Pb ISOTOPIC MAPPING OF CRUSTAL STRUCTURE IN THE NORTHERN GREAT BASIN AND RELATIONSHIPS TO Au DEPOSIT TRENDS

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ABSTRACT

A regional common Pb isotopic study of Mesozoic and Tertiary granitoids and some Tertiary volcanic rocks in the northern Great Basin provides a better understanding of the regional crustal structure and composition, and their relationship to the apparent linear alignment of gold deposits along the Carlin and Battle Mountain - Eureka trends. The Pb isotopic data allow for the subdivision of the northern Great Basin into western, central, and eastern provinces. The boundary between the western and central provinces closely follows the previously documented initial Sr (ISr) = 0.706 line and represents a narrow zone in which initial Pb and Sr isotopic ratios increase rapidly. Initial Pb vs. Pb and Pb vs. Sr isotopic ratios show strong positive correlation, and initial Pb and Sr isotopic ratios increase from west to east across these two provinces. The eastern province is characterized by plutons in which the Pb and Sr isotopic ratios are not strongly correlated and exhibit much greater variability than those in plutons from the two provinces to the west. The boundary between the central and eastern provinces is sharp and is approximately coincident with the Carlin trend in north-central Nevada. It is suggested that this isotopic boundary and the Carlin trend mark the locus of a cryptic major crustal discontinuity. The Battle Mountain - Eureka trend lies within the central province and is generally parallel to both the Carlin trend and the north-south oriented portion of the boundary between the western and central provinces as marked by the ISr = 0.706 line. It is proposed that the Pb province boundaries, the ISr = 0.706 line, and the gold deposit trends are related to crustal-scale discontinuities formed during continent-scale rifting along western North America in the latest Precambrian and that these discontinuities, which probably were originally fault systems, were reactivated or utilized by subsequent tectonic and magmatic events in the Phanerozoic.

INTRODUCTION

Two subparallel north-northwest to northwest-trending mineral belts in Nevada, the Battle Mountain-Eureka trend on the SW and the Carlin trend on the NE (fig. 1), are thought to reflect deep-seated, pre-Cenozoic crustal structures. These structures may be pre-Cenozoic faults, Mesozoic and/or Paleozoic fold axes, or uncertain features of the Precambrian basement. Both geophysical and geochemical-isotopic studies can compliment field based geologic studies of these features, and both have been successfully applied in studies of crustal structure in the northern Great Basin and the western U.S (for example Blakely and Jachens, 1991; Grauch and others, 1995; Zoback and others, 1994; Kistler and Peterman, 1973, 1978; and Kistler, 1983, 1991). Geophysical studies measure time-integrated physical parameters and attempt to distinguish

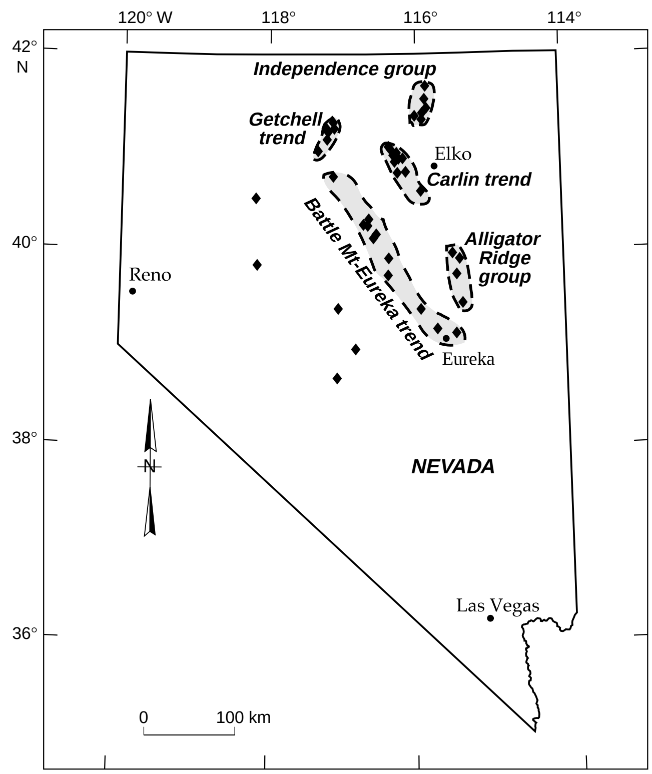

Figure 1. Location of major belts of precious metal deposits in north-central Nevada.

shallow from deep and younger from older features but are limited in temporal distinctions because the basic data are tied to present conditions and may be dominated by recent crust-mantle events. Isotopic studies have the advantage of investigating time-related features by comparing the isotopic compositions of rocks formed at different times during the geologic history of a region for systematic or significant changes. However, the sampling interval for isotopic studies is controlled by the present-day outcrop distribution of the rocks to be studied, and the result can be a very uneven geographic distribution. In comparison, the sampling interval for geophysical studies is not tied to the outcrop patterns and can be designed to provide an even geographic coverage at a chosen scale. The isotopic signatures of igneous rocks largely reflect the average characteristics of their source regions plus any later interaction with the crustal column through which they moved or into which they were emplaced and any later modification by metamorphism or hydrothermal alteration. In general isotopic signatures of granitoid rocks reflect the geochemical properties of the lower and middle crust and the mantle from which they were melted and are unlikely to reflect the upper crust, the structure of which is more readily revealed by geophysical methods. Since one goal of this study is to provide a basis for the comparison of the geophysical and isotopic data sets with respect to the crustal structure of Nevada, it is important to remember that the two methods have some fundamental differences in what features of the crust and mantle system are providing the basic data.

Kistler and Peterman (1973, 1978) and Kistler (1983, 1991) demonstrated that the distribution of Sr isotopic compositions of granitoid rocks in the northern Great Basin delineated crustal structure, particularly the location of the boundary between continental and oceanic crust as marked by the initial $^{87}Sr/^{86}Sr$ (ISr) = 0.706 line (fig. 2). Elison and others (1990) showed that the ISr = 0.706 line correlates well with the shelf-slope break defined by Early Paleozoic and Triassic strata. Farmer and DePaolo (1983, 1984) used combined Nd and Sr isotopic compositions of Great Basin granitoids to study the petrogenesis of these rocks and regional crustal structure; however, their pioneering studies were limited by the small sample suite for which Nd isotopic data were available. Bennett and DePaolo (1987) and DePaolo and others (1991) present examples of the application of Nd isotopic studies to understanding the distribution of Precambrian crustal provinces in, and the more general crustal structure of, the southwestern U.S. Farmer and Ball (1997) provide an excellent example of using Nd isotopic characteristics of Precambrian crustal provinces to determine provenance of Late Precambrian to early Paleozoic sedimentary rocks in the Great Basin. Since these rocks are potential sources for Pb in the ore minerals associated with the gold deposits in Nevada (Tosdal and others, this volume), the conclusions reached in Farmer and Ball (1997) are of general interest to the present study.

Pb and Sr isotopic data are suitable for regional scale studies because the data are relatively easy to acquire for regional-scale sample suites. Rocks and magmas derived from the mantle have low Pb concentrations (1-2 ppm or less) relative to feldspar-rich crustal rocks that typically have 10-30 ppm Pb. Because of this strong contrast in Pb concentration, the Pb isotopic composition of most granitoid rocks reflects that of the crust with which it is associated even if the magma had a significant mantle contribution to its formation. Doe and Delevaux (1973) report an early example of the application of Pb isotopic studies to Mesozoic granitoids in the western U.S. Chen and Tilton (1991) have demonstrated the usefulness of combined Pb and Sr isotopic studies in the southern Sierra Nevada. Building on the work of Zartman (1974), Wooden and others (1988), Wooden and Miller (1990) and Wooden and DeWitt (1991) used the Pb isotopic compositions of Proterozoic and Phanerozoic rocks to better define the extent and nature of the crustal provinces in the southwestern U.S. Wooden and Mueller (1988) provide a Pb isotopic characterization for the Archean Wyoming province. These studies provide the background necessary to interpret the Pb isotopic signatures of the Great Basin granitoids. It should be pointed out that the Precambrian crustal provinces of the southwestern U.S. as defined by the Pb and Nd isotopic studies mentioned above are similar in their geographic extent, but not the same (compare figures in Wooden and DeWitt, 1991, to those in Farmer and Ball, 1997). One of the areas of disagreement is the extent of the Mojave crustal province in the Nevada, Utah, and Arizona, but this difference mostly effects the details, not the main thesis, of the data interpretation provided below. Given that there are fundamental differences in the geochemical basis of the Pb and Nd isotopic systems, these differences in the extent of the crustal provinces may be real and/or rooted in sample distribution, sample types, and interpretation. A large database of Sr isotopic data and crystallization ages is already available for granitoids from the northern Great Basin. We report here on the results derived from the determination of initial Pb isotopic compositions for many of the same samples used in the studies by Kistler and co-workers (see references above and below) and for other new samples.

DATA SOURCES AND ANALYTICAL PROCEDURES

The data used herein have been determined over about a ten year period in the Pb isotopic laboratory at the U.S. Geological Survey in Menlo Park for a number of topical studies (e.g. Wright and Wooden, 1991) mostly focused on magmatic and tectonic histories and processes. Most of the data represent feldspar separates made from whole-rock crushes by conventional magnetic and heavy-liquid separation techniques.

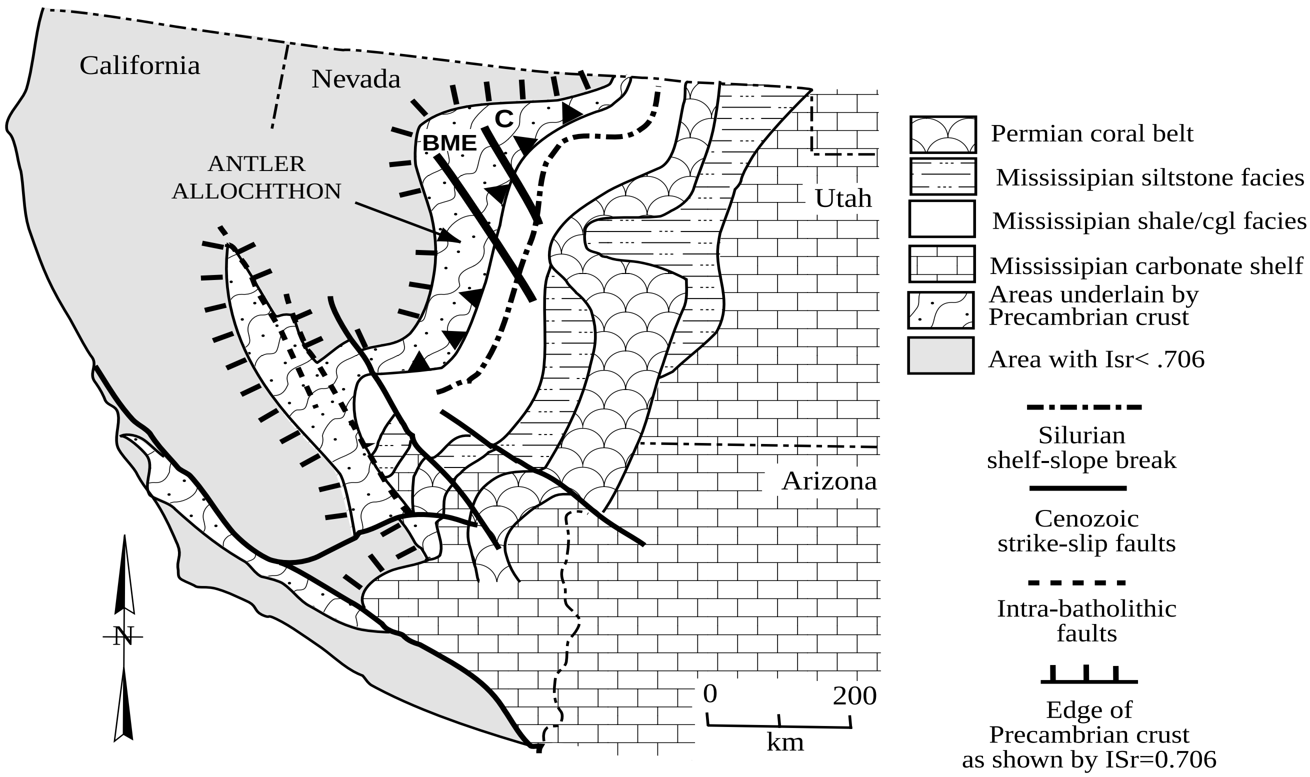

Figure 2. Outline map of California and Nevada showing the ISr = 0.706 line and Paleozoic facies boundaries (from Kistler and Fleck, 1994; Stevens and others, 1992; and Kistler, 1990). BME, Battle Mountain-Eureka mineral belt; C, Carlin.

Sodium- and particular K-rich feldspars from granitoid rocks have relatively high concentrations of Pb and very low concentrations of U and Th. The very low U/Pb and Th/Pb ratios of feldspars mean that the Pb isotopic composition of feldspars changes little with time, and a present-day isotopic composition of feldspar is a good estimate of the initial Pb isotopic composition of the feldspar and the magma (assuming equilibrium) at the time of crystallization. In the rare cases where a feldspar has a significant U/Pb or Th/Pb ratio, failure to correct for the added radiogenic Pb will make the measured Pb isotopic ratios higher than the true initial values. The Pb isotopic composition of feldspar is subject to resetting during heating events that reach about 300° C or approximately the same temperature range in which biotite K-Ar and Rb-Sr ages are reset. During such a heating event, radiogenic Pb produced in minerals or along grain boundaries where high U/Pb and Th/Pb exist migrates and is taken into the feldspar crystal structure. The Pb isotopic composition of such a feldspar will be more radiogenic that the initial composition. In Paleozoic and younger systems, the Pb isotopic ratio that is most likely to be effected by failure to correct for a significant U/Pb or Th/Pb ratio or for thermal resetting is $^{206}Pb/^{204}Pb$ because most of the U present during this time is ^{238}U, the parent of ^{206}Pb; ^{235}U (parent of ^{207}Pb) has mostly disappeared because of its much higher decay rate compared to ^{238}U, and ^{232}Th (parent of ^{208}Pb) has a lower decay rate than ^{238}U.

Some analyses used herein are from whole-rock powders used in the regional geochemical and isotopic studies of Lee (1984) and Kistler and Lee (1989). For these samples the present-day Pb isotopic composition of the whole-rock powder has been determined along with a Pb concentration by the isotope dilution technique. These data have been combined with U and Th concentration and crystallization age data (Lee, 1984; Kistler and Lee, 1989) to calculate an initial Pb isotopic concentration. Initial Pb isotopic ratios calculated from whole-rock samples carry a higher uncertainty than those measured in feldspar mineral separates because of the analytical uncertainties associated with the U and Th concentrations, and the tendency of medium- and coarse-grained granitic samples to lose U in surficial weathering environments. The most common error in initial Pb ratios calculated from whole-rock powders is for the present-day $^{206}Pb/^{204}Pb$ ratios to be under-corrected because the measured U concentration is too low as a result of U-loss during weathering. The $^{206}Pb/^{204}Pb$ ratio experiences the most change in Phanerozoic materials because of the very high ratio of ^{238}U to ^{235}U for this time interval.

Pb was separated from feldspar and whole-rock samples using the standard anion exchange resin process that utilizes HBr and HCl. All feldspar mineral separates were leached with HCl, HNO_3, and weak HF to remove labile Pb before dissolution. Pb isotopic compositions were determined in static-collection mode on a MAT 262 mass spectrometer. Thermal fractionation is monitored by running NBS-981 and -982. The empirical fractionation correction factor is 0.0011 per mass unit and its uncertainty is the largest contribution to the total analytical uncertainty of about 0.1% associated with the Pb isotopic ratios.

RESULTS

There are approximately 400 samples for which common Pb isotopic data are available (fig. 3). Sr isotopic data produced from separate studies are available for most of these samples, and the existence of these previously analyzed sample suites and Sr isotopic data was a great asset in the conduct of the present study. Observations made in the early stages of this study were that for most of the samples a strong positive correlation exists between the three Pb isotopic ratios and between the initial Sr ratio and

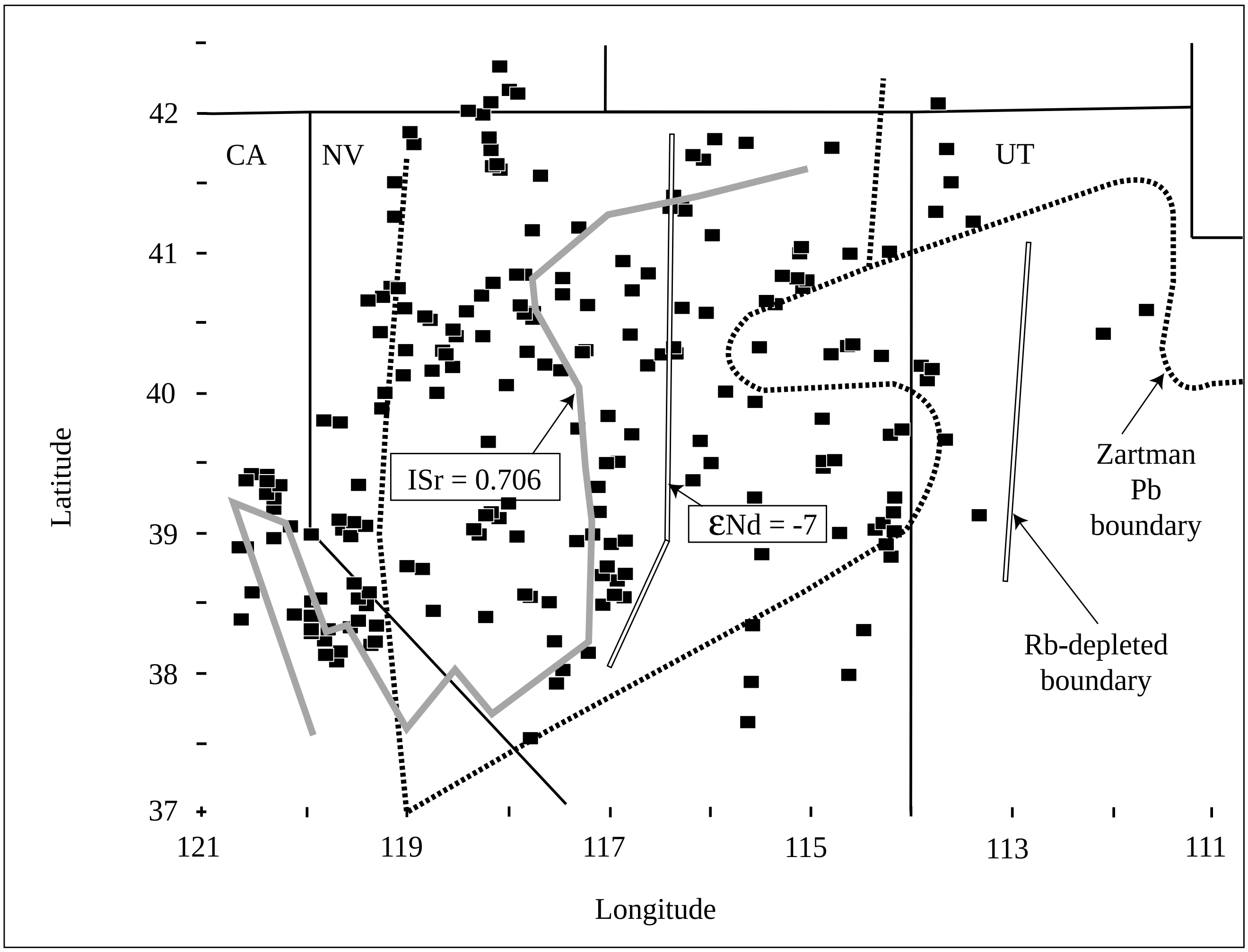

Figure 3. Outline map of California (CA), Nevada (NV), and Utah (UT) showing distribution of igneous samples used for the Pb isotopic study. The approximate boundary of the ISr = 0.706 line is shown as are the boundaries (heavy dashed lines) for the Pb isotopic provinces of Zartman (1974) and two boundaries (Rb-depleted and εNd = -7) proposed by Farmer and DePaolo (1983) from their Nd and Sr isotopic data. See text for additional discussion.

each of the Pb isotopic ratios (Wooden and Stacey, 1987; Wright and Wooden, 1991). These positive correlations, however, were not observed for many samples from eastern Nevada (fig. 4; Wooden and others, 1991, 1993). These observations were consistent with those made by Chen and Tilton (1991) for a transect in the southern Sierra Nevada. That transect in some aspects represents a telescoped version of the Nevada data set including the fact that the strong correlation between isotopic ratios is no longer observed at its eastern end. Since previous Sr isotopic studies (Kistler and Peterman, 1973, 1978; Kistler, 1983, 1991) had already established a correlation between geographic position and Sr isotopic ratio (i.e. the ISr = 0.706 line), the positive correlation between Sr and Pb isotopic ratios indicates that the Pb isotopic ratios must also be related in a regular way to geographic position. Simple plots of sample longitude vs. Pb (and Sr) isotopic values confirm this situation and demonstrate that the Pb isotopic data indicated a general increase in Pb isotopic ratios from west to east (fig. 5). However, the changes in orientation of the ISr = 0.706 line from northerly in western Nevada to east-northeast in northern Nevada and the loop defined in west-central Nevada and California (Kistler, 1983, 1991; Elison and others, 1990) indicate that no simple west to east geographic distribution of the Sr isotopic data exists across the full N-S extent of Nevada (fig. 2), and consequently none should be expected for the Pb isotopic data either. Another complication for the interpretation of the Pb and Sr isotopic data is that local geographic variations occur in the distribution of the ratios. In other words somewhat anomalous values, either higher or lower, with respect to the average of surrounding values are fairly common, and the occurrence of these values prevents a simple, monotonic contouring of the data. Some of the analytical reasons for these anomalies were discussed above, but the anomalies may also be geologic in origin and related to variations in the age and geochemical properties of the sources and/or magmatic interaction with upper crustal rocks. Regardless of the reason for the anomalies, it becomes simpler to examine the geographic distribution of the data sets in terms of ranges of values rather than simple monotonic contours. Figures 6 and 7 show the geographic distribution of selected ranges of $^{206}Pb/^{204}Pb$ (<18.7, 18.7-19.1, 19.1-19.3, 19.3-19.6, >19.6) and $^{208}Pb/^{204}Pb$ (<38.8, 38.8-39.0, 39.0-39.7, >39.7); geographic plots for $^{207}Pb/^{204}Pb$ are not shown because the much more limited range of these data result in poorer geographic resolution. Only two to three ranges of data are shown on each figure in order to minimize the problem of overlapping data points during plotting which obscure the geographic distribution of the data. The breaks at $^{206}Pb/^{204}Pb$ = 19.1 and $^{208}Pb/^{204}Pb$ = 38.8 were chosen from the Pb isotopic ratio vs. ISr plots to correspond generally to ISr = 0.706 (fig. 4*B*).

The geographic distribution of these Pb isotopic data intervals in the northern Great Basin indicates a subdivision of the region into three major provinces which for descriptive purposes will be referred to as western, central and eastern (fig. 8). The boundary between the western and central provinces corresponds closely, but not exactly, to the ISr = 0.706 line reflecting the selection criteria of the Pb isotopic data intervals. The observation that this boundary represents a narrow geographic zone across which Pb (and Sr) isotopic ratios change rapidly (figs. 5*A*, 6*B* and 7*B*) is confirmation that this boundary represents more than just a numerical division of the data set. This zone separates a broad region in central-western, northwestern, and central-northern Nevada (western province) where $^{206}Pb/^{204}Pb$ = 18.75-19.1, $^{208}Pb/^{204}Pb$ = 38.45-38.8, and ISr = 0.704-0.706, from a region in central Nevada (central province) where the corresponding ratios are 19.3-19.6, 39.0-39.7, and 0.707-0.710.

The boundary between the central and eastern provinces is best defined by the occurrence of samples with $^{208}Pb/^{204}Pb$ greater than 39.7. The western edge of this field of values defines a fairly sharp boundary that trends north-northwest and is approximately coincident with the Carlin trend (figs. 7*B*-8*A*). The distribution of samples with $^{206}Pb/^{204}Pb$ either greater than 19.6 or less than 18.7 suggests a similar but more poorly defined boundary (fig. 6*B*). Pb isotopic variations in the eastern province are more irregular than in the western and central provinces. Notable features are the reappearance of samples with $^{208}Pb/^{204}Pb$ less than 39.0 and $^{206}Pb/^{204}Pb$ less than 19.3. The eastern province may be divisible into northern and southern areas based on the occurrence of samples with $^{206}Pb/^{204}Pb$ either greater than 19.6 or less than 19.1 and $^{208}Pb/^{204}Pb$ less than 39.7 (figs. 6*B*-7*B*) The data do not define a sharp boundary between these two areas, but only a broad zone. Possible reasons for the irregular isotopic variations of the eastern province will be discussed below. The paucity of samples for Utah and southernmost Nevada prevent the clear extension of these three Pb isotopic provinces or the definition of province boundaries. However, a sufficient body of Pb isotopic data exists both for Precambrian and Phanerozoic rocks in southeastern California and for Precambrian rocks in western Arizona to conclude that the Proterozoic Mojave crustal province exists in this region (Wooden and Miller, 1990; Wooden and DeWitt, 1991). The Pb isotopic signature of Mesozoic and Tertiary igneous rocks in the Mojave crustal province is very similar to that observed for the eastern province in Nevada. It is an inescapable conclusion that the southward extension of the boundary between the central and eastern Pb provinces of Nevada must turn back to the west. Furthermore the boundary must remain north of the Proterozoic outcrops in the Mojave Desert and in the Death Valley region (unpublished Pb isotopic data show these to belong to the Mojave crustal province, Wooden and Calzia,

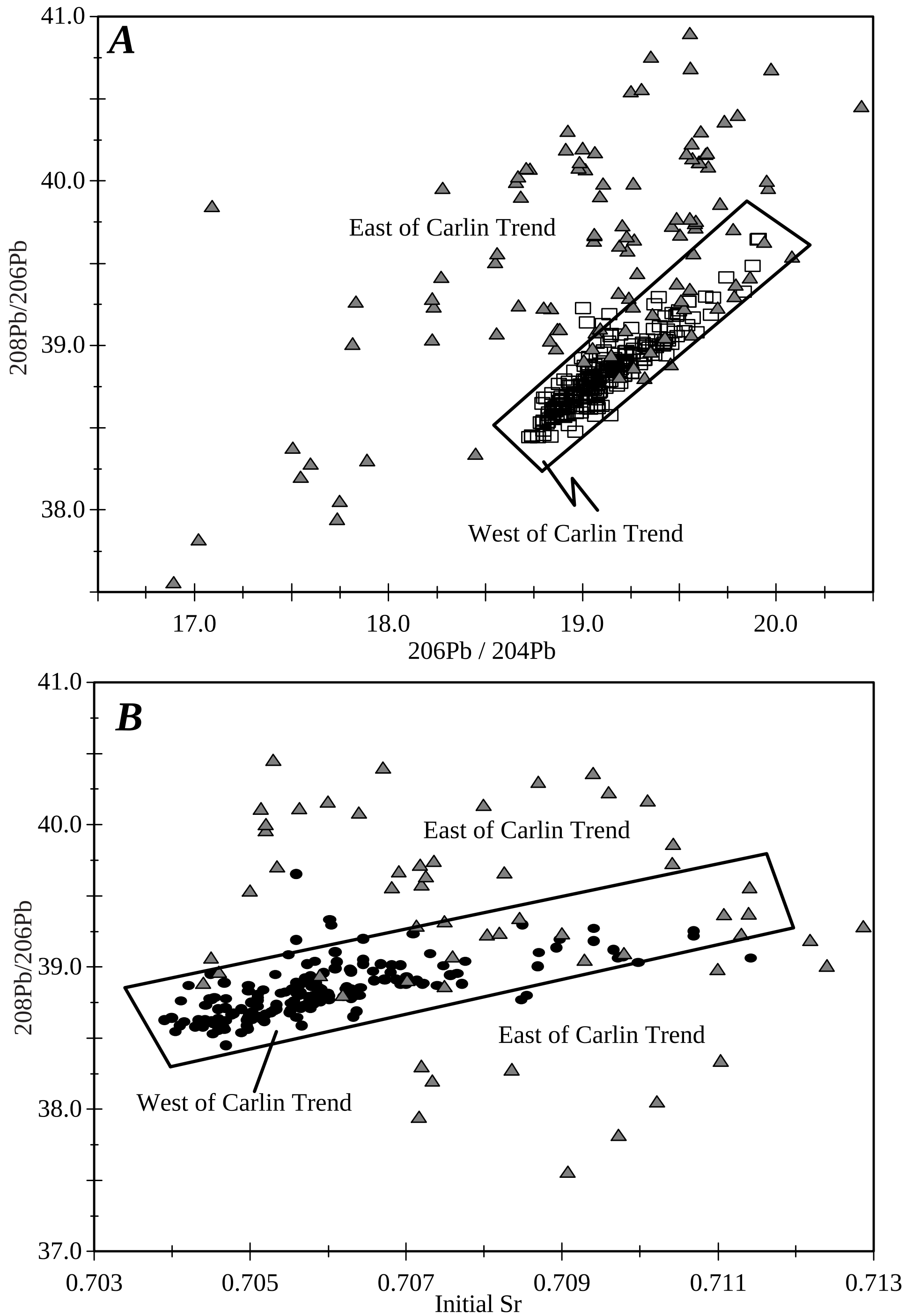

Figure 4. (***A***) Initial $^{206}Pb/^{204}Pb$ vs. initial $^{208}Pb/^{204}Pb$ for all samples. Pb isotopic compositions for samples west of the Carlin trend (open squares, within rectangular box) show a strong, tight positive correlation. Pb isotopic compositions for samples east of the Carlin trend (solid triangles) are not well correlated, and many have much higher $^{208}Pb/^{204}Pb$ relative to $^{206}Pb/^{204}Pb$ than samples west of the Carlin trend. (***B***) Initial Sr isotopic ratio vs. $^{208}Pb/^{204}Pb$ for all samples. Sr and Pb isotopic compositions for samples west of the Carlin trend show a strong positive correlation (solid circles, within rectangular box) while those from samples east of the Carlin trend (triangles) are poorly correlated and have a larger range of values.

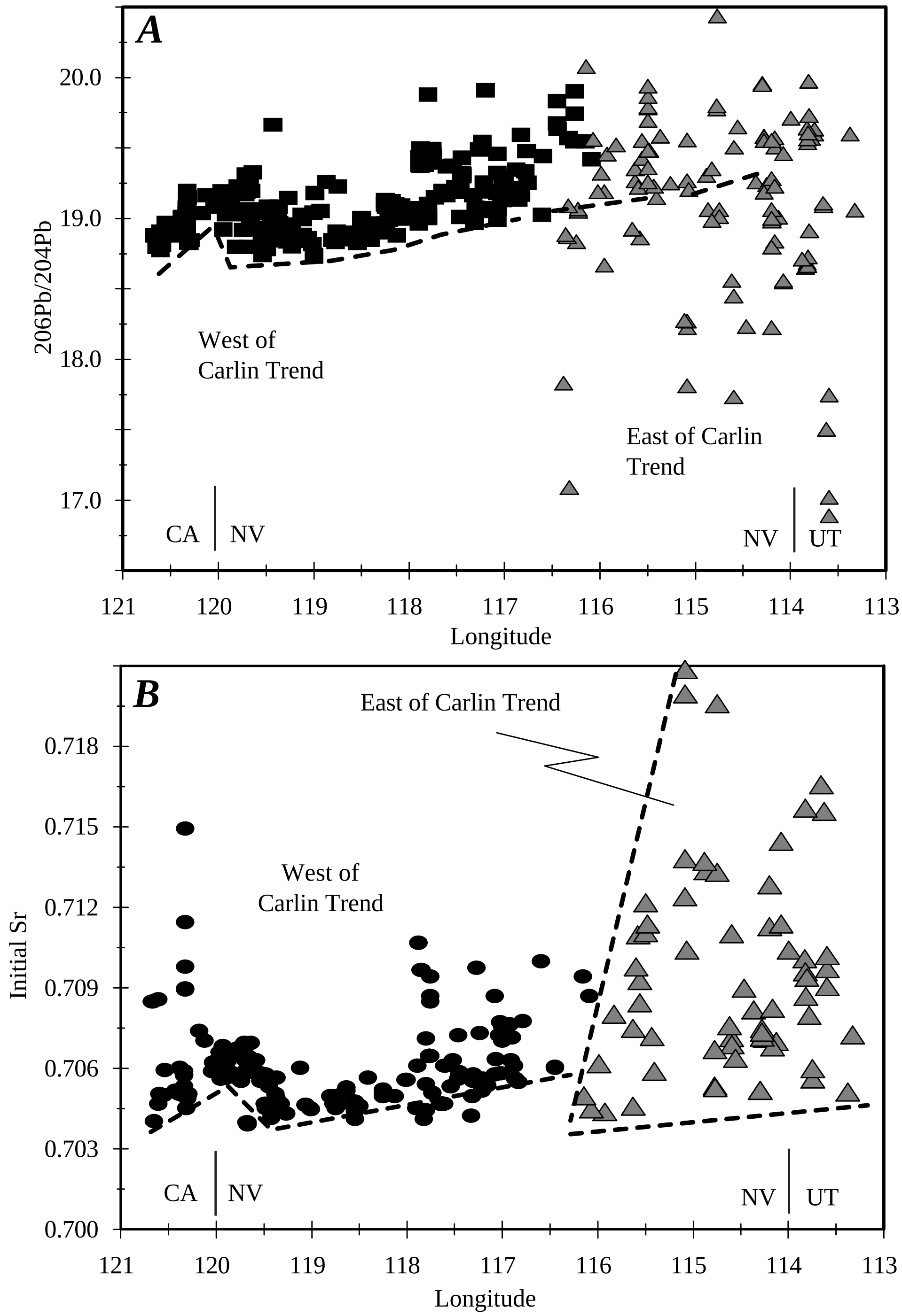

Figure 5. Variation of (***A***) initial $^{206}Pb/^{204}Pb$ Pb and (***B***) initial Sr with west longitude in degrees for all samples. Initial isotopic compositions for samples located west of the Carlin trend (solid circles) show regular variations from west to east while those east of the Carlin trend (solid triangles) range to much lower ($^{206}Pb/^{204}Pb$) and higher (initial Sr) values. These composite west to east transects indicate more apparent variation for western samples than actually exists because isotopic isopleths do not have simple north to south orientations. For example the ISr = 0.706 line and corresponding Pb isotopic values cross from 117° and 118° in central Nevada (see fig. 6-8) and then loops back to the east producing the two increasing trends in initial $^{206}Pb/^{204}Pb$ at 118 and 117 degrees longitude.

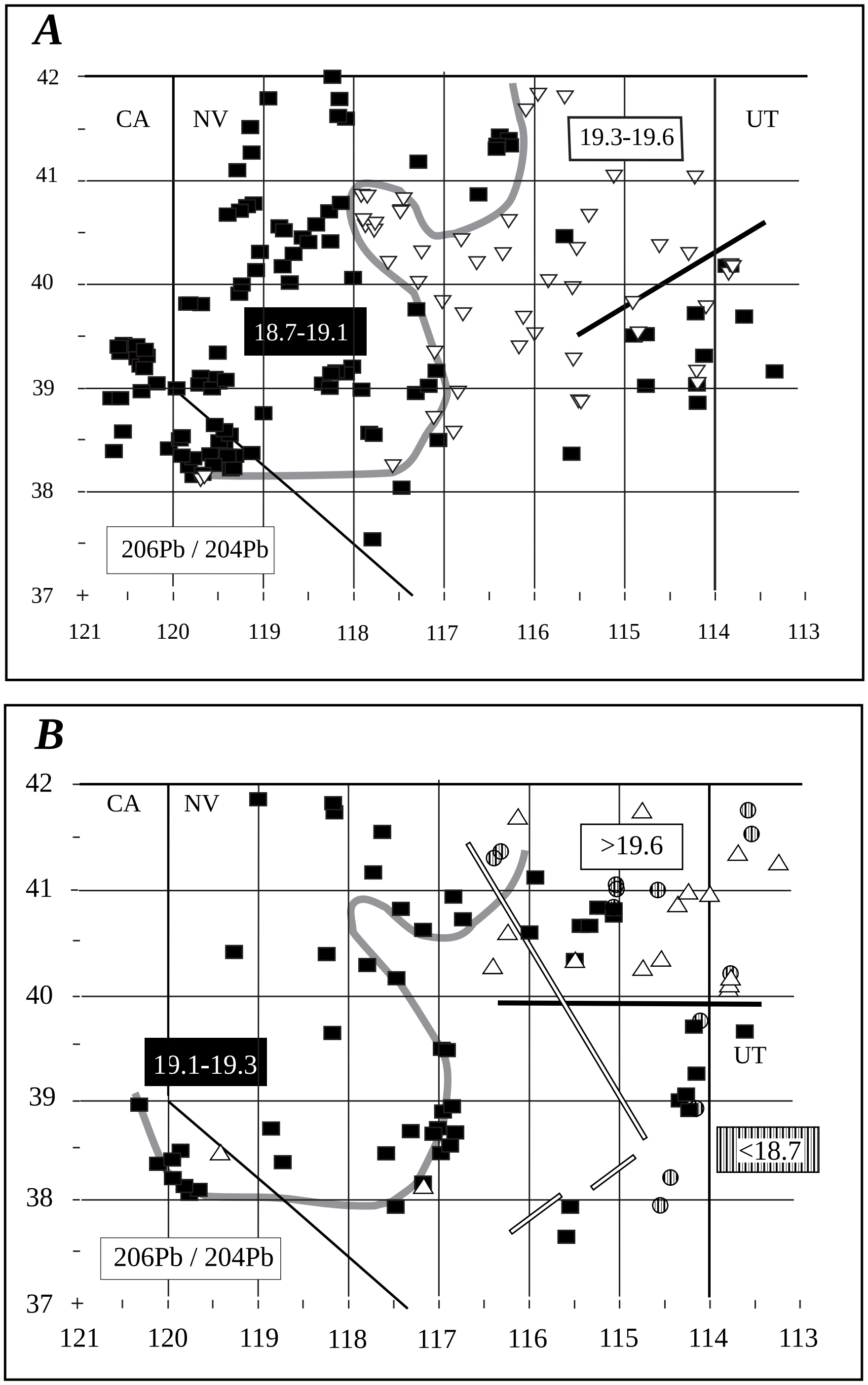

Figure 6. The geographic distribution of samples with selected ranges of initial $^{206}Pb/^{204}Pb$ in Nevada and adjoining areas of California and Utah. (***A***) Distribution of samples for only two non-overlapping ranges of $^{206}Pb/^{204}Pb$, 18.7 to 19.1 and 19.3 to 19.6. (***B***) Distribution for three ranges - less than 18.7, 19.1 to 19.3, and greater than 19.6. The ranges were plotted separately in this figure and in figure 7 to avoid visual clutter. The break at 19.1 was chosen to correspond approximately to ISr = 0.706 based on the correlation between ISr and initial $^{206}Pb/^{204}Pb$ and marks the boundary between the proposed western and central Pb isotopic provinces. The occurrence of samples with initial $^{206}Pb/^{204}Pb$ Pb less than 19.1 in eastern Nevada and Utah indicates more heterogeneous crust and may imply an age difference across the marked east to west and northeast trending lines. See text for further discussion.

1995; see Ramo and Calzia, 1996, for Nd data), and connect to the eastern portion of the transect of Chen and Tilton (1991). The southern edge of the basement gravity low of Blakely and Jachens (1991) may be related to the edge of the preserved Precambrian craton in southern Nevada. In general, the boundary between the central and eastern Pb provinces probably roughly parallels the ISr = 0.706 line and western - central Pb province boundary in Nevada until it reaches the east side of the Sierra Nevada batholith where the boundary appears to run southerly toward the Garlock fault. This boundary can be traced south of the Garlock fault through the western Mojave Desert as the western edge of the Mojave crustal province (Martin and Walker, 1992). It is possible to define provinces roughly similar to the western and central Pb provinces in Nevada there also; however, the need to restore the Tertiary tectonic disruption of this region and other geologic differences (Kistler, 1990; Miller and Glazner, 1995) make that discussion beyond the scope of this paper.

DISCUSSION AND CONCLUSIONS

Pb vs. Pb and Pb vs. Sr isotopic ratios within the western and central provinces of Nevada as defined above show strong positive correlations, increase generally west to east, have the same trends regardless of pluton age, and mimic two component mixing systems. These features are at least partially attributed to the process of averaging tens of cubic kilometers of the source region during the melting that accompanies magma production. The isotopic signature of granitoids in the western province is not entirely oceanic as compared to that of granitoids in the Klamath region of northern California (Barnes and others, 1992) and must contain a significant component derived from the continental lithosphere. The granitoid source region for the central province must have a dominant crustal component and probably represents thinned Precambrian crust and subcontinental mantle and an (underplated?) oceanic component. The Battle Mountain-Eureka mineral belt lies within the central province and roughly parallels the north-northwest-trending section of the ISr = 0.706 line (fig. 8*A*). This mineral belt lies along the east side of an area from the East Range to Battle Mountain that contains unusually radiogenic Pb and Sr isotopic compositions with respect to their geographic position (Figs. 5 and 8). The ISr = 0.706 line makes a noticeable bend around the west and north sides of this area as it turns to the east-northeast (fig. 8). These more radiogenic isotopic values are more similar to those at the eastern edge of the central province (near Carlin), and it is possible that this area has been displaced tectonically toward the west at some unknown time. The limited data set presently available indicates that less radiogenic Pb isotopic values are found immediately east of this more radiogenic area which allows for a southerly embayment in the Pb isotopic isopleths into the northern part of the Battle Mountain-Eureka mineral belt (figs. 6-8). This area of less radiogenic isotopic values is roughly coincident with the geophysical basement feature defined by Grauch and others (1995) and the northern Nevada rift of Zoback and others (1994). At the present time, however, it is not possible to correlate an isotopic feature with the south-southeastward extension of the Battle Mountain - Eureka mineral belt. This trend may simply represent the reactivation an old major crustal fault largely within the region of a thinned continental crust.

These well-organized isotopic trends end abruptly along the north-northwest-trending boundary that marks the western edge of the eastern province and approximates the position of the Carlin trend. East of this boundary, the sharpness of which suggests a major crustal fault or suture, most samples exhibit high to very high $^{208}Pb/^{204}Pb$ (and many have high $^{207}Pb/^{204}Pb$) relative to $^{206}Pb/^{204}Pb$, the range of Pb and Sr isotopic ratios expands greatly, and isotopic ratios show no simple correlation trends (figs. 4, 5, and 9). Farmer and DePaolo (1983) defined a Nd isotopic boundary based on the occurrence of granitoids with very low epsilon Nd values in this general location. The eastern province represents Precambrian crust (and subcontinental mantle?) that has experienced the least amount of modification by Late Precambrian and Phanerozoic events. As noted above, and by Wright and Wooden (1991), this province can be divided on the basis of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios into northern and southern regions along a broad east-northeasterly trending belt. The distinction between northern and southern regions is particularly sharp in the isotopic data for Tertiary igneous rocks, which can show significant differences from the isotopic data of Jurassic rocks in the same area. The characteristics of the isotopic data (fig. 9) suggest that the northern region represents the Archean Wyoming province and the southern region an Early Proterozoic province most similar to the Mojave crustal province of Wooden and Miller (1990). Wright and Snoke (1993) suggest that in the Ruby Mountains and East Humboldt Range this east-northeast-trending boundary is a relatively sharp feature that represents the continuation of the Cheyenne belt into northeast Nevada. The Nd isotopic study of the Cheyenne belt in southern Wyoming by Ball and Farmer (1991) also suggested a relatively sharp boundary that may have resulted in large part from erosion of overthrust crust. The regional isotopic data in eastern Nevada can also be modeled, however, as a broad zone of crustal mixing probably established by a combination of tectonic, magmatic, and sedimentary processes during the juxtaposition of these terranes in the Early Proterozoic and, as such, would be similar to the boundary zone between the Mojave and Arizona crustal provinces (Wooden and DeWitt, 1991). This model is preferred.

The west to east sequence of isotopic provinces across Nevada is a unique feature in the western U.S., and possibly

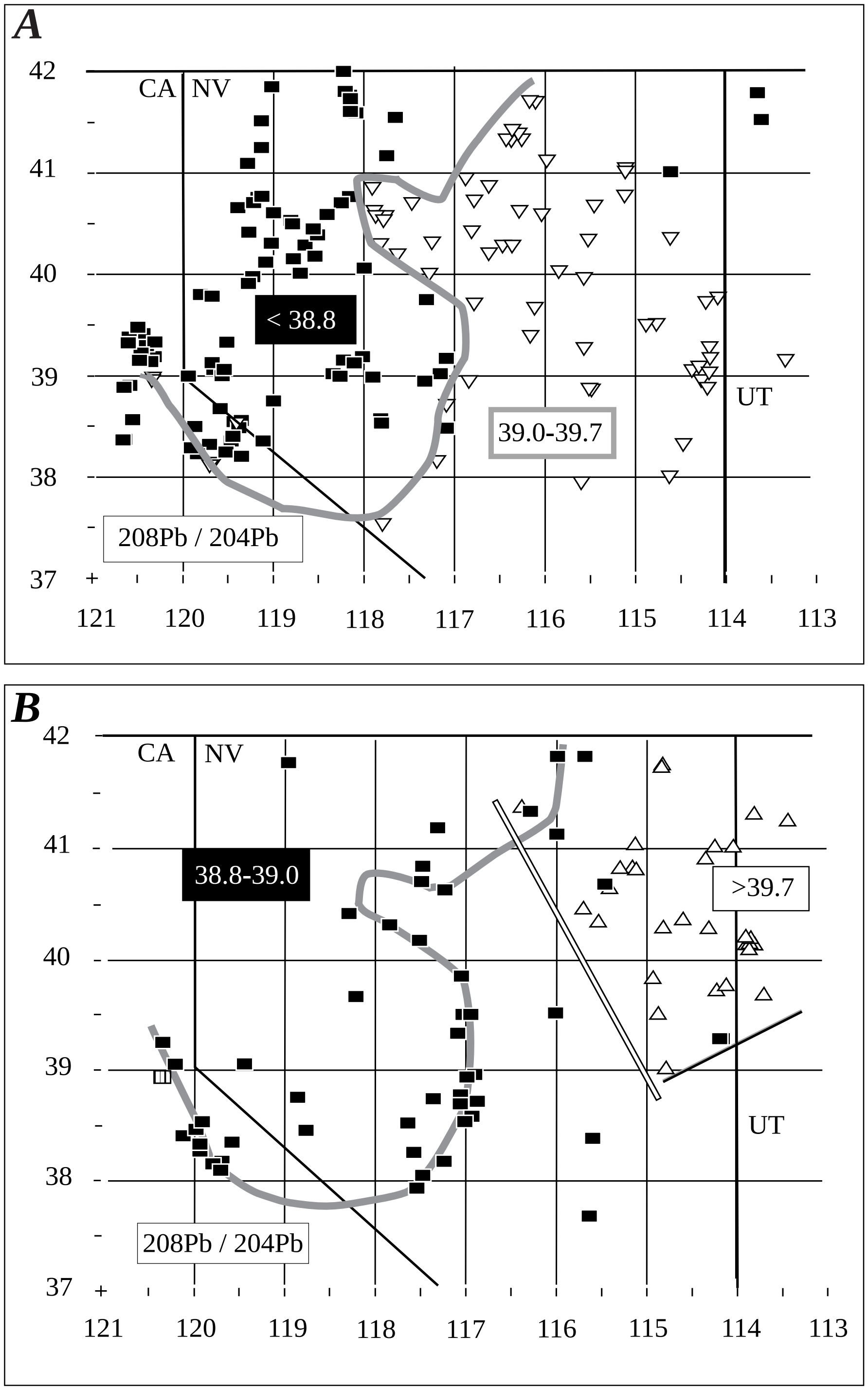

Figure 7. The geographic distribution of samples with selected ranges of initial $^{208}Pb/^{204}Pb$ in Nevada and adjoining areas of California and Utah. (***A***) Distribution of samples for two, non-overlapping ranges of initial $^{208}Pb/^{204}Pb$, less than 38.8 and 39.0 to 39.7. (***B***) Distribution for the ranges 38.8 to 39.0 and greater than 39.7. The break at 38.8 was chosen to correspond to an ISr of 0.706 and represents the boundary between the proposed western and central Pb isotopic provinces. Note the concentration of samples with $^{208}Pb/^{204}Pb$ between 38.8 and 39.0 along the western-central province boundary. The western edge of the distribution of samples with $^{208}Pb/^{204}Pb$ greater than 39.7 is proposed to mark the boundary between the central and eastern provinces. The southern extent of this range may also denote a crustal age difference in the eastern province. See text for further discussion.

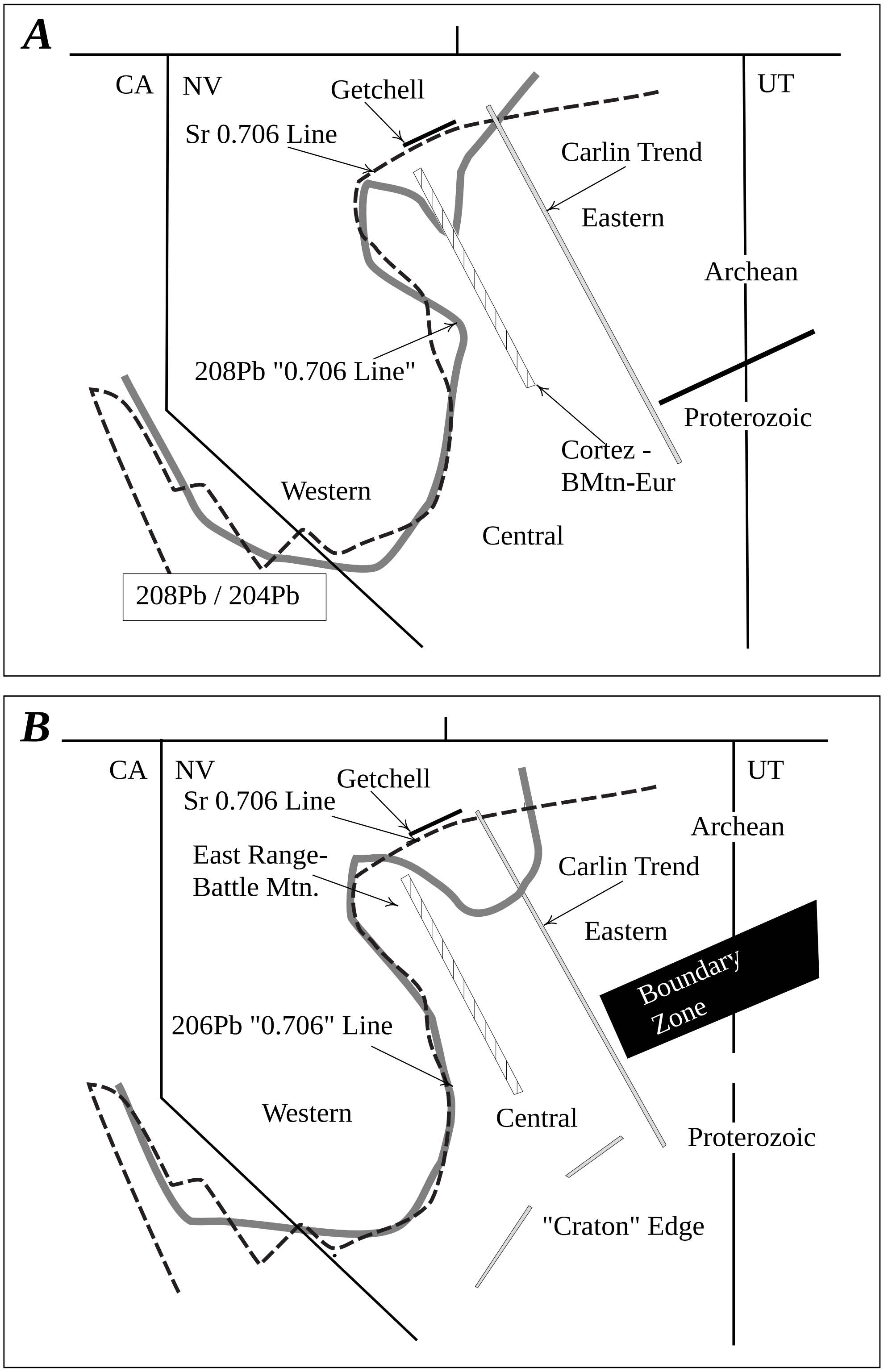

Figure 8. Summary maps of the boundaries and regions defined by (***A***) initial $^{208}Pb/^{204}Pb$ and (***B***) initial $^{206}Pb/^{204}Pb$ for Nevada and adjoining parts of California and Utah and a comparison to the ISr = 0.706 line and to Carlin, Battle Mountain-Eureka, and Getchell mineral trends. Note the difference in north-central Nevada between the ISr = 0.706 line and the lines defined by the Pb isotopic data. The break between Archean and Proterozoic crust in the eastern province is not clearly defined and probably is indicative of a gradational boundary.

in western North America. Although isotopic patterns similar to parts of what is present in Nevada can be observed elsewhere (e.g. the northern Peninsular Range is similar to the western and part of the central province), there appears to be nowhere else that the complete transition is preserved. Given the tectonic history of western North America in the Phanerozoic, particularly the north-south movement by strike-slip faults along the continental edge, it is not surprising that the character of a continental margin created in the Late Precambrian would be greatly disrupted. It is also unclear if the Late Precambrian continental margin would have experienced the exact same processes along the entire rifted margin. The general preservation of the isotopic zoning in Nevada since the Late Precambrian does, however, place constraints on the relative displacements of crust and mantle in the Phanerozoic. Although the continental margin in Nevada has experienced several shorting events, none of them could have been so severe as to greatly displace the regular pattern of isotopic zoning. Therefore a model calling for over a hundred kilometers of eastward thrusting as suggested by Wright and Wooden (1991) seems unlikely, and the contrast in the isotopic signatures between Jurassic and Tertiary intrusions in the eastern Pb province, that stimulated this model, is probably more related to differences in the depth of melting in the same crust-mantle system than to lateral movements of the upper crust. Similar arguments also hold for the Tertiary extensional events that produced the modern geomorphic pattern of the northern Great Basin. In spite of the variable geographic distribution of this extension, the zoning patterns have been preserved perhaps in part because the extension is mostly normal or parallel to the strike of the isotopic provinces and breaks the crust into discrete extensional domains of smaller scale than that proposed for thrusting events.

The most significant Pb isotopic boundary identified in

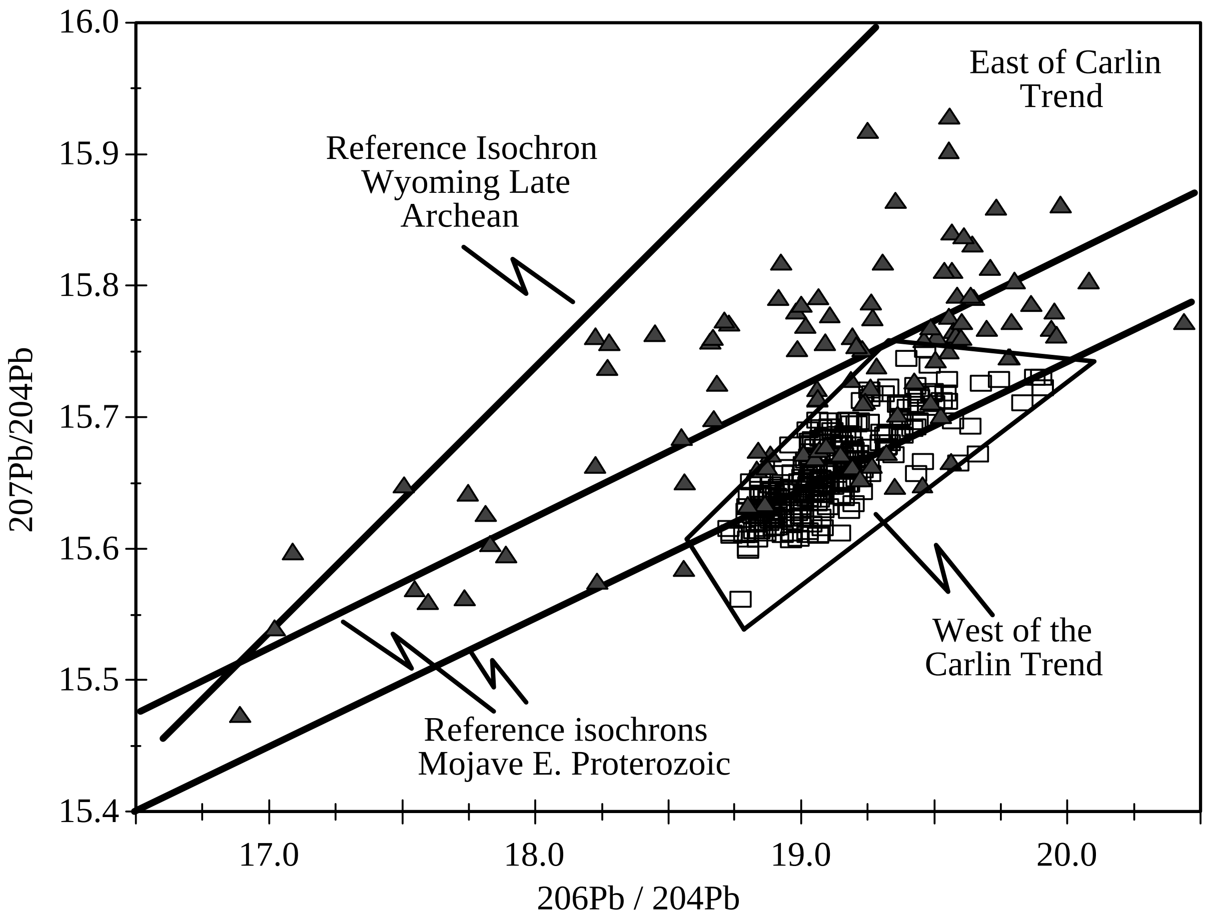

Figure 9. $^{206}Pb/^{204}Pb$ vs. initial $^{207}Pb/^{204}Pb$ on a Pb isochron diagram for all samples in this study. Samples located west of the Carlin trend (open squares) define a relatively small field compared to those east of the Carlin trend (solid triangles). References isochrons are shown for the Early Proterozoic Mojave crustal province (two parallel lines) and the Late Archean rocks of the Wyoming Province (steeper single line) and encompass most of the eastern samples. See text for additional discussion.

this study lies between the eastern and central provinces; this boundary corresponds in location and orientation to the Carlin trend. The Battle Mountain-Eureka or Cortez mineral belt shares the orientation of this boundary but is not distinguished by isotopic data. The north-trending part of the boundary between the western and central provinces that matches in location this part of the ISr = 0.706 line shares the same general north-northwest trend as the two mineral belts. The Pb province boundaries and the ISr = 0.706 line indicate the presence of major crustal-scale features. The common orientation of the Battle Mountain - Eureka mineral belt suggests that its location may have resulted from the same process that formed the other two crustal-scale features. Our interpretation of these crustal-scale features is that most resemble a regional fault system and/or sutures. Interestingly published gravity data (Grauch and others, 1995) are most supportive of this conclusion for the Battle Mountain-Eureka mineral belt, which the isotopic data do not distinguish as a major crustal boundary. These gravity data, however, are at least suggestive that the Carlin trend may also represent a geophysical discontinuity. The combination of north-northwest-trending crustal boundaries and their high angle of intersection with the east-northeast trend of the ISr = 0.706 line and stratigraphic trends in north-central and northeastern Nevada suggests a model in which major northwest-striking normal fault systems developed to accommodate an extending and thinning continental margin during Late Proterozoic rifting of the western margin of North America. Phanerozoic reactivation of these fault systems has focused younger tectonic, magmatic, hydrothermal and mineralization events, and possibly influenced even the orientations of the modern basins and ranges.

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