CHAPTER 6

CENOZOIC MINERAL DEPOSITS AND CENOZOIC IGNEOUS ROCKS OF NEVADA

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ABSTRACT

Tertiary igneous rocks in Nevada are of two fundamentally different petrochemical types that are the result of two regional tectonic regimes active in western North America during the latter half of the Cenozoic. Many hydrothermal mineral deposits in Nevada clearly reflect these two tectonic regimes and their associated igneous activity. The older petrochemical igneous type is of late Eocene through Oligocene age, is intermediate calc-alkalic in chemistry, and is related to subduction of the Pacific (Farallon) plate beneath the continental North American plate. Magma generated by subduction of the Farallon plate produced skarn and distal disseminated mineral deposits in eastern and central Nevada such as Copper Canyon, McCoy, and Mineral Hill. This regional event is probably of most importance because heat from it produced hydrothermal systems throughout central Nevada that may be responsible for many mineral deposits including some disseminated precious metal deposits in the region. Magmas related to subduction in western Nevada are latest Oligocene and early Miocene in age and were derived from the stagnant Farallon plate that was no longer subducting beneath North America by this time. These magmas passed through the highly fractured Walker Lane region in western Nevada and produced widespread and pervasive alteration and the bonanza precious metal deposits in western Nevada at Aurora, Goldfield, Tonopah, and Comstock.

The younger igneous type is of middle Miocene and younger age, is of basaltic or bimodal basalt-high-silica rhyolite composition, and is related to extension of the Great Basin by basin and range (horst and graben) faulting. In north-central, northwestern, and southwestern Nevada epithermal precious-metal and mercury deposits are related to this middle and late Miocene bimodal magmatism. Some deposits formed in this tectonic-magmatic environment include the McDermitt mercury, and the Sleeper, Seven Troughs, and Hog Ranch gold deposits in northwest Nevada; the Mule Canyon and Buckhorn gold deposits in north-central Nevada, and the Bullfrog gold district in the southwestern part of the state.

INTRODUCTION

Magmatism during Cenozoic time in Nevada is represented primarily by volcanic rocks; only small exposures of granitic rocks are present at the present level of erosion. These volcanic rocks represent two fundamentally different chemical suites caused by two different regional tectonic environments that existed in western North America during the latter half of the Cenozoic. One suite which includes the older rocks (mostly late Eocene, Oligocene, and early and middle Miocene in age), is related to northwestward-directed subduction of the oceanic Farallon plate beneath the continental North American plate along the western coast of North America; the second suite is related to volcanism associated with regional extension and rifting during the latter part of the Cenozoic (middle Miocene to Holocene).

Tertiary Igneous Geology

Nevada is fundamentally an ash-flow region and is part of a larger Great Basin ash-flow province. Most igneous rocks in this ash-flow province are classified as calc-alkaline intermediate types (Noble, 1972) and called the interior andesite-rhyolite assemblage by Cox and others (1990) and by Ludington and others (chapter 5 in this report). The total volume of ash flows (mostly welded tuffs) far exceeds that of lava flows and shallow intrusive rocks, especially during Oligocene time when the prevalence of tuff over lava was particularly great. Both tuffs and lavas that erupted in Nevada during subduction along the North American margin were unusually potassium-rich; they became more sodic during the middle and late Miocene as subduction was replaced by transform motion between the Farallon and North American plates on the San Andreas fault along the western edge of the North American continent.

The younger group of igneous rocks includes more mafic rocks and consists of extensive basalt and high-silica rhyolite. These rocks crop out over large parts of northern and western Nevada (plate 6-1). Associated with this bimodal basalt-rhyolite suite are many peralkaline lavas and ash-flow tuffs.

The regional space-time-composition pattern of the Cenozoic igneous rocks in Nevada has been described by a number of authors during the past 25 years (for a list of references, see Best and others, 1989). Starting about 43 Ma, volcanism swept southwestward across the Great Basin reaching the northeastern part of Nevada at about 42 Ma (fig. 6-1). This sweep slowed and stagnated from about 33 to 19 Ma south of 38.5°N latitude. At about 16 Ma, volcanic activity increased in western and northern Nevada associated with a new tectonic regime related to basin and range rifting, which produced a different petrochemical suite from a different source (McKee, 1971)(fig. 6-2). Thus, there are two primary factors controlling distribution and chemical characteristics of Nevada Cenozoic volcanic rocks. One is a migration of the loci of igneous activity from northeast to southwest (fig. 6-1); and the other is a composition-time correlation defined by an older calc-alkalic, rhyolite-dacite-andesite-suite which consists mostly of ash-flow tuffs and a young bimodal basalt-rhyolite suite of

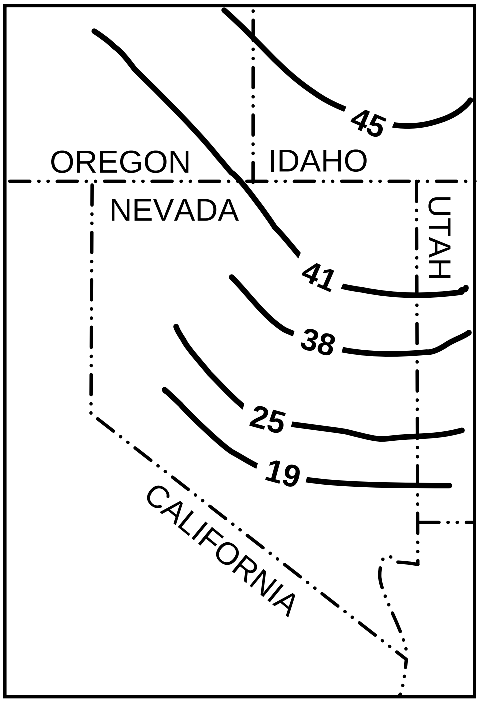

Figure 6-1. Migration of subduction-related intermediate calc-alkalic igneous activity southwest across the Great Basin in Cenozoic time. Lines are isochrons and number is the age of the isochron (in Ma). Modified from Best and others (1989).

lava flows, ash-flow tuffs, and flow-domes (fig. 6-2). The later calc-alkalic igneous activity related to the subducted, but stagnant, Farallon plate, and the first bimodal basalt-rhyolite rocks were emplaced simultaneously in middle Miocene time in western and, locally, in northern Nevada.

The parts of Nevada now blanketed by middle Cenozoic volcanic rocks were almost everywhere an erosion surface of subdued relief developed on Paleozoic and Mesozoic rocks. Only locally are prevolcanic alluvial fan or lacustrine deposits found above this profound unconformity (fig. 6-3). The most widespread units are the mostly clastic Upper Cretaceous(?) to Oligocene Sheep Pass Formation that crops out over an area of about 4,000 km^2 in east-central Nevada and the Elko Formation in the NE part of the state that is here considered to be Eocene and possibly Oligocene in age. Tertiary sedimentary rocks are not only locally beneath the volcanic deposits, but they are only a minor component within the volcanic sequence before about 17 Ma (fig. 6-3). After about 17 Ma, sedimentary rocks became markedly more abundant as sediments accumulated in the newly developed grabens formed at the beginning of basin and range extension. An exception to this generalization is in east-central Nevada where parts of the Egan, Shell Creek, and Snake Ranges contain thick sequences of conglomeratic to fine-grained strata both at the base of the Cenozoic sequence and interbedded within it (Gans and others, 1989). Water-laid tuffaceous rocks are present locally, but in many ranges the entire Tertiary sequence consists only of ash-flow sheets and associated air fall deposits (Best and Christiansen, 1991)

Lava flows. Cenozoic lavas are widely scattered throughout Nevada, but, for the most part, they appear to have been erupted in relatively small volumes as isolated domes or flows or as sequences of rocks no more than several hundred meters thick. Local exceptions include large volumes of lava in some parts of east-central Nevada (Gans and others, 1989) and a 2- to 3-km-thick sequence of dacitic lavas in the Stillwater Range of west-central Nevada (John and McKee, 1991). Lava flows comprise about 10% of the silicic volcanic rocks in Nevada. The lavas range widely in composition. Most of the older flows are calc-alkalic andesite or dacite; most of the younger flows are basalt or high-silica rhyolite, except in western Nevada where thick piles of andesitic flows occur in many places such as the Carson, Virginia, and Pine Nut Ranges south of Reno. Basaltic rocks older than about 18 Ma are almost completely absent (fig. 6-2).

Ash-flow tuffs. Cenozoic volcanic rocks in Nevada are dominantly silicic ash-flow tuffs. Several tens of thousands of cubic kilometers of pyroclastic material represented by more than one hundred ash-flow sheets was erupted mostly during late Oligocene and early Miocene time from more than fifty volcanoes most of which collapsed to form calderas (Best and others, 1989). Within single mountain ranges, as many as 20 ash-flow cooling units can reach cumulative thicknesses of as much as 2 km. Air fall ash deposits probably constitute no more than 1% of the total volume of pyroclastic material. All of the zonal variations in ash-flow deposits described by Smith (1960) have been recognized in the Nevada ash-flow sheets. Most ash-flow sheets have volumes greater than 100 km^3 and many exceed 1,000 km^3. The more crystal-rich tuffs tend to be thicker and less widespread than the crystal-poor ash-flow sheets that are relatively thin, but extremely widespread. The widespread distribution of relatively thin ash-flow sheets indicates that much less topographic relief existed at the time of their eruption than exists today. The topography was clearly not like that of the present-day Basin and Range province.

SPACE-TIME PATTERNS

The southwestward sweep of calc-alkaline volcanism from northeastern Washington-western Montana to southwestern Nevada in Paleocene through middle Miocene time (fig. 6-1) has been documented by numerous geologic studies that include detailed mapping and regional mapping supported by hundreds of radiometric age determinations. The part of this sweep that crosses Nevada includes rocks of latest Eocene to middle Miocene age. Across about half of Nevada, the southwestward progression of the inception of volcanism was at a uniform rate, and it can be tracked with good reliability in time increments as short as 3 to 4 million years isochrons as closely spaced as 3 million years can be drawn. The

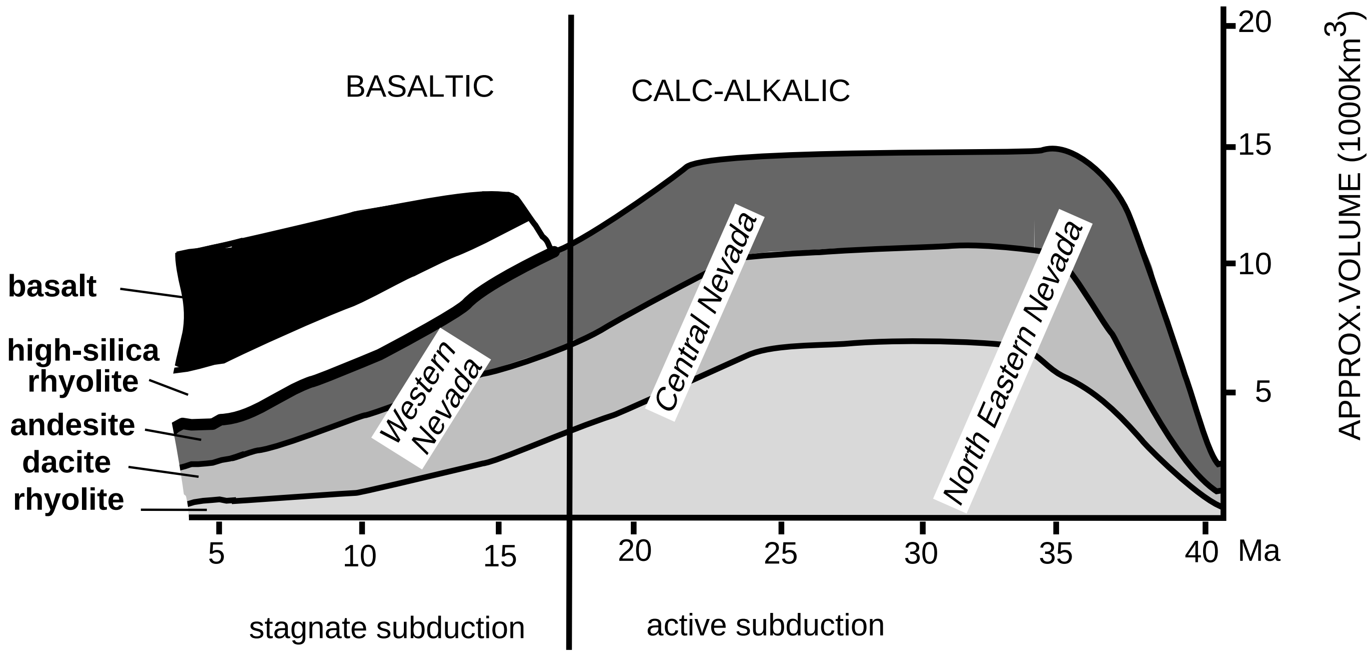

Figure 6-2. Age spectra and approximate volume of Cenozoic igneous rocks in the Great Basin. Rocks older than about 19 Ma are related to subduction of the Farallon plate.

southward progression decelerated as it moved southward, and by the time it reached south-central Nevada south of 38.5° latitude, it had decelerated to the point of near stagnation. At this latitude, there is an enormous accumulation of volcanic rocks, mostly ash-flow tuff sheets, that range in age from about 33 to 18 Ma. Volcanic rocks, as young as early Miocene in age are deposited on Oligocene rocks, and it is not possible to draw isochrons across this region. In western Nevada, thick sequences of andesitic and dacitic lavas, referred to as the western andesite assemblage by Cox and others (1990) and by Ludington and others (chapter 5), accumulated after 20 Ma and the southwest migration appears to have progressed westward, eventually to become the southern part of the Cascade arc (Noble, 1972).

In southern Nevada south of 38.5°N latitude, volcanism represents the final stages of generally northerly migrating igneous activity that started in the southern part of the Basin and Range province. The volcanic rocks of southern Nevada are not part of the middle Cenozoic southwesterly sweeping sequence of Great Basin igneous activity, but they are instead related to the regional igneous systems that produced lavas and tuffs and in western Arizona and the Mojave Desert region of California. These rocks are included in the western andesite assemblage by Cox and others (1990) and by Ludington and others (chapter 5).

Northern Nevada and regions to the north in Oregon, Idaho, and south-central Washington are characterized by widespread flows of basalt and interspersed rhyolite domes, flows, and ash deposits generally 17 Ma or younger in age (figs. 6-2 and 6-4). These middle and late Miocene volcanic rocks overlie ash-flow tuffs, lavas, and tuffaceous sedimentary rocks that represent the northwest extension of the southwesterly sweeping volcanism that moved diagonally across the Great Basin.

TIME-COMPOSITION PATTERNS

Associated with the southwestward volcanic migration across the entire Great Basin during middle and late Cenozoic time, and with emplacement of overlapping lavas in the northern Great Basin, are province-wide, time-composition patterns.

The fundamental compositional pattern is two-fold and is expressed by rock chemistry and eruptive type (lava flow or ash-flow). The older suite of rocks, those emplaced during the southwestward sweep are calc-alkalic in character and are comprised mostly of ash-flow tuff eruptions of rhyolite to dacite composition (fig. 6-2). The younger suite, found mostly in northern Nevada and Oregon and to lesser extent in western Nevada, is basaltic or bimodal basalt-rhyolite and erupted as lava flows and ash flows (figs. 6-2 and 6-4). These two very different groups of rocks are related to two different tectonic settings. Most materials of the older suite of rocks are the products of subduction-related volcanism that took place as the North American continental plate rode over a subducting oceanic (Farallon plate). In places in east-central Nevada, a sizable volume of Oligocene dacitic rocks appears to contain as much as 50% mantle material that was added to the crust by asthenospheric upwelling (Gans and others, 1989). The rocks of the younger group are

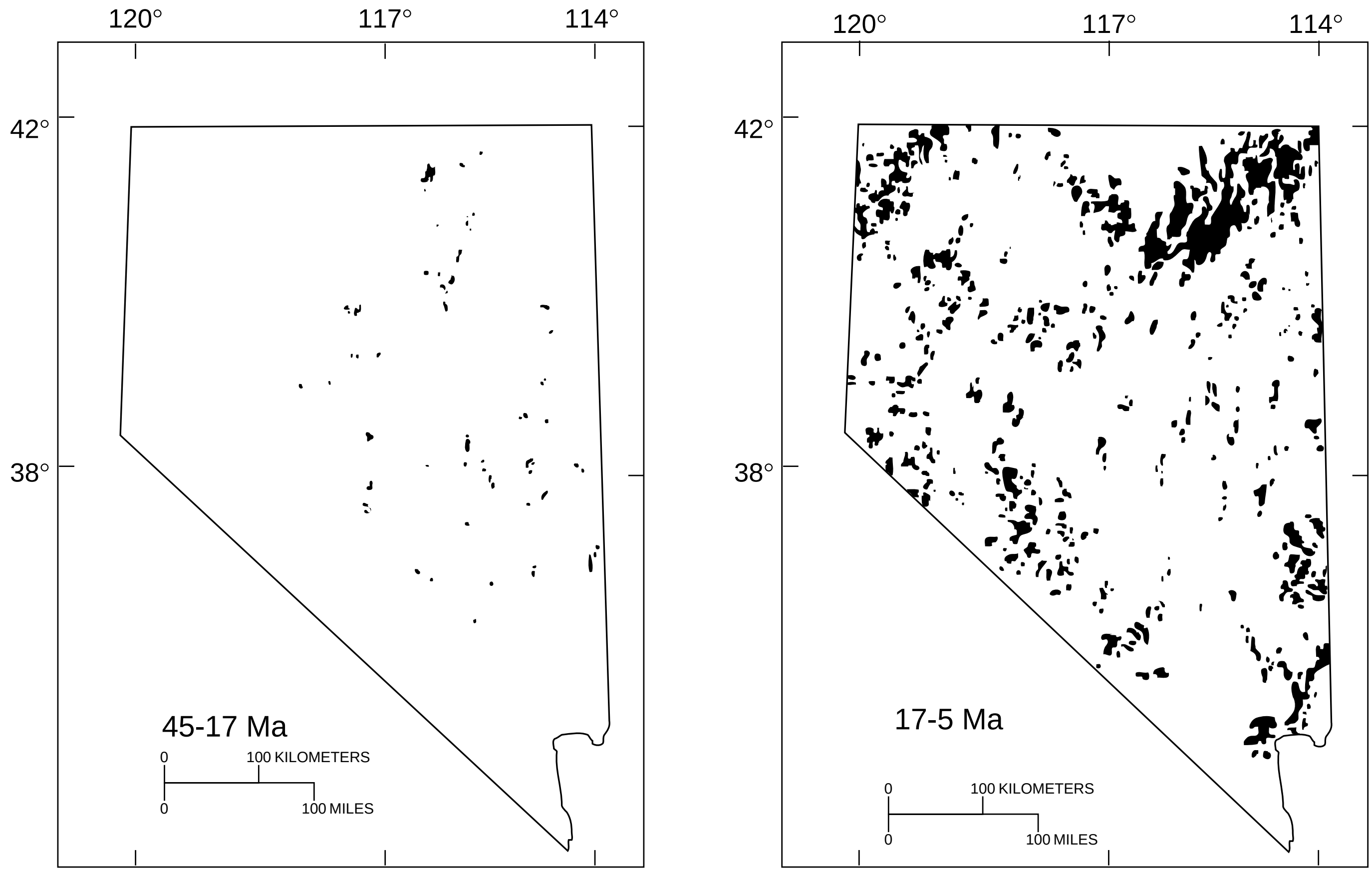

Figure 6-3. Sedimentary rocks of Cenozoic age in Nevada. These rocks lie on a regional erosion surface cut across Mesozoic and older rocks.

mantle derived, non-subduction-related basalts typical of a rift environment of which the Nevada part of the Basin and Range province is a good example.

Eocene to Late Miocene Time-transgressive Calc-alkalic Volcanism

Associated with the time-transgressive volcanism are very widespread time-composition groups of ash-flow sheets. During relatively short intervals within the continuous late Eocene to late Miocene southwestward sweep of volcanism, ash flows of similar and unique composition were erupted from numerous, widely spaced sites. They represent contemporaneous igneous types that formed from eruption of magma that developed at similar stages of crystallization. Many individual ash-flow sheets within this short age interval are so similar in their petrochemical and petrologic features that they are nearly impossible to distinguish from one another by standard petrologic and chemical techniques, yet they may be separated by hundreds of kilometers and could not have come from the same magma chamber. Probably the best example in Nevada is the late Oligocene and/or early Miocene Bates Mountain Tuff which is widespread in the center of the state and the age-equivalent Nine Hill Tuff found on the western edge of the state, about 150 km west of the westernmost outcrops of the Bates Mountain Tuff (Best and others, 1989).

In Nevada, most ash-flow tuffs can be assigned to one of five time-dependent groups based upon bulk chemical composition and on type and proposition of phenocrysts (Best and others, 1989). Four of these time-dependent compositional types are particularly widespread. The oldest is represented by voluminous and relatively thick, crystal-rich, rhyolite ash-flow sheets. These sheets range in age from about 38 to 31 Ma and are present in nearly every mountain range in central and eastern Nevada (plate 6-1). Typically, they contain 40 to 50 volume percent phenocrysts of quartz, sanidine, plagioclase, and biotite, and they tend to form massive outcrops of light-colored tuff. The next oldest tuff group is represented by very large-volume, crystal-rich, dacite ash-flow sheets. They were emplaced between about 31 and 26 Ma and account for about 25% of the total volume of ash flow in Nevada. One of the best representatives of this latter group of welded tuffs is the Monotony Tuff of southeastern Nevada probably the most voluminous ash-flow sheet in the state. Between about 30 and 25 Ma, a third

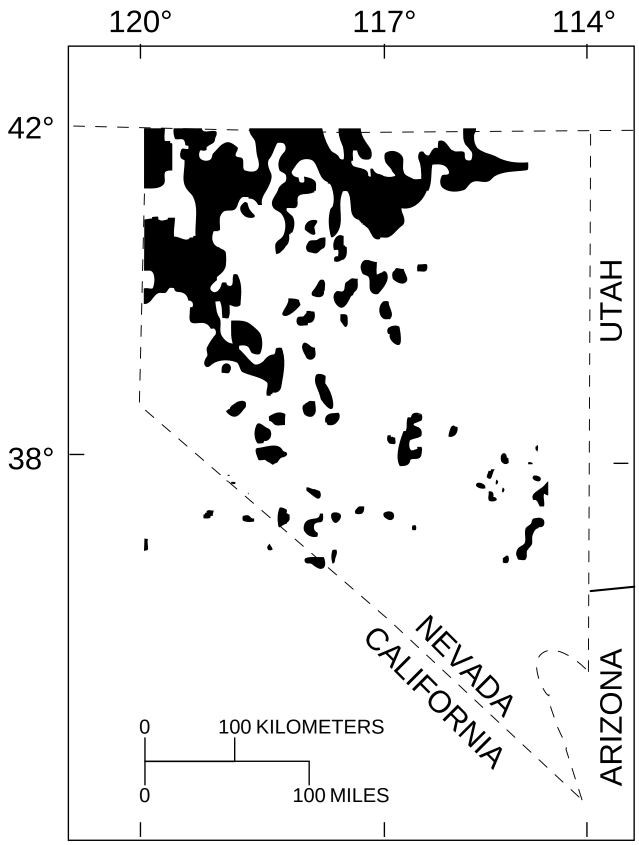

Figure 6-4. Basaltic rocks of Cenozoic age in Nevada and adjacent parts of California, Oregon, Idaho, Utah, and Arizona. These basaltic rocks are all less than about 17 Ma in age (see fig. 6-2).

group of different and distinctive ash-flow sheets were emplaced mostly in central and eastern Nevada. These tuffs are noticeable darker and more mafic than tuffs from any of the other groups. They are alkali-trachytes containing 15-20 volume percent phenocrysts of plagioclase, amphibole, biotite, pyroxene, magnetite, and a small amount of quartz and sanidine. They generally are present as relatively thin, densely welded sheets of medium to large volume. Tuffs representative of this group include the Needles Range Formation (or locally Group) of eastern Nevada, the Isom Formation of southeastern Nevada, and many informally named trachyte tuffs in central Nevada. The youngest group of ash-flow sheets mostly less than 25 Ma in age, form probably the most widespread but not the most voluminous ash-flow deposits in Nevada. These are crystal-poor rhyolite tuffs containing less than 15 volume percent phenocrysts of quartz, and some plagioclase, biotite and rarely fayalite. They are typically thin (less than 150 m thick), very densely welded, and locally have textural evidence of secondary fluid flowage (as opposed to primary turbid ash flow). The Bates Mountain Tuff of central Nevada, the Bauers Tuff Member (of the Condor Canyon Formation) of southeastern Nevada and western Utah, and the Nine Hill Tuff of western Nevada and eastern California are examples of tuffs in the group.

Lavas in Nevada clearly reflect time-related petrochemical suites. The oldest lava flows, those between late Eocene and early Miocene in age, are small-volume calc-alkalic andesites, dacites and rarely low-silica rhyolites. These are from local centers and spread for a few kilometers beyond their vents in contrast to the large-volume, widespread ash-flow sheets erupted contemporaneously. Locally, rhyolite flow-dome complexes mark the site of deeply eroded calderas whose physiographic features are now mostly gone.

Middle to Late Miocene and Pliocene Bimodal Volcanism

In middle and late Miocene time, basalt lava flows became the major eruptive type in northern and northwestern Nevada (fig. 6-4). Associated with the basalts are lava flows, ash flows and domes of high-silica rhyolite, many of which are peralkaline. The basalts are tholeiitic and are characterized by high-Al content, high concentration of Ba, low K, Rb, and Cs, and a high K/Rb ratio. Their $^{87}Sr/^{86}Sr$ values are between 0.7035 and 0.7045 (McKee and others, 1983). The rhyolites have a $^{87}Sr/^{86}Sr$ ratio that is within the range of the basalts and is too low to have been generated by partial melting of pre-Cenozoic silica crust (Noble and others, 1973). The rhyolites must have been produced by fractional crystallization of tholeiitic, low-K basalt magma which most likely originated in the upper mantle.

In the western part of Nevada, andesite lava flows similar to the older flows in the central and eastern parts of the state were emplaced at the same time as the basalts, but did not originate from the same magma chambers or magma sources. Those andesites, part of the western andesite assemblage of Cox and others (1990), are not intermediate differentiates from the mantle-derived basalt, but probably represent magmas related to the subducted but stagnant oceanic Farallon plate. Thus, two different sources creating two different suites of igneous rocks were active simultaneously in western Nevada during the last 17 million years.

CALDERAS

Catastrophic explosive eruption of large volumes of pyroclastic material from a magma chamber high in the crust creates a mass deficiency sufficient to cause collapse of the roof. The resulting caldera is more or less centrally located within the areal distribution of the erupted ash-flow sheet. Recognition of calderas in Nevada older than a few million years is difficult because they are relatively near-surface features with physiographic elements that are of smaller magnitude than the basin and range faulting that dissects them. In addition, roughly half of Nevada is covered by alluvium in the basins of the Basin and Range province (chapter 9). The calderas that have been documented (fig. 6-5) consist of dismembered parts of the volcanic system, mostly internal structures such as domes, collapse breccias, small amounts of intracaldera sedimentary rocks, and very thick and massive prisms of intracaldera welded tuff. This latter rock type is the sole evidence for the presence of an underlying caldera in many cases if the intracaldera welded tuff can be demonstrated to be part of one or more widespread ash-flow sheets. In general, calderas or the remains of caldera systems are found by careful study of the distribution of outflow sheets leading back to volcanic piles

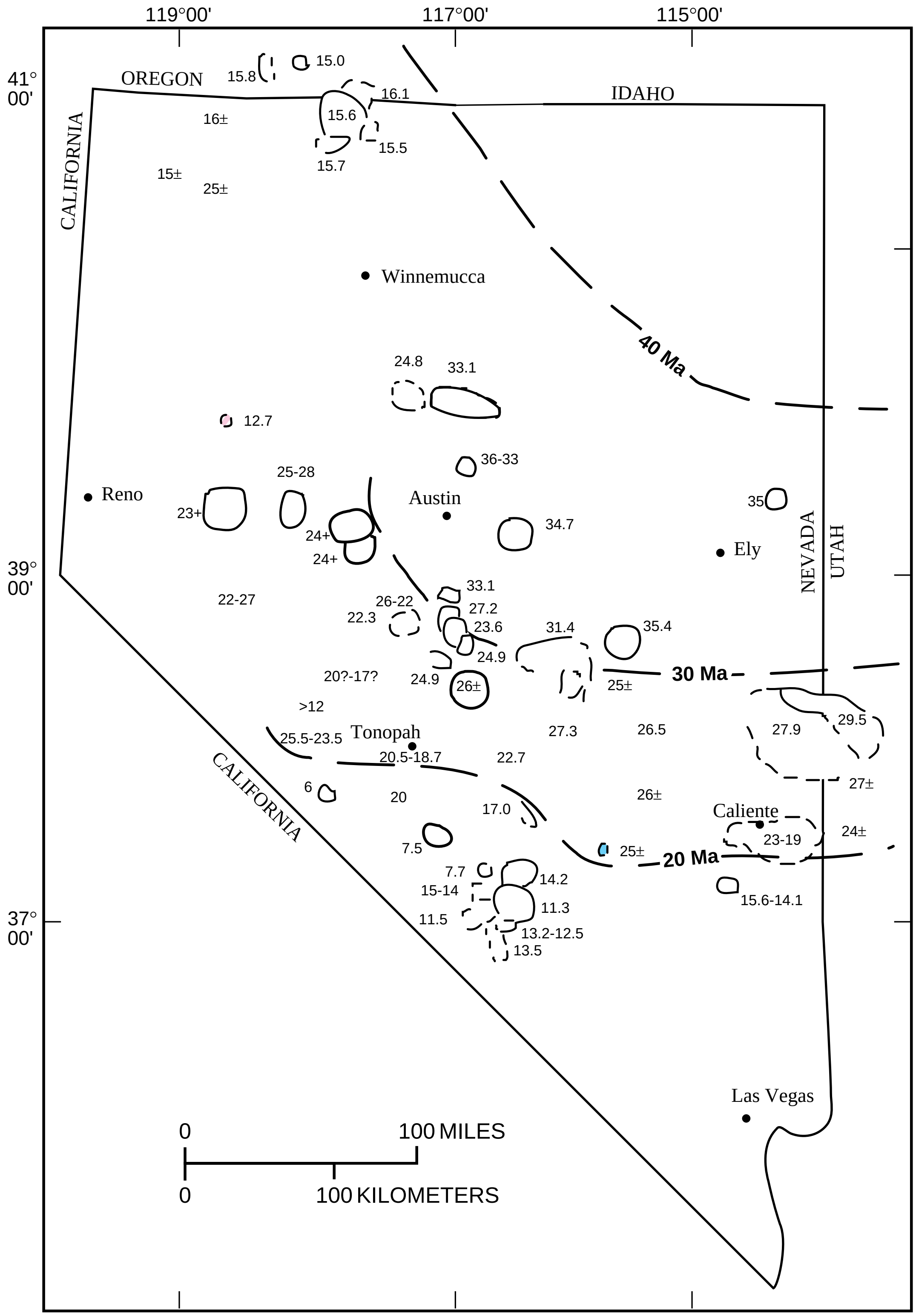

Figure 6-5. Calderas in Nevada, southernmost Oregon, and easternmost Utah. The 35 calderas outlined with their age (in Ma) have been reasonably well documented by geologic features; about 30 addtional calderas shown only by the age of volcanic rocks have been proposed but not demonstrated. Isochrons representing the leading edge of calc-alkalic volcanism are shown. Modified from Best and other (1989).

that have some of the features of a dissected caldera (Best and others, 1989). Many sheets, however, have no known source, or at best, only a conjectured one. No calderas have been identified with any certainty if there is no recognized outflow sheet.

HYDROTHERMAL SYSTEMS AND MINERAL DEPOSITS

Heat resulting from regional igneous activity and tectonism are significant factors in formation of most hydrothermal mineral deposits. This close association between igneous activity and mineralization is clearly evident in the distribution in time and space of mineral deposits in Nevada. The 228 mineral deposits and occurrences shown in plate 6-1 are selected from 1427 shown in chapter 10. The occurrence number is the same as on plates 10-1 and 10-2. Only Cenozoic deposits are shown for which there is enough information to judge their age and mineral deposit type as classed in Cox and Singer (1986). The age designation of the mineral deposit is based on more than 100 radiometric ages of mineral deposits, many unpublished, and on geologic field observations and mapping. Most of the age determinations were done by the K-Ar or the 40Ar/39Ar method. The K-Ar and 40Ar/39Ar analysis was on potassium-bearing material that was judged to be related to mineralization at a given mine or mining district. These materials include adularia, alunite, biotite, hornblende, sericite, and a few determinations on illite, kaolinite and whole rock samples. In some places unmineralized host rocks were dated giving a maximum age possible for the deposit, in some places unmineralized overlapping units were dated giving minimum age; locally both older and younger rocks occur giving a bracketed age. In general, the deposits are less than 17 million year old in western Nevada as are most of the Cenozoic igneous rocks. Deposits 17 to 34 Ma are concentrated in the igneous rocks of that age (to 34 Ma) that form a NW-SE belt crossing west central Nevada and those 34 to 42 Ma are in the northeastern part of the state.

The two fundamentally different suites of Cenozoic igneous rocks in Nevada that are caused by two different regional tectonic environments are reflected in the mineral deposits as well. The parallelism between igneous suite and mineral deposit type is strong, and, when the pre-existing tectonic framework of the region is considered in conjunction with the igneous suite, the correlation is remarkably close. Tertiary porphyry, skarn, and replacement deposits, such as Copper Canyon and McCoy in Lander County and Mineral Hill in Eureka County, are related to plutons of late Eocene or early Oligocene age and calc-alkalic affinity. Such mineralized systems are relatively uncommon as are their associated Tertiary plutons. This probably reflects the shallow level of erosion into the crust since Oligocene time in most parts of the state. Exposed Miocene or Pliocene plutons and related mineral deposits are almost nonexistent in Nevada.

The age of the disseminated, Carlin-type, precious-metal deposits, widespread in central Nevada (chapter 10), is difficult to ascertain because of the lack of material on which to make radiometric age determinations. The regional association with late Eocene and early Oligocene igneous rocks and a few radiometric ages of this age on alteration minerals near a few of these deposits suggest that at least some are of late Eocene or early Oligocene age. A probable regional source of heat necessary to drive some of the hydrothermal systems that produced mineralization was caused by the subducted Farallon plate that was responsible for the widely scattered but voluminous igneous activity in latest Eocene and early Oligocene time. This period of igneous activity and elevated regional heat flow seems to have had profound and pervasive significance and appears to be a major time of mineralization is eastern and central Nevada.

The early Oligocene to early Miocene calc-alkalic volcanism that migrated southwestward across Nevada and which produced by far the largest volume of igneous rocks in the eastern and central parts of the state is associated with relative few epithermal mineral deposits (Cox and others, 1991; chapter 10). In most places, older or existing fault systems were not pervasive or penetrative enough to facilitate hydrothermal circulation, and the eruptive centers were not closely spaced enough to create a regional fault system that enhanced widespread migration hydrothermal fluids. Only in the western part of the state, where the waning stages of this subduction-related volcanism erupted through the intensely faulted terrane of the Walker Lane, do mineral deposits clearly related to this igneous activity become common. Eastern and central Nevada at the time of calc-alkalic volcanism was a region of low topographic relief (pre-basin-and-range faulting) and relatively stable tectonic conditions. Sub-areas within this region, especially around its margins, experienced great amounts of near-surface extension (see Gans and Miller, 1983; Gans and others, 1989; Wernicke and others, 1987; John and others, 1989), but in most parts of Nevada a succession of lava flows and ash flows spread paraconformably one on another from about 40 to 20 Ma (McKee, 1988; Best and Christiansen, 1991). Locally, large eruptive centers collapsed to form calderas and, in a few cases, such as Round Mountain, this local volcanic feature was the site of hot spring-type gold mineralization.

The tuffs and lavas of central and eastern Nevada are mostly unaltered and unmineralized. In the western part of the state, in the Walker Lane, many types of alteration are present and have affected almost all rocks in the region. Large areas show effects of limonitization, silicification, and propylitization; bleaching of the rocks is pervasive in some mountain ranges. This region also contains the large and well-known bonanza precious-metal deposits such as Aurora, Bodie, the Comstock Lode, Goldfield, and Tonopah, as well as hundreds of smaller mines and thousands of prospects (plate 6-1). Most epithermal precious-metal deposits in Nevada are restricted to the Walker Lane, and they are in calc-alkalic rocks that are the eruptive phases caused by the subducted Farallon plate. Unlike older rocks related to this subducting plate and which blanket much of central and eastern Nevada, these western Nevada rocks were erupted after subduction ceased from a stagnated plate (subduction of the Farallon plate beneath western North America at this latitude had ceased by 15 Ma; Christiansen and Lipman, 1972) through a much-fractured crust. There is a clear association of widespread alteration and mineralization with the tectonically complex terrain that developed before and during the eruption of calc-alkalic rocks in the Walker Lane.

This association is less pronounced in the rest of Nevada, where relatively simple basin and range faulting post-dates the subduction-related volcanic activity by 2 to 10 million years.

In north-central and northwestern Nevada, and locally in the southwestern part of the state in and near the Bullfrog mining district, epithermal precious-metal deposits and many mercury mines are related to the middle and late Miocene bimodal igneous assemblage (plate 6-1). This relatively newly discovered group of deposits, which includes the McDermitt, Sleeper, Seven Troughs, and Hog Ranch mines, is present in close association with the silicic or rhyolitic part of the bimodal suit (Noble and others, 1988; Conrad and others, 1993). These volcanic rocks are not part of the older subduction-related system, but appear to be derived from the mantle and lower crust and are associated with late Cenozoic basin and range-type (horst and graben) crustal extension.

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