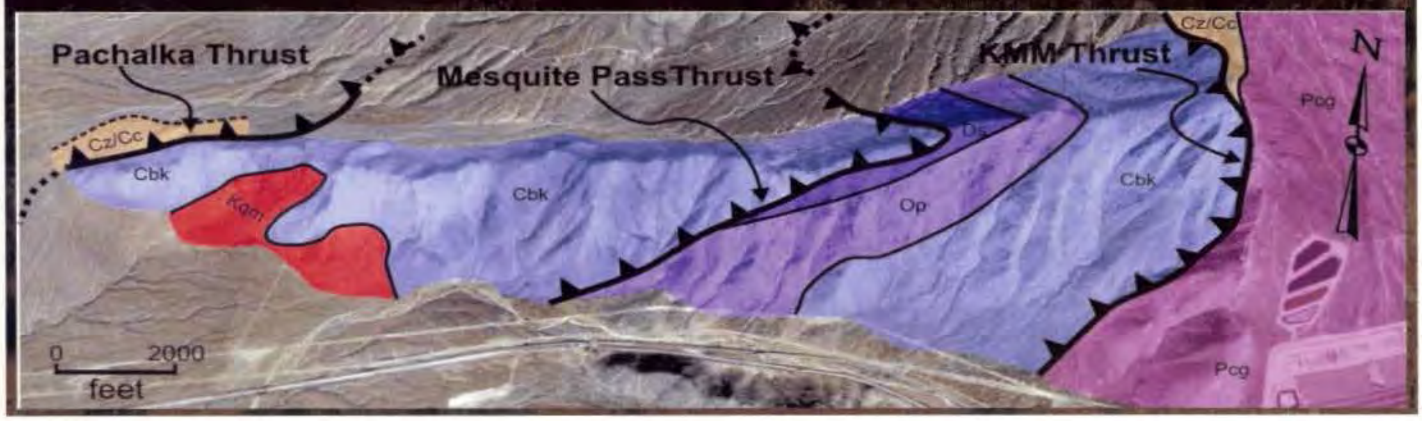
Eastern Mojave Desert Geology, Mining and Earth Resources



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Geophysical Expression of a Carbonatite Terrane in the Eastern Mojave Desert, California

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Bailey Road Overlook: Traveling east or west on Interstate I-15, take the Bailey Road exit at Mountain Pass, California. Travel due south on Bailey Road to the end of the pavement. Approximate geographic coordinates (NAD83 or WGS84): lat 35.46600°N., long 115.52852°W. (Or in degrees-minutes: lat 35°27.960'N., long 115°31.711'W.)

General topics: At this stop we discuss rock physical properties (density and magnetic susceptibility), gravity and magnetic methods, and generalized gravity and magnetic interpretations of the eastern Mojave Desert carbonatite terrane.

Introduction

The eastern Mojave Desert is host to a world-class rare earth element carbonatite deposit located at Mountain Pass, California. The deposit occurs along a north-northwest trending fault-bounded block that extends along the eastern parts of the Clark Mountain Range, Mescal Range, and Ivanpah Mountains (Figure 1). This Early to Middle Proterozoic block is composed of a 1.7 Ga metamorphic complex of gneiss and schist that underwent widespread metamorphism and associated plutonism during the Ivanpah orogeny. Subsequently, these rocks were intruded by a series of granitoids which include the 1.4 Ga (DeWitt et al., 1987) ultrapotassic alkaline suite of intrusions that are spatially and temporally associated with the carbonatite body. The temporal sequence of this intrusive suite of alkaline rocks from oldest to youngest includes shonkinite, mesosyenite, syenite, quartz syenite, potassic granite, carbonatite, and late shonkinite dikes. (See Olsen et al., 1954; Wooden and Miller, 1990; Haxel, 2005; and Miller et al., 2007.)

A thick sequence of younger sedimentary rocks unconformably blanketed the entire Proterozoic terrane. During the Mesozoic, widespread volcanism and plutonism ensued and the middle and late Mesozoic was characterized by regional crustal shortening and uplift along the Sevier fold and thrust belt. Although much of the early Cenozoic was quiescent, Miocene volcanism was widespread along the margins of the region and accompanied by significant extension. However, locally, the Mountain Pass area escaped much of this extension. (See Olsen, 1954; Burchfiel and Davis, 1971; Wooden and Miller, 1990; Tosdal, 2007; Miller et al., 2007; Theodore, 2007; and Jessey, 2013, this volume.)

In addition to the metamorphic and alkaline suite of intrusive rocks, other geologic units present in the eastern Mojave Desert include: Late Proterozoic to Ordovician limestone, siltstone, shale, quartzite and dolomite (e.g., Zabriskie Quartzite, Carrera Formation, Nopah Formation, Bonanza King Formation, Pogonip Group, Sultan Limestone, Bird Spring Formation, and Kaibab Formation); Triassic limestone, shale, and sandstone (Moenkoepi Formation); Mesozoic volcanic and sedimentary rocks that include volcanic flows, tuff, shale, sandstone, conglomerate, and limestone; a Jurassic hornblende diorite, and syenogranite to monzogranite (e.g., Delfonte volcanic rocks, Aztec Sandstone, and Ivanpah granite); Cretaceous granitoid rocks including the Teutonia batholith; and finally Tertiary and Quaternary unconsolidated deposits that include gravel, alluvial fan deposits, and alluvium. (See Olsen et al., 1954; Hewett, 1956; Burchfiel and Davis, 1971; Burchfiel and Davis, 1981; Beckerman et al., 1982; Jessey et al., 2001; and Miller et al., 2007.)

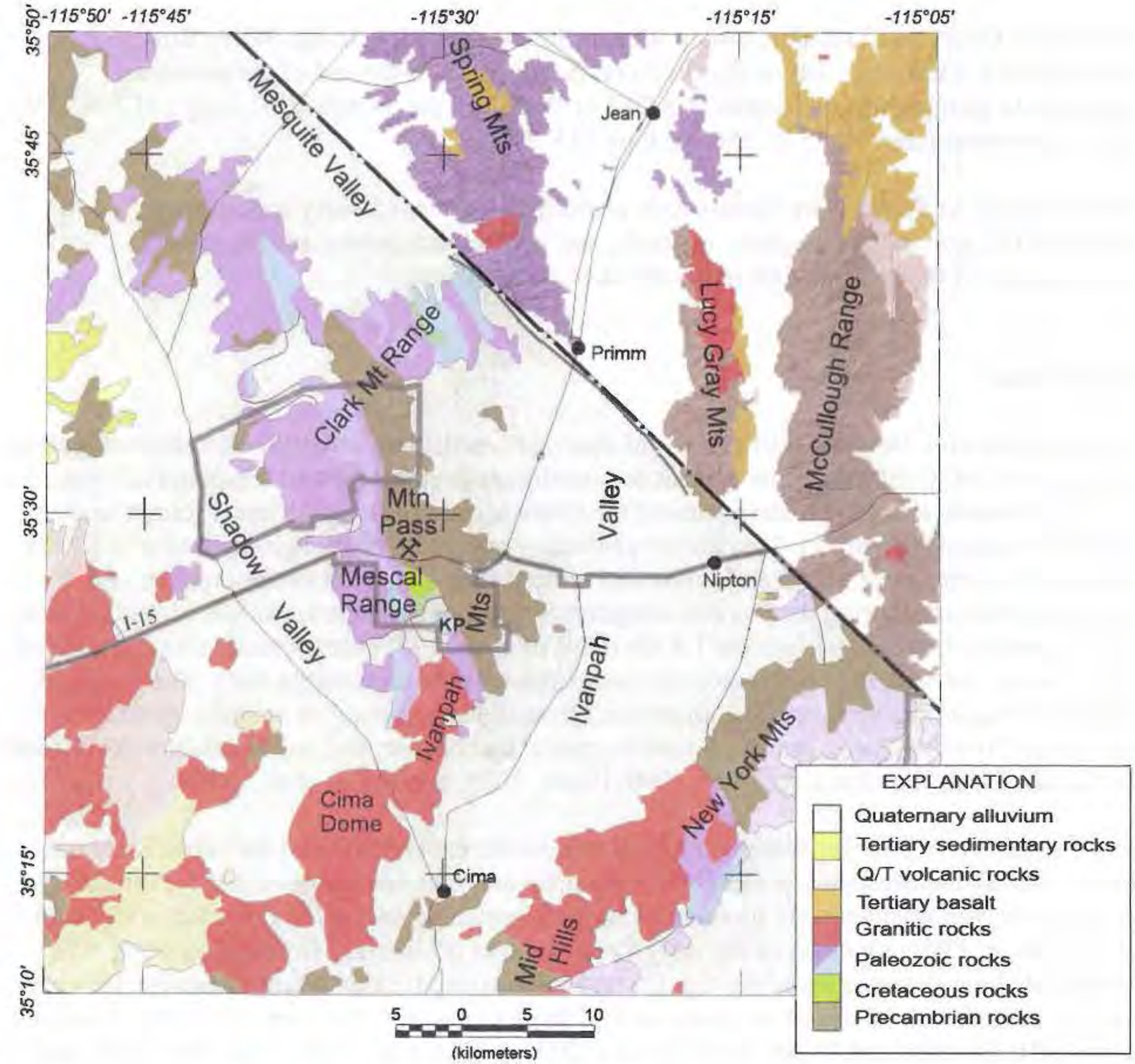

Figure 1. Simplified geologic map of the eastern Mojave Desert (modified from Jennings et al., 1977 and Stewart and Carlson, 1978). KP, Kokoweef Peak; bold gray line, boundary of Mojave National Preserve; thin black line, road; thin gray line, fault.

Physical Properties

Density and magnetic properties of rocks are important constraints for the interpretation of gravity and magnetic anomalies and are critical parameters for geophysically modeling the subsurface extent of geologic units. Physical property measurements of representative rock types in the area (Figure 2) show that 31 samples of carbonatite ore have an average saturated bulk density (the representative or in situ density) of 2,993 kg/m^3 and are essentially non-magnetic with an average susceptibility of 0.18 10^{-3} SI units, 17 samples of syenite have an average saturated bulk density of 2,670 kg/m^3 and a very weak average magnetic susceptibility of 3.50 x 10^{-3} SI units, 12 samples of shonkinite have an average saturated bulk density of 2,834 kg/m^3 and are essentially nonmagnetic with an average magnetic susceptibility of 0.11 x 10^{-3} SI units, and 28 samples of Proterozoic gneiss have an average saturated bulk density of 2,734 kg/m^3 and an average magnetic susceptibility of 1.23 x 10^{-3} SI units (modified from Denton et al., 2012). In summary, rocks associated with the carbonatite intrusive complex are denser than surrounding rocks which include the Early Proteozoic host rocks as well as the surrounding sedimentary rocks. Furthermore, most rocks sampled thus far in the carbonatite terrane are only weakly magnetic.

a) Carbonatite b) Dolomite c) Gneiss d) Granite

Rock type	Number of samples	Grain density kg/m^3	Range	Saturated-bulk density kg/m^3	Range	Dry-bulk density kg/m^3	Range	Magnetic susceptibility x10^{-3} SI	Range
a) Carbonatite	31	3068	2537 - 3628	2993	2440 - 3591	2956	2376 - 3577	0.18	0.03 - 0.61
b) Dolomite	31	2765	2659 - 2852	2734	2573 - 2847	2715	2521 - 2843	0.00	0.00 - 0.04
c) Gneiss	28	2762	2599 - 3093	2733	2574 - 3086	2716	2547 - 3082	1.23	0.01 - 7.48
d) Granite	20	2644	2591 - 2720	2617	2541 - 2704	2600	2502 - 2695	0.82	0.01 - 3.44
e) Monzogranite	11	2640	2590 - 2696	2601	2553 - 2665	2578	2526 - 2647	0.38	0.06 - 2.05
f) Quartzite	3	2724	2608 - 2805	2683	2575 - 2798	2683	2575 - 2798	0.03	0.01 - 0.05
g) Shonkinite	12	2879	2768 - 3030	2834	2647 3000	2810	2578 - 2985	0.11	0.07 - 4.45
h) Syenite	17	2710	2593 - 2825	2670	2555 - 2788	2647	2531 - 2767	3.47	0.19 - 11.46

e) Monzogranite f) Quartzite g) Shonkinite h) Syenite

Figure 2. Physical property measurements of representative rocks types in the eastern Mojave Desert (modified from Denton et al., 2013).

Gravity and Magnetic Methods

Gravity and magnetic data are collected and processed in such a way that they reflect lateral changes in subsurface density and magnetic properties, respectively. Because rock types vary in density (by about a factor of two) and have a wide range in magnetic properties (several orders of magnitude), gravity and magnetic data can then be used to infer their occurrence and resulting subsurface extent. Gravity data are typically more difficult to process than magnetic data because they require the removal of non-geologically related effects such as the tidal attraction of the moon and sun, instrument drift, changes in gravity with elevation, changes in gravity with latitude, Earth's curvature, and the surrounding topographic terrain. Magnetic data are simply corrected for diurnal variations in the Earth's magnetic field, magnetic effects of the airplane (if applicable), and for a regional geomagnetic model of the Earth.

In general, gravity and magnetic anomalies can be used to infer the subsurface structure of known or unknown geologic features, provided a physical property contrast occurs across the geologic boundaries. Gravity anomalies can, for example, reveal variations in lithology and delineate features such as calderas, deep sedimentary basins, and faults, all of which play an important role in defining the geologic framework of a region. Similarly, magnetic anomalies reveal changes in lithology and are well suited for delineating faults. In general, short-wavelength, high-amplitude magnetic anomalies are caused by moderately to strongly magnetic volcanic rocks, whereas broad circular long-wavelength magnetic anomalies reflect magnetic granitoid intrusions or other mafic basement rocks.

Generalized Gravity and Magnetic Discussion

In general, carbonatites have distinctive circular shaped gravity, magnetic, and radiometric signatures because these deposits are relatively dense, magnetic, and enriched in thorium. However, in this particular case the carbonatite stock at Mountain Pass contains very little magnetite (the most common magnetic anomaly producing mineral), thus the carbonatite deposit itself is devoid of magnetic anomalies. Similarly, the ultrapotassic alkaline suite of intrusive rocks associated with the carbonatite stock is also only weakly magnetic.

Previous gravity and magnetic studies in the eastern Mojave carbonatite terrane are limited in areal extent or are general in nature (Carlisle et al., 1980; Swanson et al., 1980, Hendricks, 2007; Langenheim et al., 2009) and much of this work was summarized by Hendricks (2007). From west to east, Shadow Valley is characterized by a 20 mGal gravity low (Figure 3) that is associated with relatively low density basin fill material. Although data coverage is sparse, gravity data indicate that the depth to basement rocks is probably about 1.5 km, based on a semi-infinite sheet assuming a 20 mGal gravity anomaly and an average density contrast between basin fill and basement rocks of 400 kg/m^3 (0.4 g/cm^3). Indeed, an iterative depth to basement method incorporating geology, gravity, and drill-hole data applied to the entire Mojave National Preserve (Figure 1) indicates that Shadow Valley reaches a maximum depth of about 1.5 km (Langenheim et al., 2009). Magnetic data are quite subdued in Shadow Valley (Figure 4), which suggests that there are no near surface magnetic rocks in this area, except in the northeastern part of the valley along the western margin of the Clark Mountain Range and within the Mojave National Preserve. Here, a moderate amplitude circular magnetic anomaly indicates the presence of magnetic volcanic rocks or more likely a granitoid intrusion below the surface.

The Clark Mountain Range, Mescal Range, and the northeast Ivanpah Mountains are characterized by gravity highs that are associated with relatively dense Cambrian dolomite with slightly higher gravity values along their eastern margins associated with Proterozoic gneiss

(Figure 3). Here, magnetic anomalies are more complex, with a magnetic high on the eastern part of Clark Mountain Range and a magnetic ridge extending southeastward from the Mountain Pass carbonatite deposit (Figure 4). The magnetic high along the eastern margin of the Clark Mountain Range is probably related to moderately magnetic Proterozoic basement rocks (Hendricks, 2007). Although Hendricks (2007) suggested that the magnetic ridge extending southeast from the main carbonatite stock may be related to the ultrapotassic rocks and carbonatite, we now know that these rocks are themselves essentially nonmagnetic and are probably not the source of the magnetic high (Denton et al., 2012). Instead, we suggest that moderately magnetic intrusions or more mafic crystalline basement rocks in the region are the source of the magnetic high. The southwestern parts of the Ivanpah Mountains are characterized by a gravity low that reflects relatively lower density granitoid rocks. Magnetic anomalies along the western parts of the Clark Mountain Range, Mescal Range, and Ivanpah Mountains are quite subdued indicating that these sedimentary rocks are essentially nonmagnetic and relatively thick (Figure 4).

Ivanpah Valley is characterized by prominent gravity and magnetic anomalies (Figures 3 and 4). These anomalies indicate that dense and moderately magnetic rocks occur along the central and western margins of Ivanpah Valley at relatively shallow depths. Indeed, in the northwestern parts of Ivanpah Valley, Cambrian to Devonian Goodsprings Dolomite and preCambrian garnetiferous gneiss are exposed in small outcrops (e.g., Hewett, 1956). Based on seismic refraction, magnetic, and gravity data, Carlisle et al. (1980) suggest that Ivanpah Valley is an asymmetric graben, deeper along the southeastern margin and that the depth to basement or thickness of "sediments" is about 2.4 km. This compares well to drill-hole data with depths to basement of 1.9 km in the southeastern part and depths of 0.7 and 1.1 km in the central part of the valley (Hodgson, 1980; Carlisle et al., 1980). Basin depths inferred from the inversion of gravity data by Langenheim et al. (2009) suggest that most of Ivanpah Valley is quite shallow, less than about 500 m near the Clark Mountain Range but may reach depths greater than about 3 km near Nipton, Nevada. About 6 km southeast of Kokoweef Peak (KP, Figure 1), Swanson et al. (1980) suggested that the Clark Mountain fault may extend southward into Ivanpah Valley rather than more easterly as mapped by Hewett (1954) based on seismic refraction and magnetic data. However, the extension of the Clark Mountain fault south of Interstate 15 is a topic of debate (Jessey et al., 2001; D.R. Jessey, written commun., 2013).

Gravity and magnetic data reveal a number of prominent geophysical anomalies throughout the eastern Mojave Desert that correlate well with mapped geology and geologic structure. Combined, these studies will improve the geologic and geophysical framework and structural interpretation of the eastern Mojave Desert carbonatite terrane.

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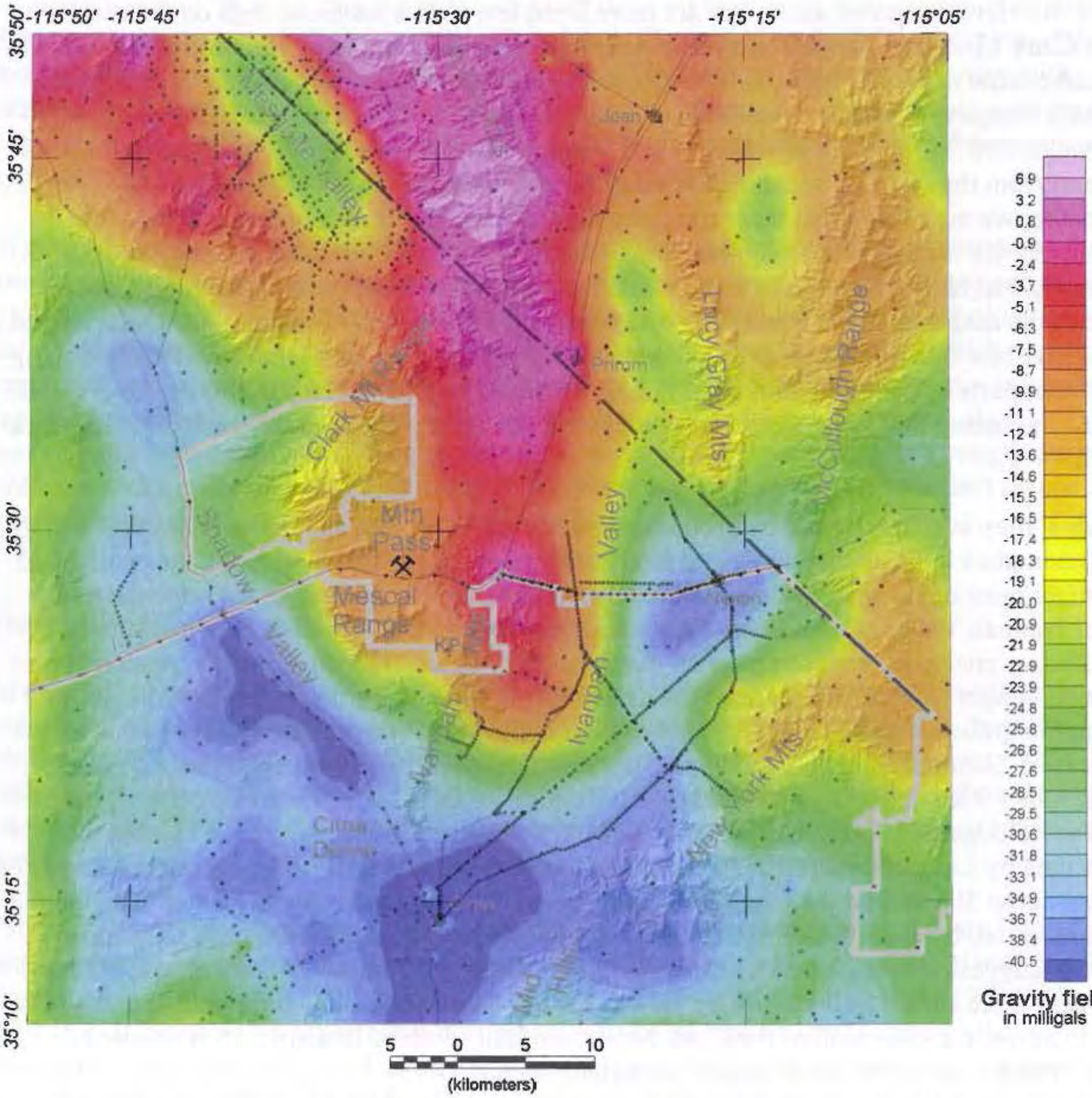

Figure 3. Isostatic gravity map of the eastern Mojave Desert over shaded-relief topography. Solid black circle, gravity station; bold gray line, boundary of Mojave National Preserve; thin black line, major road.

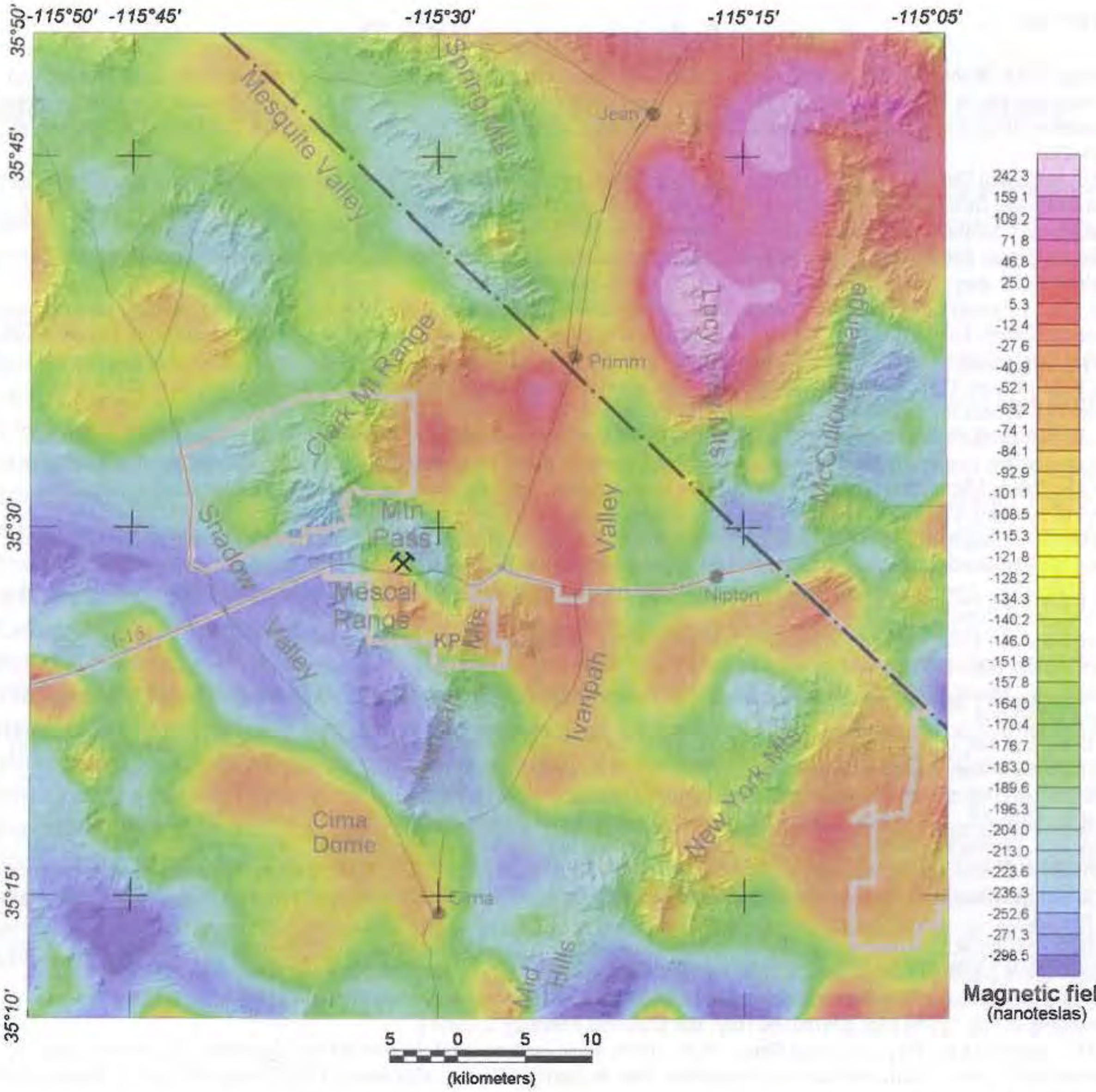

Figure 4. Aeromagnetic map of the eastern Mojave Desert over shaded-relief topography (modified from Roberts and Jachens, 1999 and Kucks et al., 2006). Although magnetic data have been continued to a common elevation above the ground of 305 m, original flightline spacings vary from 1 to 5 km and flightline elevations vary from 120 m to 305 m above the ground surface. Bold gray line, boundary of Mojave National Preserve; thin black line, major road.

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