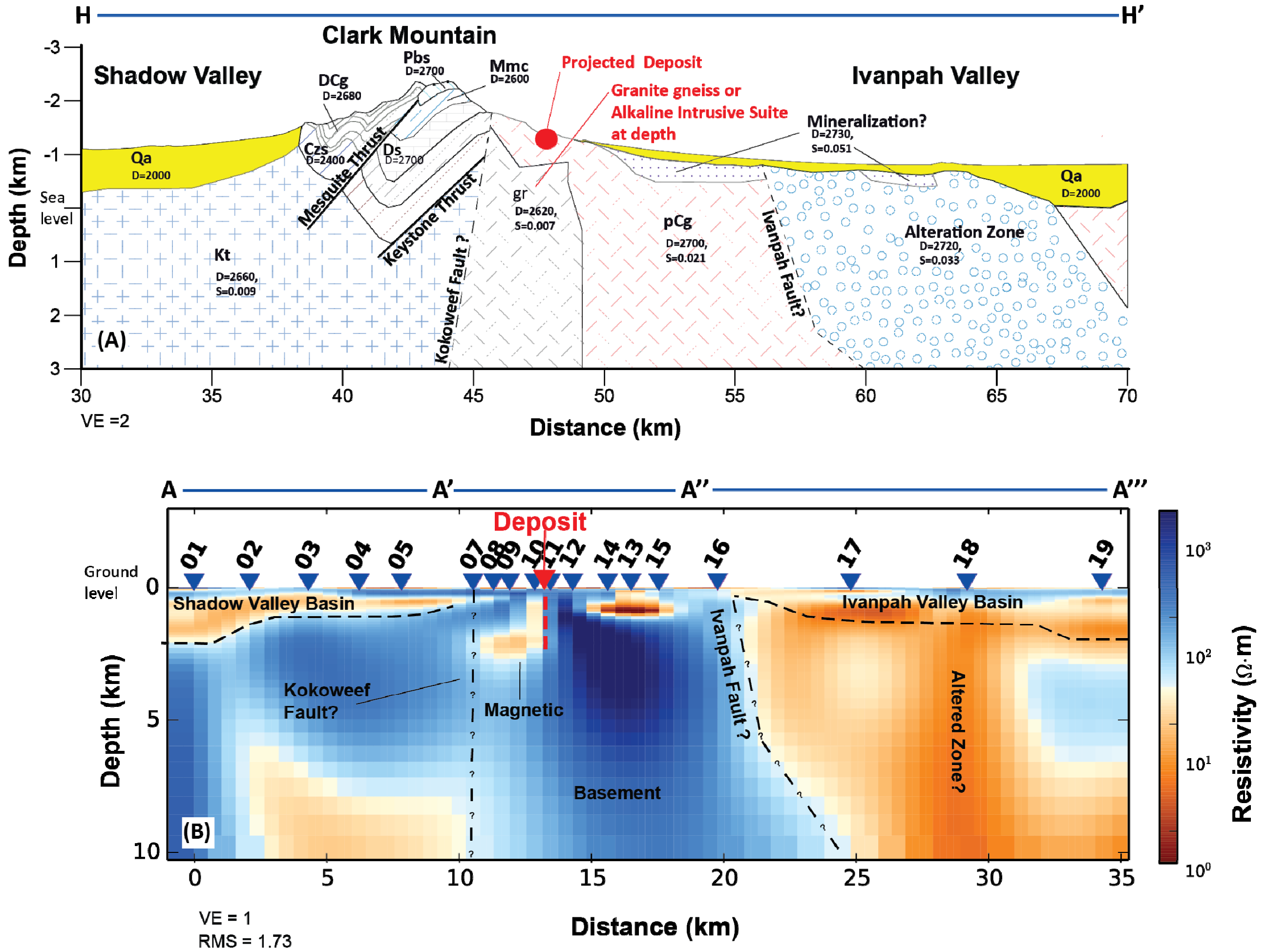

Figure 4: (A) Geologic model derived from gravity and magnetic modeling (H-H', fig. 1). Geologic symbols: pCg, preCambrian gneiss; gr, granite; Czs, Cambrian siliciclastic rocks; DCg, Devonian Goodsprings dolomite; Mmc, Mississippian Monte Cristo limestone; Pbs, Pennsylvanian Bird Spring Formation; Kt, Cretaceous Tutonia Batholith; Qa, Quaternary alluvium; D, density in kg/m^3; S, magnetic susceptibility in 10^{-3} SI units. (B) Interpreted electrical resistivity model (A-A''', fig. 1). Carbonatite deposit location is projected onto each profile by using the trend of the eastern edge of the magnetic anomaly shown in Figure 3a.