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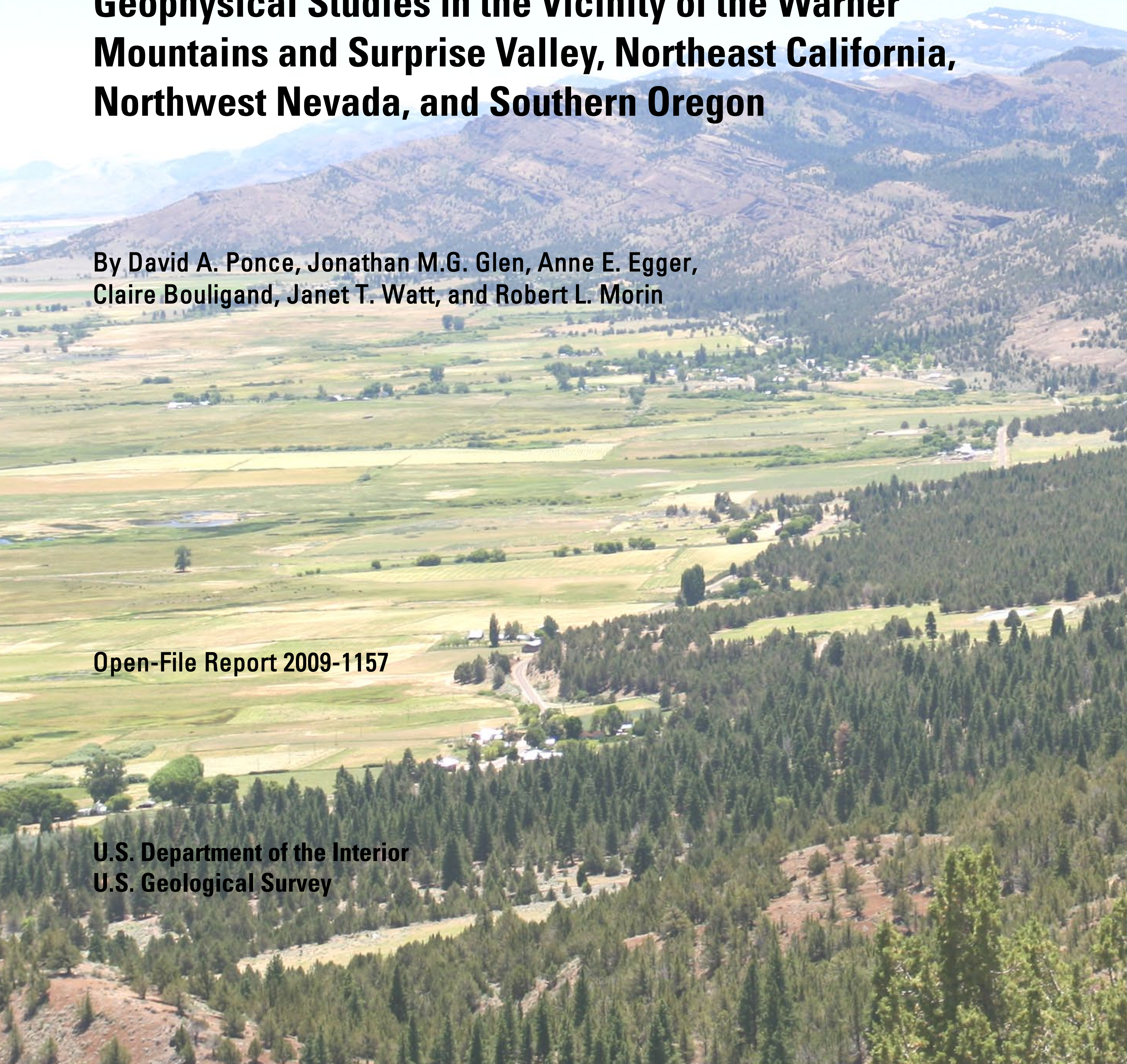
Geophysical Studies in the Vicinity of the Warner Mountains and Surprise Valley, Northeast California, Northwest Nevada, and Southern Oregon



By David A. Ponce, Jonathan M.G. Glen, Anne E. Egger,
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Open-File Report 2009-1157

U.S. Department of the Interior
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Cover: View looking south along the Warner Mountains and Surprise Valley (Photograph by A.E. Egger).

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KEN SALAZAR, Secretary

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Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia 2009

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Suggested citation:
Ponce, D.A., Glen, J.M.G., Egger, A.E., Bouligand, Claire, Watt, J.T., and Morin, R.L., 2009, Geophysical studies in the vicinity of the Warner Mountains and Surprise Valley, northeast California, northwest Nevada, and southern Oregon: U.S. Geological Survey Open-File Report 2009-1157, 19 p., 6 data files [http://pubs.usgs.gov/of/2009/1157/].

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Geophysical Studies in the Vicinity of the Warner Mountains and Surprise Valley, Northeast California, Northwest Nevada, and Southern Oregon

By David A. Ponce[1], Jonathan M.G. Glen[1], Anne E. Egger[2],
Claire Bouligand[1], Janet T. Watt[1], and Robert L. Morin[1]

Introduction

From May 2006 to August 2007, the U.S. Geological Survey (USGS) collected 793 gravity stations, about 102 line-kilometers of truck-towed and ground magnetometer data, and about 325 physical-property measurements in northeastern California, northwestern Nevada, and southern Oregon (fig. 1). Gravity, magnetic, and physical-property data were collected to study regional crustal structures and geology as an aid to understanding the geologic framework of the Surprise Valley geothermal area and, in general, geothermal systems throughout the Great Basin.

The Warner Mountains and Surprise Valley mark the transition from the extended Basin and Range province to the unextended Modoc Plateau (fig. 1). This transition zone, in the northwestern corner of the Basin and Range, is relatively diffuse compared to other, more distinct boundaries, such as the Wasatch front in Utah and the eastern Sierran range front. In addition, this transition zone is the site of a geothermal system with potential for development, and previous studies have revealed a complex structural setting consisting of several obliquely oriented fault sets (Hedel, 1984). As a result, this region has been the subject of several recent geological and geophysical investigations (Lerch and others, 2006; Glen and others, 2008, Egger and others, 2009; Lerch and others, 2009). The gravity and magnetic data presented here support and supplement those studies, and although the study area is composed predominantly of Tertiary volcanic rocks of the Modoc Plateau rocks (Jenkins, 1958; Stewart and Carlson, 1978), the physical properties of these and others rocks create a distinguishable pattern of gravity and magnetic anomalies that can be used to infer subsurface geologic structure.

Gravity, Magnetic, and Physical-Property Data

Gravity Data

Gravity data were collected between May 2006 and August 2007 and consist of 793 new stations concentrated in areas of sparse control as well as along traverses of interest (fig. 2). All gravity data were tied to primary base station ALTURAS (Jablonski, 1974) at the courthouse in Alturas, Calif., at lat 41°28.99'N. and long 120°32.46'W., with a revised observed gravity value of 979,874.30 mGal. Gravity stations were located between lat 41°00' and 42°15'N. and long

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119°45’ and 120°30’W. and are distributed across the Alturas, Vya, Lakeview, and Adel USGS 1 x 2 degree (1:250,000-scale) topographic quadrangle maps.

New gravity data were reduced using standard gravity methods (Blakely, 1995) and include the following corrections: (a) earth-tide correction, which corrects for tidal effects of the moon and sun; (b) instrument-drift correction, which compensates for drift in the instrument’s spring; (c) latitude correction, which accounts for the variation of the Earth’s gravity with latitude; (d) free-air correction, which accounts for the variation in gravity due to elevation relative to sea level; (e) Bouguer correction, which corrects for the attraction of material between the station and sea level; (f) curvature correction, which corrects the Bouguer correction for the effect of the Earth’s curvature; (g) terrain correction, which removes the effect of topography to a radial distance of 167 km around the station; and (h) isostatic correction, which removes long-wavelength variations in the gravity field related to the compensation of topographic loads.

LaCoste and Romberg gravity meter G614 and a Scintrex CG-5 gravity meter were used in this survey. Conversion of meter readings to gravity units for LaCoste and Romberg gravity meter G614 were made using factory calibration constants, as well as a secondary calibration factor (1.00036) determined by multiple gravity readings over the Mt. Hamilton calibration loop east of San Jose, Calif. (Barnes and others, 1969). For the Scintrex CG-5 gravity meter, the factory meter calibration constant was also checked and redetermined over the Mt. Hamilton calibration loop. Observed gravity values were based on a time-dependent linear drift between successive base readings and were referenced to the International Gravity Standardization Net 1971 (IGSN 71) gravity datum (Morelli, 1974, p. 18). 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 kg/m^3. Finally, a regional isostatic gravity field was removed from the Bouguer field assuming an Airy-Heiskanen model for isostatic compensation of topographic loads (Jachens and Roberts, 1981) 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. Gravity values are expressed in mGal (milligal), a unit of acceleration or gravitational force per mass equal to 10^{-5} m/s^2.

Station locations and elevations were obtained using a Trimble® GeoXT differential Global Positioning System instrument. The GeoXT receiver uses the Wide Area Augmentation System (WAAS) which, combined with a base station and post-processing using Continually Operated Reference Station (CORS) satellites, results in submeter vertical accuracy.

Terrain corrections, which account for the variation of topography near a gravity station, were computed using a combination of manual and digital methods. Terrain corrections consist of a three-part process: the innermost or field-terrain correction, innerzone-terrain correction, and outerzone-terrain correction. The innermost-terrain corrections were estimated in the field and extend from the station to a radial distance of 68 m, equivalent to Hayford and Bowie’s (1912) zone B. Innerzone-terrain corrections were estimated from Digital Elevation Models (DEMs) with 10- or 30-m resolutions derived from USGS 7.5’ topographic maps and extend from 68 m to a radial distance of 2 km (D. Plouff, USGS, unpub. software, 2006). Outerzone-terrain corrections, from 2 km to a radial distance of 167 km, were computed using a DEM derived from USGS 1:250,000-scale topographic maps and an automated procedure based on geographic coordinates (Plouff, 1966; Plouff, 1977; Godson and Plouff, 1988). Digital-terrain corrections are calculated by computing the gravity effect of each grid cell in the DEM using the distance and difference in elevation of each grid cell from the gravity station.

New gravity data were combined with pre-existing gravity data from the surrounding areas in California, Nevada, and Oregon (Griscom and Conradi, 1976; Snyder and others, 1981; Ponce, 1997; Tilden and others, 2005; Plouff, 2006; Pan-American Center for Earth and Environmental Studies (PACES), 2009). Gravity data for Oregon were downloaded from the PACES Web site (PACES, 2009), and terrain corrections and gravity anomalies were recomputed using standard programs, described above. Field-terrain corrections were not available for the Oregon gravity data set, and those with a station name prefix of 4911 (a Defense Mapping Agency source code) were on the 1930 Potsdam gravity datum rather than the IGSN71 datum. These data were replaced by the original data set collected and republished by Plouff (2006). In addition, some Oregon gravity data were discarded because of incorrect locations, elevations, or gravity values determined by visual inspection and comparisons with adjacent or duplicate stations. All gravity data were gridded using a minimum curvature algorithm at an interval of 500 m and displayed as a color-contoured map (fig. 3). Principal facts of combined new and pre-existing gravity data (3,784 stations) are given in table 1 in an Excel workbook.

Magnetic Data

Aeromagnetic Data

Aeromagnetic data were derived from statewide compilations of California, Nevada, and parts of Oregon (Roberts and Jachens, 1999, Kucks and others, 2006, R.P. Kucks, written commun., 2006) and displayed using a 1-km grid as a color-contoured map (fig. 4*A*). The regional aeromagnetic compilation consists principally of a single survey flown at 2,896 m barometric elevation with flight lines oriented north-south and spaced 3.2 km apart (California Division of Mines and Geology, 1978).

A high-resolution survey was flown over the Surprise Valley geothermal area in 1979 near Lake City, Calif. (U.S. Geological Survey, 1981), and is shown in figure 4*B*. The survey was flown at an elevation of 122 m above ground (constant terrain clearance or draped) with flight lines oriented north-northeast and spaced 800 and 400 m apart. A regional International Geomagnetic Reference Field (IGRF) was removed from the data. This map was created by digitizing contours and individual locations of maxima and minima from the originally published map and was gridded at a 10-m interval. The digitized contour data are presented in table 2, in an Excel workbook, as geographic coordinates (NAD27 datum) and total magnetic field value in nanoteslas.

In 1981, another high-resolution survey, with even lower flight-line elevation, was flown over a part of the previous survey area near Lake City (Fraser and Hoover, 1983) and is shown in figure 4*C*. The survey was flown at an elevation of 50 m above ground with flight lines oriented north-northeast and spaced 400 m apart. This map was created by digitizing the contours and individual locations of maxima and minima from the originally published map and gridded at a

10-m interval. The digitized contour data are presented in table 3, in an Excel workbook, as geographic coordinates (NAD27 datum) and total magnetic field value in nanoteslas.

Truck-Towed Magnetic Data

About 80 line-kilometers of truck-towed magnetometer data were collected along four traverses (lines 4A to 4D) shown in figures 5 and 6*A*. Magnetometer and Geographic Positioning System (GPS) data were collected simultaneously at one-second intervals using a Geometrics® G858 cesium vapor magnetometer attached to an aluminum carriage connected to the vehicle by aluminum tubing and towed about 9 m behind the vehicle. The height of the magnetometer above the ground surface was about 2 m. A portable Geometrics® G856 proton-precession base-station magnetometer was used to record diurnal variations of the Earth's magnetic field during the truck-towed magnetometer surveys.

During field operations, truck-towed magnetic data were recorded and viewed in real-time using Geometrics® MagLog software. Raw magnetic data were downloaded and processed using Geometrics® MagMap2000 software, where magnetometer and GPS data were merged. The location of the magnetometer was recorded using a Trimble® nonmagnetic Ag132 GPS receiver mounted on an aluminum frame attached to the magnetometer. The Ag132 receiver has real-time differential correction capabilities using an Omnistar satellite system, resulting in submeter horizontal accuracy. The data are presented in table 4 as geographic coordinates (NAD27 datum) and magnetic field values in nanoteslas. Diurnal variations recorded by the base-station magnetometer were removed, and the data were filtered to remove cultural "noise" such as passing cars, culverts, fences, and power lines. Individual lines have not been leveled with one another. Truck-towed magnetic locations are shown in figure 5, magnetic profiles are shown in figure 6*A*, and data are presented in table 4 in an Excel workbook.

Ground Magnetic Data

About 22 line-kilometers of ground gradient magnetic data were collected along five traverses (lines 5A to 5E) shown in figures 5 and 6*B*. These traverses were collected using a Geometrics® G858 cesium vapor magnetometer with the same survey and GPS specifications as the truck-towed magnetometer surveys. The data are presented in table 5 as geographic coordinates (NAD27 datum) and magnetic field values in nanoteslas. The height of the magnetometer above the ground surface was about 2 m. A portable Geometrics® G856 proton-precession base-station magnetometer was used to record diurnal variations of the Earth's magnetic field during the ground-magnetic surveys. Diurnal variations recorded by the base-station magnetometer were removed and the data were filtered to remove cultural "noise", such as passing cars, culverts, fences, and power lines. Individual lines have not been leveled with one another. Ground magnetic locations are shown in figure 5, profiles are shown in figure 6*B*, and data are presented in table 5 in an Excel workbook.

Physical-Property Data

Rock samples were collected throughout the study area from outcrops and from a core from drill-hole LCSH-05, drilled by AMP Resources (Benoit and others, 2005), near Lake City (fig. 7). Data include station identifier, geographic coordinates (NAD27), rock type, density, and magnetic susceptibility and are listed in table 6 in an Excel workbook. Densities were determined using the buoyancy method with an electronic balance, and magnetic susceptibility measurements were made using a Kappameter® KT-5. Grain, saturated-bulk, and dry-bulk densities were computed for each sample by weighing the sample in air (*Wa*), saturated and submerged in water (*Ww*), and saturated and weighed in air (*Was*) using the following formulas, where weights were measured in grams:

Grain density = 1,000 kg/m^3 * $Wa/(Wa-Ww)$,

Saturated-bulk density = 1,000 kg/m^3 * $Was/(Was-Ww)$, and

Dry-bulk density = 1,000 kg/m^3 * $Wa/(Was-Ww)$.

Density and magnetic susceptibility versus depth in drill-hole LCSH-05 are shown in figure 8. In general, density increases with depth, and there is a positive correlation of density and magnetic susceptibility. In particular, high densities and moderate to strong magnetic susceptibilities correlate with mafic andesitic lava flows from 550 to 650 m and from 1,300 to 1,425 m depths.

General Discussion

In general, isostatic gravity anomalies reflect lateral density variations in the middle to upper crust. Thus, gravity anomalies can be used to infer the subsurface structure of known or unknown geologic features. Gravity anomalies can, for instance, reveal variations in lithology and features, such as calderas, deep sedimentary basins, and faults, that may play a role in defining the geologic framework of the area.

In the study area, a prominent gravity high occurs over the Warner Mountains, and a more subdued high occurs over the Hays Canyon Range (fig. 3). Gravity highs in the northern part of the Warner Mountains are associated with Tertiary intrusive rocks (Chapman and Bishop, 1968; Jenkins, 1958). Prominent gravity lows occur over Surprise Valley, Long Valley, Sheldon Plateau, and Black Rock Desert. A prominent low also occurs over the Goose Lake area that extends much further to the north, but the gravity station control is poor in this area and nonexistent over the lake. In general, the gravity lows over the valleys reflect moderately deep sedimentary basins filled with lower density alluvial and volcanic deposits. Isostatic gravity data indicate the central part of Surprise Valley corresponds approximately to a 20-mGal gravity low, yielding a basin depth of about 1.5 km, assuming a density contrast of 0.4 g/cm^3 and using a semi-infinite slab approximation.

Magnetic anomalies reflect changes in the Earth's magnetic field and are generally used to infer lateral variations in the magnetization of rocks. Anomalies throughout the study area can be explained by variations in rock type and their magnetic properties across the region. Short-wavelength and high-amplitude magnetic anomalies are usually caused by volcanic rocks that are moderately to strongly magnetic. Due to the dipolar nature of magnetic sources, magnetic highs (or lows) are typically accompanied by an associated magnetic low (or high). Isolated magnetic lows, however, may be associated with altered volcanic rocks or weakly magnetic silicic and sedimentary rocks.

Magnetic highs in the study area occur over the Modoc Plateau north and west of Alturas, portions of the Warner Mountains, Hays Canyon Range, and the southwestern section of the

Sheldon Plateau (fig. 4). For the most part, magnetic highs are associated with Tertiary and Quaternary volcanic rocks (Jenkins, 1958; Stewart and Carlson, 1978; Duffield and McKee, 1986; Carmichael and others, 2006). Areas where the magnetic field is lower include southwest of Alturas, the northern end of Goose Lake, Surprise Valley, western Long Valley, and portions of the Sheldon Plateau. In general, these magnetic lows reflect less magnetic Tertiary and Quaternary sedimentary rocks in the valleys or reversely magnetized volcanic rocks. The magnetic lows within the Sheldon Plateau likely reflect less magnetic Tertiary ash-flow tuffs.

The diverse physical properties of the rocks that underlie this region are well suited to geophysical investigations. The contrast in density and magnetic properties between pre-Cenozoic crystalline basement (although not exposed) and the overlying Tertiary volcanic rocks and unconsolidated alluvium, for example, produces a distinctive pattern of gravity and magnetic anomalies. These anomalies can be used to infer subsurface geologic structure and aid in understanding the geologic framework of the Surprise Valley geothermal system (for example, Glen and others, 2008; Egger and others, 2009; Lerch and others, 2009).

Acknowledgments

We thank the following for collecting gravity, truck-towed or ground magnetic, rock samples, or physical property data: Bruce Chuchel, Matthew Coble, Joe Colgan, Christina Contreras, Steve Davis, Julia James, Bryce Johnson, Ilana Lohr-Schmidt, Annie Scofield, Henry Scott, and Carly York. We would like to thank Pat Hill for providing digitized versions of the high-resolution USGS aeromagnetic maps. We would especially like to thank Dick Benoit for allowing access to drill-core samples from the Lake City geothermal field, rancher Dean Cockrell for access to his land, and Ken Collum and Jayne Biggerstaff of the U.S. Forest Service for assistance and access to Federal lands. We also thank Bruce Chuchel and Ed Mankinen for their reviews and Tracey Suzuki for editing the report.

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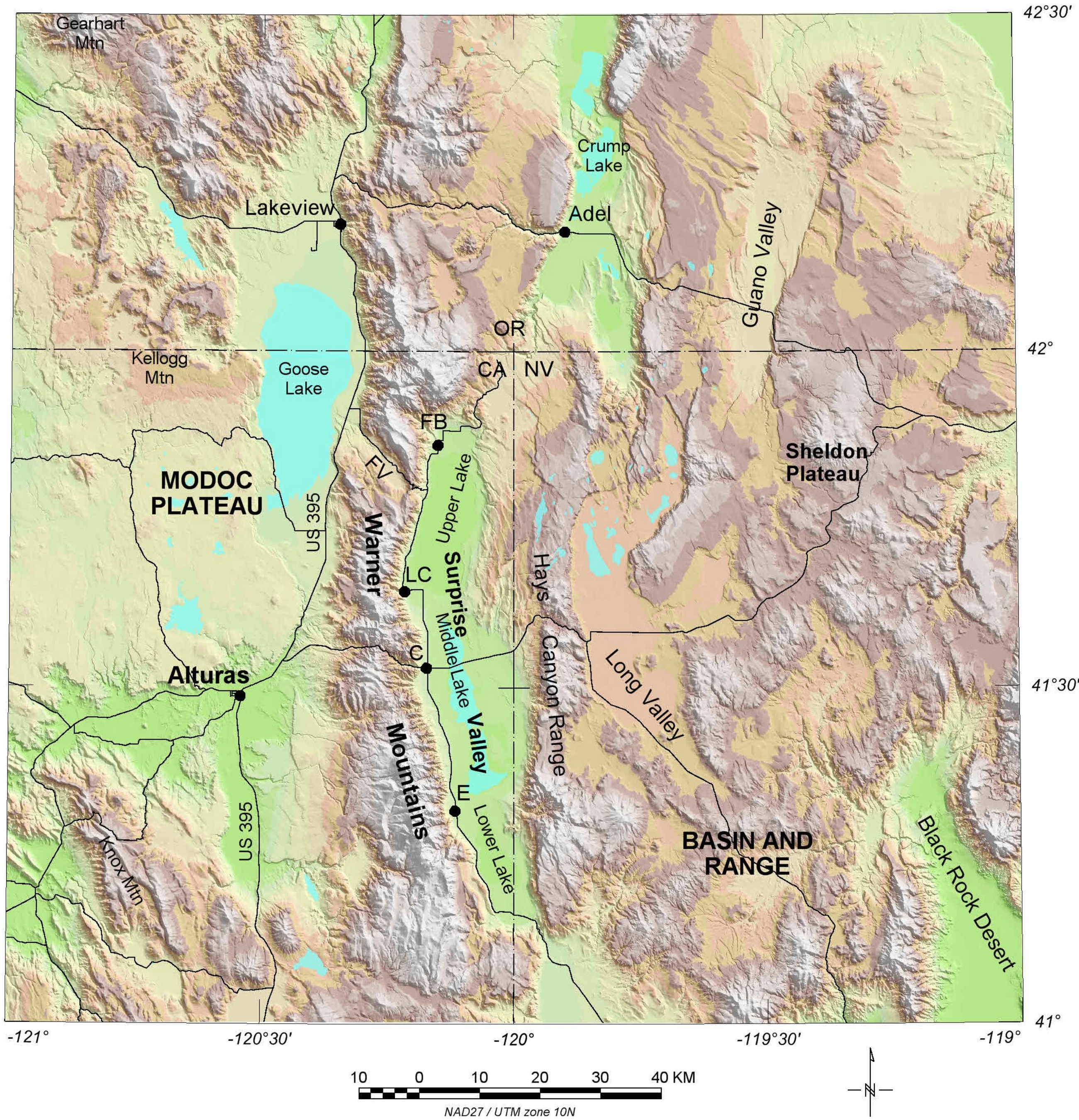


Figure 1. Index map of the Warner Mountains-Surprise Valley study area. C, Cedarville; E, Eagleville; FB, Fort Bidwell; FV, Fandango Valley; LC, Lake City.

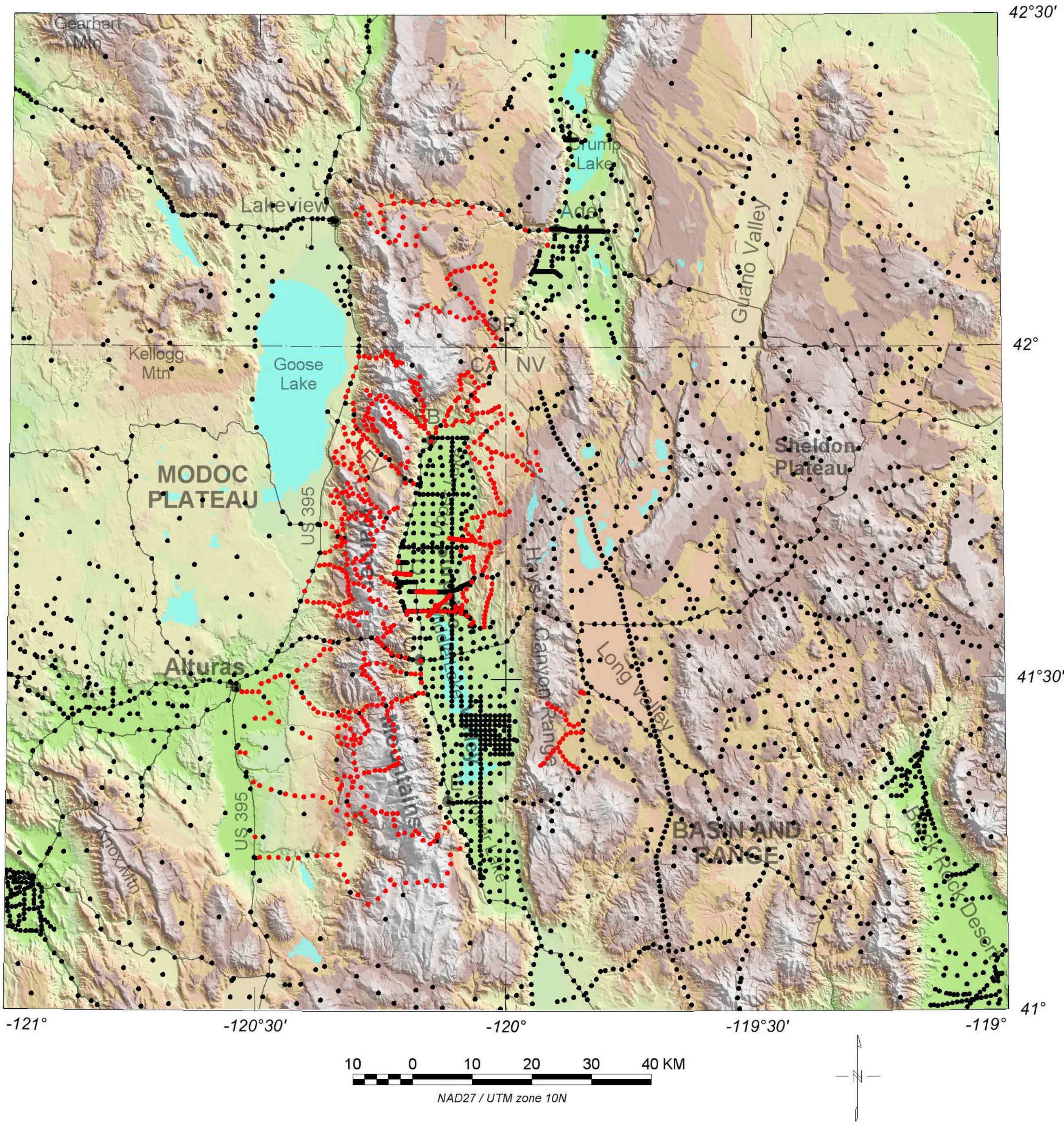


Figure 2. Gravity station location map of the study area. Red circles, stations collected during this study; black circles, pre-existing gravity stations. See figure 1 for explanation.

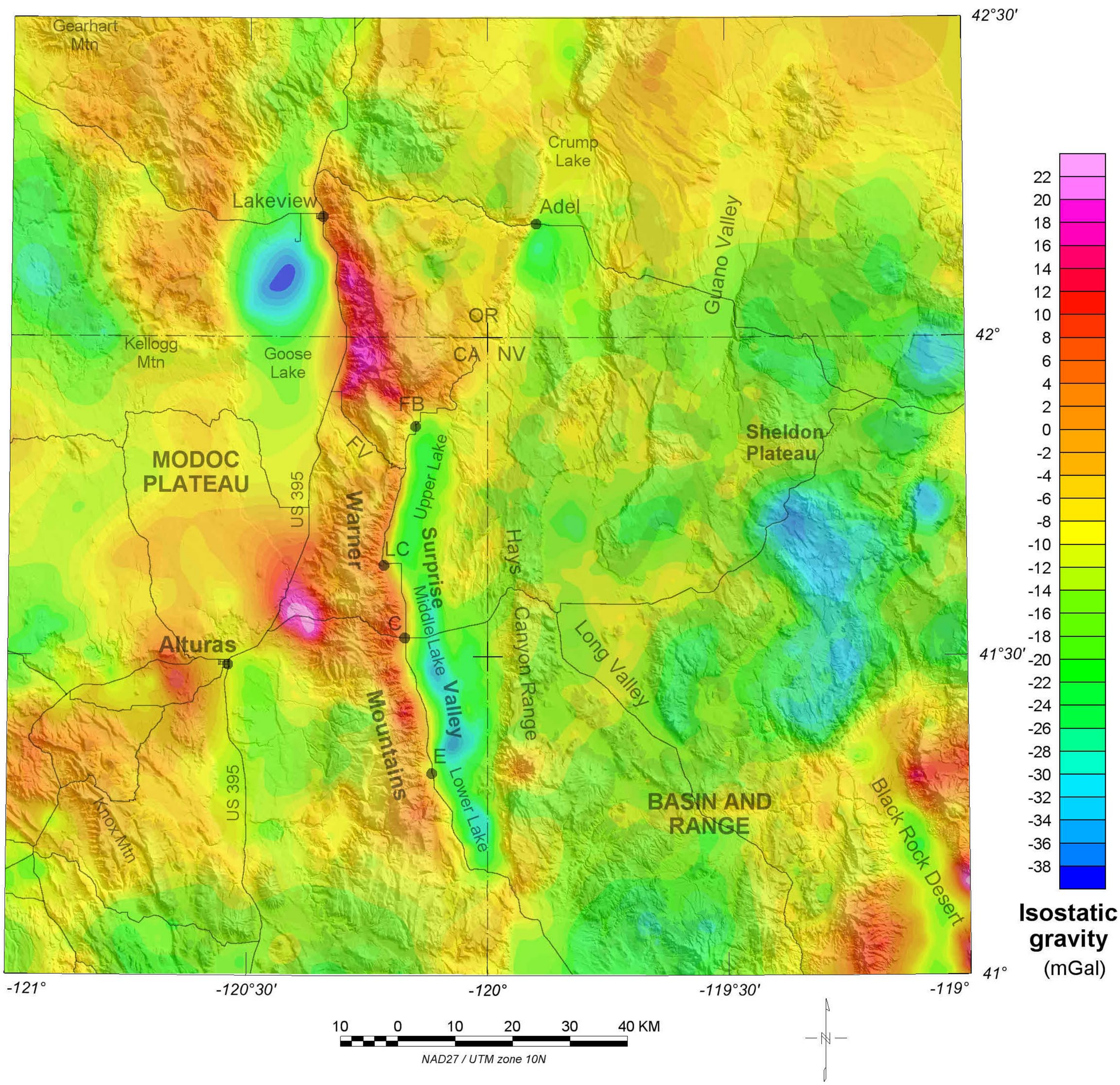


Figure 3. Isostatic gravity map of the study area. See figure 1 for explanation.

A, Aeromagnetic map

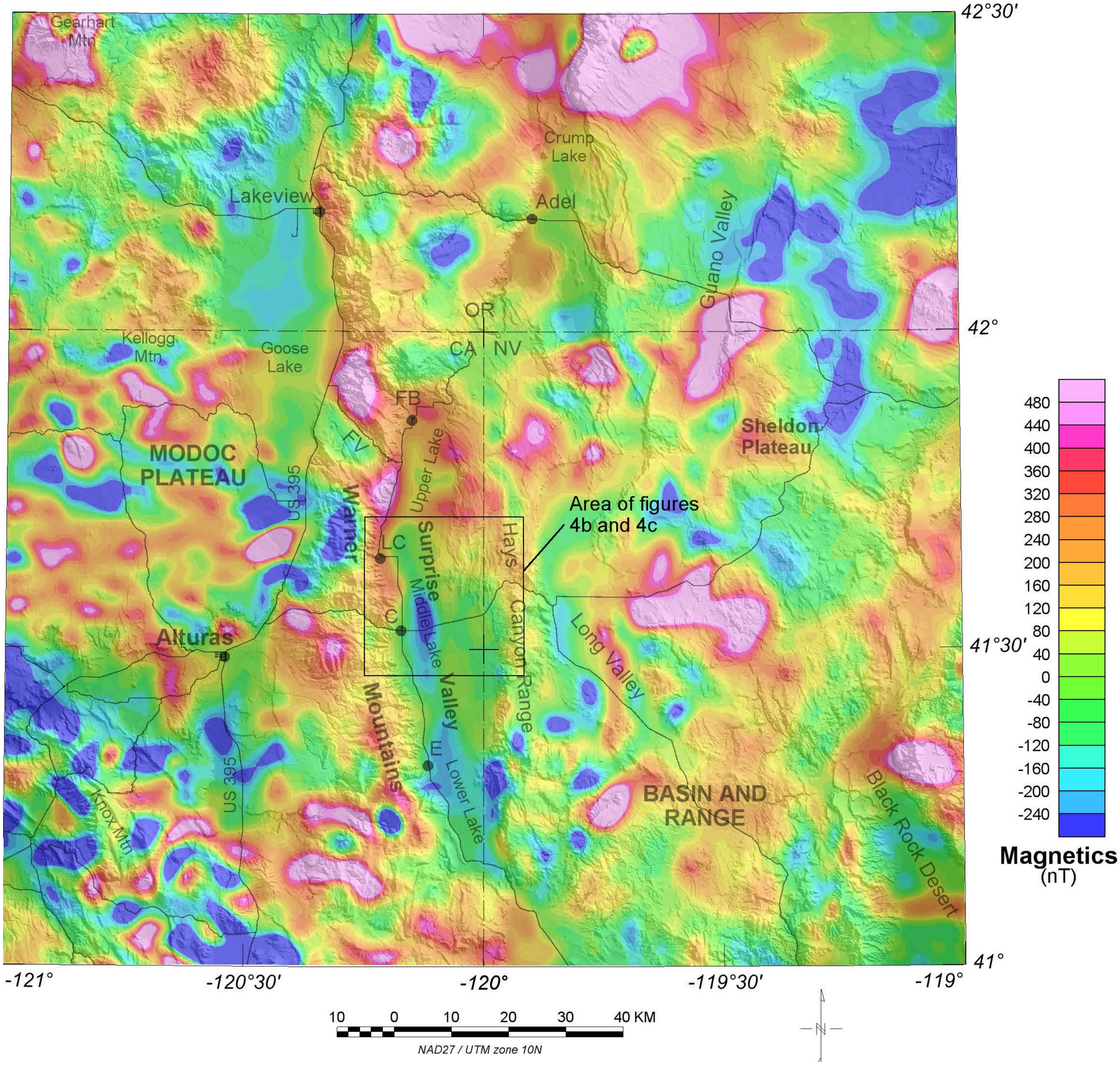
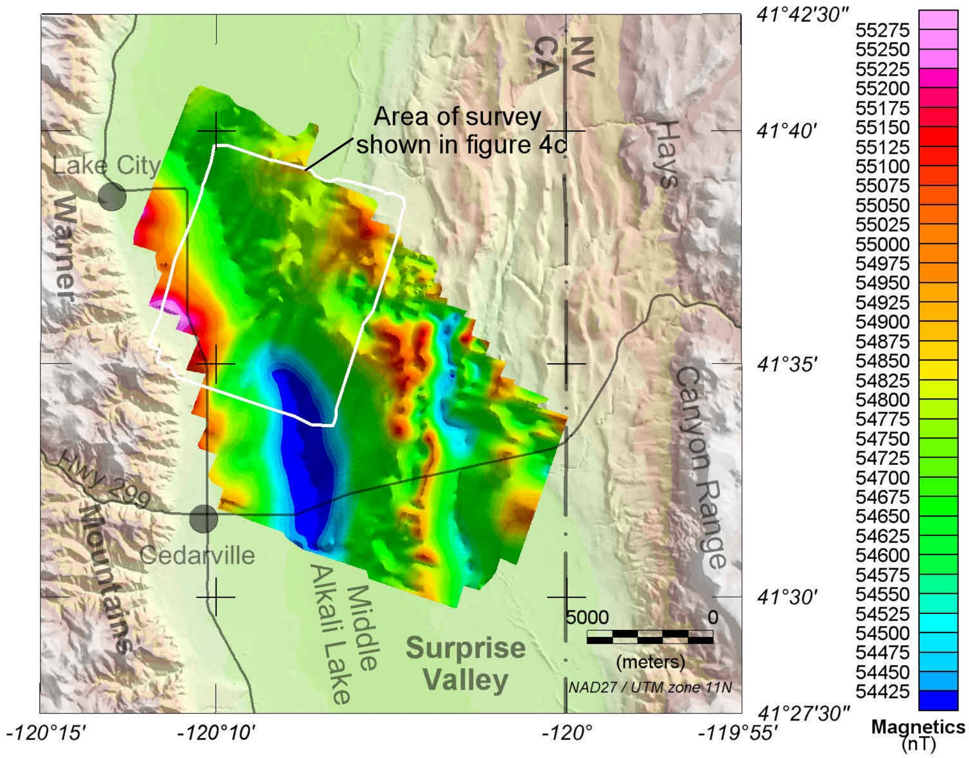
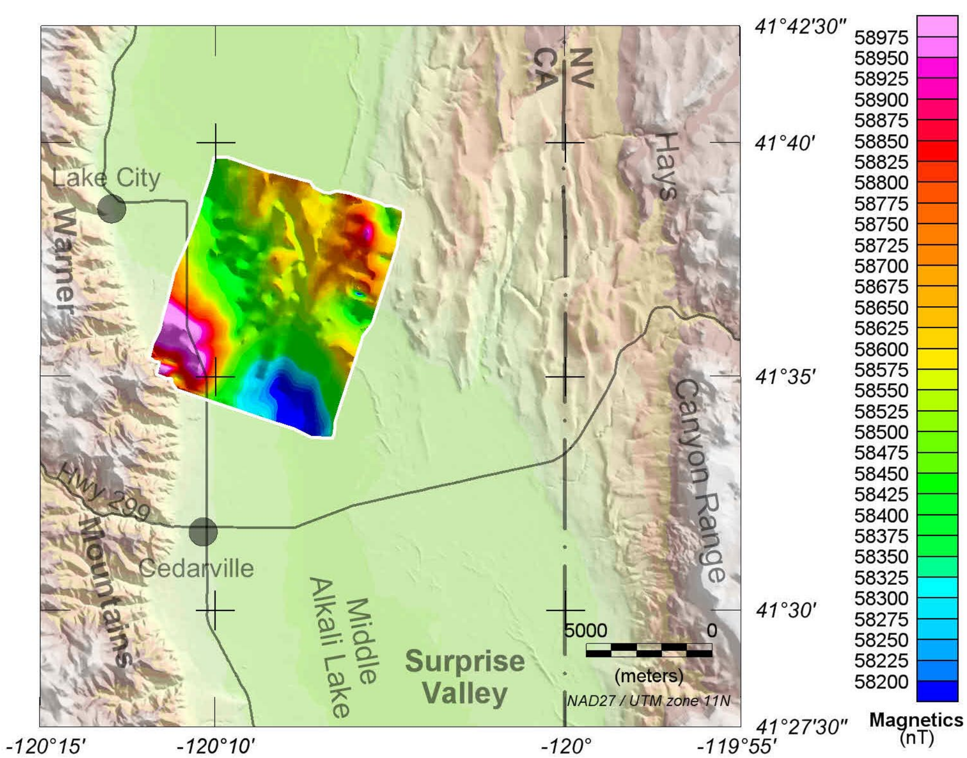


Figure 4. *A,* Aeromagnetic map of the study area. *B*, High-resolution aeromagnetic map of the Surprise Valley geothermal area (U.S. Geological Survey, 1981). *C*, High-resolution aeromagnetic map of part of Surprise Valley (Fraser and Hoover, 1983). See figure 1 for explanation.

B, High-resolution aeromagnetic map of the Surprise Valley geothermal area (U.S. Geological Survey, 1981)



C, High-resolution aeromagnetic map of part of Surprise Valley (Fraser and Hoover, 1983)



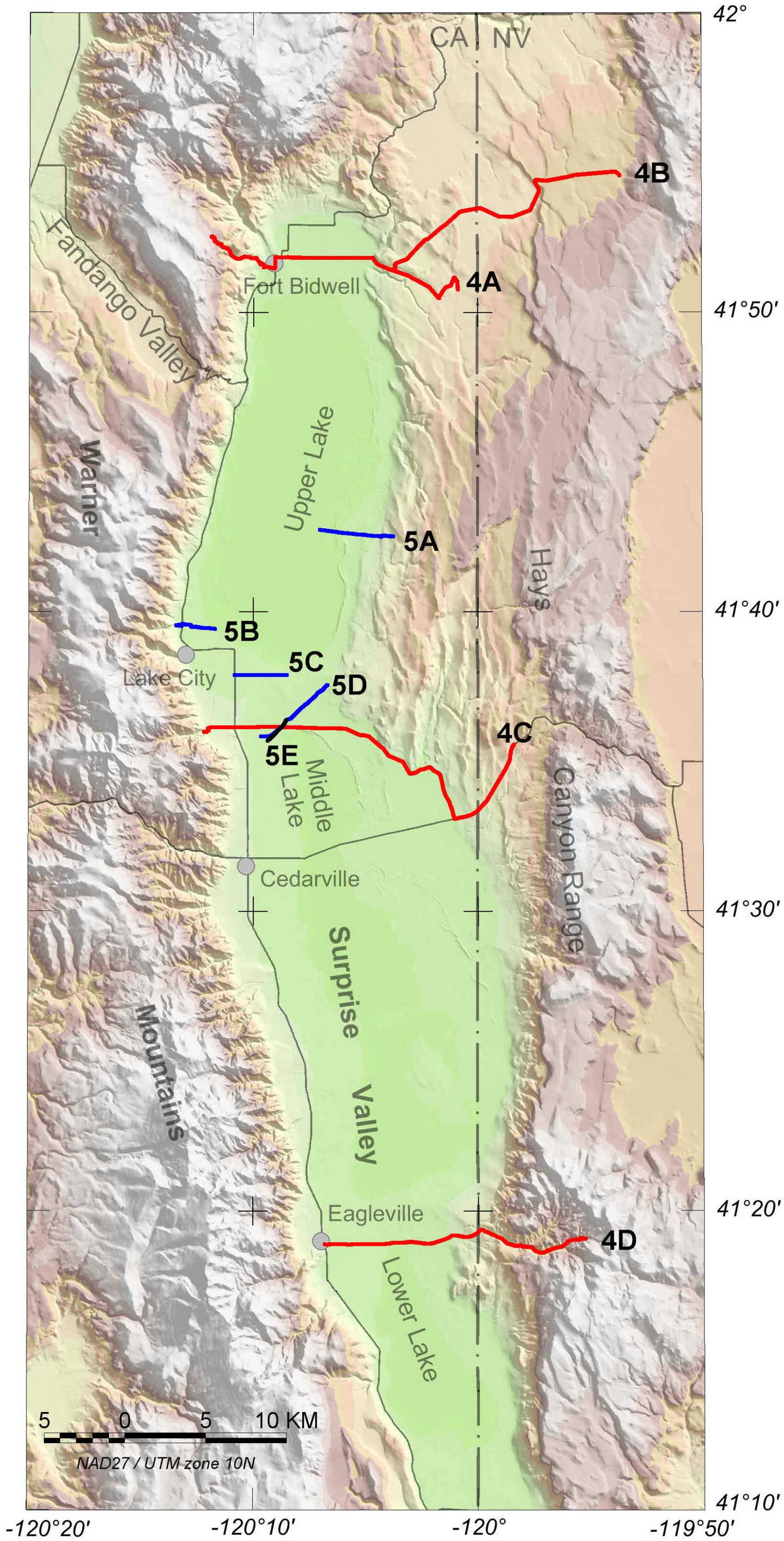


Figure 5. Location of truck-towed (red lines) and ground magnetic (blue and black lines) traverses.

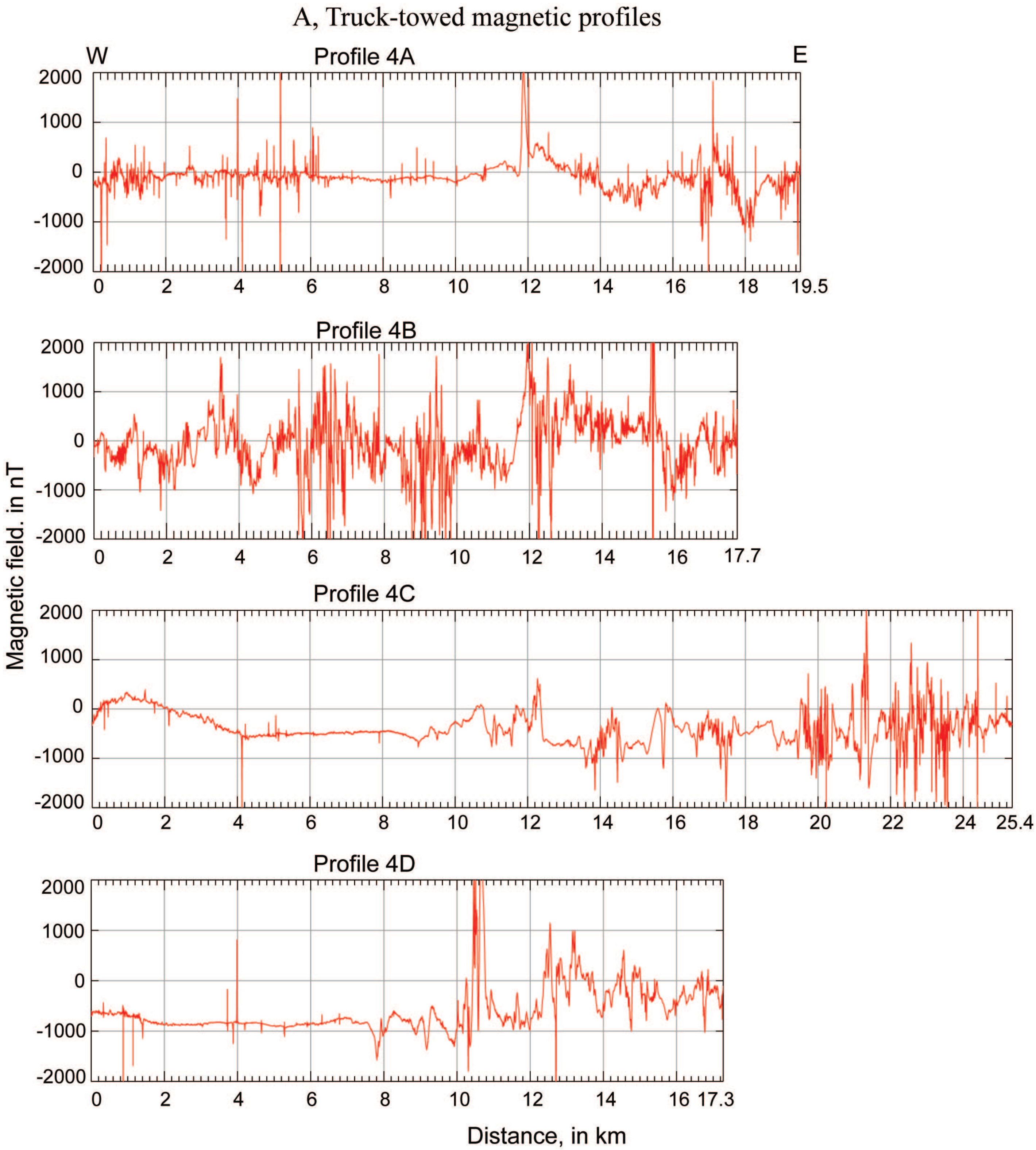
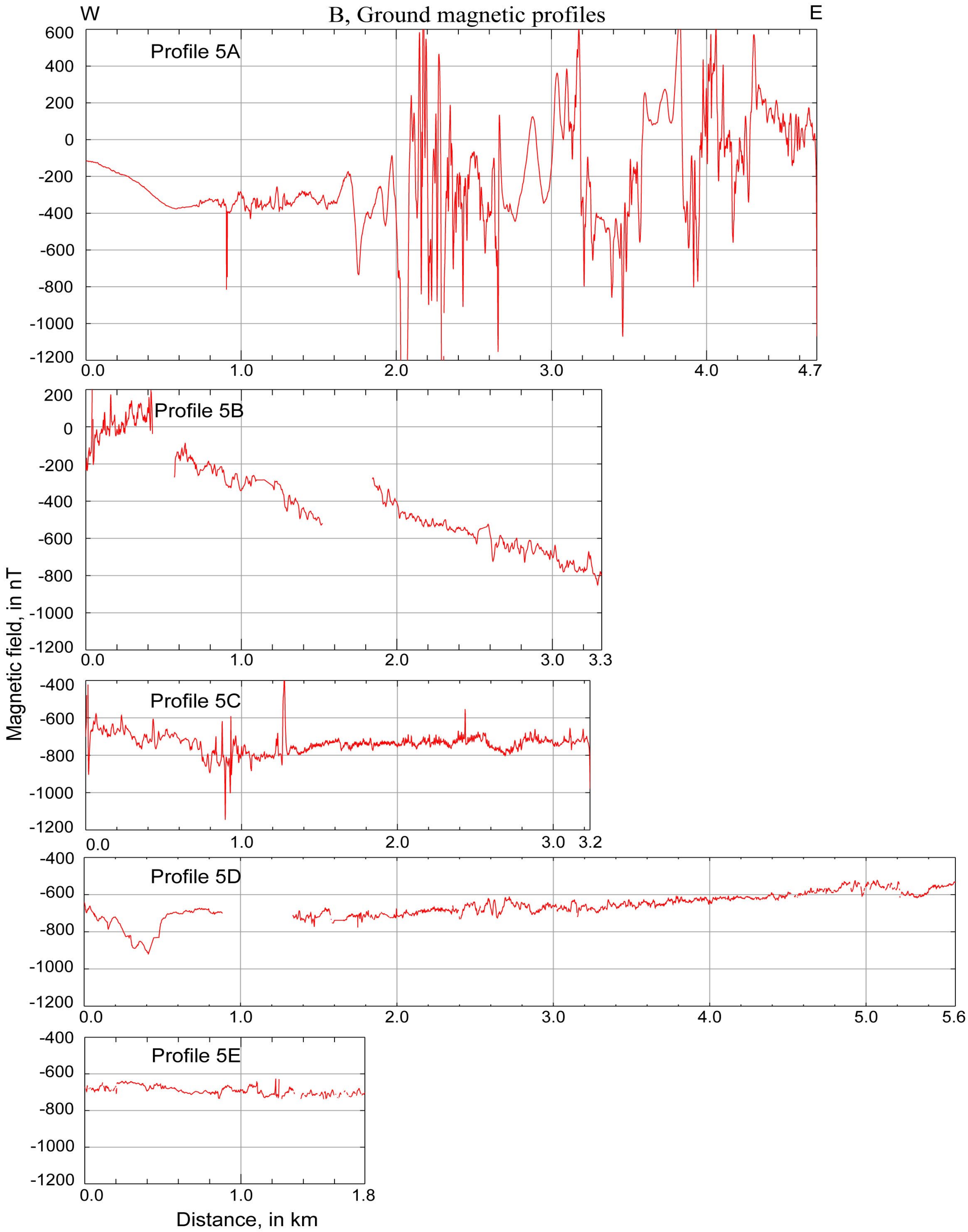


Figure 6. *A*, Truck-towed magnetic profiles. *B*, Ground magnetic profiles. See figure 5 for profile locations.



W
B, Ground magnetic profiles
E
Profile 5A
Profile 5B
Profile 5C
Profile 5D
Profile 5E
Magnetic field, in nT
Distance, in km
600
400
200
0
-200
-400
-600
-800
-1000
-1200
0.0
1.0
2.0
3.0
4.0
4.7
3.3
3.2
5.0
5.6
1.8

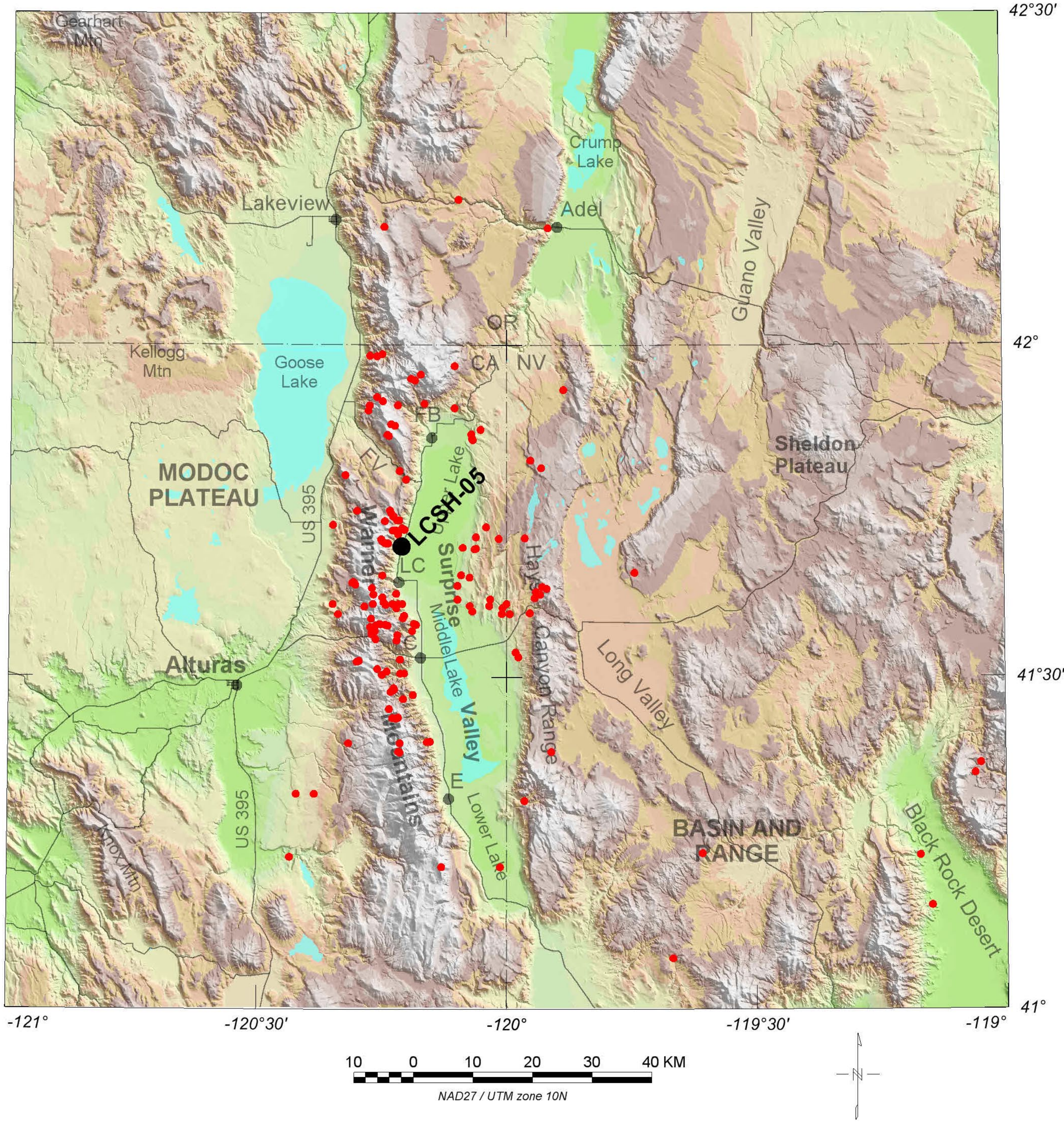


Figure 7. Map showing the location of rock samples (red circles), including core samples from drill-hole LCSH-05 (black circle). See figure 1 for explanation.

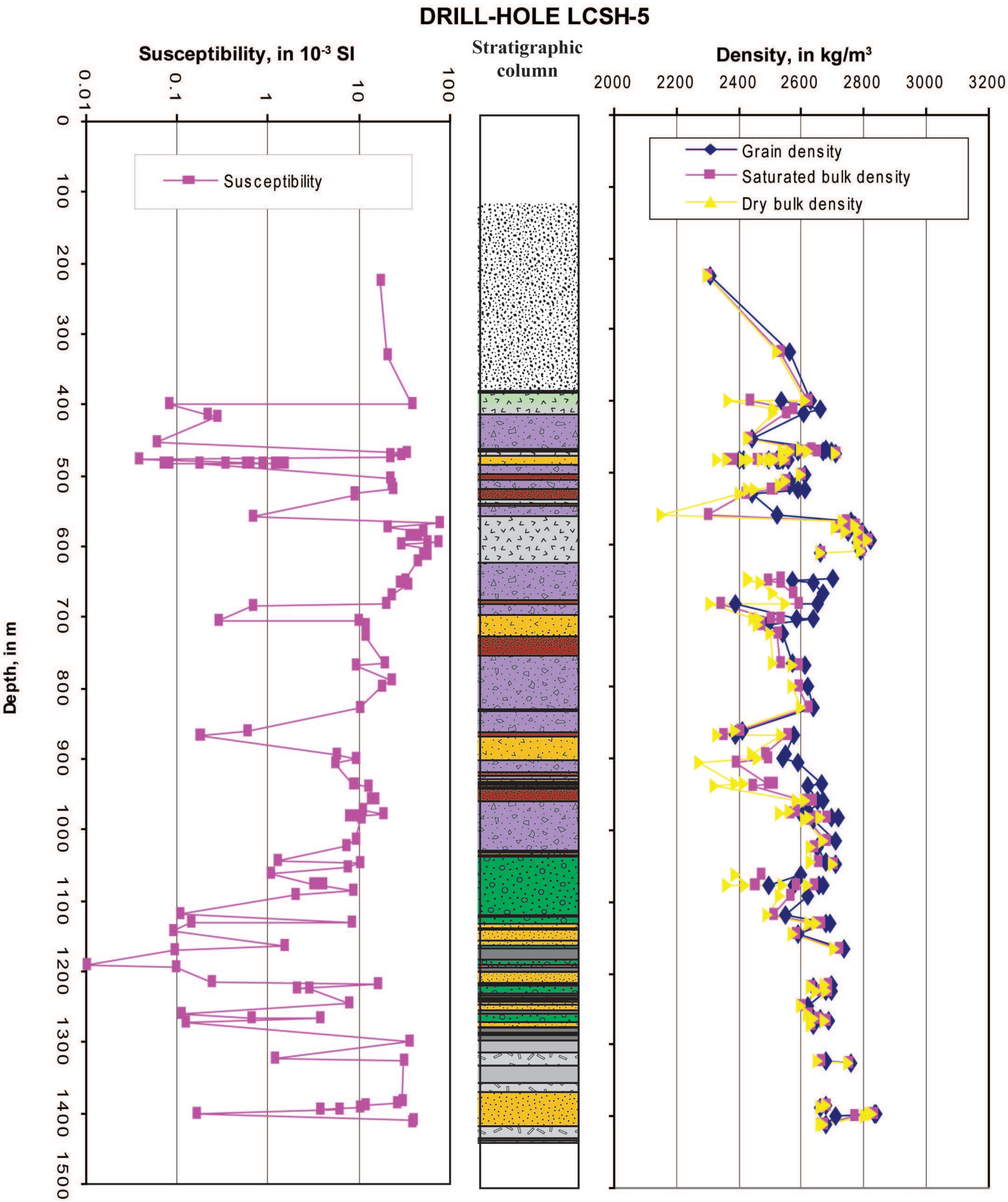


Figure 8. Density and magnetic susceptibility versus depth from core samples in drill-hole LCSH-05, northern Surprise Valley. Note the general increase in density with depth and the correlation of high density and moderately to strongly magnetic mafic andesite lava flows from about 550 to 650 m and from 1,300 to 1,425 m depths. Stratigraphic column modified from J. Colgan (written commun., 2008).

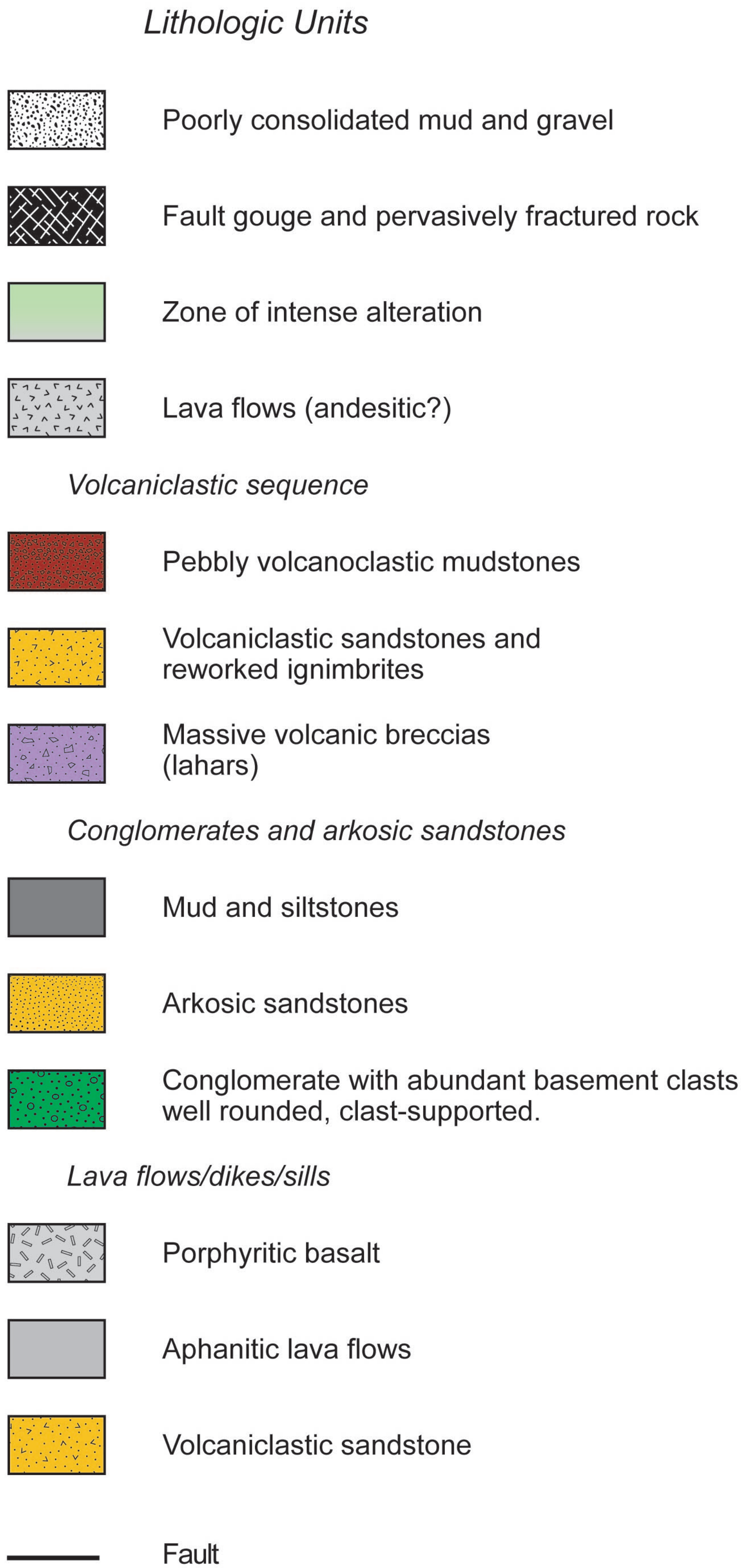


Figure 8.—Continued.