U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

RESOURCE ASSESSMENT OF THE BUREAU OF LAND MANAGEMENT'S WINNEMUCCA DISTRICT AND SURPRISE RESOURCE AREA, NORTHWEST NEVADA AND NORTHEAST CALIFORNIA—

GRAVITY MAP AND INTERPRETATION

By

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INTRODUCTION

The U.S. Geological Survey (USGS) is a party to joint interagency Memorandums of Understanding with the Bureau of Land Management (BLM) and the U.S. Bureau of Mines (USBM) to coordinate resource assessments and evaluations of BLM-administered lands. Resource assessments of BLM Resource Areas, which are conducted by the USGS, assist the BLM in meeting inventory and evaluation, resource-management planning, and other management requirements of the Federal Land Policy and Management Act of 1976. This report is part of a resource assessment of BLM-administered land in northwest Nevada and northeast California. An earlier report, which summarizes the geology and its relation to resources (Doebrich, 1996), serves as a foundation for the interpretative discussion in the present report. The 1:2,000,000 map scales of figures 3 and 5 in the presesent report match the map scales of Doebrich (1996).

The project area is composed of three contiguous BLM Resource Areas, totalling 13.5 million acres, in northwest Nevada and northeast California (figs. 1 and 2). The Sonoma-Gerlach and Paradise-Denio Resource Areas in northwest Nevada together comprise the BLM's Winnemucca District. The Surprise Resource Area is located in extreme northwest Nevada and northeast California and is part of the BLM's Susanville District, which is administered by the BLM's California state office. Henceforth in this report, the project area will be referred to as the Winnemucca-Surprise Resource Assessment Area (WSRAA).

Acknowledgments

William F. Hanna, U.S. Geological Survey, who initially supervised and coordinated the geophysical work, contributed useful ideas about organizing the study of this large area and about preliminary versions of reports. Ronald R. Wahl, Donald H. Schaefer, and Donald L. Peterson of the U.S. Geological Survey and Allen H. Cogbill, Jr. of the Los Alamos National Laboratory provided useful information about gravity data they collected in the study area. Robert F. Sikora and David A. Ponce of the U.S. Geological Survey provided information about data available in the study area. Volunteers Rex V. Allen and Edwin Nelson enthusiastically assisted the fieldwork in 1993. David A. Ponce of the U.S. Geological Survey provided a technical review of the data compilation methods and the associated principal-facts report. Other team members, including Charles E. Barker, Jeff L. Doebrich, Wendell A. Duffield, David A. John, Dawn J. McGuire, Michael S. Miller, J. Thomas Nash, Stephen G. Peters, Gary L. Raines, Don L. Sawatzky, Gregory T. Spanski, and Ted G. Theodore, provided useful geological insight for interpreting the data.

SOURCES OF GRAVITY DATA AND COMPILATION METHODS

Gravity maps that cover parts of the study area include maps by Erwin (1967), Chapman and Bishop (1968), Erwin (1974), Chevron Oil Company Minerals Staff (1975), Erwin and Berg (1977), Erwin and Bittleston (1977), Oliver and others (1982), Erwin and others (1985), Wagini (1986), Saltus (1988a, c), Schaefer (1988), and Plouff (1992). To assure that consistent and complete gravity reduction methods and formulas were applied, existing gravity data in digital format were obtained to prepare a new gravity map of the study area.

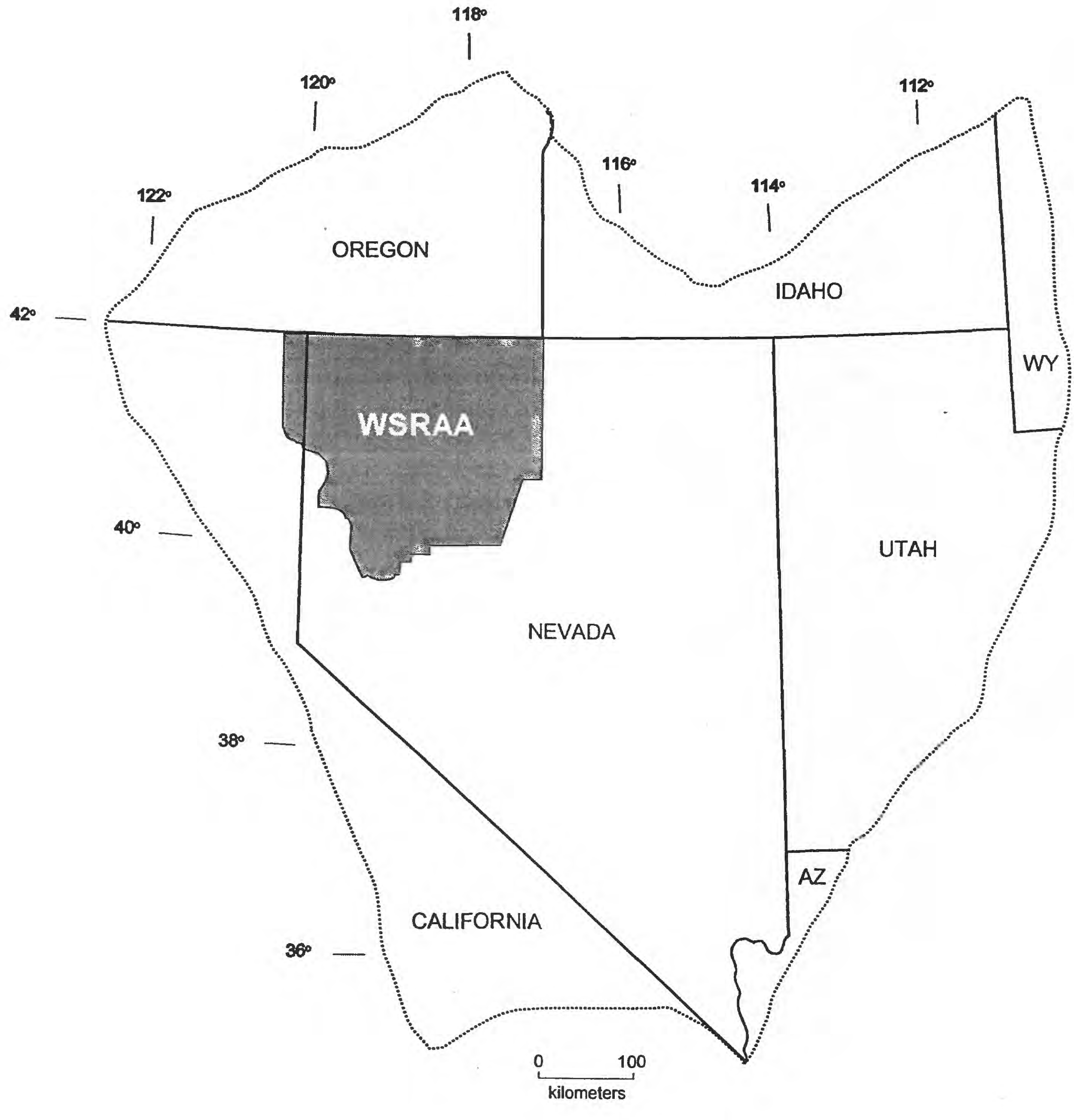

Figure 1.--Index map of Great Basin showing location of Winnemucca-Surprise Resource Assessment Area (WSRAA) (from Doebrich, 1996).

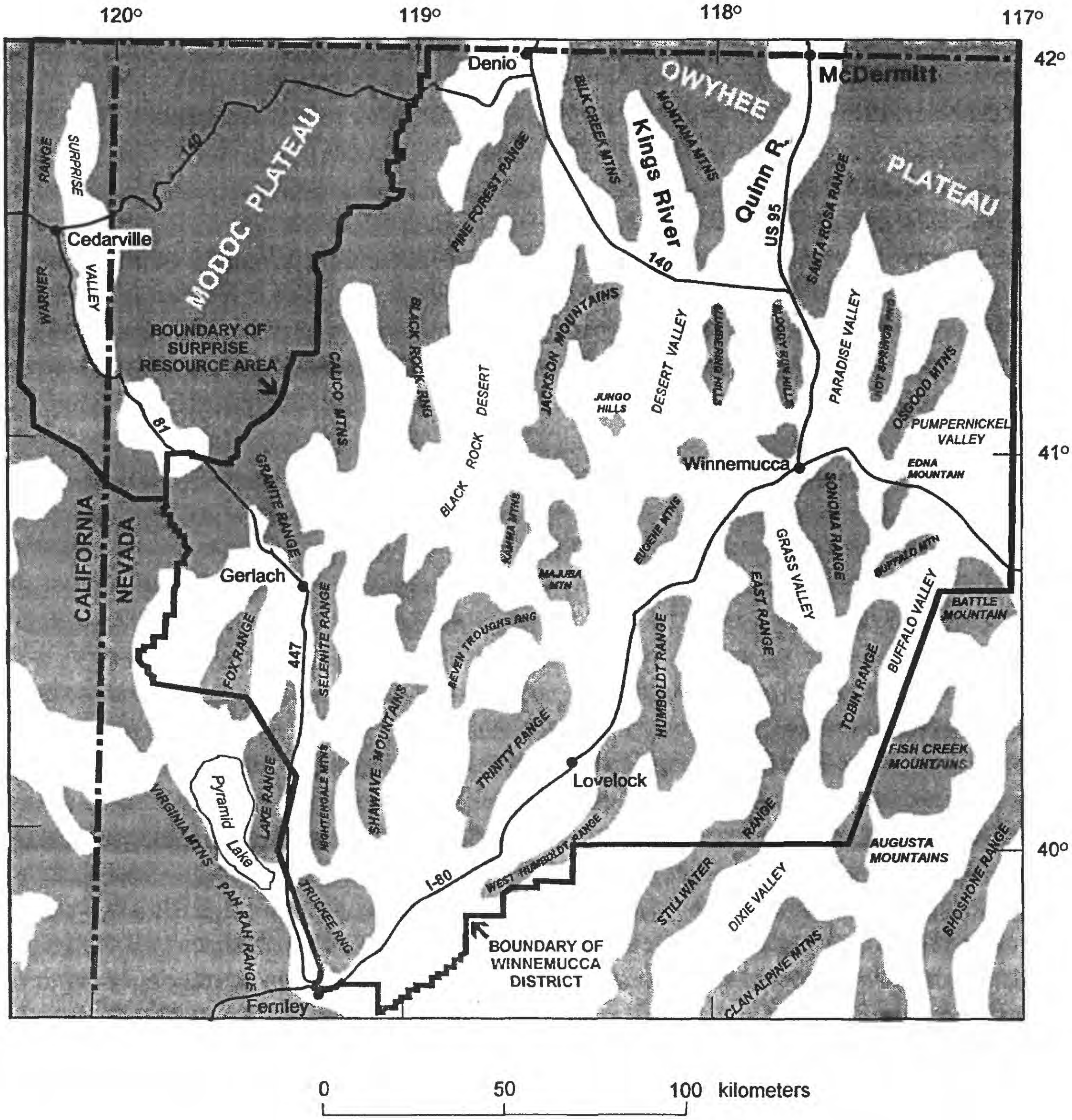

Figure 2.--Map of the Winnemucca-Surprise Resource Assessment Area showing locations of selected geographic and cultural features and Bureau of Land Management boundaries. Shaded areas depict ranges and areas of exposed rock. White areas depict alluvium covered basins. Modified from Doebrich (1996) to show Quinn River and Kings River valleys.

The initial set of gravity data, which covered the WSRAA and a band of 5 to 30 km (3 to 20 mi) outside the WSRAA (Doebrich and others, 1994, fig. 19), was obtained in digital format from a statewide compilation by Saltus (1988b) in Nevada, C.R. Roberts (written commun., 1990; Snyder and others, 1982) in California, Plouff and others (1976), and Plouff (1987b, 1994). To preserve the identity of original data sources, original data later were recovered from the Gravity Library of the Defense Mapping Agency (National Geophysical Data Center, 1984) and other published sources to replace all except 355 data points from Saltus (1988b). Additional data also were obtained from the National Geophysical Data Center (1991). Data point identification numbers, which were abbreviated or omitted by the Defense Mapping Agency, were recovered from data published by Peterson and Dansereau (1975), Crewdson (1976), Griscom and Conradi (1976), Plouff (1976b; 1977a,b), Plouff and others (1976), Robbins and others (1976), Wahl and Peterson (1976), Chapman and others (1977) Peterson and Hassemer (1977), Peterson and Hoover (1977), Peterson and Kaufman (1978a, b, c), Schaefer and Maurer (1980), Edquist (1981), Erwin (1982), Abrams and others (1984), Duffrin and others (1985), Schaefer and others (1985), Wagini (1985), Glen and others (1987), and Sikora (1991). The present compilation also includes 258 gravity observations collected in 1993 by the U.S. Geological Survey in an area of sparse coverage in and near Desert Valley (fig. 2) to the northwest of Winnemucca (Plouff, 1996).

Methods to minimize redundancy and to identify and to correct or delete erroneous data were described by Plouff (1996). Data points were omitted from a data set if it was determined that the data points were copied from an earlier source of data rather than independently established. Data points located at nearly the same location as other data points were omitted if the associated data set was determined to be less accurate than another set. Where forming a consistent pattern, repeated gravity observations by different observers at the same locations were used to validate ties of selected subsets to the same datum of observed gravity and to obtain arbitrary datum shifts to apply to data subsets. To the extent that was practical, data points were plotted on maps at scales of 1:24,000 and 1:62,500 so that redundant data points were identified, or data points with doubtful locations or elevations were corrected or omitted. Alexander Wagini (written commun., 1984) corrected locations for about 75 percent of the previously established data points in the Winnemucca 1° by 2° quadrangle.

Inasmuch as different terrain models and computer programs may have been used to reduce previous gravity data, digital terrain corrections, isostatic corrections, and calculations of gravity anomalies were done independently. Standard methods were used to calculate gravity anomalies—differences between the observed value of gravity and the estimated theoretical value of gravity. The gravity effect of isostatic compensation was minimized by subtracting the gravity effect of the mass deficiency of an assumed downward deflection ("root") at the base of the crust, which compensates for the excess mass of topography above sea level (Hayford and Bowie, 1912; Jachens and Roberts, 1981). The assumed model for isostatic compensation yields a smoothly-varying regional gravity effect (for example, Wagini, 1986, fig. 1; Plouff, 1992, fig. 1). Data points with gravity anomalies that conspicuously disagreed with nearby values (causing apparent contour "bullseyes") were deleted, to obtain the final set of 7,075 data points (figs. 3, 4).

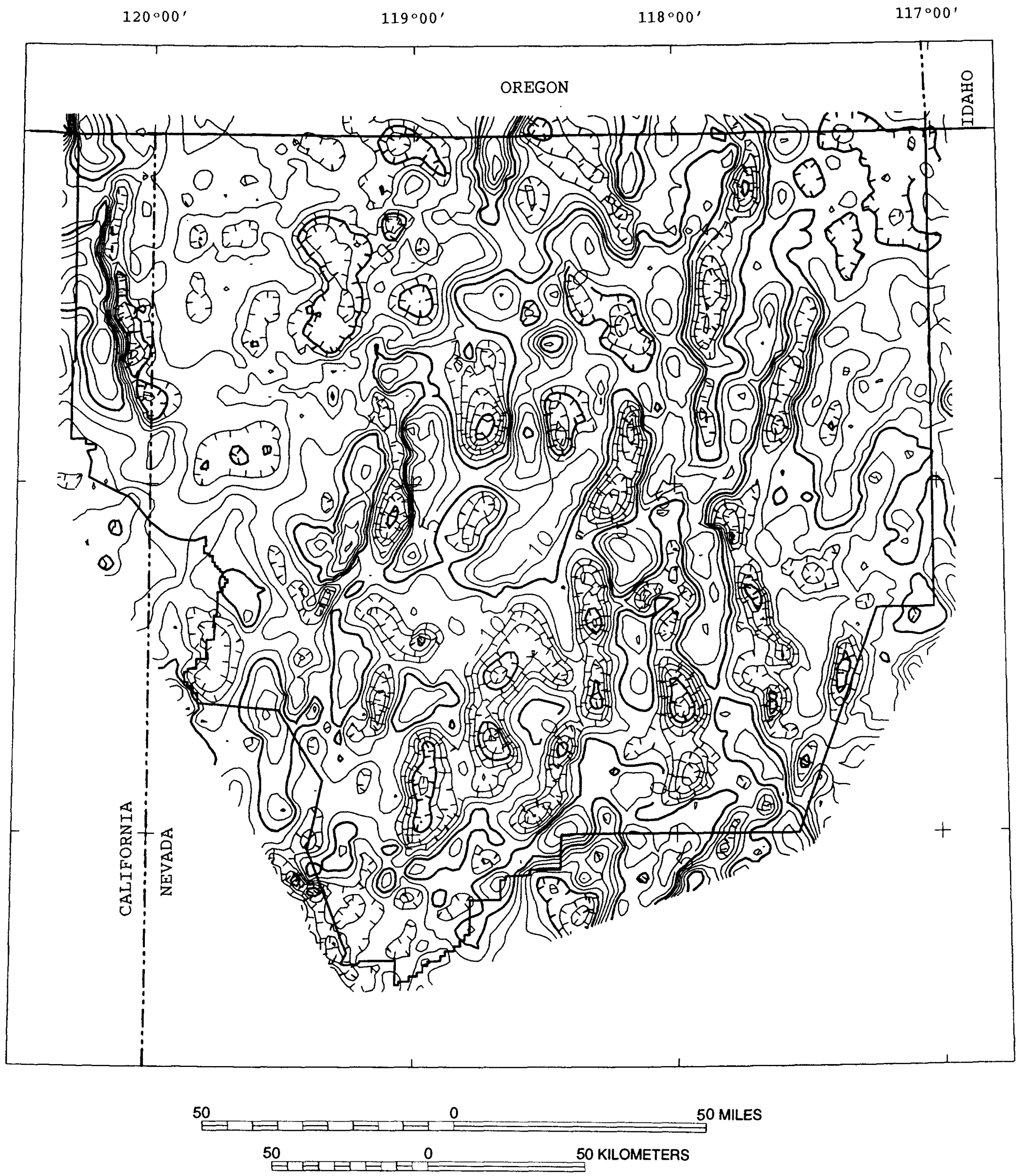

Figure 3.--Isostatic residual gravity map of the Winnemucca-Surprise Resource Assessment Area (WSRAA). Contour interval, 5 milligals. Hachures indicate closed gravity lows. Outermost thick line shows approximate border of WSRAA.

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          120°                      119°                        118°                       117°
           | 111              1   1 | 1        1 1        2 1 |   1      1   1              |
 44  1 1   | EC4 311    21  1   121 2|2   2   1111 11 11  42 2|12 3111          312         |
 13      2|253522      11     11 111 |11  22    3 22  123225 23|22111121   121 2211 2  1|1
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  1  1  12| 2  1 121313141 12221 1 |  2145BM241          121   |  119H 8122    2132       |2 1
 23   1 1 |134    2211 21 23122211 |311221BD32 1 1  1221    1|1 2133253 1 1     13   1 |1
   1 17831|  521  232322212 121   2|121 24321 1  1   22 1112|322 22411    1        33232|11
  1 115693 |   43 13123  1311 211212|112DA122111     1 144 321|4212 46222  11 1  41    3|53
      5595 |   7222321121  1214123  |1167223 2 3  1 1  3412 1|11 31651212122131223  1|  32
 221 1758  |   1422  1221 12 1122112|1  1   1   2        33144|131238 1   13  1  2 131 |211
  1  6G981 |1  1522  222231 22331121|1 22 1          112145156|B72223 1 1121  114      2|2 2
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11     98L21|1212 421322114344112 11|12 21    1      131 1    134|62  34 1  111  1221  1  |1
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 1 1    1582|1      14 223212322447131|123222     2 2     21   14 |2342  142421 1 1241 3 11| 323
        1352|       252 42111321 58111| 3           1 11   222   322|25411 1252 1    1316216  |111
 1         85|3      242  233214111323 |13          2  2    12411311|312     123113 111 EB12225| 1
   1  1  32|1  1 1 5    3222331113622|12        11 1 1212521434 1|21331 1151221 2    15712 |1 21
     1    1|211    14    3  1332222221|12          222123212136132 | 1132 157522  11 114523 |411
  1       1 | 121  353221  1 12 33212|1 2   111211   2321 3      |      22 1 11112  1644172|  1
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122 1122 11|   21                1 6BD6|      2 1 111 2132132322|1211 211   1 2 23 111   12|
41° -------------------------------------------------------------------------------------------
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  112 2111 |        1  1      7H  85548|             1 1 311213123 |211114 2 1 147311212222 |1122
   2 11  11|          12       5ETGFEB898|       111 121             | 13331351 1 214  1332221| 24
    11 112 |           11   1 EZJZN6525| 211112  1     1 1 1       |1   12111 2 13 11221422  | 121
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     11 111|   1          1  1 CKDF7  |1   1 1    21         1     1 1|11112 3   111321114 13131|12 1
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          221|  1311    31  15PJA221   |       1  2          1 132211 |212 13252   12 1432641 33|3 31
         2112|11 1 2   3    13MV95 4    1|     133331   1   2   24231 |1 11 44KP821123455 23122|131
          1 1|3 1   3232 1   1 341 3 1   |1   13   2   1   22344121 11|2 11 3BMZ6121   454 1 111|231
            1|24 131    1   1   1    3   |1 34    1     11 5542 111 1|1112135GQG211   423311153|
           11|11332    1      1 2    14   | 12   1 2    123 42531      |  12 1142G61 22234634272|1
             | 1141       1   1 2 212152 | 5   1   21      1 121      1 |21 1 1 1 311142111434853|
             |11 3      1   1222 523   3 3|26 212 2     1    315 12443|112     1 23 1 4556155443 |
             | 1122   1   1 57413 21 2 2| 153 331      11 11 1   21 |  1       113 11B8765443    |
             | 1213   1   1 85641121312 |131   412          2121111124|1 2 111131     128E46E42   |
             |  113   111121   441424211|11 1     13     1 3311 22 2 |          641   12424481    |
             |      4121121    2 34 1    |4         21121143 1     1    1|  1 1 24   11     1 1 2    |
             |     31   1 111   2 3241   |311         121 334321311   1|  2 4214   2231 113 1     |
             |    11412          1    41   |3 1   1   1 2434313242   1 |  3323351   58 21121      |
             |       54       1 21    1331|312      321 12212 3 423     |333 121223E63 2   1      |
             |       22       11 11   1 111|1221      21112233        42522|43 1 15877212241 1      |
             |        3       3 1          1|  1223232 2331      1111 1 |1 11253211111232         |
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40° -------------------------------------------------------------------------------------------
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             |          5   124 4122   41|3222   511 1242211 121 22|  33465442      2          |
             |         2533   231 411251|1   11221131 2232   3     23|53343441 1311              |
             |            123481 41 153|  131 3111     21      3 11 4|1   12   1                |
             |          1 1137355 1 14|112223          1 11   31 134|  33421                    |
             |            1 341141   11|  211 2         1   2 3   2543|4 1                       |
             |               15151 112|334   3   2   12    312 121  |                           |
             |             11442 5 21 |21221323   1222 1721         |                           |
             |            111435161   2|2111211111 2242               |                           |
             |             13233452311|2 2113 14211                   |                           |
             |               1 2443834|12 3 2 11                      |                           |
             |                11331184|3133                           |                           |
             |                 2 1 1 31|                               |                           |
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Figure 4.--Index map showing distribution of gravity data in study area. Numbers and letters indicate number of data points in 2.5-minute cells that include their south and east edges. Blank spaces indicate no data. For example, A indicates 10 data points, I and O are skipped, Y indicates 31 data points, and Z indicates 32 or more data points. **Bold print** indicates location that includes data points without map verification. North-south distances are exaggerated about 1.3 times east-west distances.

ASSESSMENT OF DATA QUALITY

Topography digitized at a spacing of 0.01 inch at a scale of 1:250,000 was converted to a grid of 15 arc seconds for the USGS elevation model of the conterminous United States and applied to gravity terrain corrections (Godson and Plouff, 1988). Model errors such as strings of apparently random numbers instead of elevations and incorrect map corner registration were corrected at the time of conversion. Other model elevation errors have been found such as an area near Creede, Colo., with 9-mGal terrain-correction errors and an area near the Nevada-Utah border (David A. Ponce, oral commun., 1994), which needed manual terrain corrections carried beyond the conventional distance for manual correction. Also, digital elevations in valleys tended to be set at one foot below the next higher 200-foot contours rather than at the correct lower elevations, thus commonly over-estimating values for gravity terrain corrections and associated gravity anomalies by 1 to 3 mGal for data points located in valleys. Digital terrain corrections for data points at topographic crests can be underestimated by as much as 20% to a distance of 900 m from the data point, for example, because topography is smoothed at a scale of 1:250,000. Inasmuch as the digital terrain model based on 1:250,000-scale topography was used to calculate gravity terrain corrections all the way to the data point for 3,925 data points in the study area, the accuracy of terrain corrections can be significantly improved by manually estimating the gravity effect of terrain to conventional distances of 400 to 900 m (1,300 to 3,000 ft) from data points (Swick, 1942; Hammer, 1939). Manual estimates or utilization of a computer program (for example, Cogbill, 1990), based on Digital Elevation Models with 30-meter grids, are needed to correctly determine the inner part of the terrain corrections for the 3,925 data points. Substituting manual estimates or digital computations based on topography digitized at a scale of 1:24,000 for the innermost part of gravity terrain corrections can improve the accuracy of that part of terrain corrections by about 10 percent (see Plouff, 1996, fig. 4).

Additional steps can be taken to improve the quality of the data. The process of plotting data and correcting locations on topographic maps at scales of 1:62,000 and 1:24,000 should be completed (fig. 4). Previously collected but unpublished data possibly could be acquired (for example, data used to prepare gravity-anomaly maps by Chevron Oil Company Minerals Staff, 1975; Trexler and others, 1981; and Trexler and others, 1982). Many of the original data collectors did not have field maps at a scale of 1:24,000, and some did not have maps at a scale of 1:62,500, thus leading to location errors that may exceed 2 km (1 mi). In order to resolve uncertainties, copies of maps and notes should be obtained from the original data collectors. Considering large gaps in data coverage, unknown shifts of the datum of observed gravity among data sets, mis-location of data not yet plotted at a scale of 1:24,000, and the digital terrain correction error, anomaly errors typically are in the range of 1-2 mGal but may exceed 4 mGal.

SUPPLEMENTARY TECHNIQUES

Preferably after the data quality is improved, other derivative maps can be prepared, and quantitative interpretative modeling can be done. Maps showing gravity gradients (Blakely and Simpson, 1986; Grauch and Sawatsky, 1989) help to delineate the regional tectonic framework, faults, edges of calderas, and steeply dipping intrusive contacts, for example. Maps of basement depths, which are derived from analysis of gravity data (Crewdson, 1978; Goldstein and Paulsson, 1979; Schaefer, 1986; Jachens and Moring, 1990), can be used to estimate the extent of pediments, to estimate practical limits to the extent of mineral exploration, and to delineate deep Cenozoic basins for petroleum and geothermal exploration. Modeling possible sources of gravity anomalies, for example, using a three-dimensional technique of Plouff (1976a), can be done in selected areas. Caution, however, should be observed in accepting models to represent a distribution of rock masses, inasmuch as a theoretically unlimited number of density distributions can result in the same gravity field observed at the surface of the Earth.

INTERPRETATION

Previous studies

A preliminary version of the present interpretative report was prepared by Doebrich and others (1994). Gravity data were interpreted as part of mineral evaluations of Bureau of Land Management Roadless Areas in and near the WSRAA by Keith and others (1986, 1987), Peterson and others (1986), Ach and others (1987), Berquist and others (1987; 1988a, b), Calzia and others (1987), Noble and others (1987a, b), Roback and others (1987), Sorensen and others (1987), Minor and others (1988), Peterson and others (1988), Turrin and others (1988, 1989), and Wallace and others (1988). Other gravity studies in and near the WSRAA were reported by Mabey (1964), the California Department of Water Resources (1965, app. C, p.135-137), Erwin (1974), Crewdson (1976), Cogbill (1979), Goldstein and Paulsson (1979), Greene and Plouff (1981), Schaefer and Maurer (1983), Plouff (1984, 1985, 1986, and 1992), Blakely and Jachens (1990; 1991), and Oliver and others (1991). Other geophysical investigations in the study area, for example, were reported by Willden (1963), Smith (1968), Callaway (1978), Keller and others (1978a, b), Kumamoto (1978), Morris (1978), Zeisloft and Keller (1978), Rytuba and others (1979), Willden (1979), Blakely (1988), Grauch and others (1988), McConnell and others (1990), Grauch and Bankey (1991), Hoover and others (1991), Pitkin (1991), and Grauch and Hoover (1993). Corbett (1991) summarized methods of geophysical exploration for precious metals in Nevada. Hoover and others (1992) provided guidelines for geophysical classification of mineral deposit models.

Relation of gravity anomalies to geology

The gravity method of geophysical exploration measures the vertical component of the acceleration of gravity. The value of gravity reflects the integrated effect of the distribution of mass throughout the Earth, but the effects of rock masses distant from the point of observation are greatly diminished in comparison to nearby masses, inasmuch as the value of gravity decreases in proportion to the square of the distance from the point of observation.

Gravity anomalies reflect lateral density changes in underlying rocks. Negative gravity anomalies (fig. 3), hereafter referred to as "gravity lows," correlate with valleys because sediments beneath valleys have substantially lower densities than the assumed 2.67 g/cm^3 reduction density. In contrast, gravity highs overlie adjacent hills and mountain ranges. Gravity lows also overlie geologic units such as ash-flow tuff, and gravity highs overlie basalt and metamorphic rocks as a result of contrasts of their densities with densities of surrounding rocks. The lowest average densities for geologic units such as unconsolidated sediments or ash-flow tuff may locally be slightly lower than 2 g/cm^3, and the average density for the densest crystalline bedrock seldom exceeds 3 g/cm^3. Therefore, density contrasts seldom exceed 1 g/cm^3 or 50%. In comparison, contrasts of physical properties such as magnetization commonly exceed 1000%.

Methods based on quantitative analysis of gravity data have been developed to delineate geologic units with significantly different rock densities in contrast to rock densities of adjacent rock units. Maximum horizontal gravity gradients delineate abrupt boundaries between adjacent rock units with markedly different densities, for example, steeply-dipping faults and intrusive contacts. Cordell and Grauch (1985) devised a method to compute gravity and magnetic gradients, and Blakely and Simpson (1986) automated a method to display alinements of dots with sizes that increase with amplitudes of gradient maxima. Grauch and others (1988) used a map of maximum magnetic gradients to delineate edges of inferred plutons in Nevada. Blakely and Simpson (1986, fig. 5) prepared a map of the steepest gradients of isostatic residual gravity for the conterminous United States.

Tectonic framework

The geology of the WSRAA portrays a complex record of Paleozoic and Mesozoic accretionary and plutonic events followed by Cenozoic extensional tectonism and magmatism (Doebrich, 1996, p.1). The complex appearance of the gravity map of the WSRAA (fig. 3) reflects the geologic complexity of this part of the Basin and Range province.

The morphology of basins and ranges primarily reflects Cenozoic tectonic fabric. The pattern of north-south elongated basins and ranges generally is interpreted as an effect of extension (strain) resulting from regional east-west tensile stress. The distribution of crustal rock densities indicated by lines that follow troughs of gravity lows and crests of gravity highs (figs. 3 and 5) may depict the Cenozoic regional tectonic framework better than present basin-range topography, which also reflects local complexities of surficial erosion, uplift, and fault zones. Lines that follow troughs of gravity lows or crests of gravity highs trace the centers of volume or mass of elongated bodies and, therefore, are deflected less by local density changes than lines along maximum geophysical gradients, which are useful to delineate density interfaces but are sensitive to local lithologic changes. Plouff (1992) correlated features on this kind of interpretative gravity map to volcanic and structural zones in the Reno 1° by 2° quadrangle. For example, apparent truncation and rotation of gravity troughs and crests to the south and to the north of location "d" (fig. 5) may indicate that a concealed zone of right lateral displacement transverse to the basin-range trend underlies location "d."

Zoback (1989, fig. 3) and Bellier and Zoback (1995, fig. 7) obtained directions of regional geologic stress based on the geometry of fault slip, analysis of earthquake focal mechanisms, and alignment of young volcanic vents. Regional tectonic fabric expressed as the distribution of anomalous mass (fig. 5) may be useful to interpolate and to extrapolate sparse geologic stress data and possibly to predict locations for future release of stress. Near-surface sites of stress release may occur along gravity and magnetic gradients that mark steep—possibly already faulted—edges of anomalous masses and above narrow intrusive masses. Profiles of closely-spaced gravity data can reveal locations of fault interfaces, and their depth extent can be estimated. For example, Grannell and Noble (1977) evaluated aerial photos, geologic mapping, and gravity anomalies in Grass Valley, Nevada, to delineate faults and a possible association of the fault pattern with

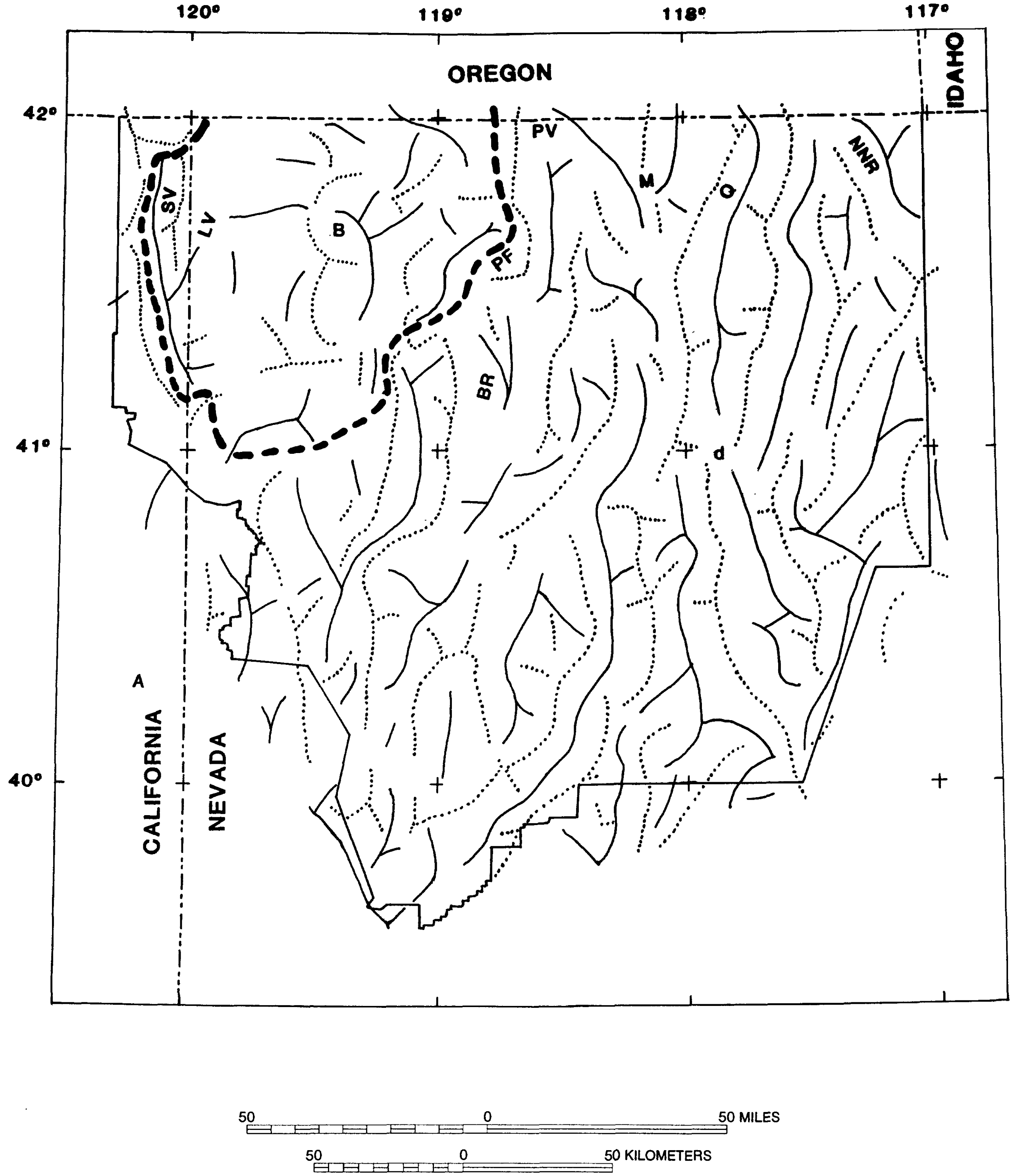

Figure 5.--Tectonic framework of WSRAA indicated by pattern of gravity anomalies. Solid line segments indicate troughs of gravity lows. Dotted line segments indicate crests of gravity highs. Thick dashed line delineates gravity gradient that encloses area discussed in text. Continuous line shows approximate boundary of WSRAA. A, Amedee Hot Springs; B, Badger Mountain caldera; BR, Black Rock Desert; d, location of alinement shifts discussed in text; LV, Long Valley; M, McDermitt caldera complex; NNR, northern Nevada rift; PF, Pine Forest Range; PV, Pueblo Valley; Q, Quinn River; and SV, Surprise Valley.

control of the Leach Hot Springs geothermal system. Abrupt changes of gravity readings over short distances, topographic steps, and abrupt changes of vegetation pattern were observed during the 1993 fieldwork in Desert Valley (fig. 2).

Northern Nevada rift

The northern Nevada rift, located in the northeast corner of the study area (location "NNR" in fig. 5), is part of an apparent north-northwest-trending fracture zone, which was first delineated in central Nevada as a nearly continuous aeromagnetic high extending for about 90 km (55 mi) across an aeromagnetic map of the Roberts Mountains (Philbin and others, 1963; Robinson, 1967, fig. 3). Mabey (1965, 1966) suggested that a swarm of dolerite dikes with high magnetization parallels and locally contributes to the amplitude of the magnetic anomaly in central Nevada, and the continuity and size of the anomaly requires a major steeply dipping, deep-seated magnetic source. Robinson (1970) estimated that the deep-seated magnetic source may extend to depths exceeding 15 km (10 mi). Robinson (1970) suggested that the major magnetic high also may be associated with an alinement of domes and mining districts (Roberts, 1960).

Stewart and others (1975) suggested that the major magnetic anomaly in central Nevada is part of a 750-km (470-mi) "Oregon-Nevada lineament," which principally was defined by alinements of faults and, therefore, was interpreted as the surface expression of a deep-seated fracture zone. Stewart and others (1975) suggested that dikes and flows exposed in the Nevada part of the lineament may reveal a major conduit between deep-seated magma sources and near-surface Cenozoic igneous rocks. Zoback (1978; Zoback and Thompson, 1978) named the Nevada part of the Oregon-Nevada lineament the "northern Nevada rift." Zoback (1978, p. 99) proposed that the crustal model for the rift is similar to the "dike underlying graben" model of Thompson and Burke (1974). In view of the correlative alinement with domes (Roberts, 1960) along part of the proposed rift, Wisser's (1960) model of uplift in mining districts accompanied by tension fissures or Bott's (1981) model of doming before rifting also may apply.

Blakely and Jachens (1991) suggested that the Nevada part of the rift extends farther to the southeast than previously proposed, and the west edge of the rift is bordered for about 250 km (150 mi) by a well-defined gravity gradient as well as the aeromagnetic high. Blakely and Jachens (1991) observed that it is difficult to interpret why this zone—formed in mid-Miocene time—sems to resist later basin-range deformation (extension). Blakely (1988, pl. 1) suggested that two other prominent aeromagnetic highs—nearly parallel to and to the west of the northern Nevada rift—also may delineate mid-Miocene rifts. Northeast-trending gravity anomalies in the WSRAA, which reflect the basin-range trend in the 80-km (50-mi) interval between the eastern of the two aeromagnetic highs and the northern Nevada rift (Doebrich and others, 1994, fig. 22), seem to be truncated or deflected by the postulated rifts (area between "NNR" and the longitude of location "d" in fig. 5).

Intrusive rocks and plutons

Exploration for mineral deposits commonly focuses on magmatic environments, where heat, pressure, the presence of fluids, and convection facilitated mineralization and mobilization. Unless replenished by the source of heat and magma, magma accumulations cool and crystallize in the subsurface to form intrusive rocks. The applicability of using geophysical methods to detect or delineate unexposed intrusive rocks depends on the size of the intrusive body, steepness and the sharpness of contacts, depth of burial, and contrast of the physical properties of the intrusive body with enclosing rocks. Massive three-dimensional intrusive bodies such as plugs, plutons, stocks, or batholiths with densities that differ significantly from surrounding country rocks are more readily detected as gravity anomalies than dispersed intrusive rocks or tabular bodies such as veins, dikes, flows, or sills.

Bott and Smithson (1967) showed examples of 10- to 40-mGal gravity lows caused by exposed granitic plutons with lower densities than surrounding country rocks. Bott and Smithson (1967) obtained thickness estimates of about 5 to 10 km (3 to 6 mi) for modeled plutons based on assumed density contrasts of 0.05 to 0.15 g/cm^3 between plutonic rock masses and surrounding country rocks . Case (1967), Behrendt and others (1969), Witkind and others (1970), and Ponce (1984, fig. 11) also showed examples of prominent gravity anomalies that apparently delineate partly exposed or wholly concealed plutons. Inasmuch as the density contrast between plutonic rocks and adjacent pre-Cenozoic rocks is small or possibly reversed in algebraic sign for mafic intrusive rocks (Griscom and Halvorson, 1994) and the gravity data coverage is sparse, the gravity effect of intrusive rocks typically can only be lumped with the effect of adjacent pre-Cenozoic rocks in the WSRAA. Grauch and others (1988, sheet 2) found that tracing magnetic gradients over boundaries between rocks with different magnetizations is a more sensitive method to delineate plutons with moderate to high magnetization in the WSRAA than tracing gravity-anomaly gradients over boundaries between rocks with different densities. Furthermore, for the gravity method to provide constraint in delineating intrusive bodies, the present gravity data coverage and accuracy of gravity reduction parameters—primarily elevations and terrain corrections—would need to be improved.

Calderas

A caldera is a large volcanic depression with a diameter substantially greater than that of included vents, no matter what the steepness of the walls or form of the floor (Williams, 1941; Bates and Jackson, 1987). Most calderas are "collapse calderas" formed by collapse of the roof of a magma chamber due to removal of magma by voluminous pyroclastic or lava eruptions or by subterranean withdrawal of magma" (Bates and Jackson, 1987). Lipman (1984) viewed deeply incised calderas as useful windows into the tops of shallow-level batholiths (for example, Schweickert, 1976), from which magma was derived. Although it is usually stated that calderas collapse in response to partial evacuation of an underlying magma reservoir by pyroclastic or lava eruptions, Williams and McBirney (1979, p. 225-226) stated that "Cauldron subsidence and subsurface movements of magma are probably more important causes of collapse than are eruptions that drain support from the substructure."

"Resurgent cauldrons are defined as cauldrons (calderas) in which the cauldron block, following subsidence, has been uplifted, usually in the form of a structural dome" (Smith and Bailey, 1968, p. 613). Smith and Bailey (1968, p. 613) defined seven stages in the development of resurgent cauldrons, perhaps spanning a million years: 1) regional tumescence and generation of ring fractures; 2) caldera-forming eruptions; 3) caldera collapse; 4) preresurgence volcanism and sedimentation; 5) resurgent doming; 6) major ring-fracture volcanism; and 7) solfatara and hot-spring activity. As illustrated by the evolution portrayed by Smith and Bailey (1968), the development and recession of a magma system apparently consists of many interwoven and repeated processes including magma growth, diapirism, doming (tumescence, inflation), extension (Hon and Fridrich, 1989), subsidence (detumescence, deflation), bimodal differentiation, density stratification, faulting, venting, ring-fracturing, volcanism, caldera formation, sedimentation, and resurgence. Magmatic systems may pulsate in response to variable influx of heat and magma, upward increase of melt productivity, buoyancy, volatile pressure, fracturing of brittle rocks at areas of weakness, overcoming the weight and impermeability of overburden, redistributing magma (leakage) to places of less resistance, depletion by extrusion, and roof foundering.

Nearly circular forms of volcanoes, cone-sheet fracture zones (Fridrich and others, 1991), dikes radiating from central plugs, ring fractures, intracaldera fill, resurgent domes, and alteration haloes, reflect locations of cupolas of underlying magma or later plutons with the same or smaller diameters. In contrast to volcanoes, which are vulnerable to erosion and have less density contrast with surrounding rocks, concealed collapse calderas can be detected as prominent gravity lows (Healey, 1968; Plouff and Pakiser, 1972; Lipman, 1984; Plouff, 1987a, fig. 6; and Carle, 1988), inasmuch as sediments and interbedded ash-flow tuff that commonly fill the structural depressions are less dense than surrounding country rocks. Near-vertical walls of deeply dissected calderas and steep gravity gradients near peripheries of unexposed calderas (Plouff and Pakiser, 1972, fig. 5) as well as ring structures indicate that underlying magma columns at shallow depth, which alternately extruded upward from a larger reservoir and drained into the reservoir, probably have approximate shapes of vertical circular cylinders (Roberts, 1970, p. 335; Yoshida, 1984, p. 8508). Scandone (1990), however, suggested that some types of calderas have conelike chimneys that flare upward from collapsed magma chambers. Competent (brittle) roof rocks may have been arched and battered in pistonlike fashion by pulses of stress focused at the tops of magma plugs projecting upward from larger magma reservoirs before the integrity of roof rocks failed by hydraulic fracturing or by tension fractures (apical graben) opened as a consequence of doming (Wisser, 1960), or the magma crystallized, subsided, or was dispersed. During this repetitive process, sidewalls would be abraded to form a smoother form of least resistance at the sides and greatest stress at the apex, magma batches would consolidate, and volatile (Blake, 1984) and melt fractions would buoyantly accumulate near the top of the magma column.

Inasmuch as magma cupolas, shattered roof rocks (Scandone, 1990; Keith, 1993), and calderas with resurgent plugs have nearly the same center of symmetry, and the magma will have crystallized to densities nearly the same as surrounding basement rocks, it is difficult to separate gravity anomalies caused by former magma cupolas from other effects. For example, although the Long Valley caldera in California is well exposed and exhibits prominent resurgent doming, the application of many geophysical methods were needed to delineate possible magma masses concealed beneath about 4 km (3 mi) of roof rocks (Rundle and Hill, 1988). A large gravity low that remains after the gravity effect of rocks related to the Long Valley caldera have been accounted for by modeling (Carle, 1988, fig.14) extends westward beneath the Sierra Nevada and possibly may reflect a larger magma reservoir, from which the Long Valley magmatic system was derived.

The McDermitt volcanic field near the northern edge of the WSRAA includes seven ash-flow sheets with a central 30- by 45-km (20- by 28-mi) structure that consists of four nested calderas (Rytuba and McKee, 1984) (location "M" in fig. 5). The nested calderas—reflected by complex gravity lows—are bounded by a horseshoe-shaped gravity high that opens to the north. The gravity pattern is complex as an effect of resurgent doming, unroofing, and the occurrence of thick sediments beneath Quinn River Valley to the east and Kings River Valley to the west. Based on mapping a set of nearly concentric ring faults in the hills to the west and exposures of an ash flow capping parts of the Santa Rosa Range to the east, which is apparently equivalent to ash-flow tuff associated with the Hoppin Peaks caldera, Rytuba and McKee (1984, fig. 4 and p. 8624-8625) concluded that most of the Hoppin Peaks caldera is concealed beneath sediments and is delineated by a prominent gravity low in Quinn River Valley (location "Q" in fig. 5). Based on geologic and magnetic mapping, Rytuba and McKee (1984, figs. 1, 3, and 5b) also inferred that a caldera mostly is concealed beneath Pueblo Valley, Oreg. (gravity low north of location "PV" in fig. 5).

Greene and Plouff (1981) interpreted coincident gravity and aeromagnetic lows in the WSRAA as reflections of an underlying 17- by 23-km (11- by 14-mi) caldera (location "B" in fig. 5; Badger Mountain caldera in Doebrich, 1996, fig. 10). Assuming a density contrast of 0.2 g/cm^3 between volcanic wallrock and the enclosed sediments and ash-flow tuff, Greene and Plouff (1981) estimated the thickness of the caldera fill as 2,700 m (8,900 ft). A later gravity survey (Plouff, 1987b) extended the gravity low more than 20 km (12 mi) southward, thus contributing to interpretations of subsurface geology by Ach and others (1987) and Turrin and others (1988). The shape of the gravity low is smoother than the pattern near McDermitt, Nev., because the effects of erosional unroofing and basin-range faulting are greater near McDermitt.

Regional gravity low in northwest part of WSRAA

The pronounced northerly basin-range trend, which is interpreted as a manifestation of crustal extension, is absent within most of a broad gravity low in the northwest part of the study area (partly enclosed by thick dashed line in fig. 5). The broad gravity low extends westward from the Pine Forest Range to include Surprise Valley (locations "PF" and "SV" in fig. 5). Assuming a density contrast of 0.2 g/cm^3 between Cenozoic volcanic rocks and pre-Cenozoic rocks, Plouff (1984) suggested that a westward gravity decrease of about 15 mGal may reflect the terracelike edge of an underlying 1.8-km (1.1-mi) section of Cenozoic rocks to the west of the Pine Forest Range where denser pre-Cenozoic rocks crop out. After extending the area of the gravity survey to California and Oregon (Plouff, 1987b), Plouff (1985) speculated that a line (thick dashed line in fig. 5) centered along nearly connected gravity gradients, which, except for a minor protuberance along the east edge, includes only Cenozoic volcanic rocks, calderas, volcanic depressions, and sediments, roughly may delineate edges of an underlying hypothetical upper crustal silicic Cenozoic magma system of batholithic dimension—100 km (60 mi) across. A section of more than 3.6 km (2.2 mi) of Cenozoic rocks is exposed along the eastern front of the Warner Range (fig. 2) near the west edge of the gravity low (McKee and others, 1990). Blakely and Jachens (1990, p. 19,445 and pl. 2) interpreted the broad gravity low as part of a structurally-bounded segment of the Cascade arc underlain by upper crustal rocks with low densities, which extend nearly 400 km (250 mi) northeastward from Lassen Peak, California, to McDermitt, Nevada. Blakely and Jachens (1991, p. 795), however, stated that "an enormous area of low gravity" to the southeast in Nevada between latitudes 37° and 40.5° "strongly correlates with the distribution of middle and late Tertiary volcanic rocks and may reflect silicic intrusions within the mid-crust and upper crust that are the counterparts of volcanic rocks at the surface."

Plouff's (1985) interpretation that a Cenozoic batholith may be the principal source of the gravity low in northwest Nevada followed the rationale of similar interpretations of major gravity lows in Colorado (Case, 1967; Plouff and Pakiser, 1972) and California (Plouff, 1987a). Case (1967, p. 8) noted that "Because the regional gravity low cuts indiscriminately across the mountain ranges and across a variety of Precambrian lithologic units, and because of the close correlation of lows with the Mount Princeton and Twin Lakes intrusions, most of the regional low is inferred to be caused by a relatively shallow but largely concealed Tertiary batholith of low density." Large Tertiary batholithic masses do not crop out in the San Juan Mountains Tertiary volcanic field and cauldron complex in Colorado to the south of Case's (1967) area, but Plouff and Pakiser (1972) suggested that a subvolcanic Cenozoic batholith is delineated by gravity gradients along the edges of a major gravity low. Although the amplitude of the San Juan Mountains gravity low was slightly reduced, delineation of the peripheral gravity gradients, which cross apparently thin Precambrian rocks in the Needle Mountains without significant deflection, was clarified by later isostatic gravity reduction. On the basis of key features including a centrally-located caldera and steep peripheral gravity gradients that cross surface rocks of diverse age without significant interruption, Plouff (1987a, p. 3) speculated that a 25- by 75-km (15- by 45-mi) gravity low between Bridgeport and Markleeville, Calif., may outline a steep-sided batholithic source of Cenozoic volcanic rocks near the east flank of the Sierra Nevada. These gravity lows and other prominent gravity lows, which may be associated with Cenozoic batholiths in volcanic terrane of the western United States, would blend with the regional gravity background were it not for the steepness and geologically cross-cutting characteristics of peripheral gravity gradients. Steep edges of the underlying magma accumulations may reflect a combination of magma coherence, high magma viscosity, the form of resistance of the rocks being intruded, and the mechanism of emplacement.

Topographic expressions of parts of Long Valley and the Black Rock Desert (indicated by "LV" and "BR" in fig. 5), three alignments of magnetic highs and gradients (Doebrich and others, 1994, fig. 22), and the occurrence of concave-to-the northwest gravity troughs and ridges that extend beyond 50 km (30 mi) to the east and southeast outside the gravity low (fig. 5) are consistent with the concentricity of peripheral gravity gradients that define the regional gravity low in northwest Nevada. Rytuba and McKee (1984, p. 8626) suggested that a pre-existing area of regional subsidence extending tens of kilometers outward from the area of incipient caldera formation is associated with the McDermitt volcanic field. Erosion of the uppermost rocks and sediments, crystallization, and complex intrabasement distributions of mass resulting from later tectonic and magmatic events, however, may have distorted a clear definition of peripheral gravity gradients that might have delineated the area of subsidence and magma accumulation beneath the McDermitt volcanic field.

Valleys and basins

Gravity lows associated with valleys are the most conspicuous anomalies on the gravity map of the WSRAA (figs. 2 and 3), inasmuch as these anomalies have the largest amplitudes, commonly persist to long distances, and are bounded by steep gravity gradients along one or both sides. The gravity lows do not simply follow stream channels but generally reflect the thickness of underlying sediments and consequently reflect the shape of the topography of bedrock beneath valleys. Gravity highs clearly delineate topographic highs beneath valleys, inasmuch as density contrasts between sediments and bedrock generally exceed 0.4 g/cm^3. For example, a prominent basement fault block that extends southward from the Calico Mountains is revealed beneath the Black Rock Desert by a gravity high (figs. 2 and 3). Except for offsets due to the effect of density changes within sediments and within bedrock beneath valleys, locations of gravity minima overlie locations of the thickest sediments in valleys.

Most gravity lows associated with valleys in the WSRAA have their largest gradients near edges of the gravity lows and have nearly symmetrical shapes (fig. 3). High gravity gradients near edges of gravity lows primarily reflect rapid subsidence along the youngest steeply-dipping normal faults or fault zones, which are exposed or inferred along the base of prominent topographic scarps, for example along the west edge of Surprise Valley (Slossen, 1974). Older normal faults or fault zones of a distributive fault system may be concealed basinward within and beneath sediments (for example, Slossen, 1974) in a stairstep fashion, as inferred from gravity models (Plouff, 1965) and as inferred from sets of normal faults in pediments and along range fronts (for example, Gilluly and Masursky, 1965, pl. 1). Due to erosion accompanying rapid downdropping along a succession of range fronts, normal faults or fault zones dip steeper than the interface between the sediments and the underlying bedrock and may have an accumulative throw that exceeds the elevation difference between the base of the sediments beneath the valley and the top of the range. Gravity contours are concentrated asymmetrically along the west side of Surprise Valley, thus indicating that most of the normal faulting and associated subsidence is located near the west side of the valley and that a steep density interface exists in the basement beneath the west side of the valley.

Because of exploration for hydrocarbon, mineral, water, and geothermal resources as well as academic interest, numerous books, conferences, and tasks forces have been devoted to interpreting origins of sedimentary basins (for example, Cloetingh and others, 1993 and 1995; and Busby and Ingersoll, 1995). Stewart (1978, fig. 1-10) related the origin of valleys in the Basin and Range province to models of horsts (mountain ranges) and graben (valleys) or tilted blocks over a plastically extending substratum or over downward-flattening listric faults. On the basis of geologic studies and seismic reflection data, Anderson and others (1983) described basin-range structure as composed of steep normal faults, deep listric normal faults, or sharply-curving listric faults that merge downward with a detachment surface, but none of the three structural models was interpreted as a stage or generalized to explain basin-forming processes. Thompson and Burke (1974, p. 229, fig. 16) suggested that "gravitational sliding and tilting in response to deeper primary faulting" and a dike system originating deep beneath Dixie Valley, Nev., could explain apparent surface extension rather than listric faulting, for which "serious geometric problems would ensue at the ends of basins."

Although valleys in the WSRAA (fig. 2) and other parts of the Basin and Range province may extend as straight lines for long distances, thus reflecting a regional state of stress, the gravity map of the WSRAA (fig. 3) indicates that the valleys are subdivided into individual depocenters. Inasmuch as underlying magma reservoirs are the source of ash-flow tuff generally associated with calderas, the suggestion by Rytuba and McKee (1984) that a gravity low in Quinn River Valley (figs. 2, 4, and 5) delineates the Hoppin Peaks caldera concealed beneath the valley is consistent with the magma dike model of Thompson and Burke (1974). On the basis of distribution of Tertiary tuff adjacent to valleys, substantial thicknesses of tuff beneath alluvium in drillholes, and low gravity values, Snyder (1983) and Snyder and Healey (1983) suggested that vents and tuff-filled calderas are concealed beneath Big Smoky and Monitor valleys in central Nevada. Primarily based on nearby thick layers of ash-flow tuff, the occurrence of oval-shaped basins, regional doming, discontinuity of border faults, changes of valley strike, anomalous fluid chemistry, high heat flow, and persistence of gravity lows beyond valleys, Plouff (1986) speculated that magmatic intrusion and subsequent fracturing and subsidence may have played roles in the origins of many basins and valleys. On the basis of anomalous shear wave attenuation and variations of seismic velocities recorded from local earthquakes, Walck and Clayton (1987), Walck (1988), Ho-Liu and others (1988), and Sanders and others (1988) suggested that an anomalous body imaged between depths of about 3 to 9 km (2 to 6 mi) beneath Indian Wells Valley, east-central California, probably contains magma. One might also speculate that surficial faults and swarms of local earthquakes beneath Indian Wells Valley record subsidence of the basin floor into a magma reservoir. The westward offset of the deepest part of the seismically anomalous body and comparable westward bulge of the gravity low over Indian Wells Valley (Plouff and Isherwood, 1980, fig. 2) indicate that the source of magma continues westward beneath Mesozoic plutonic rocks exposed along the east edge of the Sierra Nevada.

The possible association between magmatism and the formation of basins and valleys in the WSRAA also could play a role in localization and maturation of hydrocarbon deposits. For example, Blank and Grow (1992) proposed that a batholith initially was emplaced in Cretaceous time but with "renewed heating and possible magmatism in the Tertiary...had a major role in the tectonic evolution of the Railroad Valley-Grant Range region," east-central Nevada and "probably influenced the configuration of youthful extensional structures such as the Railroad Valley graben." Their interpretation was based on the occurrence of outcropping and buried plutonic rocks, arching of the range, drillhole data, high heat flow, seismic data, magnetic data, and gravity data. The gravity low associated with Railroad Valley—nearly 175 km (110 mi) in length—consists of colinear depocenters 30 to 50 km (20 to 30 mi) in length. A locus of steepest gravity gradients—approaching 11 mGal/km (7 mGal/mi)—along the east edge of the gravity low is located 2 to 10 km (1 to 6 mi) west of the east edge of the valley, roughly coincides with a line of springs and groundwater seeps, and apparently delineates the trace of a major concealed range front fault zone (Blank and Grow, 1992). All six of the producing oil fields are located on margins of the deepest, 43-mGal gravity low, "probably no coincidence" (Blank and Grow, 1992), which overlies at least 4.2 km (2.6 mi) of Cenozoic rocks and sediments. Duey (1983) previously suggested that oil entrapment is controlled by faults in Railroad Valley, and oil generation probably is an effect of recent local heating by intrusive rocks. Hulen and others (1994) stated that the geothermal system—less than 2.5 Ma in age—near the oil field, however, is caused by deeply-circulating meteoric waters rather than "a modern magmatic heat source."

Gravity data in the WSRAA can be analyzed to model the configuration of sediments in basins, which may provide information to understand the geologic history of basins and consequently may help to estimate resource potential in the WSRAA. Qualitative inspection of gravity maps can detect and map previously unknown basins revealed by gravity lows and can delineate topographic steps or compositional changes associated with fault zones delineated by gravity gradients. Inasmuch as most basins in the WSRAA are either elongate in shape, or the thickness of sediments is small compared to the width of nearly circular basins, methods of two-dimensional analysis—with simplifying assumptions about rock densities—can be applied (for example, Mabey, 1960; Pakiser and others, 1960, 1964; Kane and Pakiser, 1961; and Plouff, 1965). Jachens and Moring (1990) developed and Saltus and Jachens (1995) applied a computer method to estimate the depth to pre-Cenozoic bedrock beneath Cenozoic sediments and volcanic rocks. Their method isolates the gravity effect of Cenozoic rocks by subtracting from observed gravity anomalies the regional gravity field associated with pre-Cenozoic bedrock. Further depth constraint for their three-dimensional models can be obtained from drillholes through the sediments and from seismic measurements. Standard sections for densities of sediments and volcanic rocks as a functions of depth are assumed by Jachens and Moring (1990). The area of the regional gravity low in the northwest corner of the WSRAA, however, is too extensive to provide depth constraint needed to define the gravity-anomaly field of pre-Cenozoic bedrock.

Gravity models depend on simplifying assumptions and are vulnerable to inherent ambiguity. Significant errors of depth and the shape of the concealed bedrock interface can result if the configuration of the assumed regional background is incorrect. A regional gravity field that excludes the effect of Cenozoic rocks usually is assumed to smoothly join the ends of two-dimensional gravity models or to continuously blend along edges of three-dimensional gravity models. Apparent gravity datum shifts on opposite sides of valleys, however, make it difficult to determine the shape of the regional gravity background, for example, across Warner Valley, Oreg. (Plouff and Conradi, 1975) to the north of the WSRAA and Surprise Valley, Calif. (fig. 3). Gravity gradients near the edge of valleys can be steeper than accounted for by dip of the bedrock interface, for example, near Marble Hill in the Reno quadrangle (Plouff, 1992), therefore indicating that the density of bedrock outside the valley is significantly denser than rocks at the same level beneath sediments to the southeast of Pyramid Lake, Nev.. Gravity gradients that border Walker Lake in west central Nevada and the valley to the south persist southward along strike beyond the valley across Tertiary and Mesozoic rocks (Plouff, 1987a), therefore indicating that basement rocks beneath the valley are significantly less dense than basement rocks outside the valley.

Although combinations of the fastest and least attenuated acoustic paths are difficult to trace through sediments, seismic refraction surveys can provide constraint for analyses of gravity surveys of valleys. Goldstein and Paulsson (1979), however, obtained an unrealistically low bedrock-to-sediment density contrast of 0.06 g/cm^3 for the best fit of gravity profiles to seismically-determined bedrock depths beneath Grass and Buena Vista Valleys, which may result from density contrasts not accounted for within the underlying bedrock and within valley fill. The combination of seismic refraction surveys and closely-spaced gravity surveys near edges of valleys and basins can separate which part of peripheral gravity gradients is associated with the contrast in density between sediments and bedrock and which part is associated with superimposed intrabasement density contrasts.

Battle Mountain heat flow high and geothermal systems

Rapid lithospheric extension and heat sources related to the Battle Mountain heat flow high, which covers most of the southeastern part of the study area, have been attributed to intrusion of basalt as dikes or underplating at the base of the crust (Lachenbruch and Sass, 1978). Blackwell (1983, p. 82-83) suggested that the composite source of anomalous heat flow primarily consists of intrusive magmas with basaltic compositions, and the role of consequent extension, which generally is viewed as a manifestation of underlying crustal stretching, is to provide space in which to transport and store magma and consequently heated fluids. The cause-effect role of extension is complicated, however, inasmuch as Lipman (1992, p. 490), for example, demonstrated cases, in which "crustal magmatism is the unambiguous cause of intense extension." Although extensive geologic and geophysical investigations, including a prominent role for gravity prospecting, have been made since major geothermal exploration began in the mid-1970's in the study area, upper crustal geophysical models clearly associated with the Battle Mountain heat flow high have not yet been developed (Woods, 1974; Callaway, 1978; Crewdson, 1978; Isherwood and Mabey, 1978; Keller and others, 1978a, 1978b; Kumamoto, 1978; Morris, 1978; Zeisloft and Keller, 1978; Goldstein and Paulsson, 1979; Flynn and others, 1982; Benoit and Butler, 1983; and Wright, 1983).

Anomalous heat flow provides a comon thread that links geothermal, hydrocarbon, and mineral exploration. Barker (1995) stated: "Reconstructed thermal histories of the Carson Sink and Buena Vista Valley areas, indicate petroleum is presently being generated. Mechanisms for petroleum generation are rapid burial (140 m/m.y.) in a high geothermal gradient (45° to 110° C/km), and hydrothermal and contact metamorphism." Hydrothermal systems associated with magma reservoirs can facilitate the maturation and mobilization of organic matter during the formation and localization of petroleum and epithermal mineral deposits (Bonham and Giles, 1983; Simoneit, 1983, p. 215; White and Heropoulos, 1983).

Woods (1974) stated that numerous hot springs and hot flowing artesian wells in Surprise Valley "provide conclusive evidence that a heat source underlies this area at a relatively shallow depth." Hose and Taylor (1974), however, stated that hot springs and other geothermal manifestations could result from a hydrothermal system in which meteoric waters percolate downward to a depth at which rocks are normally hot, are heated, and ascend to the surface along deeply penetrating basin-range faults. Therefore, proximity to a shallow magmatic source would not be a requirement to form a geothermal system. Wilt and others (1993) stated that deep thermal waters "communicate" from a thermal system in granitic and metamorphic basement rocks at depths of 1.5-2 km (1 mi) beneath the surface to surface hot springs via normal faults at Amedee Hot Springs to the southwest of the WSRAA (location "A" in fig. 5). As discussed in the last section, Hulen and others (1994) studied isotopic compositions of hydrogen and oxygen in thermal waters to conclude that a geothermal system in Railroad Valley is caused by deeply-circulating meteoric water rather than a "modern" magmatic heat source. Although hot water is less dense than cold water and, hence, would rise buoyantly through *in situ* meteoric water and would flow with minimal resistance through crushed rocks in fault zones, causes for focusing and ascent along basin-range faults without underlying magmatic or tectonic pressure and without cooling and dilution, however, seem difficult to visualize. A system wholly dependent on recirculated meteoric water without a shallow heat source seems insufficient to account for hot springs near boiling temperatures (Renner and others, 1975, table 4) and exceptionally high heat flow such as heat flow of 7.2 HFU (300 mW/m^2) determined in a bedrock drillhole near Luning, Nev. (Munroe and Sass, 1974, p. 3-116). Anomalously high seismic delay times and clusters of shallow microearthquakes near Luning, Nev. (VanWormer and Ryall, 1980), and a history of repeated volcanism indicate that shallow magmatic sources cannot be precluded as sources of high heat flow.

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Note for "List of new publications......."

Open-File Report 97-99. Resource assessment of the Bureau of Land Management's Winnemucca District and Surprise Resource Area, northwest Nevada and northeast California—Gravity map and interpretation By Donald Plouff, 31p.

This report, "Resource assessment of the Bureau of Land Management's Winnemucca District and Surprise Resource Area, northwest Nevada and northeast California--Gravity map and interpretation," Open-File Report 97-99, by Donald Plouff (1997), is part of a series of reports to evaluate the resource potential of an area of federal lands administered by the Bureau of Land Management in northwest Nevada and northeast California. Sources of gravity data, reduction methods, and the quality of the database of 7,075 data points are discussed. Previous gravity surveys and interpretative reports for the study area are listed. The relation of gravity anomalies to the geology of the study area is discussed.