INTRODUCTION

Geophysical investigations of Mountain Pass, California, were conducted as part of an effort to study regional crustal structures as an aid to understanding the geologic framework and mineral resources of the eastern Mojave Desert. The study area encompasses Mountain Pass, which is host to one of the world's largest rare earth element (REE) carbonatite deposits. The deposit is found along a north-northwest-trending, fault-bounded Paleoproterozoic block that extends along the eastern parts of the Clark Mountain Range, Mescal Range, and Ivanpah Mountains (fig. 1). This Paleoproterozoic 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, at about 1.7 Ga (Wooden and Miller, 1990). The Paleoproterozoic rocks were intruded by a Mesoproterozoic (1.4 Ga) carbonatite body and associated ultrapotassic alkaline intrusive suite (Olsen and others, 1954; DeWitt and others, 1987; Premo and others, 2016). The intrusive rocks include, from oldest to youngest, shonkinite, mesosyenite, syenite, quartz syenite, potassic granite, carbonatite, carbonatite dikes, and late shonkinite dikes (Olson and others, 1954).

METHODS

A high-resolution radiometric survey of Mountain Pass was flown by CGG Canada Services Ltd. (CGG). This helicopter survey, which was flown at flightline spacings of 100 and 200 m, a flightline azimuthal direction of 70°, a nominal flightline elevation above ground of 70 m, and an average sampling distance of about 30 m, consists of about 1,814 line-kilometers (fig. 2). Tie lines, which were spaced at 1-km intervals, were flown in a flightline azimuthal direction of 160°. Closely spaced lines flown at low elevation are needed to resolve small-scale features and improve signal-to-noise ratio.

Data were collected using a Radiation Solutions RS-500 spectrometer and processed by CGG, using standard radiometric-surveying techniques (see, for example, International Atomic Energy Agency, 2003) that include corrections for both aircraft and cosmic background radiation, radon background, Compton scattering effects, and variations in altitude. Aeroradiometric surveys measure the intensity and energy spectrum of gamma-ray radiation from the three most common naturally occurring radioelements: potassium (^{40}K), thorium (^{232}Th), and uranium (^{238}U). For ^{232}Th and ^{238}U, the source of the gamma-rays comes from their thallium (^{208}Tl) and bismuth (^{214}Bi) decay products, respectively, and, thus, concentrations for Th and U are referred to as "equivalent concentration," assuming radioactive equilibrium. The concentrations of these radioelements can be used together to estimate changes in geochemistry and lithology.

Data, which were gridded at a 20-m interval, are expressed as percent K (Map A), parts per million (ppm) equivalent Th (eTh) (Map B), and ppm equivalent U (eU) (Map C). Although gamma rays are of high energy and frequency, they attenuate rapidly in rocks and soil, partly owing to Compton scattering, and they can only be detected from about the upper 50 centimeters (cm) of the Earth's surface and mostly from the upper 30 cm (International Atomic Energy Agency, 2003, p. 114).

DISCUSSION

Carbonatite deposits typically have distinctive geophysical signatures because they are relatively dense, magnetic, and radiogenic. Specifically, the carbonatite and alkaline intrusive suite at Mountain Pass is ultrapotassic and contains relatively significant amounts of K, Th, and U, which can be delineated using airborne radiometric surveys. Values for K concentration range from −0.12 to 3.59 percent, with a mean of 1.22 percent; for eTh, from −0.74 to 180.20 ppm, with a mean of 8.16 ppm; and for eU, from −0.22 to 17.03 ppm, with a mean of 2.03 ppm. Negative concentrations were obtained over water or some alluvial deposits. Verplanck and others (2014) provided a deposit model for carbonatite- and alkaline-intrusion-related REE mineralization, and they described some of the geophysical tools used to assess these deposits. These radiogenic features are briefly discussed below (from northwest to southeast), and their locations are labeled on the maps and figure 1 (for example, locs. 1a, 3b):

- Very low concentrations of K, eTh, and eU correlate with Paleozoic dolomite, limestone, and other sedimentary rocks that are thrust against Proterozoic basement terrane along the western margin of the study area (locs. 1a, 1b, 1c)
- Moderate concentrations of K and low concentrations of eTh and eU delineate Mesozoic volcanic rocks in the Mescal Range (loc. 2)
- Moderate concentrations of K, eTh, and eU correlate with a small felsic body in the Clark Mountain Range (loc. 3a) and a Jurassic granite in the Ivanpah Mountains (loc. 3b)
- High concentrations of K, eTh, and eU correlate with the Birthday shonkinite (loc. 4a), the Sulphide Queen carbonatite body (loc. 4b), and the remainder of the alkaline intrusive suite composed of shonkinite, syenite, and granite (locs. 4c through 4h). High concentrations of K in the alkaline intrusive suite are due primarily to biotite mica, phlogopite, and potassium feldspars. High concentrations of eTh and eU are present because Th and U have the same valance and similar atomic radii as REEs and can substitute in various REE-related minerals
- Concentrations of K are variable across the Paleoproterozoic gneissic terrane along the central and eastern parts of the study area. Numerous linear, northwest-trending, moderate concentrations of K, eTh, and eU throughout the gneissic terrane (locs. 5a through 5i) reflect various changes in basement lithology or geochemistry, structure, or faults
- Prominent and mostly northeast-trending, moderate concentrations of K, eTh, and eU along the western margin of Ivanpah Valley (locs. 6a through 6f) reflect alluvial and eolian deposits derived from the Proterozoic basement terrane
- Moderate concentrations of K, eTh, and eU along Piute Valley (loc. 6g) are probably derived from alluvial and eolian deposits from a combination of Paleozoic metavolcanic and Proterozoic basement rocks
- Some high concentrations of K, eTh, and eU are associated with anthropogenic features such as tailings, dumps, and disturbed areas west of the carbonatite (locs. 7a, 7b, 7c) and an isolated eTh and eU anomaly southeast of the carbonatite body (loc. 7d).

The diverse physical properties of rocks that underlie the study area are well suited to geophysical investigations. Contrasts in radiogenic signatures between Paleoproterozoic crystalline basement, rocks of the Mesoproterozoic carbonatite body and the associated alkaline intrusive suite, Paleozoic carbonate rocks, Mesozoic granitoids, Tertiary volcanic rocks, and unconsolidated alluvium, for example, produce a distinctive pattern of radiometric anomalies that can aid in understanding the geologic framework and mineral resource potential of the eastern Mojave Desert.

ACKNOWLEDGMENTS

We thank David Grenier of CGG Canada Services Ltd. for coordinating and facilitating the detailed aeroradiometric survey. We also thank Jared Peacock and Daniel Scheirer of the U.S. Geological Survey (USGS) for their reviews, and map editor Taryn Lindquist (USGS) for comments and suggestions.

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EXPLANATION FOR MAPS A, B, AND C

4a **Location of radiometric anomaly discussed in text**

Outline of carbonatite body and associated alkaline instusive suite

Carbonatite or alkaline intrusive dike

Faults—Solid where location is accurate; dashed where location is inferred; dotted where location is concealed

Fault, unspecified or unknown sense of slip

Thrust fault—Sawteeth on upper plate

Normal fault—Hachures on upper plate

MNP **Boundary of Mojave National Preserve (MNP)**

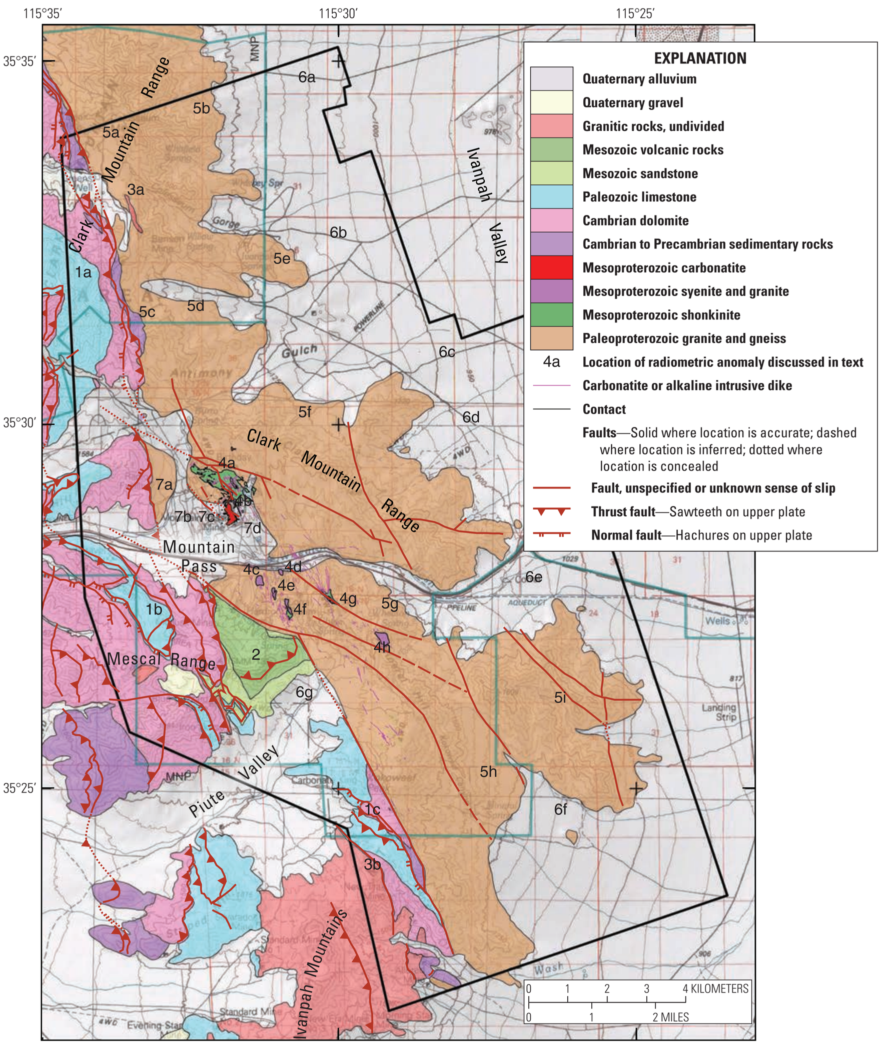


Figure 1. Map showing simplified geology of study area (modified from Olson and others, 1954; Miller and others, 2007). Black outline, area of radiometric survey; green line, boundary of Mojave National Preserve (MNP). Base map from U.S. Geological Survey 1:100,000-scale quadrangles: Ivanpah, 1985; Mesquite Lake, 1985; contour interval, 50 m; thin, red horizontal and vertical lines are township and range boundaries.

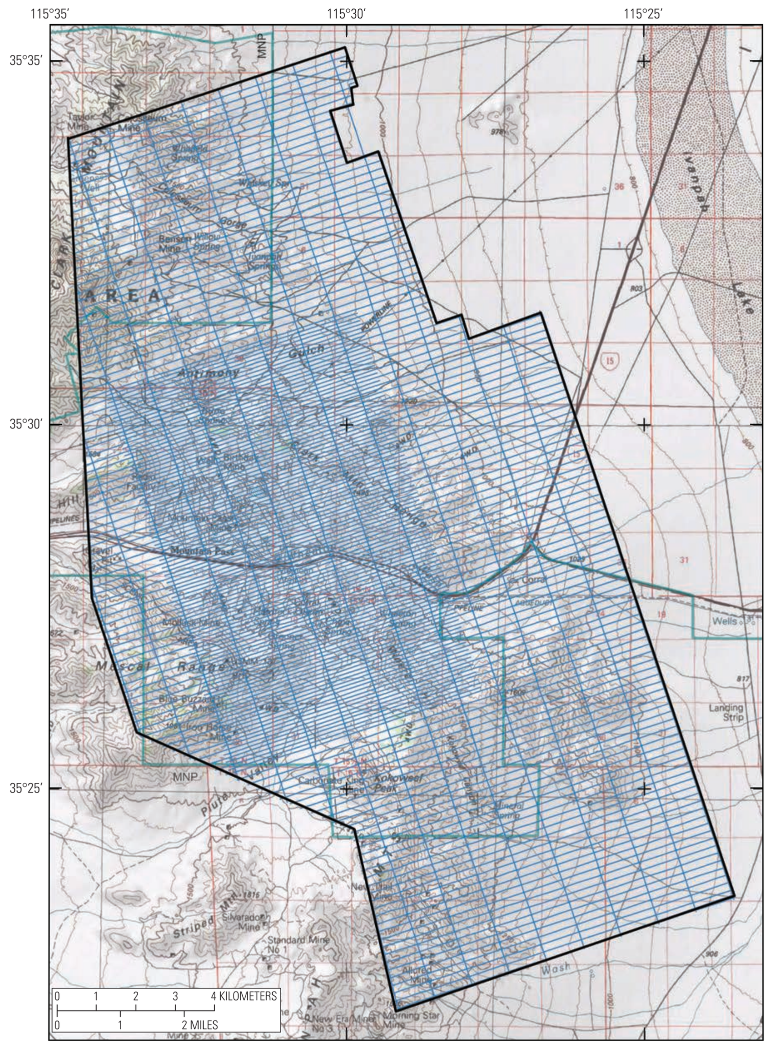
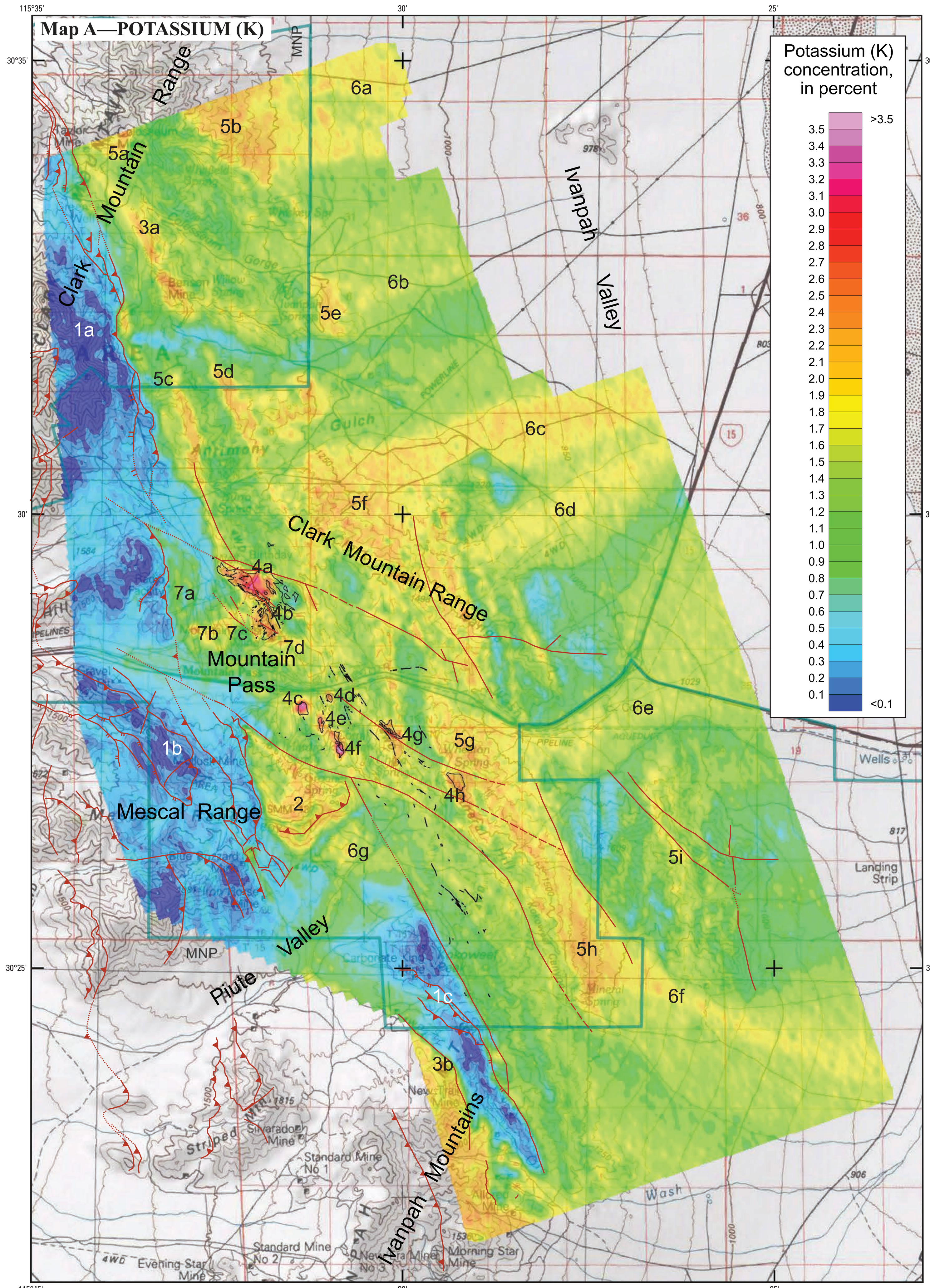
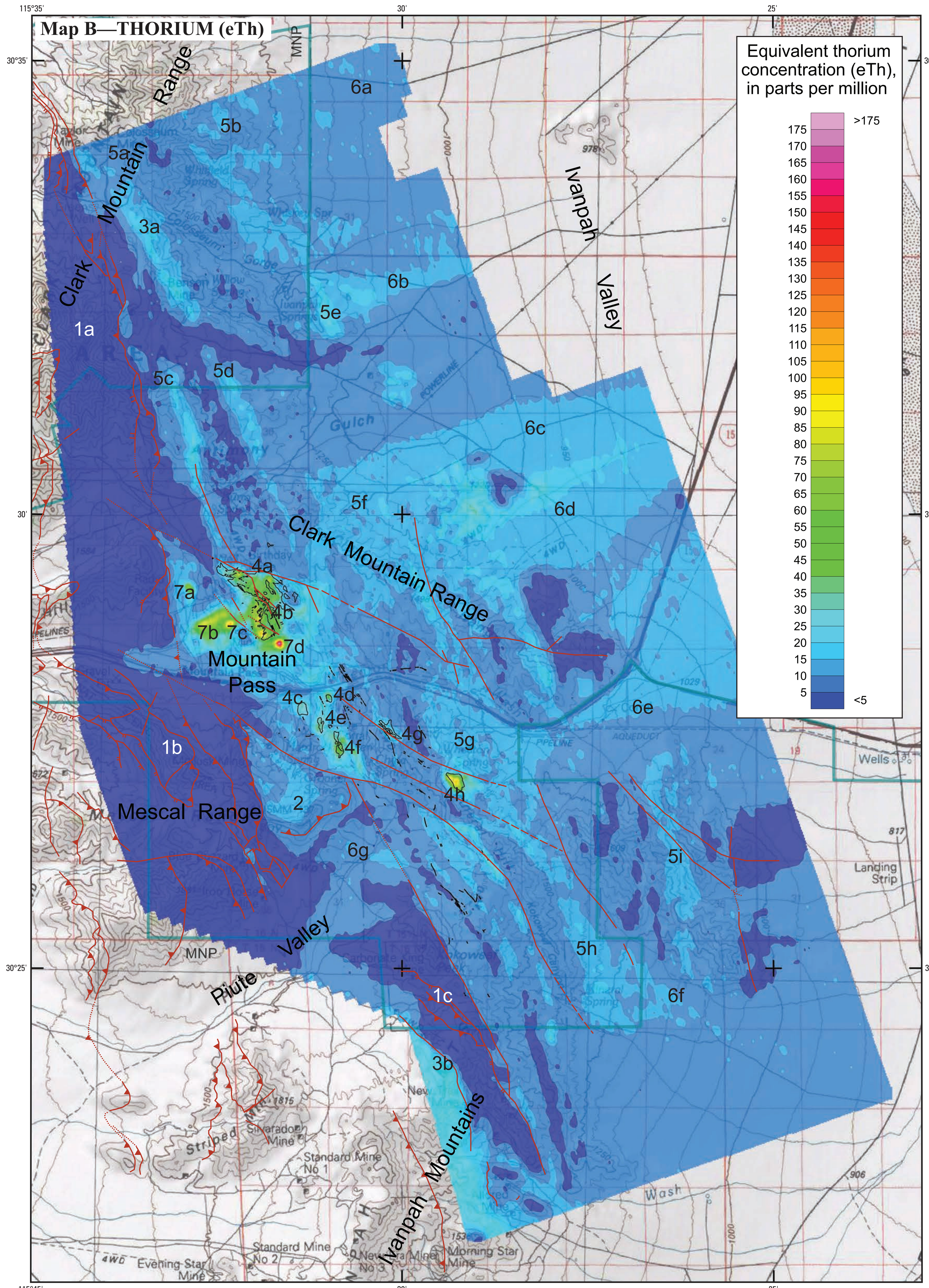
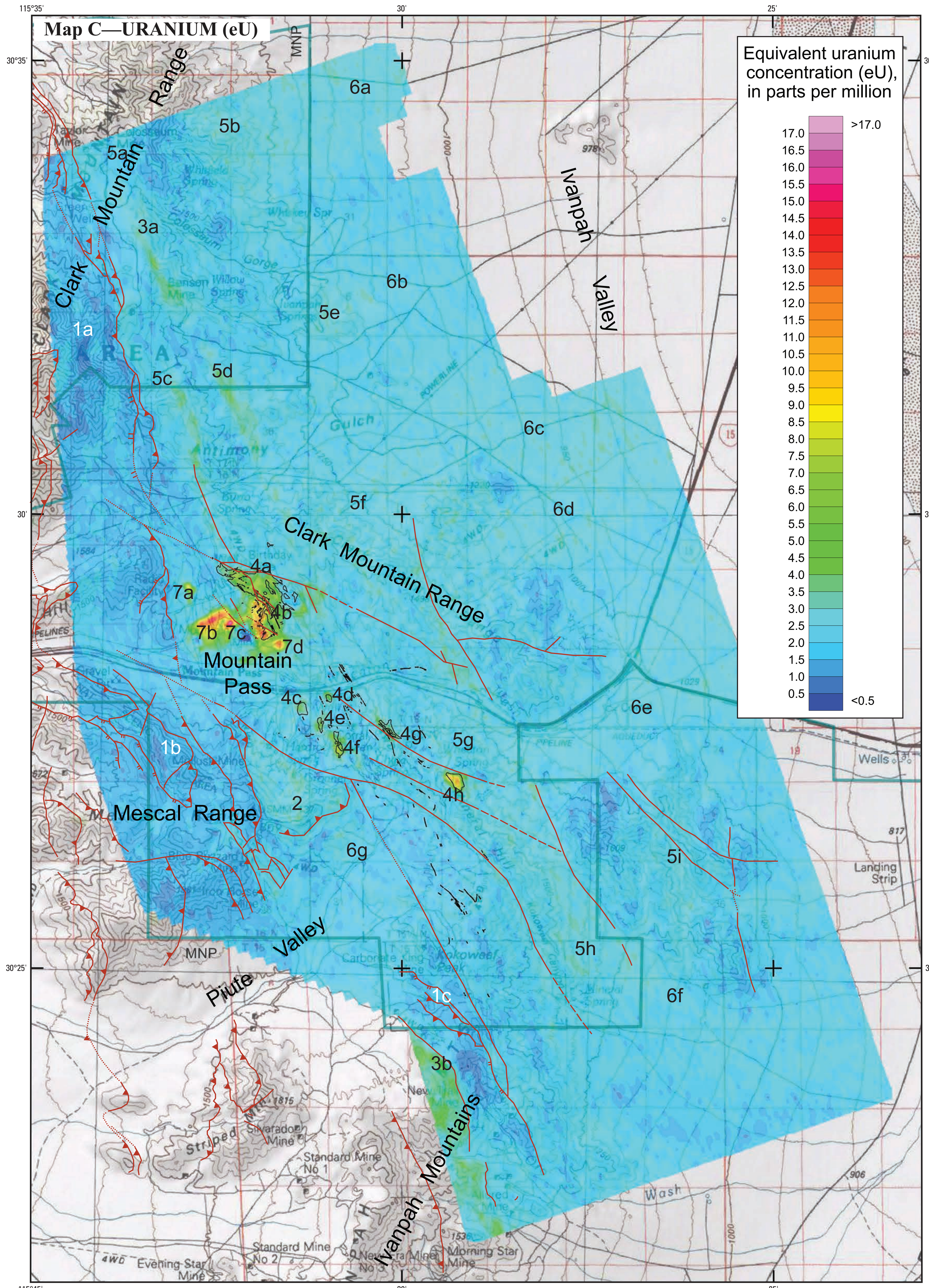


Figure 2. Index map showing location of flightlines (blue lines) within area of radiometric survey (thick black outline). Green line, boundary of Mojave National Preserve (MNP). Base map from U.S. Geological Survey 1:100,000-scale quadrangles: Ivanpah, 1985; Mesquite Lake, 1985; contour interval, 50 m; thin, red horizontal and vertical lines are township and range boundaries.







Base map from U.S. Geological Survey 1:100,000-scale quadrangles: Ivanpah, 1985; Mesquite Lake, 1985

Universal Transverse Mercator projection, Zone 11N, North American Datum of 1983 (NAD 83)

APPROXIMATE MEAN DECLINATION, 2019

SCALE 1:62 500

1 ½ 0 1 2 3 4 5 MILES

1 .5 0 1 2 3 4 5 6 7 KILOMETERS

CONTOUR INTERVAL 50 METERS

MAP LOCATION

Data compiled in 2018

GIS database and digital cartography by D.A. Ponce and K.M. Denton

Edited by Taryn A. Lindquist; digital cartographic production by Katie Sullivan

Manuscript approved for publication April 19, 2019

Airborne Radiometric Maps of Mountain Pass, California

By

D.A. Ponce and K.M. Denton

2019

ISSN 2329-132X (online)
https://doi.org/10.3133/sim3412C

Digital files available at https://doi.org/10.3133/sim3412C

Suggested citation: Ponce, D.A., and Denton, K.M., 2019, Airborne radiometric maps of Mountain Pass, California: U.S. Geological Survey Scientific Investigations Map 3412–C, scale 1:62,500, https://doi.org/10.3133/sim3412C.