CHAPTER 2

THICKNESS OF CENOZOIC DEPOSITS AND THE ISOSTATIC RESIDUAL GRAVITY OVER BASEMENT

Robert C. Jachens, Barry C. Moring, and Paul G. Schruben

INTRODUCTION

Mineral deposits in Nevada are not distributed uniformly throughout the state, but instead occur preferentially within pre-Tertiary basement rocks. Although basement is exposed over only about 20% of Nevada, this exposed basement is host to about two-thirds of the known base and precious metal deposits and prospects (M. Sherlock, oral commun., 1988). The specific locations of deposits within the basement often are controlled by such factors as host rock type, folds, faults, and proximity to intrusions. Assuming that the 80% of the basement that is concealed beneath Cenozoic deposits contains a mineral endowment similar to that of the exposed basement, knowledge of the composition, structure, and depth of burial of the concealed basement is crucial to any analysis of mineral resources of the state. In this section we present the results of a study of the concealed basement of Nevada based on gravity data.

ANALYSIS OF GRAVITY DATA

Purpose

Analysis of the regional gravity data from Nevada was undertaken with two main objectives—to define the configuration of the upper surface of basement (here defined as all pre-Tertiary rocks, but also including granitoids of Tertiary age) and to produce a gravity map that only reflects variations of density within the basement. Both objectives contribute directly to the analysis of the mineral resources of Nevada, the first by specifying the three-dimensional distribution of potential host rocks and the second by placing constraints on the density, and therefore, the permissible lithology, of the concealed basement rocks. Secondary information of potential importance to the mineral resource investigation such as the location of faults, shear zones, calderas, concealed plutons, and other major crustal features can be derived from an analysis of these products alone and in combination with geological, geochemical, and other geophysical data.

Data and Methodology

Gravity data were taken from Saltus (1988a) and comprise approximately 71,000 point observations. These data were used to produce a Bouguer gravity anomaly map (Saltus, 1988b), an isostatic residual gravity map (based on an Airy-Heiskanen model for buoyant support of topography), and various derivative gravity maps of the state (Saltus, 1988c). We have chosen to use the isostatic residual gravity values as the starting point for our analysis because these data more clearly reflect shallow density distributions than the more commonly used Bouguer gravity values (Jachens and Griscom, 1985; Simpson and others, 1986).

The most striking characteristic of the isostatic residual gravity map of Nevada (fig. 2-1) is the pervasive regional pattern of long, narrow gravity highs and lows. This anomaly pattern is closely correlated with both the local topography and the near-surface geology: gravity highs typically occur over ranges where basement rocks are near the surface; gravity lows occur over intervening basins filled with young, low-density volcanic and sedimentary deposits. The predominant nature of this anomaly pattern reflects the strong difference in density between the rocks that make up the basement and the deposits that overlie them, and the magnitudes of the anomalies are a function of the thickness of low-density deposits.

A longer wavelength, more subtle pattern of gravity variations also is apparent on the residual gravity map, most readily seen as broad regions of high gravity in the northern and southern parts of the state compared to generally lower values present throughout the center. This broad pattern is an expression of density variations within the basement.

We developed a method designed to separate the observed isostatic residual gravity field of Nevada, *Gr*, into its component parts: the field, *Gb*, caused by density variation within the basement, and the field, *Gc* , caused by variations in thickness of Cenozoic deposits (Jachens and Moring, 1990), as shown schematically in figure 2-2. The process is iterative, where an initial estimate of *Gb* is refined through successively more accurate estimates of *Gc*. This method directly yields a map of the thickness of Cenozoic deposits based on assumed variations of density with depth in these deposits. The method has the following steps:

1. The first approximation to *Gb* is found by calculating a smooth field that satisfies only those gravity measurements made on outcrops of basement rock. This is only a crude approximation because gravity measured on basement outcrops will be influenced by the gravitational effects of low-density deposits in nearby basins.

2. This first approximation to *Gb* is subtracted from *Gr* to obtain a first approximation to *Gc*. This field serves as the basis for estimating the thickness, *h*, of Cenozoic deposits by solving the equation

   $Gc=2\pi gr(h)h$

   for *h* at each appropriate intersection of a regular geographic grid (grid cells 2 km on a side) that covers

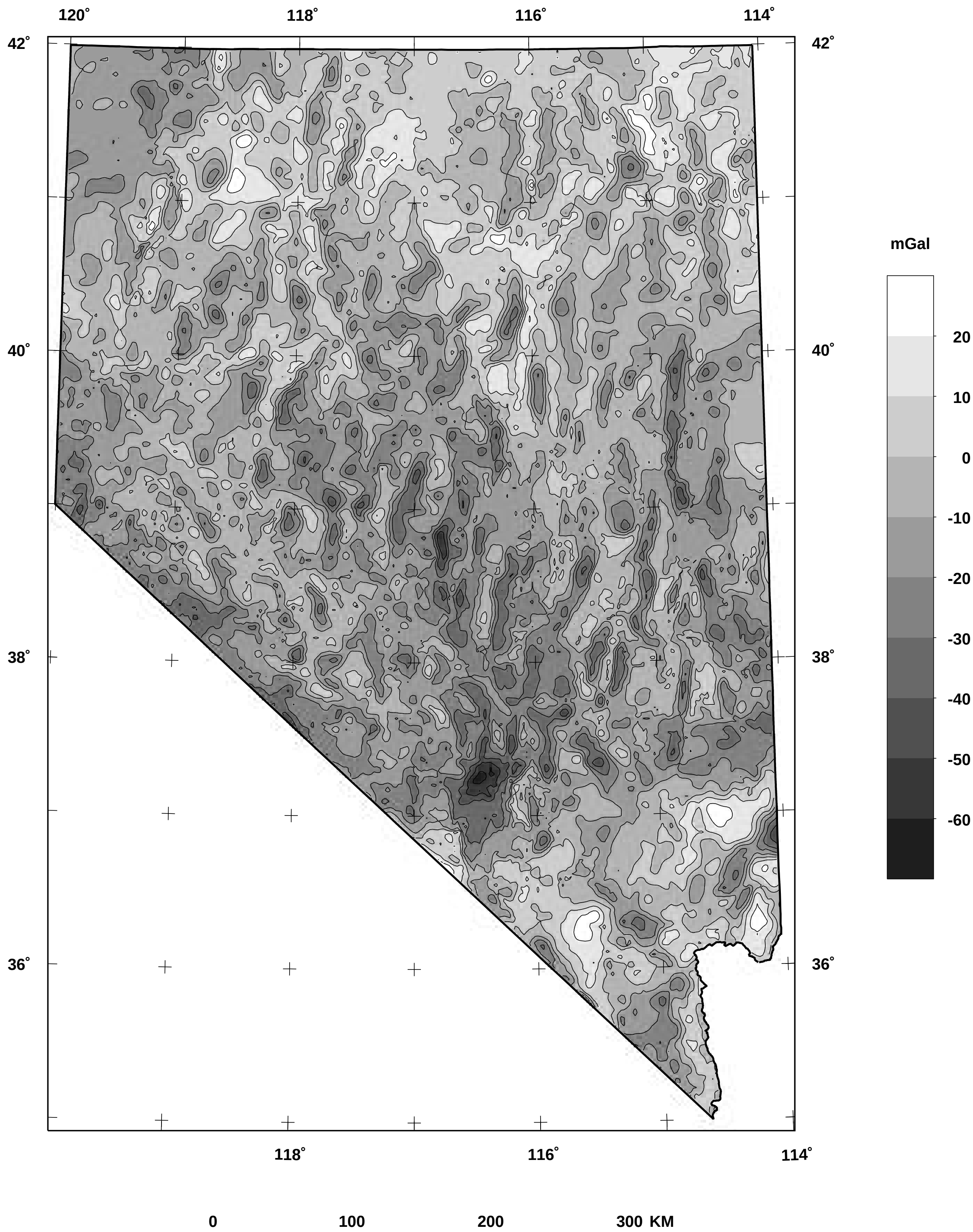

Figure 2-1. Map showing isostatic residual gravity field of Nevada. Shaded interval 10 mGal. (After Saltus, 1988c.).

DENSITY-DEPTH FUNCTIONS USED TO DERIVE
MAPS OF BASEMENT GRAVITY AND THICKNESS
OF CENOZOIC DEPOSITS

Depth range below surface (m)	Density contrast with basement (g/cm3)	
	Sedimentary section	Volcanic section
0-200	-0.65	-0.45
200-600	-0.55	-0.40
600-1200	-0.35	-0.35
> 1200	-0.25	-0.25

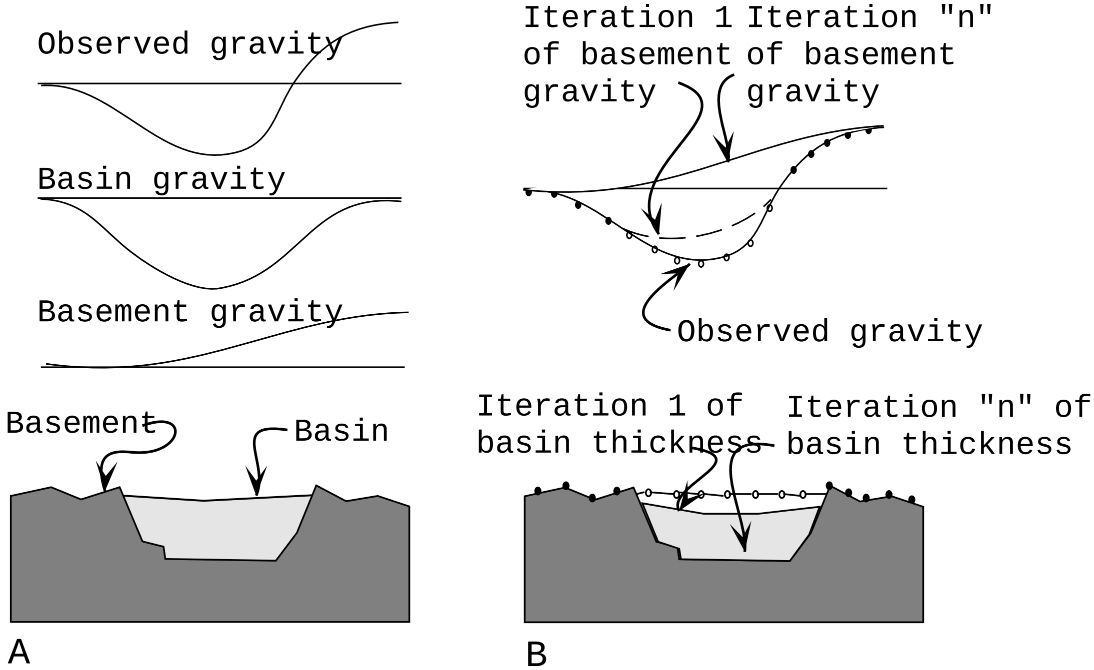

Figure 2-2. Schematic diagram of the iterative process used to partition the residual gravity field of Nevada into a "basement" component and a "basin" component. Curves labeled "Iteration 1" represent the first approximation to the basement gravity field (upper) and the first approximation to the thickness of Cenozoic deposits (lower).

the entire state. In this equation, *g* is the universal gravitational constant and *r(h)* describes the variation of density with depth in the Cenozoic deposits. Estimates are made only for those grid intersections where Cenozoic deposits occur at the surface, and different density-depth functions are used depending on whether the surface deposits are sedimentary or volcanic. These functions (fig. 2-2) were derived from a compilation of published borehole studies, seismic velocities, and measurements on surface rock samples (Jachens and Moring, 1990).

3. The gravitational effect *Gc* based on these thickness estimates is calculated and used to correct the gravity measurements made on outcrops of basement rock (Jachens and Moring, 1990). Steps 1, 2, and 3 are then reapplied to provide a second approximation to *Gb* and *Gc*. Iterations continue until the differences between two successive approximations of *Gb* are negligible (usually between 6 and 10 iterations).

Details of the gravity separation procedure are given in Jachens and Moring (1990).

Results and Limitations

The primary products of the separation procedure described above are shown on plate 2-1. The basement gravity is shown in color with each color-band corresponding to an interval of 5 mGal. Superposed on the basement gravity are black contours showing the thickness of Cenozoic deposits. Contours corresponding to thicknesses of 0.5 km and 1.0 km are labeled. The remaining unlabeled contours correspond to depth intervals of 1.0 km for an assumed constant density contrast of -0.25 g/cm^3. Because the assumed constant density contrast is an oversimplification of the actual density distributions in the deeply buried deposits, the unlabeled contours should be viewed as representative of the geometric forms of the basins, rather than actual depth contours. This presentation can be viewed as the gravity equivalent of seismic reflection time-sections which show the geometry of the reflectors but not calibrated depths. Outlines of basement outcrops (Stewart and Carlson, 1978) are shown on plate 2-1.

The separation procedure appears to have been successful although verifying the basement gravity map with other data is more difficult than establishing the uncertainties associated with the predicted thickness of Cenozoic deposits. For the basement gravity map, comparison of plate 2-1 with the original residual gravity map (fig. 2-1) shows that the major long-wavelength features are present on both and that the procedure has not generated new anomalies on the basement gravity map that cannot be found by close inspection of the original map. Moreover, the pervasive short-wavelength grain of figure 2-1 is absent.

To test the accuracy of the thickness map, the predicted values of deposit thickness were compared to values of depth to basement contained in logs of wells drilled through Cenozoic deposits. The results of this comparison for 225 wells are shown as a histogram in figure 2-3. Only wells that were interpreted by the drillers to have penetrated basement in the top 1.2 km and which had sufficient nearby gravity coverage to effectively constrain the calculation (generally

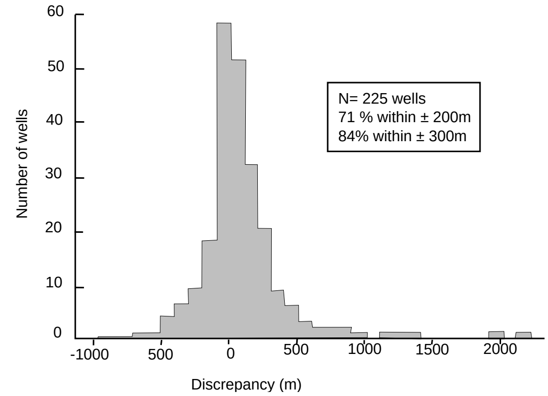

Figure 2-3. Comparison between measured thickness of Cenozoic deposits from drill holes and inferred thickness based on gravity analysis, for wells that penetrated basement at total depths less than 1,200 m. Discrepancy = Predicted - Measured (in m).

gravity stations within 2-3 km of the well site) are shown. For this set of wells, observed and predicted depths to basement agree to better than ±200 m in about 70% of the cases and to better than ±300 m in about 85% of the cases. Agreement is much poorer for wells that penetrated basement deeper than 1.2 km, most likely because of the unrealistic model density distribution below this depth.

Although the results of the comparisons discussed above suggest that the basement gravity and cover thickness information portrayed on plate 2-1 is reasonably reliable, the method that was used to generate this information has certain unavoidable limitations that must be understood by anyone attempting to use the results. The sources of these limitations and a brief discussion of their effects are given below.

Gravity Station Distribution

Gravity data are distributed unevenly over Nevada and, as a result, the reliability of the predicted cover thickness, and to a lesser extent the basement gravity, varies from place to place. Ideally, for a map at the scale of plate 2-1, gravity data points are needed every 2 to 3 km in areas covered by Cenozoic deposits and at somewhat wider spacing over the areas of basement rock outcrop. These conditions are met in some areas but not in others. For specific areas of interest, the user should refer to the gravity station plot at 1:750,000 given by Saltus (1988b) to determine local coverage.

Computational Grid Spacing

All computations were performed with a grid of 2 km spacing. Thus, even in areas where the gravity data are spaced closer than 2 km, features with characteristic dimensions less than about 6 km are not accurately portrayed. For example, steep basin edges, such as those formed by near-vertical faults, appear more gentle on the cover thickness map.

Density/Depth Model

The general agreement between the predicted thickness of Cenozoic deposits and the depth to basement determined by drilling indicates that the density/depth model used in the computations is representative of a statewide average density distribution in the depth range between 0 and 1.2 km. This is particularly true for areas with sedimentary deposits at the surface, but less so for areas with exposed Cenozoic volcanic rocks because both the density information and the well control are poorer there. Locally, these models may be in error because the subsurface density data are not adequate to permit specifying unique density/depth models for individual basins or parts of basins. Uncertainties in the local density/depth model primarily affect the predicted thickness of Cenozoic deposits but the basement gravity map should be relatively insensitive to them.

Scale of Concealed Anomaly Sources

The primary function of the separation procedure is to partition the gravity field into a component reflecting density variations within the basement and a component indicative of the thickness of Cenozoic deposits. The method appears to be effective for basement gravity anomalies with characteristic dimensions greater than the separation between basement outcrops. However, problems can occur for cases where anomalous basement density distributions of limited size are completely covered by Cenozoic deposits (e.g., a small, low-density intrusion contained within the basement and concealed beneath a broad alluvial plain). In such cases, the "basement" anomaly will be falsely interpreted to reflect a change in thickness of the Cenozoic cover. The northwest corner of Nevada is particularly susceptible to problems from this source because here over 6,000 km^2 are covered by Cenozoic deposits with no basement exposures in the area. Only with significantly improved well control or other information on the depth to basement could these problems be avoided.

High-density Volcanic Deposits

The separation procedure depends on the contrast in density between basement rocks and the overlying Cenozoic deposits. Most Cenozoic deposits are significantly lower in density than the underlying basement but a few rock types may be quite dense. Volcanic rocks of basaltic or andesitic composition may have densities approaching those of the basement rocks and the estimates of thickness for them will be too small. Fortunately, Cenozoic mafic volcanic rocks are not volumetrically important in most areas of Nevada.

Detached Basement Blocks

Large slide-blocks of basement rock engulfed by younger deposits occur in some places in Nevada, especially near large calderas. If these blocks are not recognized as slide-blocks but rather are treated as outcrops of basement rock, both the basement gravity map and the predicted Cenozoic deposit thickness will be in error. In general, the basement gravity will be anomalously low over unrecognized slide-blocks, and of course, the cover thickness will be zero. We believe we have correctly identified most of the basement slide-blocks but future research and mapping may reveal others.

INTERPRETATION

Thickness of Cenozoic Deposits

Perhaps the most important result of the gravity analysis related to mineral resources is the conclusion that vast new areas of Nevada may be amenable to exploration for basement-hosted mineral deposits. As mentioned in the Introduction, basement is exposed over only about 20% of the state, but this 20% hosts about two-thirds of the state's base and precious metal deposits and prospects. According to plate 2-1, another 20% of the state is covered by young deposits that are thick enough (>1 km) to put the underlying basement effectively out of reach of most current exploration techniques. The remaining 60% of Nevada has basement that, although concealed, lies at a depth of less than 1 km. This area of concealed but shallowly buried basement represents an important target for future mineral exploration.

Mineral deposits often occur in association with caldera structures and a knowledge of the locations of calderas can be used to focus exploration for certain mineral deposits. Because calderas generally are sites of thick accumulations of low-density volcanic rocks deposited during the caldera-forming eruptions, Cenozoic calderas in Nevada for which thick volcanic deposits are still preserved should be reflected in the contours on plate 2-1. Figure 2-4 shows a map of the inferred distribution of thick sections of Cenozoic volcanic rock (and possible calderas) in Nevada.

The shaded areas on figure 2-4 represent those places where thick sections of Cenozoic material (>1 km as inferred from the gravity data) coincide either with outcrops of Cenozoic volcanic rock or with short wavelength magnetic anomalies that suggest the presence of volcanic rock in the upper 1 km of the crust (see chapter 3 for a map of shallow magnetic sources in Nevada and a discussion of magnetic volcanic rocks). Outlines of known or inferred Cenozoic calderas (chapter 5) are shown for reference.

Two large areas of northern Nevada, one in the extreme northwest corner of the state and the other along the northern border at longitude 117°W, are blanketed by volcanic rocks having ages in the range 6-17 Ma (Stewart, 1980). Although the two areas appear quite similar on geologic maps, the thickness contours on plate 2-1 indicate that the northwestern corner contains a thick volcanic sequence, whereas deposits in the north-central area are substantially thinner. The thickness of volcanic deposits in both areas is imprecise because (1) the density/depth function is poorly known below 1 km depth, and (2) no basement outcrops exist anywhere in the areas on which to establish the basement gravity field. In spite of these admitted uncertainties in the total thickness of volcanic deposits, the crust in the northwestern corner of

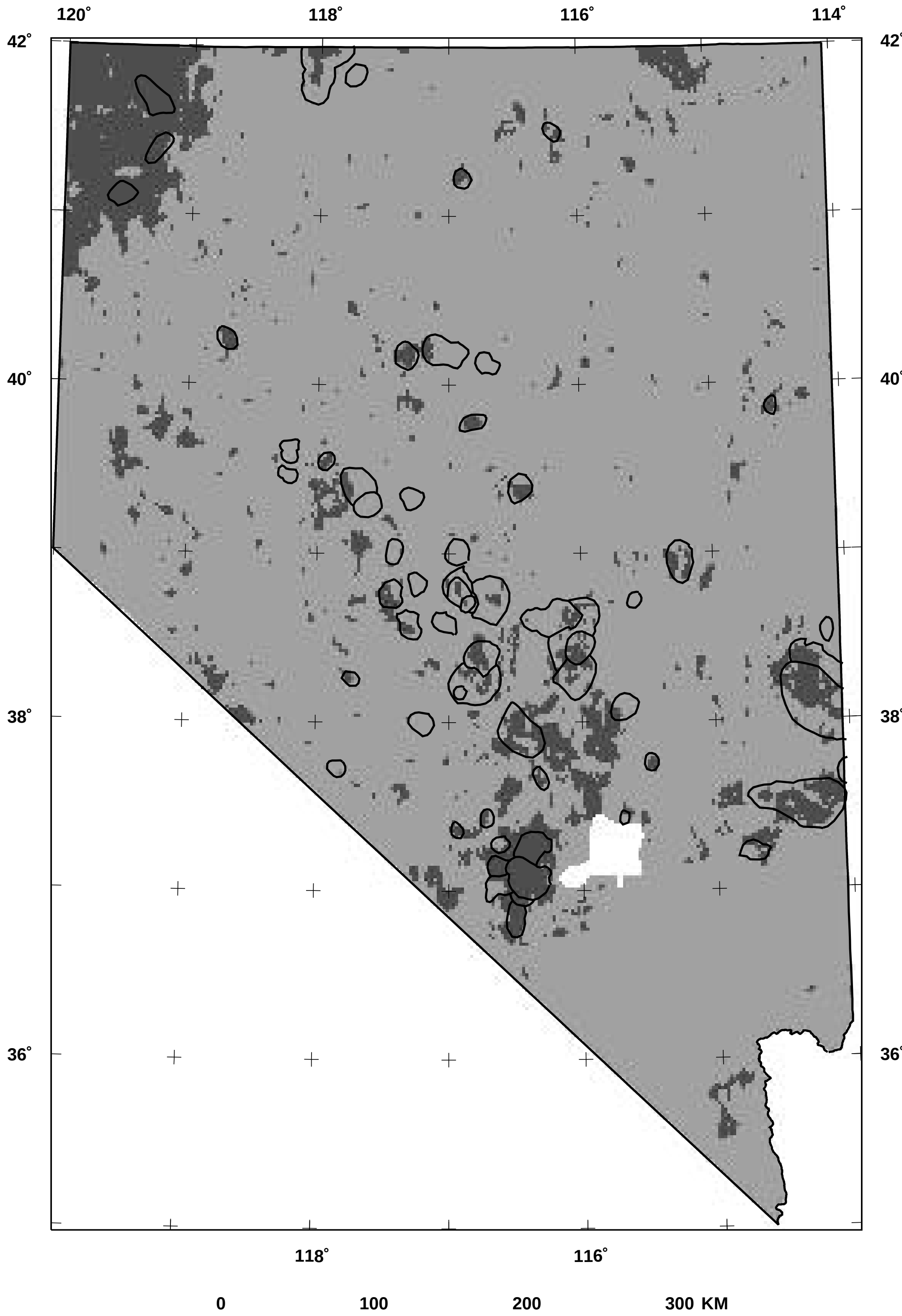

Figure 2-4. Areas inferred to be covered by thick (>1 km) volcanic deposits of Cenozoic age (shaded). Heavy lines show outlines of Tertiary calderas.

Nevada must be significantly different from anywhere else in the state, and, if pre-Tertiary basement is present at depth, it must lie beneath a considerable thickness of Tertiary volcanic rock.

Basement Gravity

The dominant feature of the basement gravity of Nevada (plate 2-1) is the enormous area of low gravity that spans the entire state between about latitudes 37°N and 40°N. Background gravity values here are roughly 15 mGal more negative than in the areas to the north and south. In many places the transition from low to high background gravity values takes place over relatively short distances suggesting that the density distributions that produce these anomalies are shallow. Estimates from both the northern and southern transition zones indicate maximum depths to the tops of the sources in the range of 5 to 10 km.

Although the sources for this major gravity low appear to be shallow, they most likely are concealed throughout much of the area. Some of the gradients that define the borders of the low occur over exposed pre-Tertiary basement, yet seem to bear little relation to the basement rocks. Commonly the transition occurs completely over continuous basement outcrop where the exposed Paleozoic rocks do not change composition or structure. The regional gravity low reflects pre-Tertiary basement rock, but its strongest correlation with the surface geology is with the distribution of Cenozoic volcanic rocks that rest on the basement (fig. 2-5, on page 2-9). The gravity low encompasses most of the volcanic rocks with ages between 17 and 43 Ma (Stewart, 1980) although exceptions occur in the northern part of the state near longitude 116°W and 119°W. Interestingly, even in these two anomalous areas, the volcanic rocks mostly fall in local gravity lows, ones that are smaller in amplitude and isolated from the main regional low.

The consistent relationship between broad gravity lows and the distribution of 17-43 Ma volcanic rocks is perhaps most clearly seen locally along the eastern part of the state near latitude 37°N. Here the great southwestward sweep of Tertiary volcanism (chapter 6) terminated at the location which now corresponds to the transition from low to high gravity values, leaving an amagmatic zone to the south that now is characterized by higher gravity. Eaton and others (1978) noted the same relationship between gravity and the southern terminus of Tertiary volcanism through examination of the Bouguer gravity field. Based on these observations, likely sources for the broad gravity low are silicic intrusions that are the counterparts of the volcanic rocks at the surface. Most of these intrusions remain concealed although some intrusive rocks of Tertiary age have been exposed by erosion (Stewart, 1980).

Numerous local gravity lows also are caused by intrusive bodies of Mesozoic age. The deepest gravity lows occur over Mesozoic plutonic rocks of the Inyo batholith and in the Sylvania and Palmetto Mountains along the western edge of the state between 37°N and 40°N (fig. 2-6, on page 2-10). These lows represent the easternmost lobes of the deep gravity low that characterizes the eastern Sierra Nevada batholith (Jachens and Griscom, 1985). The low over the eastern part of the Sierra Nevada batholith is caused by low density granitic rocks that make up the upper 10 km of the batholith (Oliver and others, 1993). Other prominent local gravity lows are associated with the Belmont and Manhattan plutons, and with plutons in the Toiyabe Range, Dry Hills, Cortez Mountains, Bilk Creek Mountains, near Duffer Peak, and near Austin (fig. 2-6).

Some local gravity highs appear to be associated with mafic igneous bodies. An east-west high (lat 40°N, long 117.5-119°W, fig. 2-6) peaks over outcrops of the gabbroic rocks of the Humboldt lopolith (Speed, 1976). The gravity anomaly extends beyond the outcrop area suggesting that these mafic rocks may be more extensive in the subsurface. A linear gravity high follows the Colorado River in extreme southeastern Nevada and lies partly over large exposures of Tertiary plutonic rock (fig. 2-6). Simpson and others (1990) attribute this high to young, dense intrusive bodies at depth that manifest themselves at the surface as mafic dike swarms.

An intriguing spatial coincidence between the basement gravity and ore deposits was pointed out by V.J.S. Grauch (Grauch and others, 1995). She observed that numerous sediment-hosted gold deposits of the Cortez trend lie along one of the stronger linear anomalies on the basement gravity map, the gravity gradient the trends southeastward across the north-central part of the state (fig. 2-6). These deposits are part of the Battle Mountain-Eureka mineral belt, identified by Roberts (1966) on the basis of the alignment of many types of mineral deposits. Blakely and others (1990) and Grauch and others (1995) attempted to quantify this relationship and to extend it to other parts of Nevada, with some success. The correspondence between the location of the sediment-hosted gold deposits of the Cortez trend and the strong southeast-trending gravity gradient suggests that this gradient might be an effective guide in exploring for concealed gold deposits.

Regionally extensive gravity gradients often mark crustal-scale subsurface structures such as terrane boundaries, suture zones, other major faults and shear zones, rifts, plutonic boundaries, and zones of crustal thinning (Simpson and others, 1986; Blakely and Simpson, 1986). In many cases such structures are thought to control the locations of mineral deposits and districts [for example, see Roberts (1966), Bagby (1989), Kutina and Hildenbrand (1987), Berger and Bagby (1990)]. Although many of the regional gravity gradients shown on the basement gravity map (plate 2-1) reflect major crustal boundaries whose nature remains to be determined, their correlation with mineral deposits suggests that further study of the basement gravity field of Nevada should provide new information to guide the search for undiscovered mineral resources.

ACKNOWLEDGMENTS

This work was done as part of a team effort directed toward the analysis of the mineral resources of Nevada. Our contribution to this effort benefitted greatly from the leadership of Don Singer and from the numerous stimulating discussions with Barney Berger, Rick Blakely, Dennis Cox, Tien Grauch, Don Huber, Steve Ludington, Ted McKee, Maureen Sherlock, and Joe Tingley.

REFERENCES

Bagby, W.C., 1989, Patterns of gold mineralization in Nevada and Utah, *in* Shawe, D.R., and Ashley, R.P. eds., United States Gold Terranes—Part I: U.S. Geological Survey Bulletin 1857-B, p. B11-B21.

Berger, B.R., and Bagby, W.C., 1991, The geology and origin of Carlin-type deposits, *in* Foster, R.P., ed., Gold Metallogeny and Exploration: London, Blackie and Son, p. 210-248.

Blakely, R.J., Jachens, R.C., and Sherlock, M.G., 1990, Bulk mineable precious metal deposits and crustal structure: a statistical comparison, *in* Dean, D.A., Benedetto, K.M.F., and Durgin, D.C., eds., Southern extension of the Carlin trend: influence of structure and stratigraphy on gold deposition: Geological Society of Nevada, Field Trip #4 Guidebook, p. 30-38.

Blakely, R.J., and Simpson, R.W., 1986, Approximating edges of source bodies from magnetic or gravity anomalies: Geophysics, v. 51, p. 1494-1498.

Cox, D.P., and Singer, D.S., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Eaton, G.P., Wahl, R.R., Prostka, H.J., Mabey, D.R., and Kleinkopf, M.D., 1978, Regional gravity and tectonic patterns: Their relation to late Cenozoic epeirogeny and lateral spreading in the western Cordillera, *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 51-91.

Grauch, V.J.S., Jachens, R.C., and Blakely, R.J., 1995, Evidence for a basement feature related to the Cortez disseminated-gold trend and implications for regional exploration in Nevada: Economic Geology **(in press).**

Jachens, R.C., and Griscom, A., 1985, An isostatic residual gravity map of California—A residual map for interpretation of anomalies from intracrustal sources, *in* Hinze, W.J., ed., The utility of regional gravity and magnetic anomaly maps: Society of Exploration Geophysicists, Tulsa, p. 347-360.

Jachens, R.C., and Moring, B.C., 1990, Maps of the thickness of Cenozoic deposits and the isostatic residual gravity over basement for Nevada: U.S. Geological Survey Open-File Report 90-404, 15 p., 2 sheets, scale 1:1,000,000.

Kutina, J., and Hildenbrand, T.G., 1987, Ore deposits of the western United States in relation to mass distribution in the crust and mantle: Geological Society of America Bulletin, v. 99, p. 30-41.

Oliver, H.W., Moore, J.G., and Sikora, R.F., 1993, Internal structure of the Sierra Nevada Batholith based on specific gravity and gravity measurements: Geophysical Research Letters, v. 20, no. 20, October 1993, p. 2179-2182.

Roberts, R.J., 1966, Metallogenic provinces and mineral belts in Nevada: Nevada Bureau of Mines and Geology Report 13, Part A, p. 47-72.

Saltus, R.W., 1988a, Gravity data for the State of Nevada on magnetic tape: U.S. Geological Survey Open-File Report 88-433, 20 p.

Saltus, R.W., 1988b, Bouguer gravity anomaly map of Nevada: Nevada Bureau of Mines and Geology Map 94A, 1 sheet, scale 1:750,000.

Saltus, R.W., 1988c, Regional, residual, and derivative gravity maps of Nevada: Nevada Bureau of Mines and Geology Map 94B, 4 sheets, scale 1:1,000,000.

Simpson, R.W., Howard, K.A., Jachens, R.C., and Mariano, J., 1990, A positive gravity anomaly along the Colorado River extensional corridor: Evidence for new crustal material?: Eos, American Geophysical Union Transactions, v. 71, p. 1594.

Simpson, R.W., Jachens, R.C., Blakely, R.J., and Saltus, R.W., 1986, A new isostatic residual gravity map of the conterminous United States with a discussion of the significance of isostatic residual anomalies: Journal of Geophysical Research, v. 91, p. 8348-8372.

Speed, R.C., 1976, Geologic map of the Humboldt lopolith and surrounding terrane, Nevada: Geological Society of America Map and Chart Series MC-14.

Stewart, J.H., 1980, Geology of Nevada: Nevada Bureau of Mines and Geology Special Publication 4, 136 p.

Stewart, J.H., and Carlson, J.E., 1978, Geologic map of Nevada, scale 1:500,000.

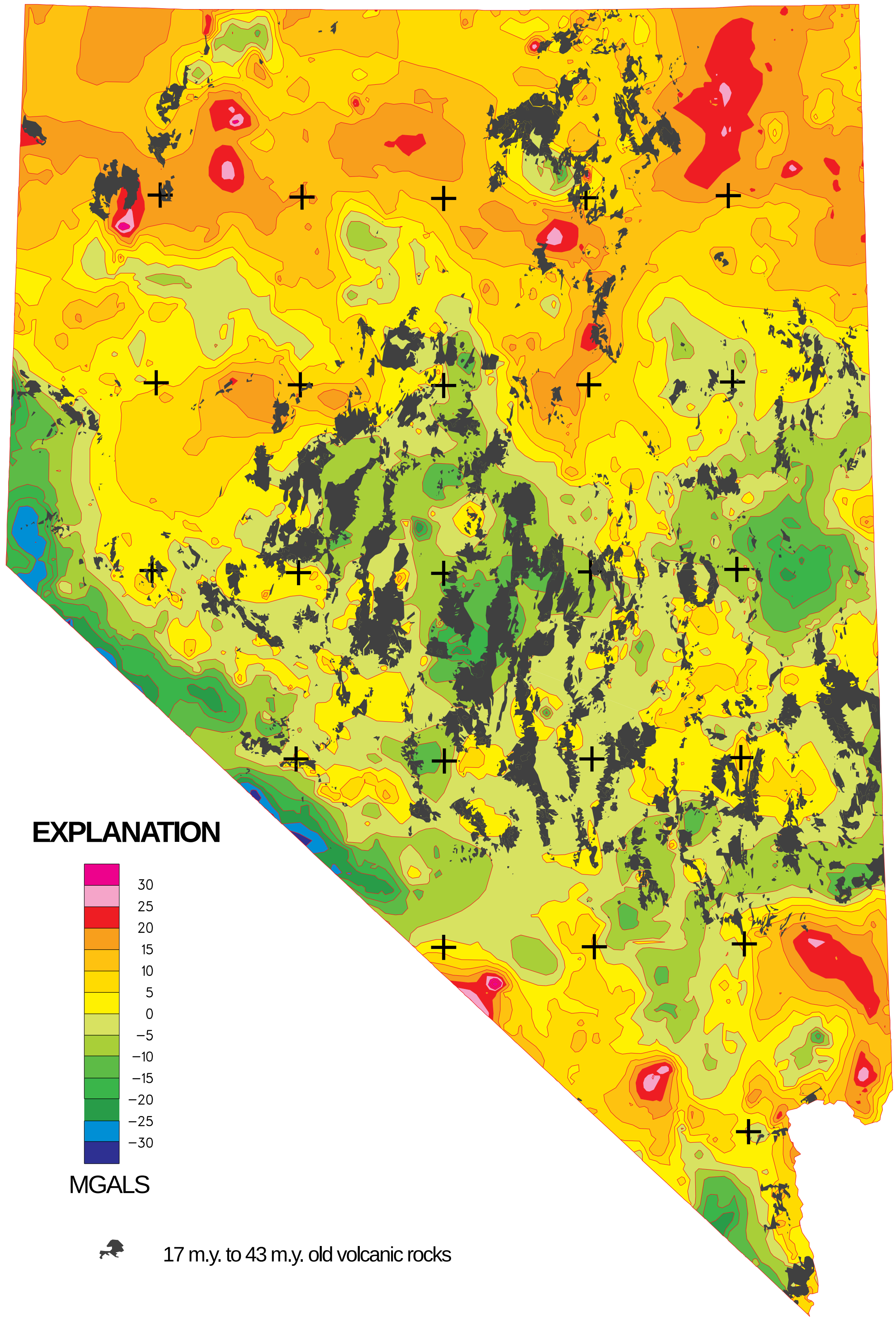

Figure 2-5. The basement gravity field of Nevada (in color) with the distribution of volcanic rocks deposited between 43 and 17 Ma (Stewart, 1980) shown in black. Color contour interval 5 mGal.

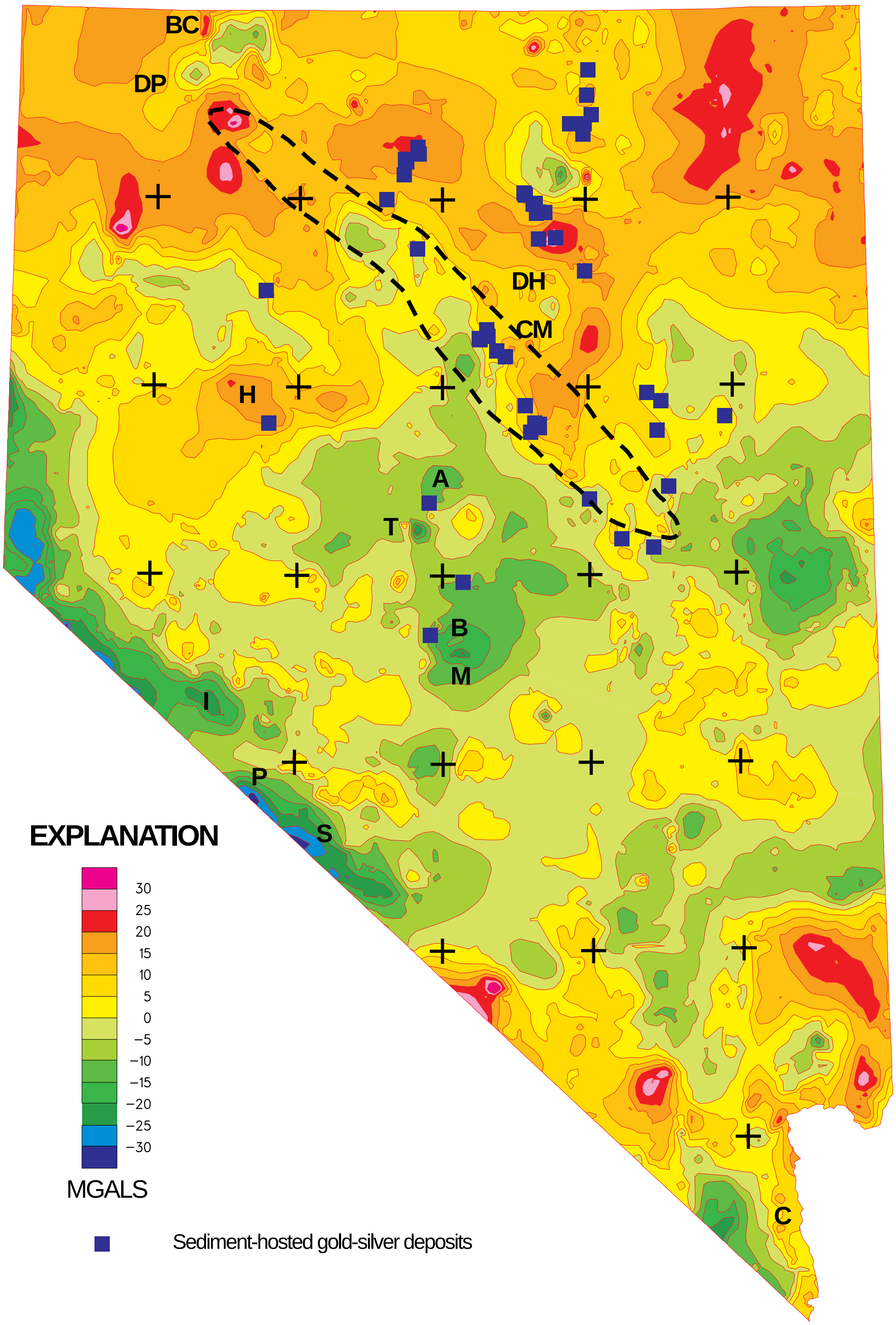

Figure 2-6. Map showing the basement gravity field of Nevada (in color) relative to some types of mineralization. Boxes show sediment-hosted gold-silver deposits (model 26 of Cox and Singer, 1986). Dashed line shows the outline of the Battle Mountain-Eureka mineral belt (Roberts, 1966). Letters indicate intrusive bodies discussed in text: A-Austin; B-Belmont pluton; BC-Bilk Creek Mountains; C-Colorado River region; CM-Cortez Mountains; DH-Dry Hills; DP-Duffer Peak; H-Humboldt lopolith; I-Inyo Mountains; M-Manhattan pluton; P-Palmetto Mountains; S-Sylvania Mountains; T-Toiyabe Range. Color contour inteval 5 mGal.