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THE TECTONIC FRAMEWORK OF MAGMATISM AND
MINERALIZATION IN THE WESTERN UNITED STATES

J. S. EMPSALL

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"Therefore a miner, since we think he ought to be a good and serious man, should not make use of an enchanted twig, because if he is prudent and skilled in the natural signs, he understands that a forked stick is of no use to him, for as I have said before, there are natural indications of veins which he can see for himself without the help of twigs."

Georgius Agricola, in *De Re Metallica*, 1556

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INTRODUCTION

The western United States is one of the world's important mineral provinces. Beginning with the California gold rush in 1848, this region has supplied much of the wealth and raw material that is the foundation for the American economy. Initial production was primarily gold and silver, metals which created wealth to be used elsewhere in the economy. Later, emphasis shifted towards production of base metals to be used as feedstock for industry. With the increasing cost of energy, the exploitation of uranium, coal, and oil shale resources will assume increasing importance.

Although the western United States has been intensely explored and mined for the past 100 years, new discoveries continue to be made and the rate of production of minerals continues to increase. For the exploration geologist, however, the "natural indications of veins" are becoming more inconspicuous as the more easily detectable mineral deposits are found. Since additional discoveries must continue in order to maintain the present rate of production, geologists will have to resort to "natural signs" that may have been overlooked in the past. An underlying purpose of this dissertation is to elucidate some of these signs.

Plate tectonic theory has greatly improved our understanding of geologic processes, including the formation of mineral deposits. The gross distribution of most mineral deposits in the western United States is not dissimilar to the simple island arc models of metallogenesis. However, plate tectonic models are in danger of becoming "enchanted twigs" because they tend to de-emphasize other factors which may be important controls on mineralization. In detail, the distribution of mineralization in the western United States does not show the regularity envisioned by plate tectonic models because of the influence of these other factors.

This dissertation attempts to indicate some of these factors and their relationship with plate tectonics by reviewing the interactions between magmatism, mineralization, and tectonic environments. The emphasis is on metallic mineral deposits associated with magmatic processes because this group has historically been the most important in the western United States. However, the brief coverage given to non-metal deposits and mineralization associated with sedimentary processes necessarily leaves an incomplete picture. The conclusions, hopefully, will not be detracted by this omission.

The relationship between magmatism, tectonism, and mineralization can be illustrated by reviewing the present tectonic environment of the western United States. The present characteristics of the basement provide data for establishing the present environment. These relationships can then be extrapolated to earlier periods for which less data is available. Also, the present characteristics of the basement are the products of past tectonic events, and thus are indicators of previous tectonic environments. Before proceeding with this review, the following summary provides background information on the tectonic history of the western United States, and defines some of the terminology used in this report.

Tectonic History of the Western United States

The western United States has had a complex tectonic history traceable from Archaean time. Precambrian crystalline rocks underlie the interior of the western United States, but do not crop out and are presumed to be absent at depth in the westernmost portion (King, 1976; figure 1). The oldest radiometric dates, from zircons of detrital origin in gneisses of the Beartooth Mountains, Montana (figure 1), have yielded ages in excess of 3100 Ma. Much of the basement of Wyoming yields rather consistent Kenoran ages of about 2750 Ma, indicating this region is an extension of the Superior province of the Canadian Shield. Basement with Hudsonian ages (1600-1800 Ma) lies to the north and south of Wyoming. The northern boundary is gradational while the southern is sharp, occurring along the Mullen Creek-Nash Fork shear zone (figure 48). No Kenoran dates are known south of this shear zone, and there is a strong possibility that no Archean rocks ever existed in this region, suggesting that the rest of the crystalline basement of the western United States was added after the Kenoran event (King, 1976). Some regions of this basement have been affected by Elsonian (about 1350Ma) and Grenville (900-1000 Ma) events. The three Proterozoic orogenies correspond with emplacement of granitic batholiths in the basement.

The origin of the western margin of the Precambrian North American continent is poorly understood. The margin may be related to slow outward building of the continent by accretion, or it may be related to rifting events that preceded (1450 Ma) and/or followed (900? to 650 Ma) deposition of the Belt Supergroup (Stewart, 1978a). The Belt Supergroup, the oldest relatively unmetamorphosed supracrustal rocks in the western United States (1450 to 900? Ma), was deposited in a deep epicratonic trough in northern Idaho, western Montana, and easternmost Washington (figure 2a).

References for base map and figure 1

- Chapin and Seager, 1975
Drewes, 1981
King and Beikman, 1974
Stewart, 1974
Stewart, 1978
Stewart and Poole, 1978
The New Oxford Atlas, 1975

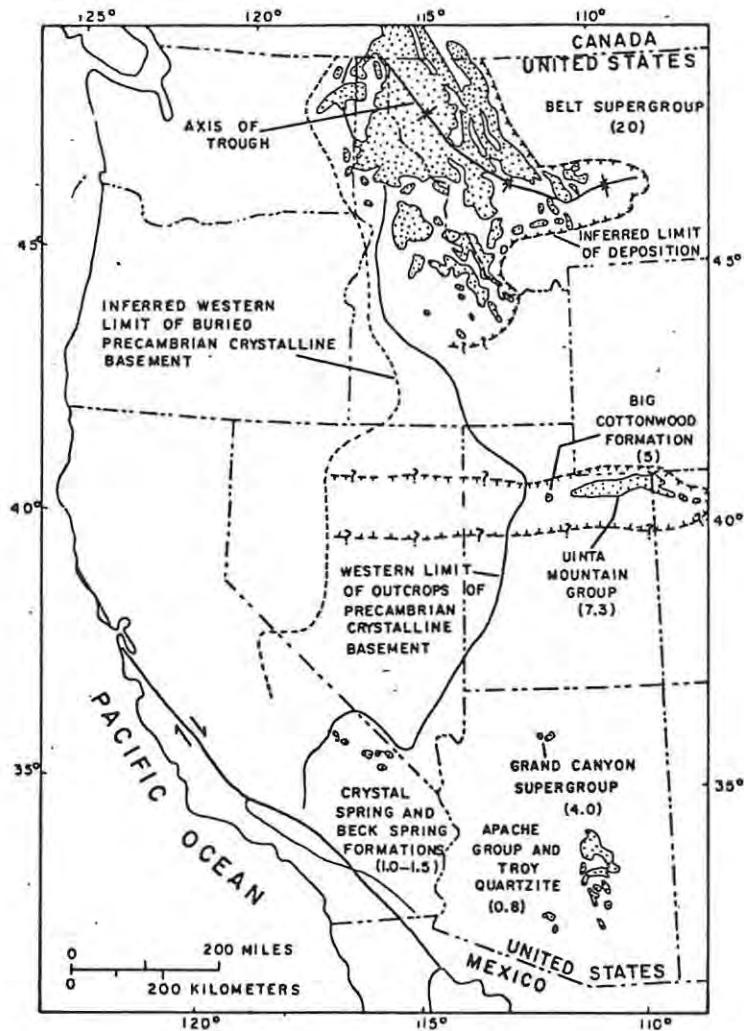


Figure 2a. Distribution and inferred basins of deposition of the Precambrian Belt Supergroup and temporally equivalent rocks (1,450 to 900? Ma) and known and inferred western limit of Precambrian crystalline basement rocks (2,400 to 1,450 Ma). Numbers are maximum thicknesses in kilometers. From Stewart (1978a).

The Belt and temporally equivalent rocks, up to 20 km thick, consist mostly of argillite, shale, siltstone, quartzite, and locally abundant dolomite, limestone, and conglomerate. Relatively thin mafic lavas and gabbroic or diabase sills occur locally. Similar, but less extensive deposits include the Uinta Mountains Group in Utah; the Unkar Group, Apache Group, and Troy Quartzite in northern and central Arizona; and the Pahrump Group in southeastern California (figure 2a). These sequences have been interpreted as deposits formed in embayments extending eastward from an ocean basin along the western margin of the North American continent. The deep trough of

the Belt Supergroup may represent a failed arm of a three-armed rift system related to a pre-Belt continental separation (Stewart, 1978a).

Belt rocks were mildly deformed and slightly metamorphosed by the East Kootenay orogeny, prior to deposition of post-Belt rocks. The nature of this orogeny is not clear, but it may be related to closure of an earlier rift (Stewart, 1978a).

Following the East Kootenay orogeny, the Cordilleran geosyncline developed along the western margin of the craton. These rocks can be divided into four major sequences or assemblages: (1) a diamictite and volcanic sequence of Precambrian age (900 ? to 800 ? Ma), (2) a miogeosynclinal terrigenous detrital sequence (figure 2b) ranging from 650 ? to 540 Ma, (3) a miogeosynclinal carbonate sequence of middle Cambrian to late Devonian age (540 to 340 ? Ma), and (4) a Cambrian to Devonian eugeosynclinal siliceous and volcanic assemblage (Stewart, 1978a). The last sequence occurs in thrust plates overlying the miogeosynclinal sediments, and its original geographic position in relationship with these sediments is uncertain (Coney and others, 1980).

The diamictite and volcanic sequence is a locally thick, but discontinuous succession characterized by diamictite, mudstone, argillite, sandstone, conglomerate, and locally thick units of mafic volcanic rocks which are in part tholeiitic. These features suggest the sequence may represent initial deposition in a post-Belt rift that formed the continental margin (Stewart, 1978a). The miogeosynclinal terrigenous detrital sequence, usually lying unconformably on the diamictite-volcanic sequence, consists of a westward-thickening wedge of shallow water quartzites, siltstone, and minor conglomerate, limestone, and dolomite. It ranges from a few hundred meters thick in the eastern part of the Cordillera, to over 6000 m thick in central and eastern Nevada (Stewart, 1978a). The thick miogeosynclinal sequence of carbonate with minor amounts of shale and quartzite conformably overlies the terrigenous detrital sequence. The thickness ranges from less than 2000 m in the east to over 10,000 m in central and eastern Nevada. The carbonates were deposited in shallow to moderately deep water (Stewart, 1978a). The miogeosynclinal assemblages are thought to represent a continental terrace deposit along a passive continental margin. Figure 2c shows the similarity between the Cordilleran geosyncline, and the present-day Atlantic margin of the United States.

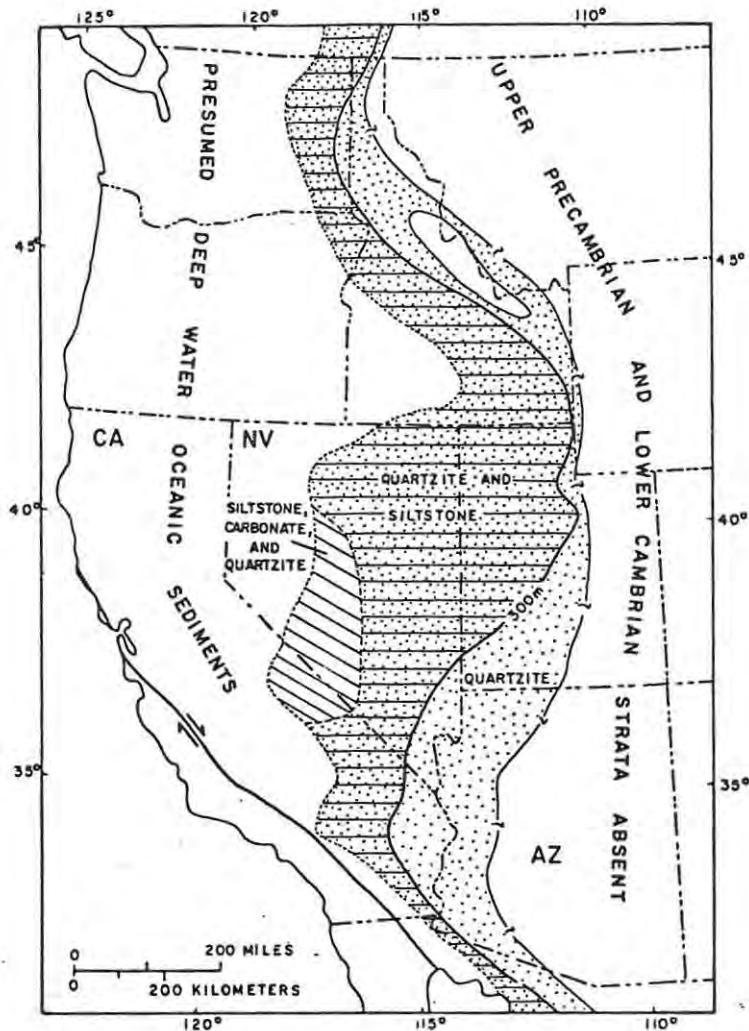
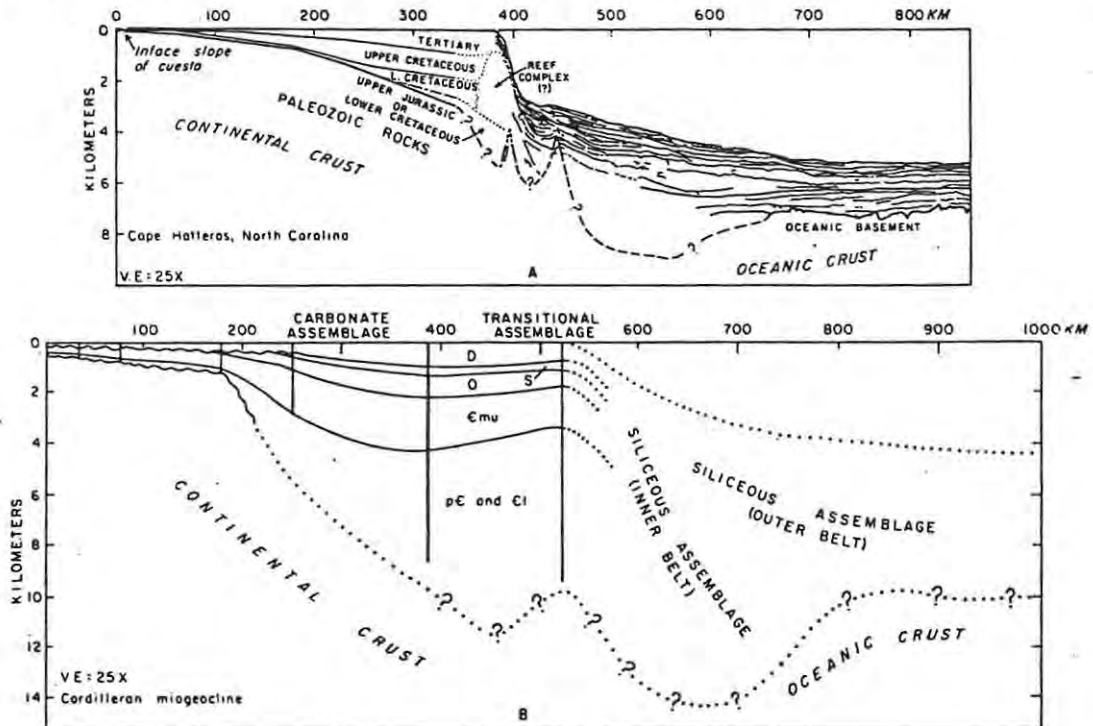


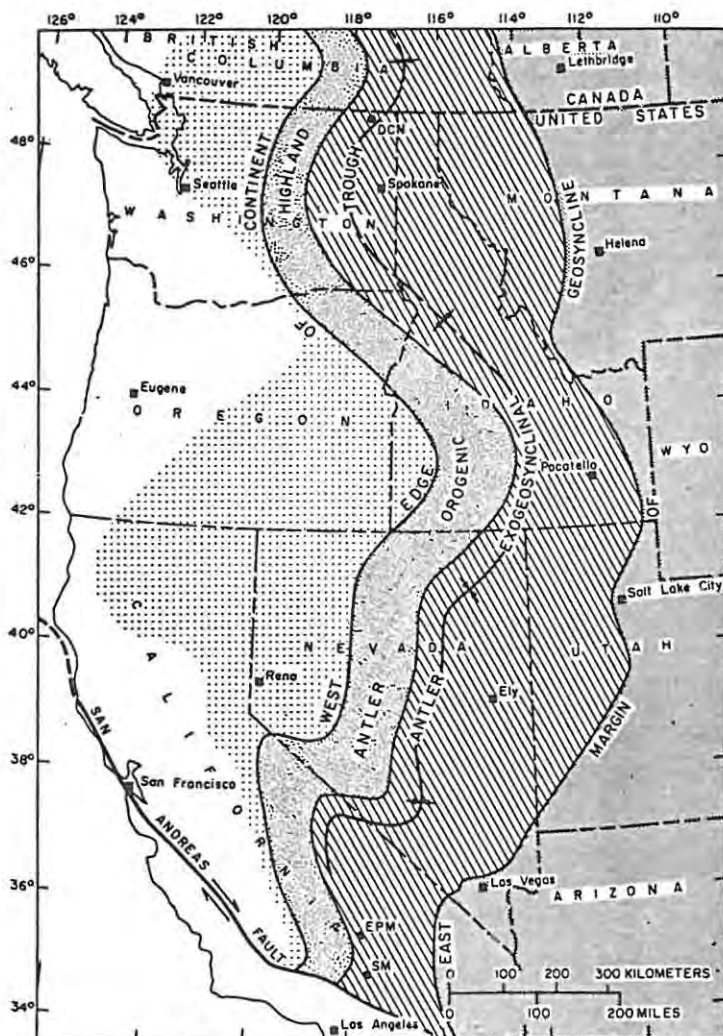
Figure 2b: Distribution, facies and 300 m isopach of upper Precambrian and lower Cambrian terrigenous detrital sequence. From Stewart (1978a)

Figure 2c: Cross sections comparing Cordilleran miogeocline with present-day miogeocline along continental margin of eastern North America. A, Section at Cape Hatteras, North Carolina; B, Cordilleran miogeocline showing distribution of assemblages. From Stewart and Poole (1974).



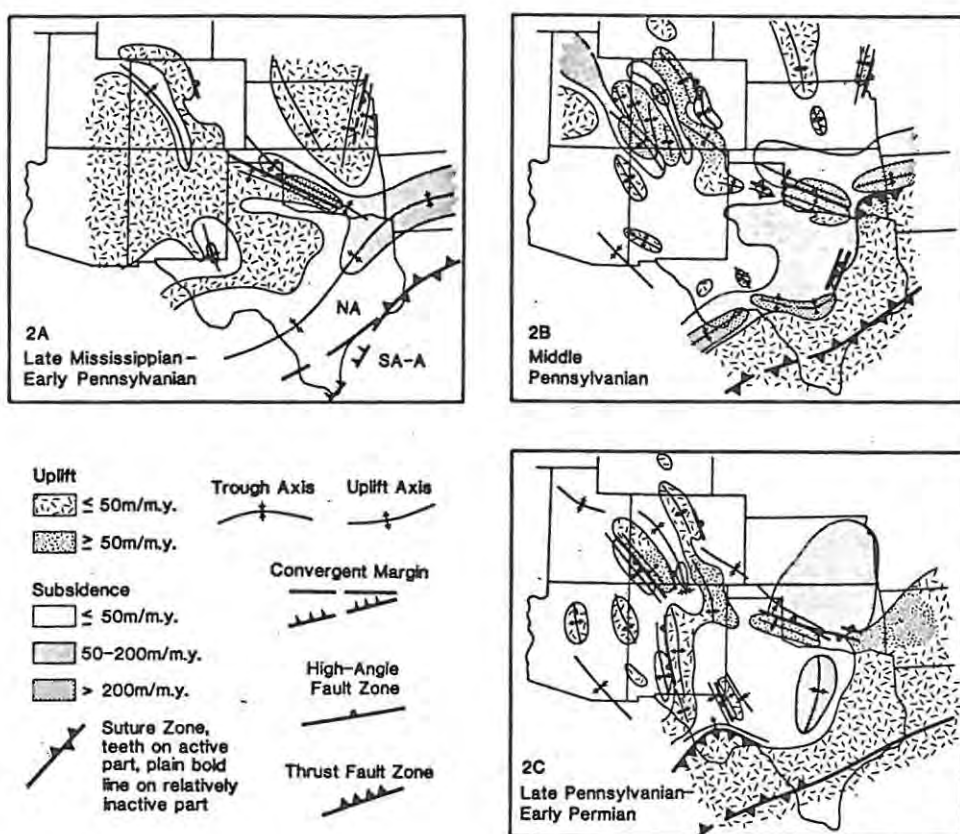
Sedimentation in the Cordilleran geosyncline was terminated by the Antler orogeny (375 to 300 Ma), a deformational event characterized by major thrusting in Nevada (figure 22) with no associated magmatism or metamorphism. The subsequent Sonoma orogeny (280 to 200 Ma) is a similar tectonic event. These two orogenies are thought to be related to accretion of island arc and oceanic terranes to the margin of the North American continent. These terranes may represent Paleozoic and early Mesozoic island arcs, developed along the continental margin (Burchfiel and Davis, 1975), or fragments of crust that were formed in tectonic settings far removed from the western United States (Coney and others, 1980). Both orogenies developed highlands in central Nevada that shed clastic wedges of flysch deposits eastward over the Cordilleran miogeosynclinal sediments (figure 2d).

Figure 2d: Index map of western United States showing upper Devonian and Mississippian structural and depositional framework (partly restored). Cratonic platform in compact stippling; Devonian continental shelf in cross-hatching and random stippling; oceanic area in diffuse stippling. Antler orogenic highland developed on outer continental shelf in latest Devonian time. From Poole (1974).



Within the craton, the Ancestral Rocky Mountains were formed during Pennsylvanian time by NW- to NNW-trending basement-cored uplifts (figure 2e; Kluth and Coney, 1981). The uplifts were bounded by narrow zones of faults and separated by deep basins filled with up to 4 km of terrigenous sediments and evaporites (Burchfiel, 1979). The Ancestral Rocky Mountains are similar to and spatially coincide with much of the region with subsequent Laramide basement-cored uplifts. This deformational event appears to be related to the Ouachita - Marathon orogeny in the south-central United States, rather than with orogenies in the Cordillera (Kluth and Coney, 1981).

Figure 2e: Paleotectonic map for intervals of time in Pennsylvanian. NA, North America; SA-A South America--Africa. From Kluth and Coney (1981).



Shortly after the Sonoma accretion event (late Triassic time), an Andean-type magmatic arc developed on the western margin of the North American plate. This arc apparently remained active during the major part of Mesozoic time, and is characterized by the emplacement of granitic batholiths along the continental margin (figure 29) and major thrusting within the interior of the Cordillera (figure 1). Uplifts developed in conjunction with the thrust belts, shed debris into a foreland basin that extended as far east as Iowa (figure 2f). Additional terrane was accreted to the continental margin along the subduction zone, while detrital sediments, represented by the Great Valley sequence, filled forearc basins. The sedimentary basins reached their greatest extent in late Cretaceous time (95 to 65 Ma), as shown in figure 2g. This corresponds with the culmination of thrust faulting and slightly post-dates the emplacement of granitic batholiths. The Mesozoic magmatic episode is loosely termed the Nevadan orogeny, while thrust faulting and associated deformation is referred to as the Sevier orogeny.

With the waning of the magmatic arc in late Cretaceous and early Tertiary times, the locus of magmatism shifted into the continental interior (figure 30). This period of diminished magmatic activity coincided temporally and spatially with the development of basement-cored uplifts within the craton (figure 1). Thrust faulting terminated in the central Cordillera, but continued in the northern and southern portions of the region with basement-cored uplifts. This style of deformation and magmatism, known as the Laramide orogeny, persisted from 75 to 40 Ma over much of the interior of the Cordillera.

Widespread volcanism developed in the northern Cordillera during late Laramide time, and spread southward into the Great Basin during Oligocene time (figures 32 and 33). A similar style of magmatism developed throughout the southwestern United States. This ignimbrite "flare up" appears to be related to the initiation of an extensional tectonic environment, represented by the development of metamorphic core complexes (Davis and Coney, 1979) and graben structures (eg. Rio Grande rift). With continued crustal extension during Miocene time, the western United States experienced regional uplift, while basin-range block fault structures developed in the Basin and Range province (figure 7). Also, the composition of magmatism changed from calc-alkaline to a bimodal basalt-alkalic rhyolite suite. This style of tectonism has continued to the present time.

The details of this tectonic history, and their relationship with magmatism and mineralization, are discussed in the remainder of this dissertation.

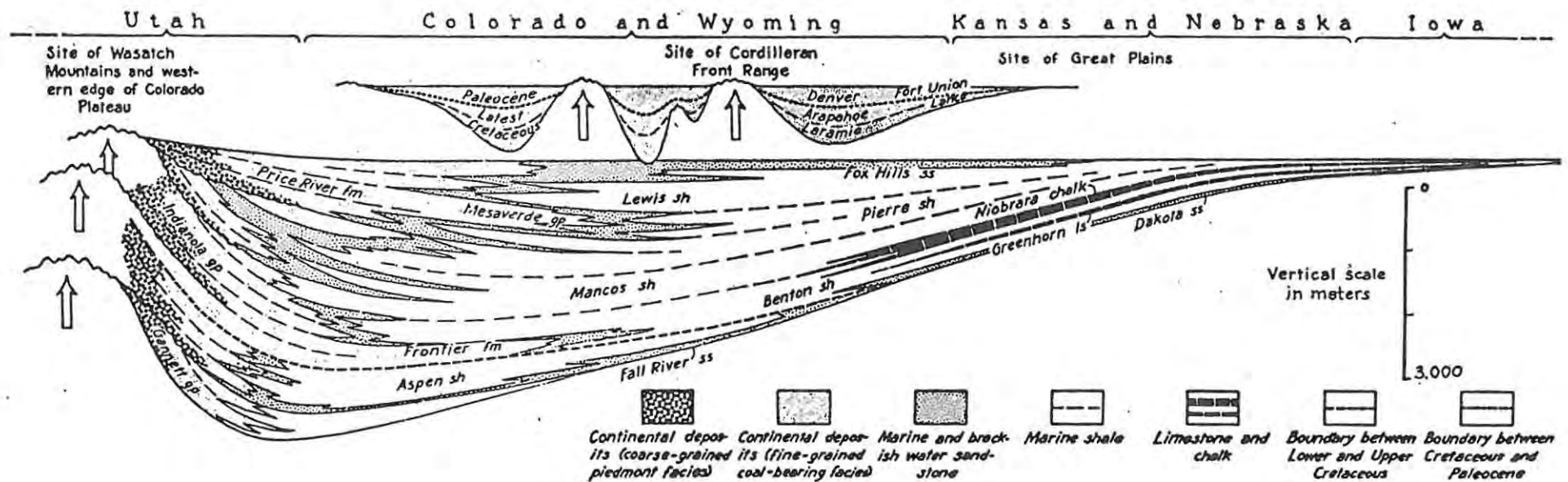


Figure 2f: Stratigraphic diagram of Cretaceous deposits that were laid down in a seaway along the eastern side of the Cordilleran region, in a section from Iowa to Utah. The latest Cretaceous and Paleocene deposits, which have a different habit from the remainder, are shown in a separate diagram above. From King (1977).

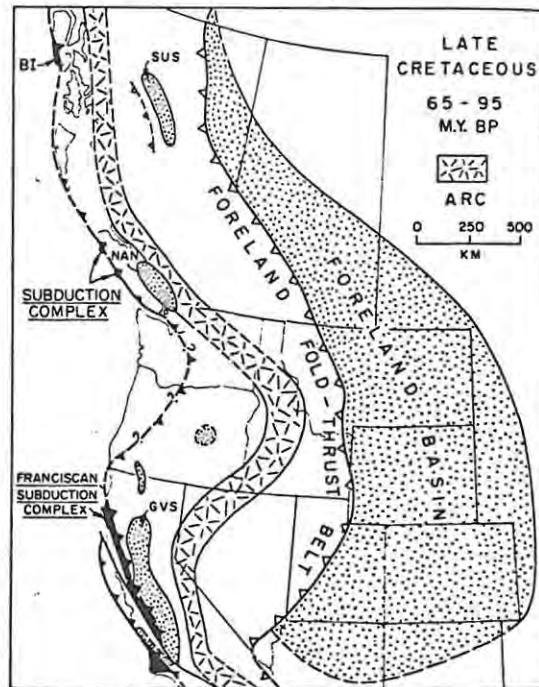


Figure 2g: Cordilleran arc-trench system in Late Cretaceous time. GVS, Great Valley sequence. From Dickinson (1976).

THE CRUST AND UPPER MANTLE OF THE WESTERN UNITED STATES

The crust and upper mantle is both a product of and a control on tectonic processes. In the western United States, the crust and upper mantle show considerable inhomogeneity in their physical characteristics, reflecting the long period of tectonic activity that has affected the region. Most of these inhomogeneities are products of recent tectonic activity. However, others apparently have persisted for long periods of geologic time, and have repeatedly controlled tectonic processes. Therefore, while the present physical characteristics of the crust are most useful as indicators for present and recent tectonic events, some features also may provide insights into older tectonic processes. This is an important principle since most mineral deposits in the western United States are related to earlier tectonic events, rather than to the present cycle. Also, the complexities of the present can give some indication of complexities which probably existed in the past, thereby indicating the inherent dangers in using simplistic tectonic models.

Physiographic Provinces

Physiographic provinces are defined as regions with similar geologic structure, topography, and climate. They usually coincide with areas that have similar tectonic environments, indicated by the fact that many abrupt changes in the physical properties of the crust and upper mantle approximately coincide with the boundaries of physiographic provinces. The western United States has been subdivided into a number of physiographic provinces (figure 3) which indirectly reflect the present and past tectonic environments. The following is a brief review of these physiographic provinces.

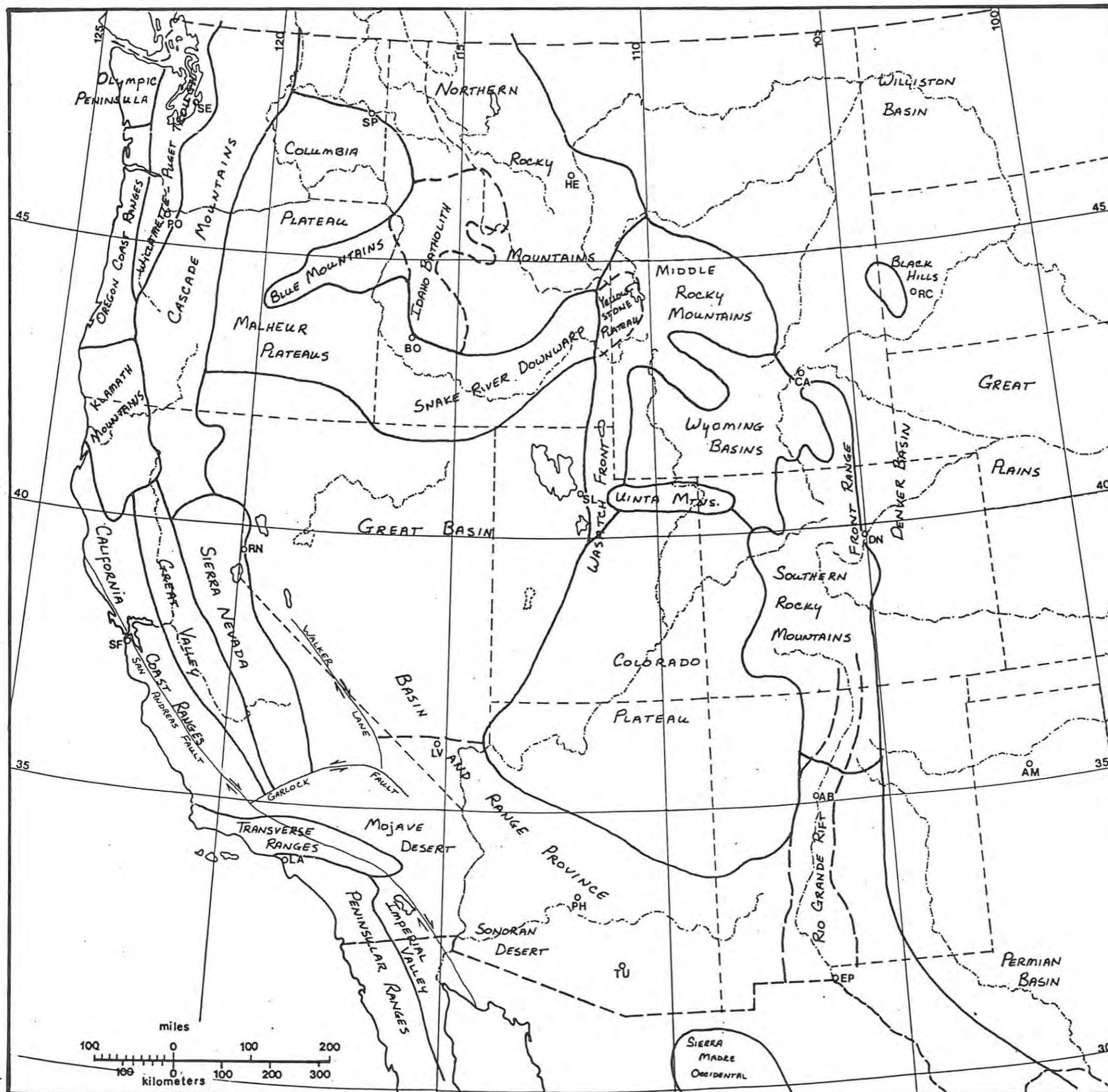
A series of coast ranges with diverse geologic characteristics extends along the western margin of the United States. The Peninsula Ranges are composed of metamorphosed early Mesozoic eugeosynclinal rocks intruded by Mesozoic granitic plutons. The ranges are controlled by NNW-trending block faults. In most respects, this province is similar to the Sierra Nevada. The Transverse Ranges are composed of a complex assemblage of Precambrian basement, Paleozoic sediments, Cretaceous plutons, and small Tertiary basin deposits. The ranges are controlled by E-W - trending block faults, probably related to the San Andreas system. The California Coast Ranges are composed of a complex basement of Mesozoic and minor amounts of Precambrian rocks, Franciscan melange,

Figure 3. Physiographic provinces of the western United States.

— Province boundary
- - - Sub-province boundary

References

- Guild, 1978
- King and Beikman, 1974
- Stewart, 1978



and Tertiary basin deposits (marine and continental). The ranges consist of a series of sub-parallel, NW-trending ridges controlled by fault slices in the San Andreas system. The Klamath Mountains are similar in composition to the Sierra Nevada, consisting of Paleozoic and Mesozoic eugeosynclinal rocks (including obducted oceanic crust) intruded by Jurassic plutons. The mountains are formed by a broad warping in the crust. The Oregon Coast Ranges are composed of early to middle Tertiary sediments with interbedded marine pillow basalts in an uplifted anticlinorium. The Olympic Peninsula is similar, but also includes a metamorphosed mid-Tertiary eugeosynclinal sequence thought to represent oceanic island tholeiites (Cady, 1975). Considering the variety of structural controls and tectonic environments, varying from transverse faulting in California to a recently terminated (?) subduction zone in the Pacific northwest, there is no simple explanation for the persistent uplift that occurs along the Pacific coast.

A series of elongated valleys parallel to the coastline lie immediately inland from the coast ranges. The Imperial Valley is a pull-apart basin (Crowell, 1974) filled with 6-7 km of Pliocene - Quaternary alluvial sediments. The valley represents the northern extension of the Gulf of California and may be underlain by oceanic crust. The Great Valley is a complex synclinorium structure with up to 15 km of upper Jurassic - lower Cretaceous marine sediments in a prismatic wedge of turbidites, partially thrust onto the Franciscan melange in the coast ranges (Dickinson and Rich, 1972). Continued subsidence has resulted in Tertiary and Quaternary marine and alluvial deposits. The Great Valley is thought to represent a forearc basin (Dickinson, 1974). The Puget Trough - Willamette Valley is a complex synclinal structure of Eocene and Oligocene marine sediments, overlain by recent alluvial deposits. This structure may represent a small backarc rift behind the coast ranges, or a forearc basin associated with the early Cascade volcanic arc. Like the coast ranges, the coastal valleys have very different tectonic histories but a similar physiographic form.

There are two groups of major mountain ranges in the western United States; the linear Sierra Nevada - Cascade ranges that occur 100-150 km inland from the Pacific Coast, and the diverse Rocky Mountains that form the eastern margin of the Cordillera. The Sierra Nevada are part of a

more extensive terrane of Paleozoic and Mesozoic eugeosynclinal rocks intruded by Mesozoic batholiths. The range is a NNE-trending, W - tilted block with normal faulting on the east and smaller, high angle reverse faults on the west. The Cascade Mountains are a typical volcanic arc, being composed of Eocene to Pleistocene (predominantly Oligocene and Miocene) calc-alkaline volcanic rocks (mainly andesite) with several prominent Quaternary volcanic cones. The volcanic pile has been intruded by quartz diorite and granodiorite batholiths which are exposed in erosional windows. The range is formed by volcanic accumulation and uplift on block faults. The Pacific mountain provinces and the valleys and ranges to the west are the only physiographic provinces that are parallel to the postulated mid- to late Cenozoic subduction zone along the Pacific coast. The remaining physiographic provinces are variably controlled by other tectonic elements that are not obviously related to the subduction zone, or to other plate tectonic processes.

The Northern Rocky Mountains contain a mixture of geologic and tectonic elements. The Idaho batholith, Blue Mountains, and northeast Washington are broadly similar geologically to the Sierra Nevada, consisting of Paleozoic and Mesozoic eugeosynclinal rocks intruded by Mesozoic stocks and batholiths. Northern Idaho and northwest Montana are composed predominantly of rocks of the Precambrian Belt Supergroup, while a mixture of miogeosynclinal sediments with Laramide and Tertiary intrusives and volcanics covers the remainder of the region. The major portions of the ranges are composed of long, narrow, NW-trending folds and thrust blocks. The eastern border with the Great Plains is marked by major thrusting.

The Middle and Southern Rocky Mountains (including the Black Hills) are similar to each other, being formed by broad-back uplifts and domes within the North American craton. Typically, the ranges consist of a core of Precambrian metamorphic rocks draped by a relatively thin sequence of Paleozoic and Mesozoic miogeosynclinal and shelf sediments. The Wyoming ranges (King, 1977) along the margin of the Great Basin in Utah and Wyoming are similar in structure to the northern Rockies, being composed of Paleozoic and Mesozoic miogeosynclinal sediments in closely packed folds and thrust slices. General trends of the ranges in the central Rockies are NW to E-W, while the southern Rockies have a N to NNW trend. Locally, Laramide and mid-Tertiary volcanics and intrusives are abundant, with thick, mid-Tertiary to Quaternary volcanic

piles present in the Yellowstone - Absaroka region of Wyoming and the San Juan Mountains of Colorado, and intrusives concentrated in crustal structures such as the Colorado lineament (Warner, 1978).

Most of the Rocky Mountains have a broadly similar tectonic history. The tectonic deformation that formed the individual ranges mostly occurred during the Laramide orogeny, while the present physiography is a product of erosional denudation during regional mid- to late Tertiary and Quaternary uplift. Intracratonic basins with Paleocene and Eocene continental sediments are found on the margins of many ranges in the central and southern Rocky Mountains. These include the Wyoming Basins, the Denver Basin, and several basins along the margin of the Colorado Plateau.

Between the two major mountain ranges, the Cordillera contains a variety of smaller ranges, basins and plateaus. The largest area is covered by the Basin and Range province. This is subdivided into the high desert of the Great Basin, the low deserts of southern California, Arizona, and New Mexico, including the Mojave and Sonoran deserts; and the Rio Grande rift. This province consists of sub-parallel ranges with intervening basins formed by normal listric (?) faulting. The faulting probably is related to recent crustal extension. The province has undergone variable amounts of regional uplift. These structures have been superimposed upon several earlier tectonic features. The Great Basin is largely developed within the Paleozoic Cordilleran geosyncline, while the low desert Basin and Range and the Rio Grande rift developed within the North American craton. Laramide and Tertiary magmatism is extensive in all areas of the Basin and Range province. Predominant trends of the basins and ranges are N - NNE in the Great Basin and Rio Grande rift, while WNW - NW is the major trend elsewhere. The Great Basin has experienced more regional uplift, remains more tectonically active, and is less eroded than the low deserts.

The Colorado Plateau is an uplifted tableland which shows comparatively little deformation. It is covered by shelf deposits of the Cordilleran geosyncline and detrital deposits of the Rocky Mountain geosyncline. Igneous activity is marked by a few laccoliths in the interior and major Tertiary volcanic fields on the margin (the San Juan Mountains on the NE, the Datil-Mogollon volcanic field on the SSE, the San Francisco volcanic field on the SW, and the High Plateaus volcanic field on the W). Deformation consists of gentle folding, forming broad uplifts and

intervening basins. Aside from the Paradox Basin of Pennsylvanian age, which is related to Ancestral Rocky Mountains, these basins mostly are of Paleocene and Eocene age. Most, such as the Uinta, San Juan and Piceance basins, are found near the margin of the plateau and are closely associated with uplifts in the adjacent Rocky Mountains. The basins are filled with continental clastic and lacustrine sediments.

The Columbia Plateaus include the Columbia Plateau of southeastern Washington and northeastern Oregon, the Malheur plateaus of central Oregon, and the Snake River downwarp of Idaho. These areas are characterized by extensive mid- to late Cenozoic, basalt - rhyolite bimodal volcanism. The Columbia Plateau, one of the largest flood basalt provinces in the world, consists of up to 5000 m of Miocene tholeiitic basalt. There has been relatively little deformation except around the Blue Mountains. Volcanics in the Malheur plateaus and Snake River downwarp are generally younger than the Columbia Plateau (Pliocene and Pleistocene), and have a more variable composition, possibly related to the composition of the underlying crust. The Columbia Plateau is thought to be underlain by oceanic crust, while the rest of the province is underlain by continental crust. The southern portion of the Malheur plateaus has been affected by basin-range faulting, while the eastern Snake River plain is an active downwarp. The Yellowstone volcanic field lies on the northeast extension of the Snake River downwarp, and probably represents the active extension of this province.

The Great Plains, consisting of virtually undisturbed Phanerozoic sediments, represent the foreland of the Cordillera. Gentle folding and warping of the crust has formed numerous basins, the largest of which is the Williston Basin. Smaller warps, such as the Denver and Raton basins, are found along the margins of the Rocky Mountains. The Great Plains form a gentle slope, rising from 300 m at Kansas City to over 2 km at the base of the Rockies, a distance of approximately 950 km.

Topography and Age of Uplift

The Cordillera of the western United States is an anomalously large area of regional uplift. The uplifted area is 1700 km across, compared with only 700-900 km in Mexico and Canada (figure 4). Within the Cordillera, there are several major areas of uplifts and topographic lows (figure 5).

The area with the highest elevation, in Colorado, forms a N-S

elongated uplift which is coincident with the Southern Rocky Mountains province. A more discontinuous N-S - trending uplift, consisting of the Beartooth, Teton, Wind River, and Uinta uplifts in the central Rocky Mountains, and the Tushar Mountains in the High Plateau volcanic field of southern Utah, forms the eastern border of the Great Basin. The Sierra Nevada form a less extensive uplift on the western border of the Great Basin. Broad uplifts also are found in the central portion of the Great Basin of eastern Nevada, the Datil-Mogollon volcanic field of southwestern New Mexico, and the Idaho batholith - Challis volcanic field. Narrow ranges such as the Cascades do not stand out in figure 5, due to the use of a topographic filter.

The major topographic lows mostly are confined to Pacific coastal areas. These include the Puget Trough - Willamette Valley - Oregon Coast Ranges, the Great Valley - California Coast Ranges, and the Imperial Valley - Sonoran Desert regions. Within the uplifted continental interior, other prominent lows include the Columbia River Plateau, the Snake River downwarp, the Rio Grande rift, and a low in the middle of the Colorado Plateau. Within the Great Basin, topographic lows are found on the eastern and western margins, in the vicinity of the Great Salt Lake and the Carson Sink respectively.

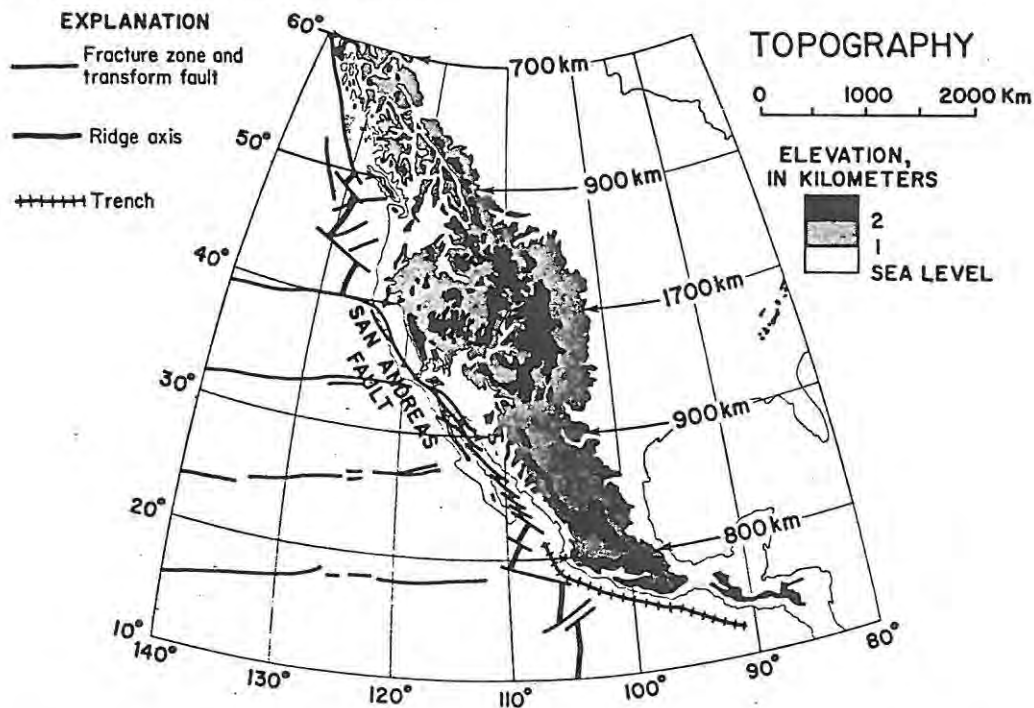


Figure 4: Regional topography of the Cordilleras of North and Central America. Arrows and kilometer figures indicate width of terrain more than 1 km above sea level. Note doubling of this width between lat 35° and 47° N and its lack of alignment with the latitudinal span of the San Andreas fault. From Eaton and others (1978).

In addition to correlating with many of the physiographic provinces, the topographic pattern shows several other features with important tectonic implications. For example, the area with the most extensive uplift does not coincide with areas affected by the most severe deformation, but rather lies within the western margin of the craton. The topography also suggests the Colorado Plateau has a crude basin shape, while the Great Basin is broadly arched, with a high rim on the eastern and western margins.

The ages of uplifts are difficult to quantify, and only a few areas have been well documented. Nevertheless, these areas probably are representative of the region as a whole. In the central Sierra Nevada, Tertiary uplift is estimated at 3450 m. Uplift probably began before 25 Ma, but two thirds of the uplift is estimated to have occurred in the last 10 million years, and one fourth in the last 3 million years, indicating that the rate has been accelerating (Huber, 1981). The southwestern Colorado Plateau began to rise sometime in the middle Tertiary, with about one half of the 2000 m of uplift occurring in the last 5.5 million years. During this last period, the adjacent Basin and Range province rose 500 m. Therefore, approximately one half of the Colorado Plateau uplift is related to a regional event and one half is related to movement on marginal faults (Lucchitta, 1979). Elsewhere, evidence for uplift of the plateau dates to 18 Ma (Best and Hamblin, 1978). Uplift of 2000-3000 m in the Great Basin has not been precisely dated, but a late Cenozoic age seems most likely (Stewart, 1978). This age approximately coincides with the onset of basin-range faulting. In southwestern Arizona, the development of a regional unconformity between 20 to 17 Ma (Eberly and Stanley, 1978) suggests a period of regional uplift immediately before the onset of basin-range faulting. The Rio Grande rift was initiated in Oligocene time (32 Ma in the south, 27 Ma in the north), and probably was accompanied by regional uplift. The graben and adjacent southern Rocky Mountain region has been uplifted 1100 m since the middle Miocene, much of that during the last 7 to 4 million years (Chapin, 1979). The central and southern Rocky Mountains is one of the few areas where the record of Laramide uplifts is well preserved. These were followed by regional uplift, mostly in mid- to late Cenozoic time. Regional uplift in the Cascade Mountains also is thought to have occurred toward the end of the Miocene.

The evidence cited indicates that most of the Cordillera has experienced a regional uplift in the last 25 million years, with some of the more tectonically active areas also showing fault controlled uplifts. Geodetic measurements and recent fault movements indicate the uplift is continuing at present. It is important to note that most of the uplifted areas are not experiencing significant orogeny or magmatism, demonstrating that these three processes are not necessarily temporally or spatially related. The extent and nature of earlier uplifts which may have been associated with earlier orogenic events, such as the Nevadan or the Laramide orogenies, is difficult to establish due to obliteration by subsequent tectonic events.

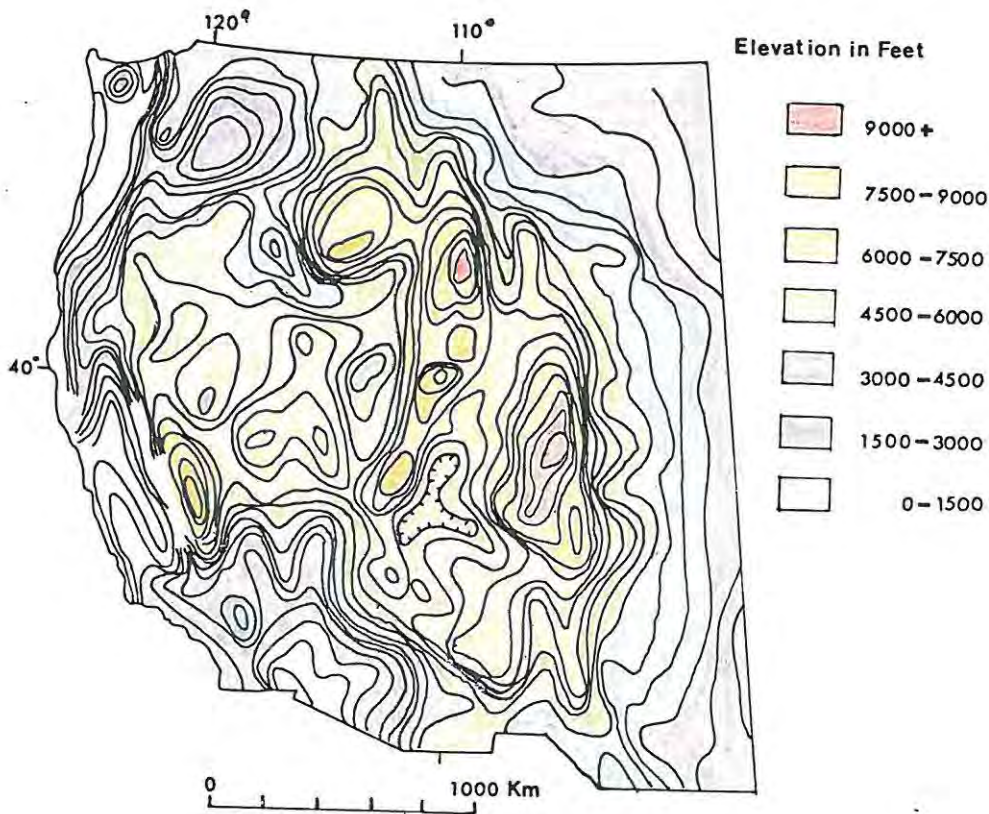


Figure 5: Regional topography (mean values averaged over 1° squares). Modified from Eaton (1979).

Recent Faulting and Seismicity

There are two major types of late Cenozoic fault systems in the United States: (1) strike-slip faults, generally related to the San Andreas system, and (2) extensional normal faults, generally located in the Basin and Range province. Current stress patterns have been postulated by fault-plane solutions and recent movements on these faults. These in turn have been used to construct models of mid- to late Tertiary plate motions and resulting tectonism.

The San Andreas system is a transform fault zone that is thought to be part of the present boundary between the North American and Pacific plates (Atwater, 1970). The right lateral movement represents the relative motion between the plates. Post-Oligocene offset on the San Andreas system is estimated at 350 km, with most of it (approximately 275 km) occurring during post-Miocene time (Atwater, 1970). The San Andreas system is postulated to have developed as a result of the intersection of the East Pacific Rise (a spreading ridge) with a subduction zone along the western margin of North America, approximately 29 Ma (figure 6). This caused a change in plate geometry and the development of a transform fault system along parts of the western margin of North America. Since plate tectonic models suggest 1400 km of offset between the North American and Pacific plates in the last 23 million years, other similar fault systems may have taken up some of this movement. These might include off-shore faults along the margin of the continental shelf, as well as other active and inactive faults within California that are parallel with the San Andreas system. Stress also could have been transmitted into the continental interior, causing right-lateral shearing and tensional faulting (Atwater, 1970). The Walker Lane (figure 1) may be an example of the former. Total right-lateral displacement along the Walker Lane probably is 130 to 190 km, occurring in part as fault slip and in part as a more pervasive large-scale drag (Stewart, 1978). The northern Intermountain seismic belt in Montana also has a significant right strike-slip component (Smith, 1978).

High angle extensional faulting extends throughout much of the western Cordillera of North America, with the best development found in the Basin and Range province (figure 7). Primary movement is vertical, but components of strike-slip displacement sometimes are present. These faults form a series of horst and grabens which are superimposed on older tectonic features. Fault trends vary from NW to NNE, with one trend

generally dominant in a given region. Faulting was initiated between 17 and 14 Ma, and remains active in the Great Basin. Faulting may have been initiated in the southern portion of the province and migrated northward (Dickinson and Snyder, 1979). However, evidence for this postulation is tenuous. There is some evidence that the faults flatten with depth (Proffett, 1977), suggesting they may form a series of listric faults. Such evidence is lacking in most areas, however. Variations in estimates for the amount of extension in the Basin and Range are largely the result of disagreement on the amount of listric faulting. Estimates range from 8% to more than 100% (50 to 600 km), with most estimates between 10% and 35%. The Rio Grande graben may have total extension of 100% to 150% (Chapin, 1979). First motion studies indicate the present direction of extension in the Great Basin is NW-SE (Stewart, 1978). According to the Atwater (1970) model, basin-range faults are a result of oblique tensional fragmentation related to movement on the San Andreas system.

Seismic activity in the western United States corresponds closely with areas of Quaternary faulting (Smith, 1978). Present seismicity may not necessarily be indicative of seismic activity in the recent past. However, present seismic belts do correspond with areas that have exhibited other geophysical and geological characteristics that have controlled late Cenozoic tectonism.

The Pacific coast of California is the most seismically active area. The complex pattern of seismicity is closely associated with the San Andreas system, and represents interaction between the Pacific and North American plates.

Seismicity in the western interior of the Cordillera is characterized by earthquakes that occur in broad zones, up to 150 km wide, and that have shallow focal depths, seldom exceeding 20 km (Smith, 1978; figure 8). This observation puts a restriction on the depth of brittle deformation of the lithosphere and also corresponds with a low velocity zone found within the crust over much of the region (Stewart, 1978). The location of these seismic belts roughly corresponds with the boundaries of several physiographic provinces. For example, the Intermountain seismic belt follows the eastern margin of the Basin and Range province through Utah and Idaho to Yellowstone, at the northeast termination of the Snake River downwarp, before turning northwest into the northern Rocky Mountains. Here, it roughly follows the Laramide thrust belt. Another seismic belt, along the western margin of the Basin and Range in southwestern Nevada,

coincides with the Walker Lane. An ENE-trending belt across southern Nevada corresponds with a change in the topographic character and the trends of the ranges (Eardley, 1962), an abrupt change in topography (figure 5) and gravity (Eaton, 1979; figure 14) and marks the southern limit of late Cenozoic volcanism (Stewart and others, 1977). Secondary seismicity occurs around the margins of the Colorado Plateau, in central Idaho, and in eastern Oregon and Washington (Smith, 1978).

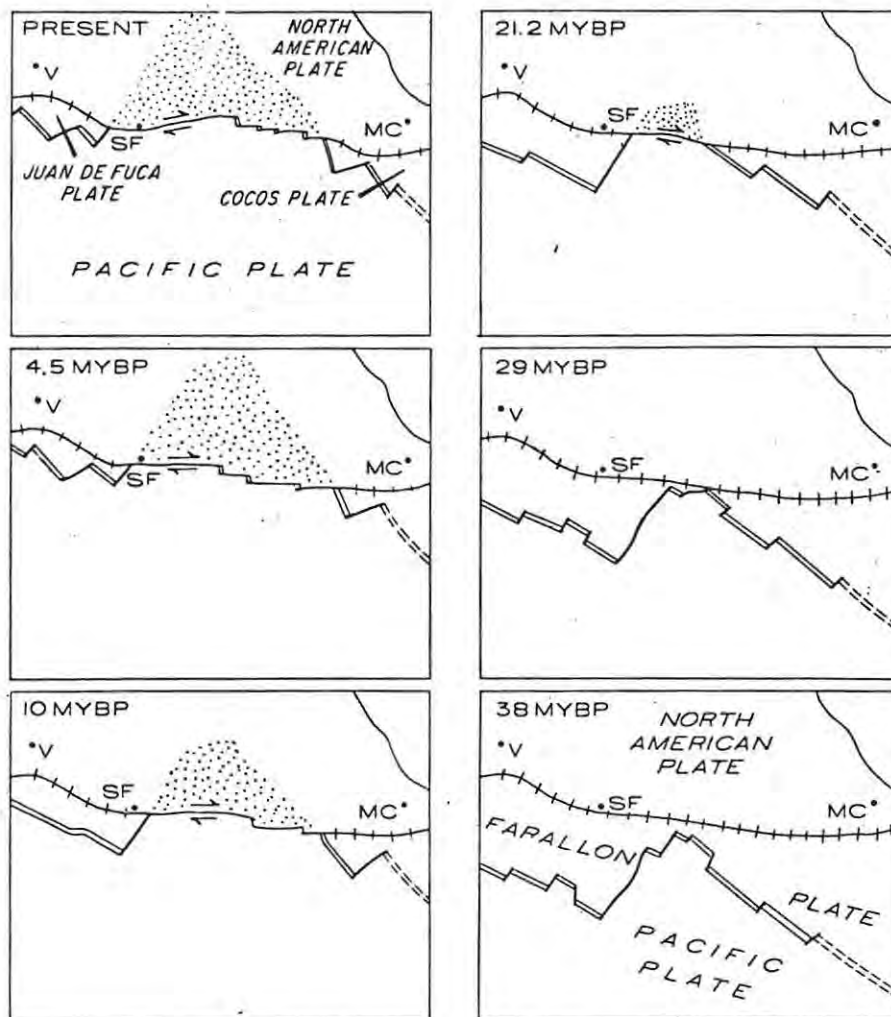


Figure 6: Plate tectonics in the vicinity of western North America at various times in the Cenozoic Era. Double lines, spreading ridges; lines with cross bars, trenches; single lines, transform faults; dotted areas, "hole" in subducting Farallon plate; V, Vancouver; SF, San Francisco; MC Mexico City. After Atwater and Molnar (1973).

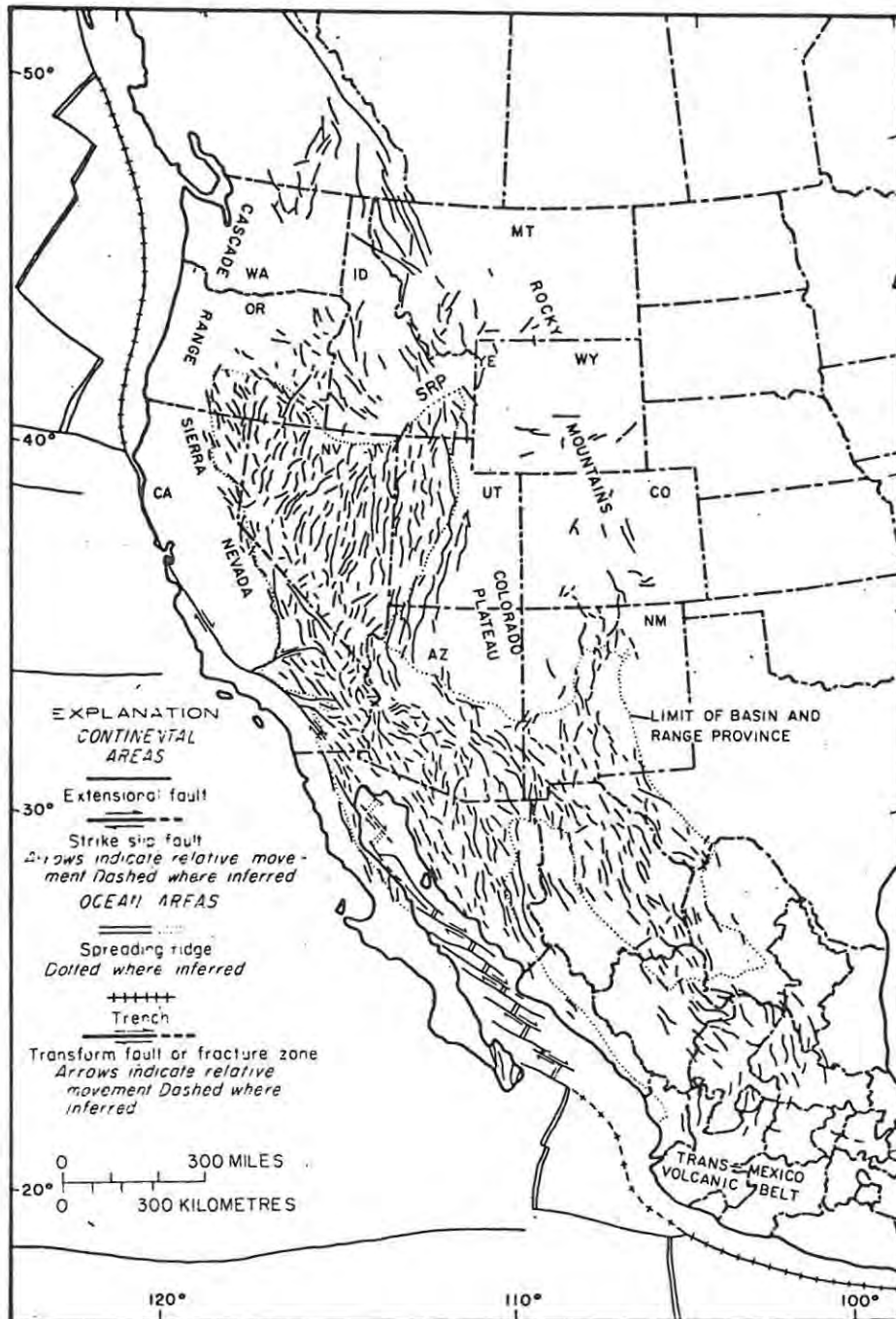


Figure 7: Distribution of late Cenozoic extensional faults and a few major strike-slip faults in western North America. From Stewart (1978 a).

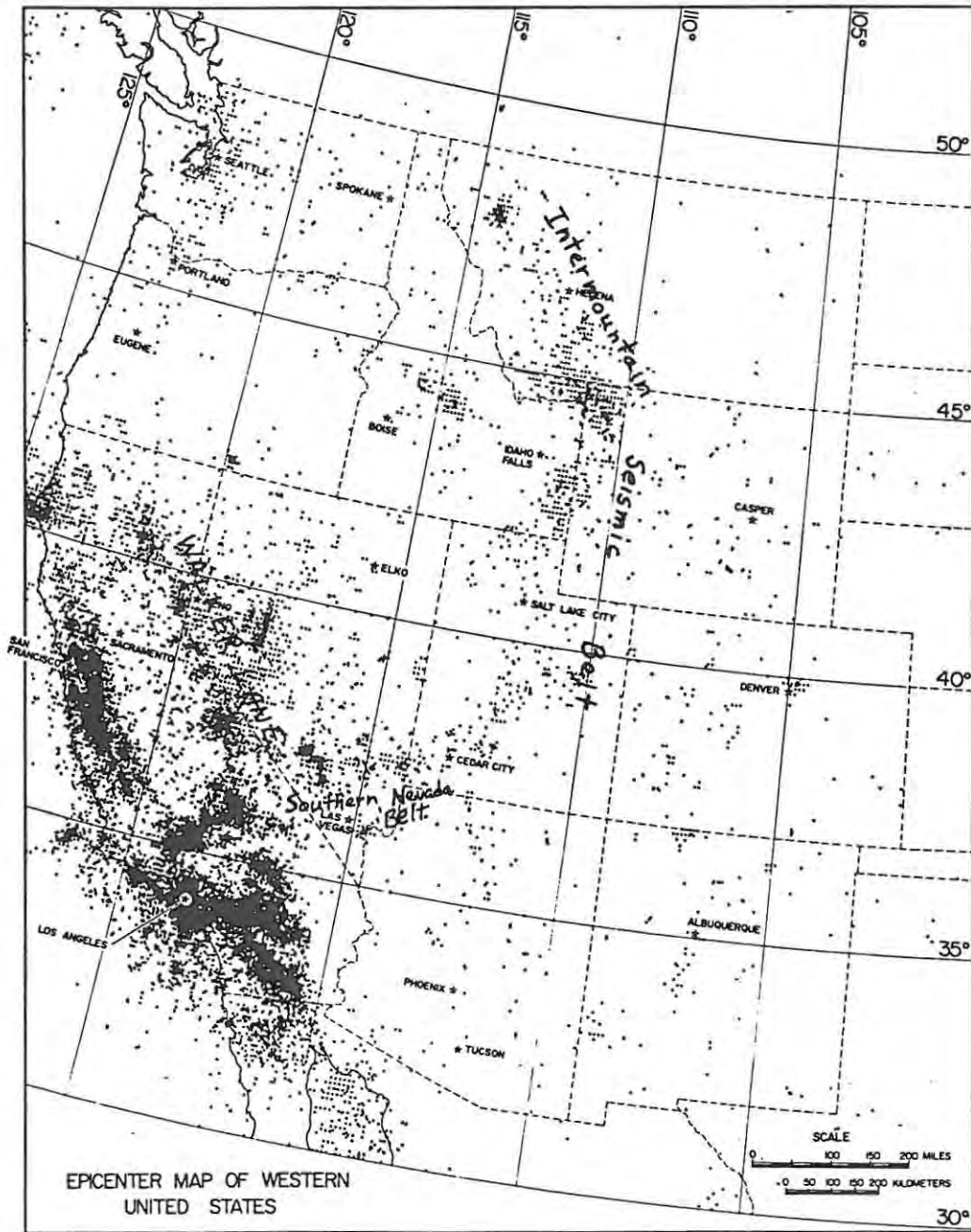


Figure 8: Epicenter map of the western interior of the United States. From Smith (1978).

Regional Structure of the Crust and Upper Mantle

Seismic waves from explosions have provided the most reliable and detailed information on the thickness and characteristics of the crust and upper mantle in the Cordillera. Figure 9 shows models of crustal types derived from seismic sections. Continental crust generally ranges from 30 to 50 km thick and is composed of two or three layers: a sediment layer (0-5 km thick), an upper layer (10-20 km thick), and a lower layer (15-25 km thick). The different layers are identified by different P-wave velocities, generally 2 to 4 km/second in the sedimentary layers, about 6 km/second in the upper continental crust, and 6.5 to 6.9 km/second in the lower crust (Condie, 1976). At the base of the crust, the Moho discontinuity generally is well defined by an abrupt P-wave velocity increase to about 8.0 km/second (P_n velocity), marking the top of the upper mantle. The mantle beneath the continents usually is characterized by a high velocity lid ($V_p > 7.9$ km/second) underlain by a low velocity zone ($V_p < 7.8$ km/second). The top of the low velocity zone, generally 60-70 km deep, marks the base of the lithosphere. This zone may extend to 100-200 km (Condie, 1976).

The different seismic properties of layers in the earth are caused by compositional differences, phase changes, and/or partial melting. Layers in the crust probably are the result of compositional differences, but the origin of deeper layers remains speculative. The low velocity zone in the mantle probably is related to partial melting.

Geophysical data indicates the crust and upper mantle are laterally inhomogeneous. The inhomogeneities may reflect changes in the tectonic environment. For example, there may be considerable variation in the depth of the Moho and of the low velocity zone in the mantle. Velocity gradients in the crust may be variable, and the various layers may be marked by gradational rather than distinct changes. Locally, the gradients may be reversed and low velocity zones are present in the crust.

Depth contours to the top of the Moho in the western United States are shown in figure 10, while the P_n velocities in the top of the mantle and the location of a low velocity zone within the crust are shown in figure 11. These contours are of variable reliability, due to large variations in the density of sample points. Also, the crust and upper mantle are much more complex than indicated on these maps, but there is insufficient detailed information for a regional compilation. There is an obvious correspondence between changes in the thickness of the crust, variations

in P_n velocities, and the boundaries of physiographic provinces (figure 3). Another important feature is the low P_n velocities throughout the region. These values are usually greater than 8 km/second in most areas of the world (Prodehl, 1979; figure 9).

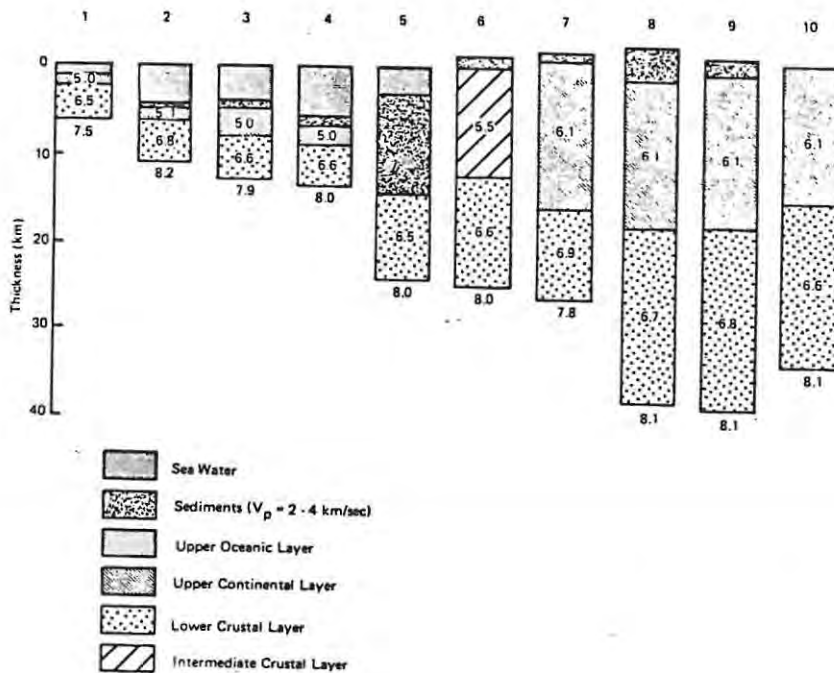


Figure 9: Seismic sections of various crustal types. P-wave velocities in km/second. Key: (1) oceanic rise; (2) ocean basin; (3) marginal-sea basin (4) trench; (5) inland-sea basin; (6) island-arc; (7) Basin and Range province; (8) Phanerozoic orogenic area; (9) platform; and (10) shield. From Condie (1976).

Figure 10. Crustal thickness in the western United States.

--- Contours to the top of the Moho, in km below the surface

Notes

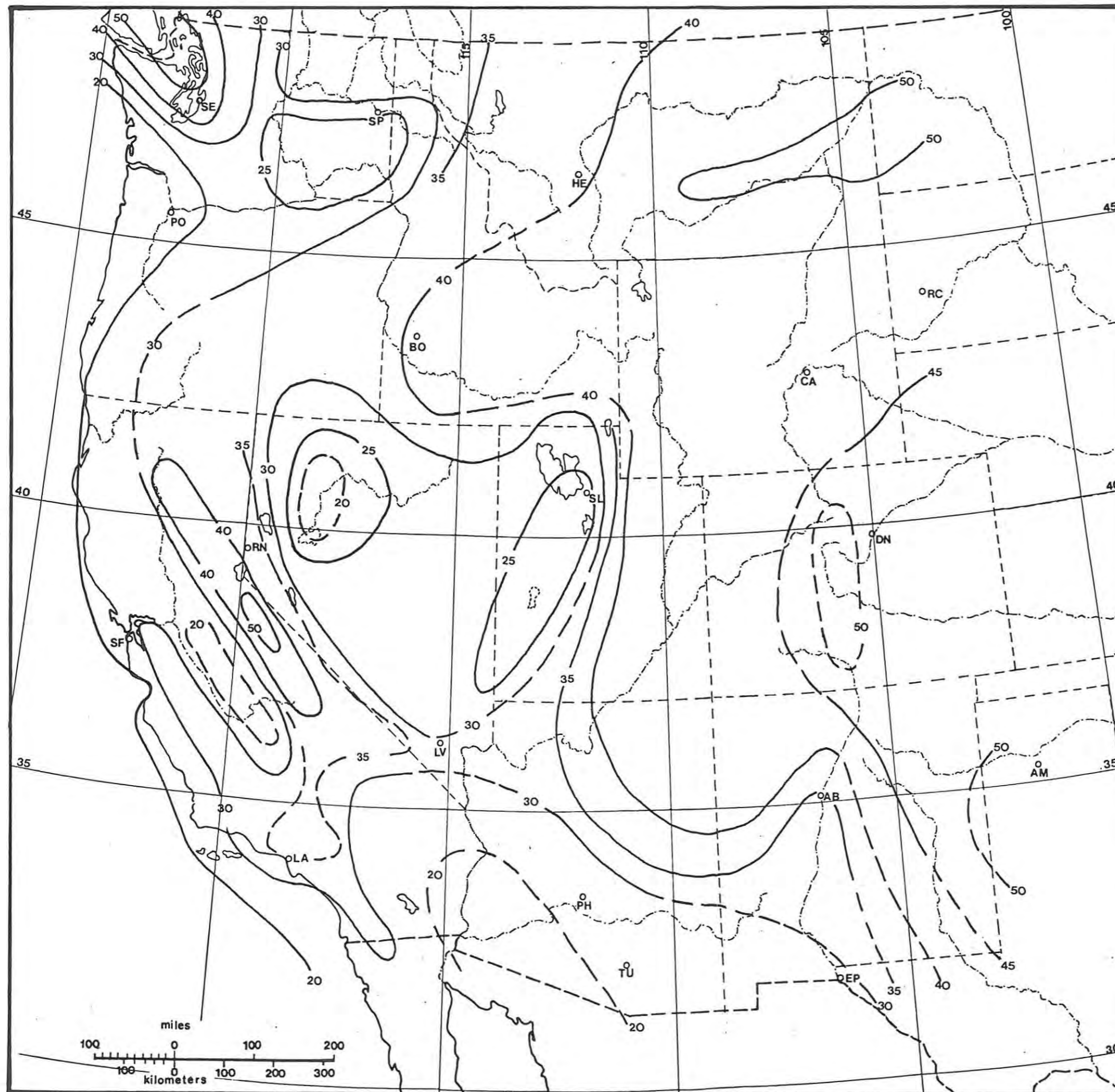
The depth to the Moho is generally taken as the depth of the strongest velocity gradient in the transition zone between the crust and mantle. This transition zone may be sharp, or up to 10 km thick, leading to varying interpretations.

Data points are very unevenly distributed.

Data is of variable quality and has been interpreted by different methods.

References

- Keller and others, 1979
- Prodehl, 1979
- Smith, 1978
- Thompson and Burke, 1974



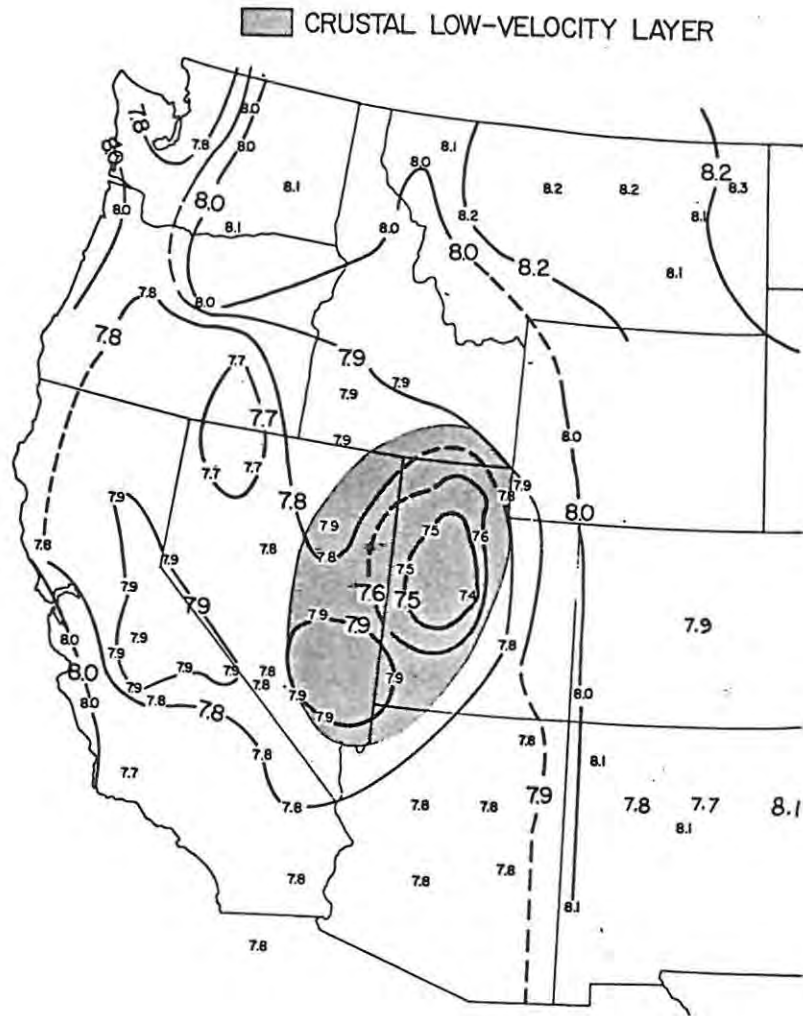


Figure 11: Map of P_n velocities in km/second. Modified from Smith (1978), with additional data from Prodehl and Pakiser (1980), and Keller and others (1979).

The Great Basin region contains anomalously thin crust due to thinning of the lower crustal layer (Condie, 1976; figure 9). The thinnest areas correspond with the topographic lows on the eastern and western margins of the basin. The eastern part of the basin contains a widespread low velocity layer in the crust (figure 11). This layer is greater than 3.5 km thick, and begins at a depth of 5-6 km. The low velocity zone may be the result of increased pore pressure from dehydration reactions accompanied by high temperature, or of partial melting and/or granitic intrusives (Condie, 1976; Smith, 1978). The Great Basin area, particularly the eastern portion, also has unusually low velocities in the top of the mantle. In some areas, the low velocity zone in the mantle is thought to immediately underlie the crust (Condie, 1976; figure 9).

Other areas with thin crust include the Columbia Plateau, the Great Valley of California, the Sonoran Desert - Imperial Valley region, and the Rio Grande rift. Like the Great Basin, the Rio Grande rift appears to be directly underlain by a low velocity zone in the mantle (Keller and others, 1979). The Sierra Nevada are underlain by crust up to 50 km thick, while a slight thickening of the crust to over 50 km is associated with the southern Rocky Mountains. A zone of crustal thinning within the Rocky Mountains (not shown) appears to lie along the eastward extension of the Uinta uplift (Prodehl and Pakiser, 1980). The crust beneath the Colorado Plateau thickens to over 40 km from the margins toward the center on the west, south, and southeast. The mantle is capped by a relatively thin (15-20 km) high velocity lid, and the top of the low velocity zone is at 60 km. P_n velocities under the Colorado Plateau are lower than expected in a stable region (Keller and others, 1979). The Great Plains show a typical platform profile (figure 9), with a crust approximately 50 km thick and the top of the low velocity zone at approximately 100 km (Keller and others, 1979).

Heat Flow

Heat flow is defined as the product of the thermal gradient and the thermal conductivity at a given site on the earth's surface. Thermal gradients are usually determined in drill holes, while thermal conductivity is measured from representative rock samples. Heat flow values are significantly affected by: (1) the age and intensity of the last magmatic event, (2) the distribution of radioactive elements in the crust, and (3) the amount of heat flowing up from the mantle (Condie, 1976). Heat

flow patterns also may be complicated by regional hydrology and thermal refraction due to structurally related thermal conductivity contrasts (Blackwell, 1978).

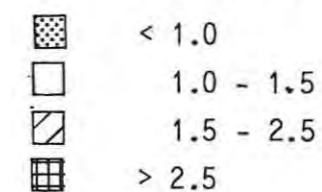
Figure 12 is a compilation map of heat flow distribution in the western United States. The most prominent feature is the large zone of high heat flow (> 1.5 HFU) that includes most of the interior portion of the Cordillera. Prominent areas with very high heat flows include the Rio Grande rift, the Snake River downwarp, the northern portion of the Great Basin, the southern Cascade Range, the Imperial Valley and the Geysers area north of San Francisco. The Pacific coastal region, excluding the San Andreas system, has anomalously low heat flow. A prominent low in the Snake River downwarp is related to hydrological phenomena (Blackwell, 1978).

Although this type of presentation of heat flow data does indicate significant correlations of heat flow with tectonic elements, it is not entirely satisfactory for tectonic analysis because: (1) a significant portion of the heat flow is controlled by the distribution of radioactive elements in the upper crust, and (2) other methods for transferring energy from the mantle to the crust are not measured. Important nonconductive mechanisms for energy release from the mantle include: (1) thermal energy stored in the crust, (2) energy flow from volcanism, (3) energy from intrusive activity and hydrothermal convection, and (4) energy released during earthquakes and faulting (Blackwell, 1978). Figure 13 is a semi-quantitative attempt to evaluate the amount of energy reaching the surface after removal of the effects of heat flow perturbations and non-conductive energy losses related to structure, volcanism, regional aquifer systems, and hydrothermal convection. The effects of radioactivity in the upper crust also have been removed. Thus, this figure is a more accurate indication of the energy transfer from the mantle and lower crust into the upper crust.

Several of the prominent highs and lows in figure 13 are the same as those in figure 12 (eg. Pacific coast, Imperial Valley, Oregon Cascades, Geysers area). The most important change is the two linear belts of high heat flow. One linear belt extends along the west side of the Great Basin, while the other extends from Yellowstone and the northeastern Snake River downwarp along the east side of the Great Basin and wraps around the southern margin of the Colorado Plateau. These are areas of very recent volcanism and/or tectonic activity. A local high in the Rio Grande rift

Figure 12. Heat flow in the western United States.

Contours are in heat flow units (HFU)

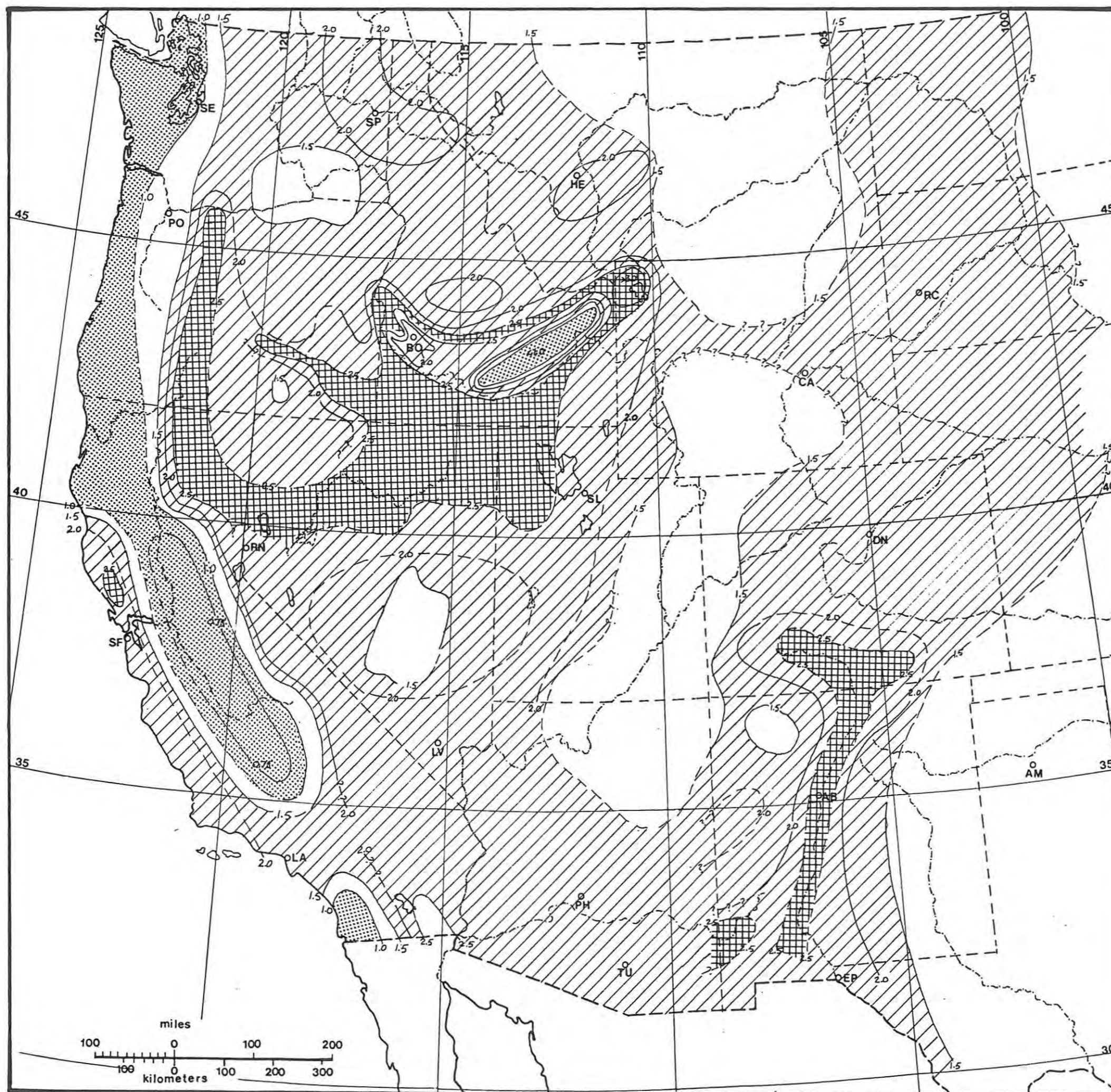


Note

Since compilation of this map, the data base for the western United States has more than doubled. Subsequent maps may show significant variations and refinements (Blackwell, 1978).

Reference

Blackwell, 1978



also correlates with recent volcanism. Areas with heat flows of 2-3 HFU generally correlate with areas with extensive volcanism less than 17 Ma (the onset of basin-range deformation), while areas with heat flows of 1.5-2.0 HFU correlate with those areas with volcanism greater than 17 Ma (Blackwell, 1978).

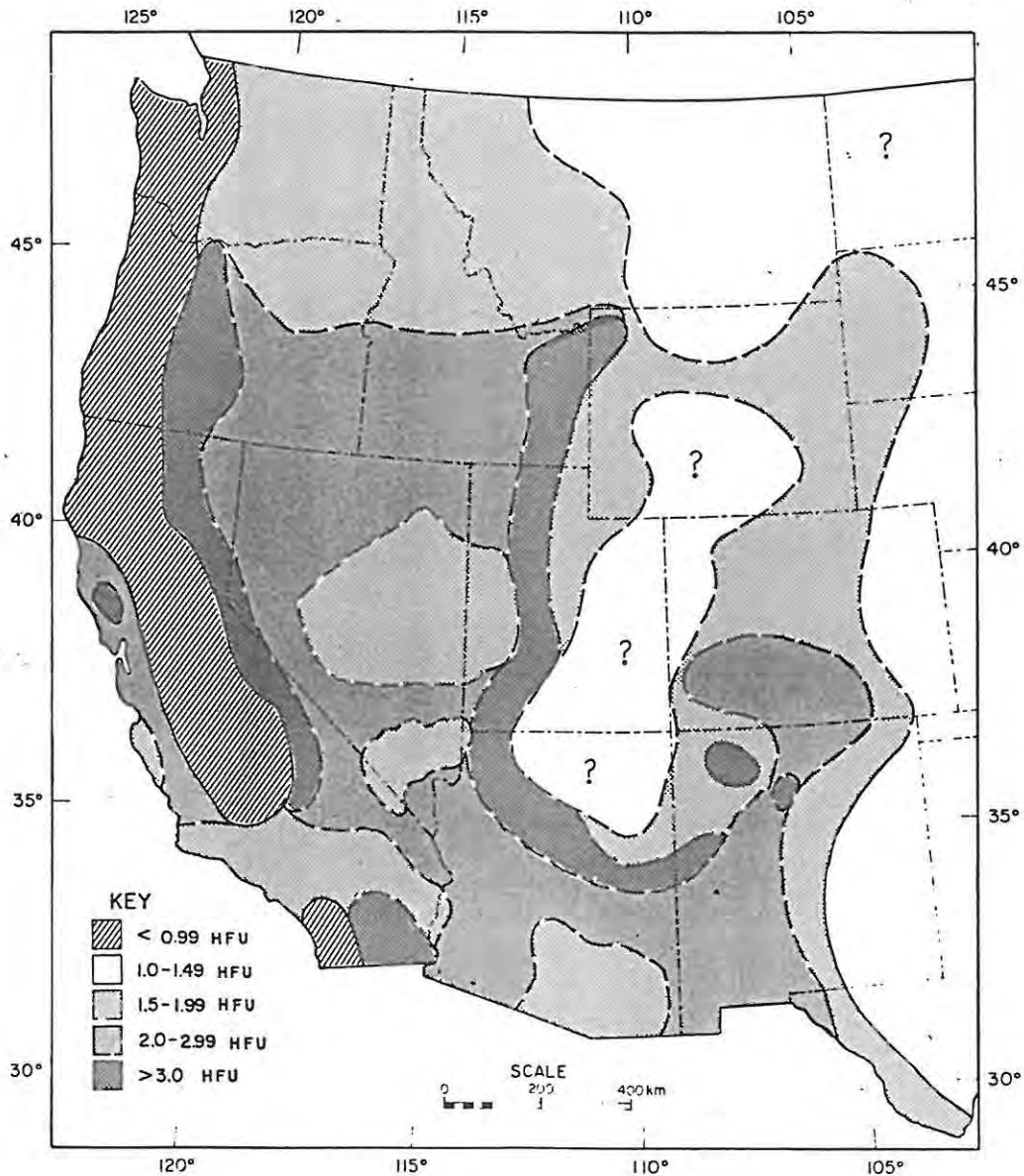


Figure 13: Energy-flux map of the western United States. Contours are in heat flow units (HFU). From Blackwell (1978).

Regional Gravity

Gravity anomalies reflect departures from radially symmetrical, mass homogeneity in a concentrically layered earth. For this reason, their patterns and relation to other geophysical and geological parameters can be used to infer something about the constitution of the lithosphere and underlying asthenosphere (Eaton and others, 1978). There are three types of gravity anomalies that can be used for interpretation of regional gravity surveys. Free-air anomalies only apply a correction for the elevation difference between the station and sea level. Simple Bouguer anomalies add a correction for mass difference between the station and sea level, while complete Bouguer anomalies also include a terrane correction. Isostatic anomalies take into account density contrasts within the crust and upper mantle. The choice of anomaly types is dependent on the number of assumptions one wishes to make on the nature of the earth. Free-air anomalies incorporate the fewest number of assumptions. They reflect all departures from mass homogeneity, including the mass of material above the datum plane. Since the Cordillera is characterized by large variations in regional elevations, anomalies related to elevation differences tend to mask other effects. Conversely, isostatic anomalies can only be calculated by using detailed models of the crust and upper mantle, and assuming a model for isostatic adjustment. The necessary information is not available on a regional scale for the western United States. For these reasons, the regional gravity map shown in figure 14 shows simple Bouguer anomalies. The absence of terrane corrections was partially compensated for by gridding (Eaton and others, 1978).

Figure 14 demonstrates that the gravity field alone does not provide comprehensive insight into the nature of the crust, lithosphere, and asthenosphere (Eaton and others, 1978). For example, the interiors of the Great Basin and Colorado Plateau have identical gravity values, although their crustal thickness differs by 15 km. The southern Great Basin and northern Sonoran Desert sections, on the other hand, have nearly identical crustal thicknesses, but gravity values differ by 100 mgal. Since the gravity anomalies in figure 14 have long wavelengths (> 100 km), they reflect lateral density variations beneath the observable surface geology. Thus, the gravity anomalies probably reflect complex interrelationships between densities and thicknesses of layers in the crust and upper mantle, and require input from other geophysical parameters to be used for interpretation.

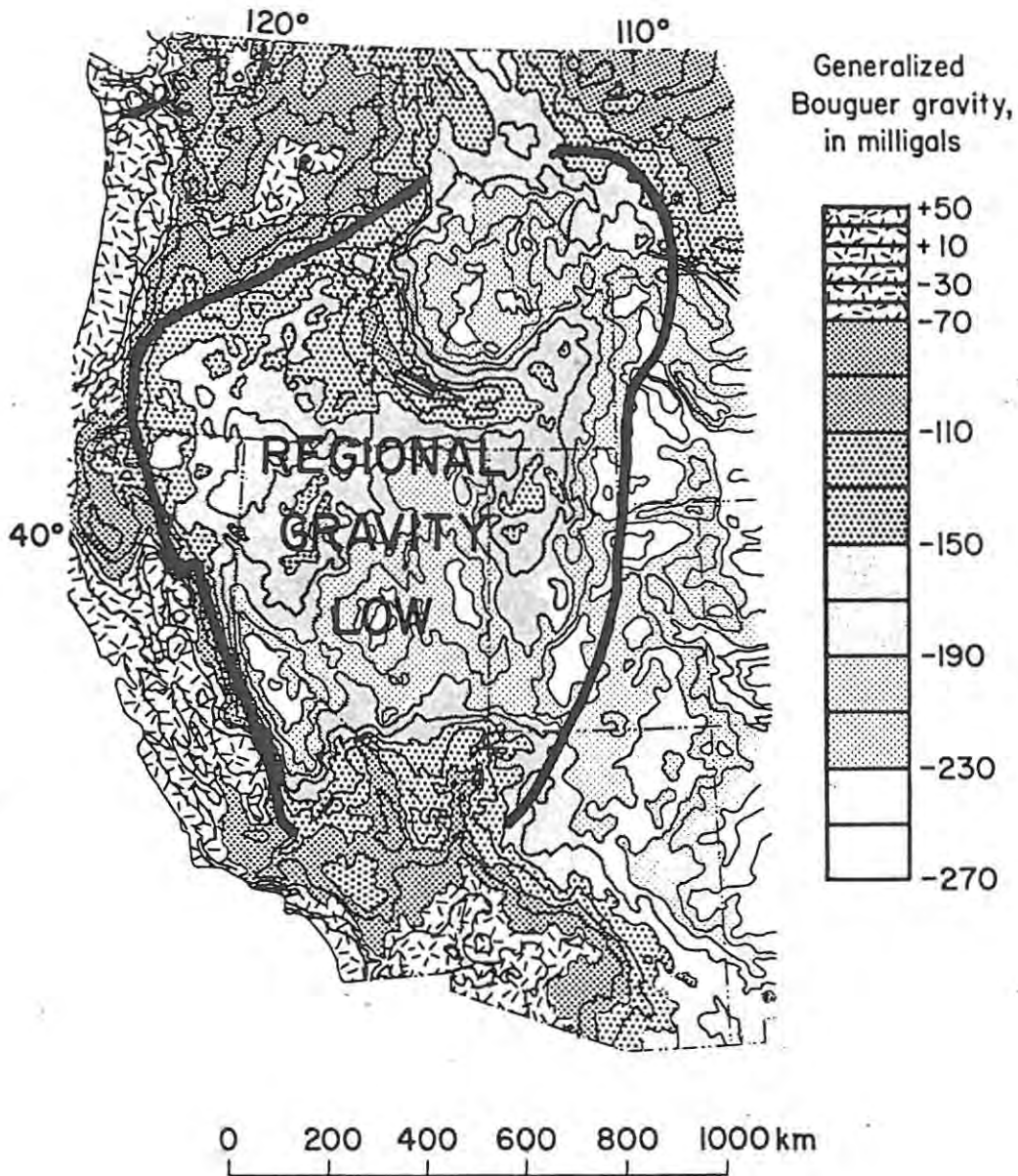


Figure 14: Generalized simple Bouguer anomaly map. From Eaton and others (1978).

The Bouguer anomalies do show an excellent correlation with regional topography (compare figures 5 and 14), suggesting isostatic compensation (Eaton and others, 1978). There are two main concepts of isostasy. The Pratt theory assumes that the density of the rock columns in the outer shell of the earth varies laterally above a constant depth of compensation and is expressed as a function of elevation on the earth's surface. The Airy theory proposes that the outer shell has a nearly constant density, and that the depth of compensation varies as a function of the thickness

of the columns (Condie, 1976). As seismic studies indicate both lateral variations in P-wave velocities (and therefore, in densities) as well as variations in crustal thickness (and probable depths of compensation), both the Airy and Pratt concepts probably contribute to isostatic compensation in the Cordillera (Condie, 1976; Prodehl and Pakiser, 1980).

The compensation level across the Cordillera is difficult to establish, particularly in areas with structural complexity, but probably varies from within the crust to within the upper mantle. For example, the crustal thickness of the Colorado Plateau is insufficient to explain all of the elevation, so low density mantle material also must be involved (Thompson and Zoback, 1979). Other areas, such as the Sierra Nevada, have a thick crust and the compensation level probably is within the crust. The situation is further complicated by variations in heat flow, since density is partially controlled by thermal phenomena. However, the parallelism between the generalized topography and Bouguer isogals is remarkable for an area undergoing active tectonism. This implies that the crust is extremely weak, and isostatic equilibrium is maintained by lateral flowage in the lower crust, and/or upper mantle (Gilluly, 1973; Thompson and Burke, 1974).

Although regional gravity surveys have limited value by themselves for interpretation of the crust and upper mantle, abrupt changes in the pattern of gravity anomalies can be used to identify some lateral discontinuities. For example, the northeast trending discontinuity in Oregon (the northwest border of the regional gravity low in figure 14) may be a significant crustal feature as it also corresponds with the northwest limit of the Mesozoic batholiths, the southern limit of thick Columbia River basalts, an average elevation change of 900 meters, and the northwest limit of extensional faulting. It also corresponds with the northwest margin of the Blue Mountains physiographic province. Eaton and others (1978) suggest this may represent the boundary between normal rifted continental crust to the SE and younger Cenozoic volcanic crust (or former oceanic crust?) to the NW. The southern margin of the Great Basin also shows a gravity discontinuity that correlates with the ENE-trending seismic belt and an elevation change. More localized gravity features can also be useful. For example, gravity lows in the San Juan Mountains and the Colorado mineral belt (not shown) probably are related to silicic Tertiary batholiths at depth (Prodehl and Pakiser, 1980), while gravity anomalies over Yellowstone indicate the presence of a magma chamber at depth (Eaton

and others, 1975). The symmetrical pattern of gravity values in the Great Basin suggested to Eaton and others (1978) that the pattern was formed by extensional, thermomagmatic episodes in the late Cenozoic history of the lithosphere (i.e. some sort of mantle plume). The northwest lineation of the pattern suggests that the earliest extension in the Great Basin was NE-SW, as opposed to the present NW-SE.

Regional Magnetism

Airborne magnetism probably is the best regional geophysical method for examining the upper crust. Data can be collected faster, cheaper and in more detail than by other methods. Also, magnetic surveys can reveal the products of both local and regional events that have been preserved from earlier geologic time to a greater degree than other kinds of geophysical surveys. Magnetic anomalies reflecting events in Precambrian time are still apparent over large areas. These features are very important as they reflect crustal features which may have repeatedly controlled later tectonic events.

Regional magnetic anomalies may be related to a number of sources. They may reflect upper crustal rock types, or isothermal surfaces of Curie point distribution (Condie, 1976). Major near surface intrusives and volcanics often have a magnetic signature. Magnetic anomalies may also be related to structural discontinuities, such as major faults or age province boundaries. The trends of magnetic anomalies may differ from the present tectonic trends, suggesting they are related to older lithological or structural elements in the crust at intermediate depths.

Although most of the Cordillera has been covered by airborne magnetometer surveys, only a limited amount of the data has been compiled on a regional map scale. The only regional studies are those of Zietz and others (1969), Zietz and others (1971), Stewart and others (1977), and Mabey and others (1978). These studies have found several important regional features which are reviewed below.


Aeromagnetism of the Colorado Plateau, southern Rocky Mountains, and Great Plains shows the characteristics of anomalies in the Precambrian crystalline basement. The basement in these regions usually is overlain by relatively thin, weakly magnetic sediments and the effects of Phanerozoic magmatism and orogenesis are limited in most areas. There are two broad NE-trending magnetic anomalies in the basement of the western United States. These zones are usually marked by discontinuities or lineations of magnetic

contours, rather than by distinct absolute values. One of these, the Colorado lineament (Warner, 1978), can be traced on aeromagnetic maps from the Grand Canyon, through Utah and Colorado, and onto the Great Plains (figures 15 and 16). The northwest margin of the lineament roughly coincides with the Mullen Creek - Nash Fork shear zone, a basement fault zone which separates terrane > 2400 Ma in central Wyoming from younger basement (< 1750 Ma) in Colorado. NE-trending mylonites within the lineament give dates of less than 1750 Ma (Warner, 1978). The Colorado mineral belt lies along the southeastern margin of this lineament. Northwest of the lineament, in northwestern Colorado and eastern Utah, the basement shows E-W magnetic trends that parallel the Uinta Mountains. The late Precambrian sediments of the Uinta Mountains were deposited in an E-W - trending basin, and later uplifted in a broad E-W - trending block during the Laramide orogeny. Thus, the two major magnetic trends in this region reflect basement structures which controlled sedimentation in late Proterozoic time, deformation during the Laramide orogeny, and magmatism in the Laramide and mid-Tertiary orogenies. A third, NW-trending magnetic lineation in the basement of the Colorado Plateau corresponds with the Pennsylvanian-age Uncompahgre uplift.

The other major NE-trend can be traced from the eastern Snake River downwarp, through Yellowstone, and onto the Great Plains of Montana (Eaton and others, 1975). There is no expression of this trend in the limited exposures of basement, but the coincidence of the magnetic lineations with the Snake River plain, and the cross-cutting relationship with other tectonic provinces suggest the magnetic anomalies are related to a major basement structure. The mid-Miocene to Recent volcanism in the Snake River plain and Yellowstone systematically decreases in age from SW to NE, suggesting magmatism is propagating along the basement structure. To the northeast of the volcanic field, several faults in the Great Plains parallel and coincide with the magnetic trend. The Snake River - Yellowstone trend also divides a basement to the northwest with NW-trending magnetic anomalies from a basement to the southeast with NE-trending anomalies (figure 15).

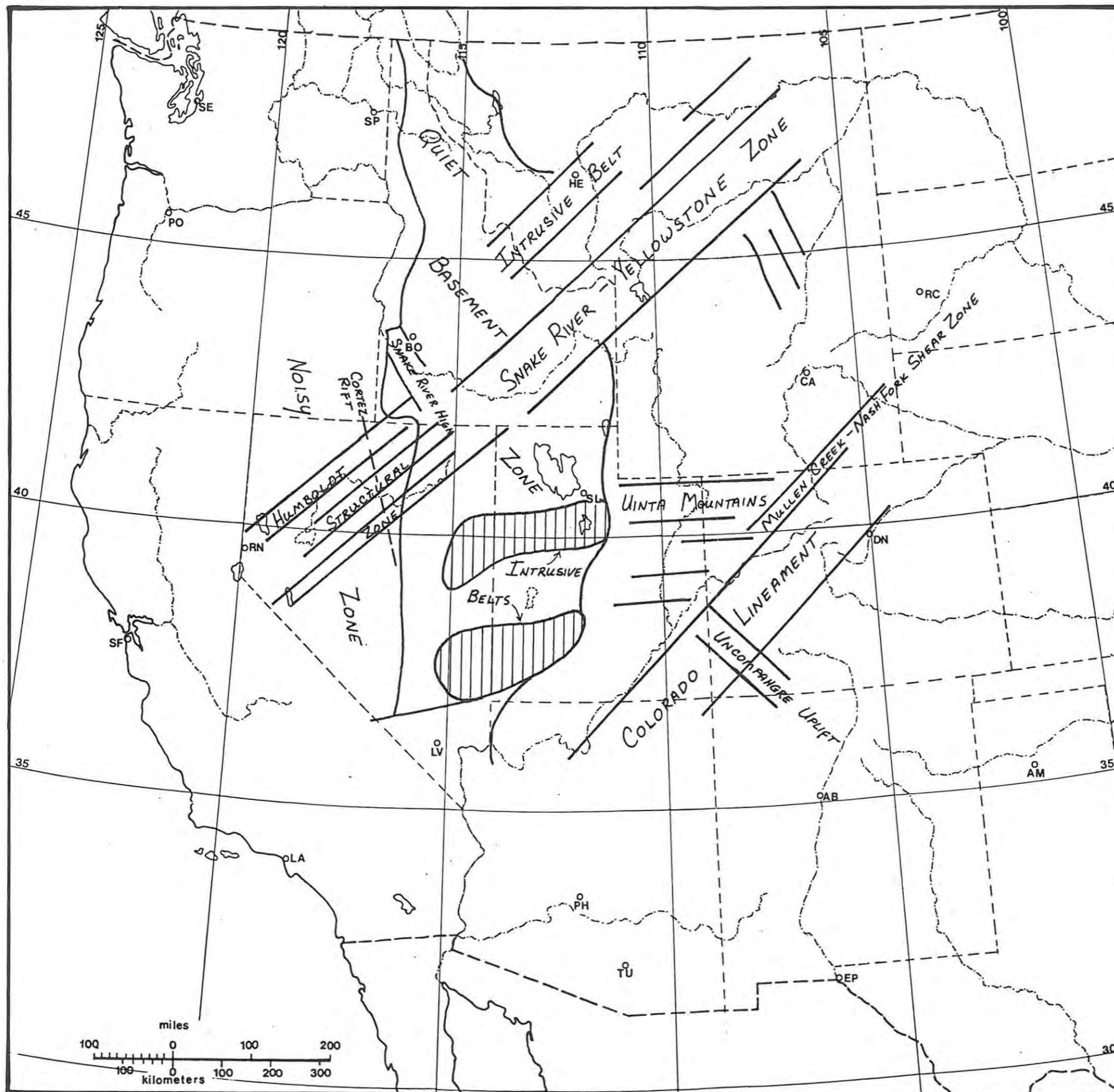
Mabey and others (1978) and Rowan and Wetlaufer (1981) have extended this trend to the southwest into northern and western Nevada. The Humboldt structural zone (figure 15) is not particularly well defined by magnetics. However, it does coincide with Landsat lineaments, a zone of major NE-trending faults, the NE-trending Battle Mountain heat flow high of

Figure 15. Major aeromagnetic features in the western United States. These features include lineations or trends in contoured data, as well as regions which have a characteristic magnetic signature.

 Intrusive belts

References

- Mabey and others, 1978
- Stewart and others, 1977
- Warner, 1978
- Zeitz and others, 1969
- Zeitz and others, 1971



Lachenbruch and Sass (1978), gravity linears, and an area with nearly continuous volcanic activity since late Eocene time (Rowan and Wetlaufer, 1981). The zone also contains a high concentration of metal mining districts and most of the hot spring activity in Nevada, as shown by Blackwell (1978, figure 8-4).

The magnetic signature of the basement also shows regional variations. One of the major aeromagnetic features of the Cordillera is a "quiet basement zone" trending N-S through eastern Nevada, western Utah and much of Idaho (figures 15 and 17; Mabey and others, 1978). Within this zone, magnetic anomalies from basement rocks are subdued. The eastern boundary coincides with the margin of the Cordillera geosyncline - Great Basin - Sevier thrust belt. The western margin is near the miogeosyncline - eugeosyncline transition, as well as the axes of the topographic high and of the symmetrical gravity features in the Great Basin. In Idaho, the boundaries approximately coincide with the Idaho batholith and the Belt Supergroup. The cause of the "quiet zone" is not obvious, but may be related to a combination of thick weakly magnetic sedimentary cover and a shallow Curie isotherm, due to high heat flow (Mabey and others, 1978; Stewart and others, 1977).

Abundant magnetic anomalies are found to the west of the "quiet zone" in Nevada, Oregon and Washington. These are related to Cordilleran eugeosynclinal sequences and Nevadan-age intrusives in Nevada and in the Blue Mountains, as well as thick Cenozoic volcanics of the Columbia Plateaus in Oregon and Washington. The major magnetic trends in western Nevada are N-NNW and WNW, oblique to the present tectonic fabric. These trends more closely reflect patterns of volcanism preceding basin-range tectonics.

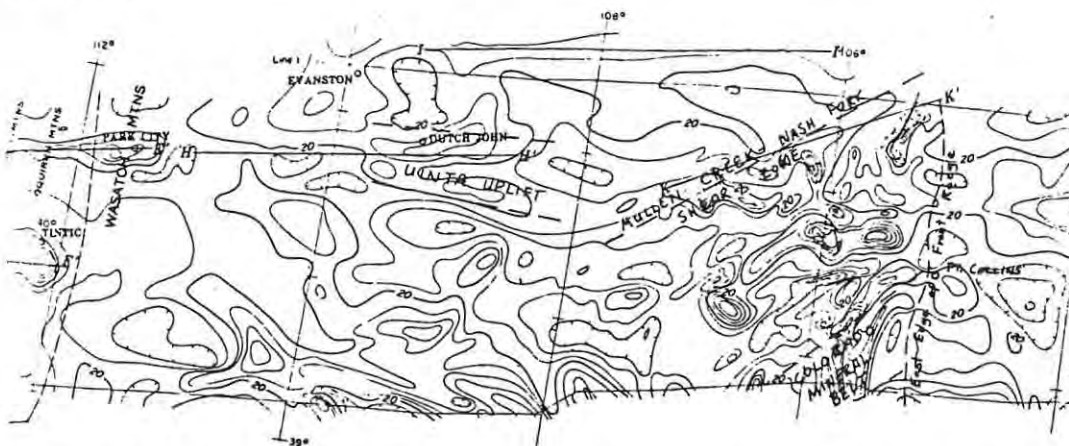


Figure 16: Aeromagnetic survey from the Colorado Front Range to Salt Lake City, Utah. Modified from Zeitz and others (1969).

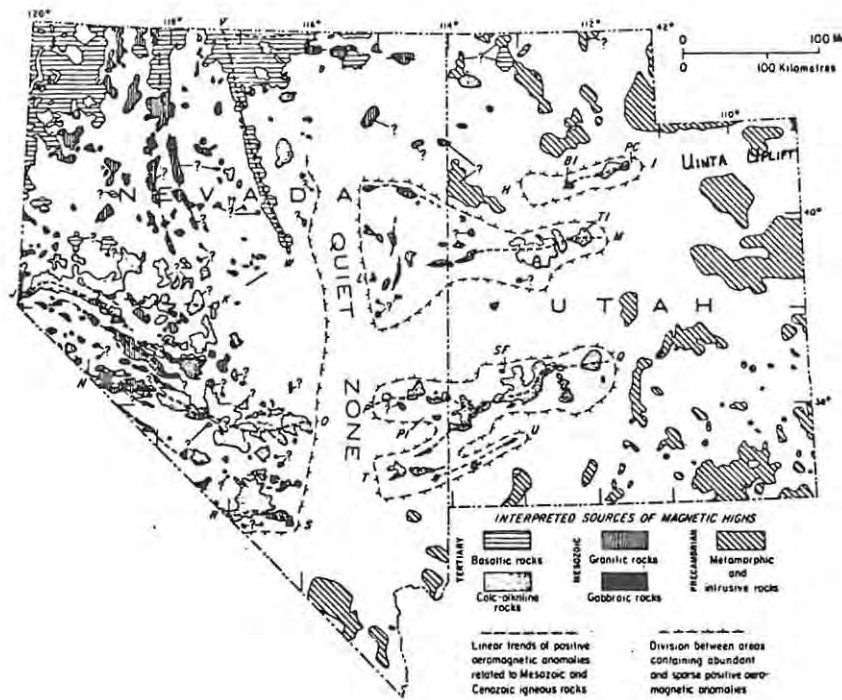


Figure 17: Interpreted sources of magnetic highs in Nevada and Utah. Mining districts: BI, Bingham; PC, Park City; TI, Tintic; PI, Pioche; SF, San Francisco. From Stewart and others (1977).

Major near surface intrusives and major volcanic fields may also be the source of linear belts of magnetic anomalies. Two E-W - trending belts in the "quiet zone" of Nevada and Utah are particularly distinctive (figures 15 and 17). These belts correlate with zones of late Mesozoic and Tertiary intrusives and abundant volcanics (Stewart and others, 1977). The northern belt is aligned approximately with the E-W - trending Uinta uplift. Each belt contains two E-W - trending mineral belts which include virtually all of the significant base and precious metal deposits of Utah and several important districts in Nevada. The southern boundary of the southern belt coincides with the previously mentioned ENE-trending seismic zone across southern Nevada. Although there is no direct evidence, the alignment of magmatic activity suggests these belts are controlled by basement structures.

Several other belts of magnetic anomalies coincide with zones of magmatism. A NE-trending belt in Idaho and western Montana includes numerous Laramide intrusives with associated mineral deposits (Zeitz and others, 1971; figures 15 and 18). A narrow NNW-trending magnetic high in north central Nevada is caused by a dike swarm of Miocene basalts (figure 17). These are thought to be related to the initiation of basin-range tectonism, so the feature is termed the Cortez rift (Mabey and others, 1978). A magnetic high related to Snake River basalts in southwestern Idaho is nearly parallel to the Cortez rift, and may also be related to a zone of rifting. These features also indicate that the initial direction of extension in the Great Basin was NE-SW.

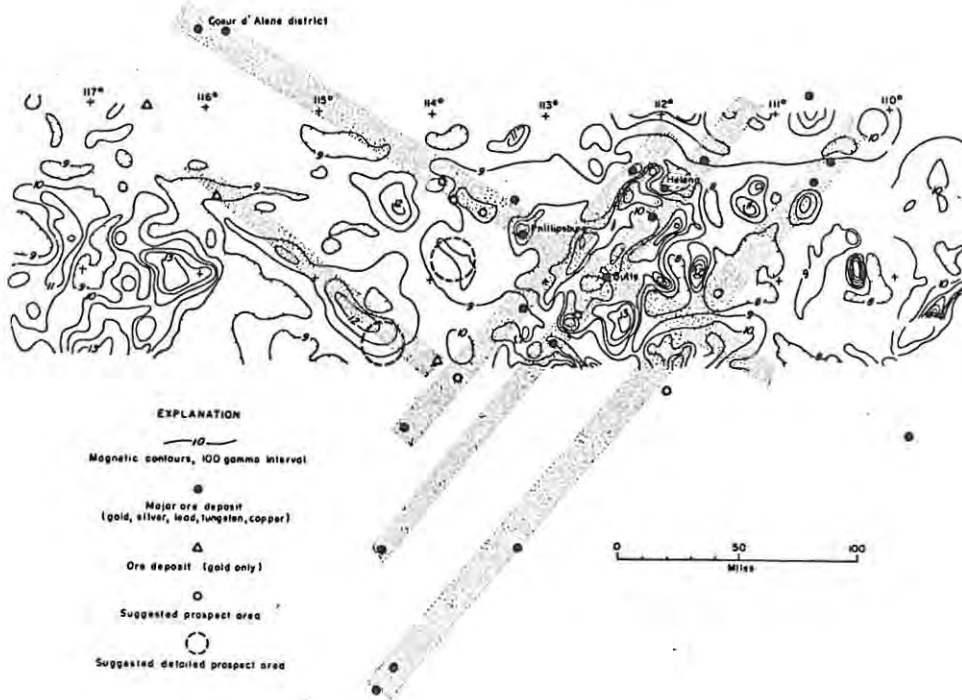


Figure 18: The spatial coincidence of magnetic linear features with mining districts in Idaho and Montana. From Zeitz and others (1971).

Regional aeromagnetic coverage of western Washington and Oregon, California, southern Arizona and New Mexico is not available. However, similar types of magnetic features undoubtedly are present in these areas.

Summary and Interpretation of Geophysical Data

This review of structures and regional geophysical data in the western United States demonstrates the complexities of the crust and upper mantle.

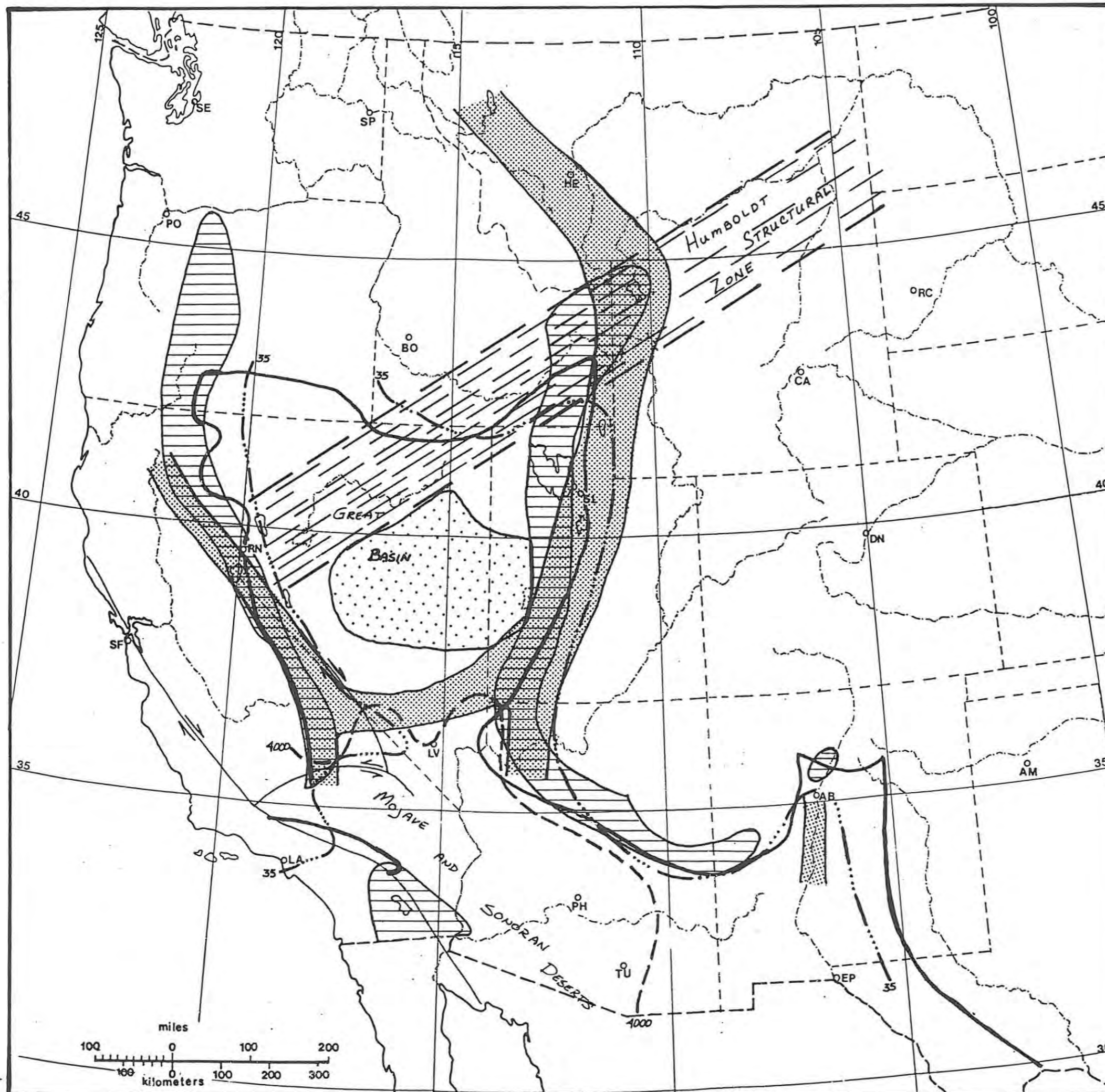
Typically, large areas have similar geophysical properties and are separated from other homogenous areas by sharp to gradational discontinuities. Often these areas coincide with physiographic provinces, demonstrating the interrelationships between geophysical properties, topography, and physiography. Discontinuities and significant variations in geophysical properties may also be present within otherwise homogenous areas. The present geophysical properties of the crust and upper mantle in the western United States provide information on present tectonic processes as well as indicating features that controlled earlier processes.

The Basin and Range province provides examples of the interrelationships of crustal and upper mantle features. The entire province is characterized by extensional faulting (figure 7), thin crust (figure 10), and high heat flow (figure 12). Much of the province is characterized by low P_n velocities (figure 11), indicative of partial melting in the upper mantle. Other properties differ sharply between and within the various subprovinces of the Basin and Range (figure 19). For example, the Mojave and Sonoran deserts (approximately outlined by the 4000 foot contour, figure 19) are characterized by lower elevations, higher gravity values, and less seismicity (except in the vicinity of the San Andreas system) than the rest of the province. Also, the ranges have been more deeply weathered than elsewhere since range front faults have been inactive for up to 9 million years. There are no zones of unusually high heat flow and energy flux (except in the vicinity of the Salton Trough) and there has been only minor Recent volcanism. These properties suggest a relationship between regional uplift and tectonic activity, seismicity, energy flux, and volcanism.

The eastern and western margins of the Great Basin (figure 19) are marked by belts with high energy flux and high seismic activity. They are also sites of abrupt changes in average elevation (figure 5), recent volcanism, active faults (figure 8) and rapid changes in crustal thickness (figure 19). Similar changes are associated with the Rio Grande rift and, to a lesser extent, the southern margin of the Colorado Plateau. These correlations suggest active tectonism is intimately related to crustal and upper mantle structural variations.

Another important feature shown on figure 19 is the ENE-trending seismic zoning, cutting across southern Nevada. This zone approximately coincides with a change in regional elevation and a zone of slightly higher energy flux, as well as a change in direction of basin-range faulting (figure 7),

Figure 19. Combined geophysical data.



- Border of Basin and Range Province (from figure 3)
- - - 4000 foot topographic contour (from figure 5, closely corresponds with the -130 mgal contour from figure 14)
- ▨ Seismic zones (from figure 8)
- 35 km contour of depth to Moho (from figure 10)
- ▩ High energy flux (from figure 13)
- ▤ Low energy flux (from figure 13)
- ▨ Humboldt Structural zone (from figure 15)

a change in the regional magnetic signature (figure 7), the southern limit of Miocene volcanism, and the northern outcrop limit of Precambrian crystalline basement (figure 1). The crustal thickness in this zone is complex and not fully resolved. (Compare Prodehl, 1979, figure 88 with Smith, 1978, figure 6-2.) The exact relationship of these various features is not understood, but this zone probably represents a major crustal discontinuity.

The Humboldt structural zone cuts across physiographic boundaries as well as containing regions with similar geophysical properties. This zone is characterized by NE-trending fractures and magnetic and gravity linears, as well as a zone of high heat flow (figure 12), numerous hot springs (Blackwell, 1978, figure 8-4), and very recent volcanism. Areas in Nevada experienced nearly continuous volcanic activity from 43 to 6 Ma (Rowan and Wetlaufer, 1981, figure 10), while volcanism in the Snake River downwarp has been propagating to the northeast from 10 Ma to the present (eg. Yellowstone). This belt is thought to represent a zone of crustal weakness that may have existed since the Precambrian (on the basis of magnetic linears in the basement under the Great Plains).

Other areas of the Cordillera show similar types of relationships between the various geophysical and structural properties of the crust and upper mantle. However, most are not as spectacular, probably because the Great Basin, Rio Grande rift, and Snake River downwarp are more tectonically active than other areas (with the exception of the San Andreas system). Also, data is rather sparse for the Pacific Northwest, while the pattern in California is highly complex and fragmented due to active transform faulting.

Several broad generalities can be made about the correlation of various geophysical properties. For example, areas with low topographic elevations usually have a thin crust, the major exception being the Great Basin. Also, most tectonically and volcanically active belts are thermal boundaries and/or areas of unusually high energy loss (Blackwell, 1978). Gravity contours correlate very well with topographic contours, indicating regional isostatic equilibrium. Most magnetic linears that are at oblique angles to the orogenic belt are in areas underlain by Precambrian crystalline basement, suggesting these features were formed by earlier orogenies. Magnetic linears also appear to show a better correlation with magmatic belts and associated hydrothermal ore deposits than to other geophysical features.

Regional geophysical data from the Cordillera has been used to relate plate tectonics to the development of the present major tectonic features. The major tectonic features considered are the San Andreas transform system, the Cascade volcanic arc, basin-range structures, and regional uplift of the Cordillera. The Cascade volcanic arc is similar to other volcanic arcs developed at consuming plate margins (eg. the Andes) and present activity probably is related to a subduction zone off the Oregon - Washington coast. (See Coney, 1978). Likewise, magnetic anomaly patterns in the northeastern Pacific Ocean suggest the present episode of strike-slip motion in the San Andreas fault system was initiated by subduction of an oceanic spreading center approximately 29 Ma (Atwater and Molnar, 1973). Most theories on the origin of basin-range faulting also are directly or indirectly related to this same event, and can be grouped into four main categories: (1) oblique tensional fragmentation associated with right-lateral transform faulting (Atwater, 1970), (2) back-arc spreading related to mantle upwelling and associated spreading above a subduction zone (Scholz and others, 1971), (3) spreading along the subducted East Pacific Rise (McKee, 1971), and (4) spreading related to mantle plumes caused by deep-mantle advection (Smith and Sbar, 1974). Present geophysical evidence indicates the Basin and Range province is experiencing extensional stress, while the high heat flow indicates activity in the lower crust or upper mantle. There is no evidence to indicate if mantle-crust activity is caused by extension (Atwater concept), or is the cause of extension (other three concepts).

Regional uplift has been ascribed to: (1) thermal expansion of the lithosphere by deep mantle plumes or hot spots, a subducted ridge, or by frictional heating by movement along the lithosphere-asthenosphere interface, (2) volumetric expansion by partial melting, hydration reactions, introduction of volatiles, or phase changes, and (3) crustal thickening by underplating, subduction at a shallow angle, thrust faulting, or other processes involving a horizontal mass transfer of material (McGetchin, 1979). Various plate subduction models have been proposed to generate one or more of these processes, usually involving only one of the major physiographic provinces. However, regional uplift has occurred more or less synchronously in various regions such as the Colorado Plateau, southern Rocky Mountains, Great Basin, and Sierra Nevada. The relationships of these uplifts with a particular plate tectonic event is difficult to establish. Rather, uplift appears to be related to a regional event in

the crust and upper mantle which may be only indirectly related to plate tectonic processes.

In conclusion, much of the present tectonic activity in the Cordillera appears to be directly related to features in the crust and upper mantle. Most of these features are thought to be products of recent plate interactions, but some have been preserved from earlier orogenic cycles. A variety of different plate tectonic models have been formulated to explain recent tectonic events in the western United States. These models give reasonable explanations for the development of tectonic features near the plate margins, such as the San Andreas fault system, and the Cascade Range. However, the diversity of plate tectonic models proposed to explain tectonic processes in the continental interior, such as in the Basin and Range province, the Colorado Plateau, and the Rio Grande rift, reflects the fact that tectonism in these areas does not show a clear relationship to plate tectonic processes. Considering this lack of agreement for the most recent events, one should be wary of models for earlier tectonic events (including those presented in the following sections), as these are based on a smaller data base.

THE TECTONIC FRAMEWORK OF MAGMATIC ENVIRONMENTS

"To attribute magmatism more than 700 km from the outcrop of a subduction zone to activity along that zone is simply to assert that all magmatism of intermediate chemistry is related to plate tectonics and to prejudge the whole problem." James Gilluly, 1971

The western United States has a long history of magmatic activity, with each period characterized by unique distributional and compositional patterns. These changing patterns appear to be related to changes in the tectonic environment, and can provide useful data for determining the characteristics of that environment. Although magmatism in one period may show some similarities with magmatism in other periods, there is no true repetition of styles or patterns of magmatism, i.e. magmatism in the western United States shows a long term evolutionary pattern rather than a cyclic pattern. Whether this reflects a peculiarity of this region, or represents long-term evolution of tectonic and magmatic processes within the earth is beyond the scope of this report.

An understanding of magmatic processes in the western United States is particularly important for understanding the distribution of metallic mineral deposits, since nearly all of these deposits show a direct association with magmatism. For this reason, the magmatic history of this region and its correlation with tectonic processes are reviewed in the following sections.

Precambrian and Paleozoic Magmatism in the Craton

The nature of the tectonic environment of the western United States during the Archean and lower Proterozoic is not well understood. Investigations have been hampered by discontinuous, limited exposures (outcrops of Precambrian rocks are limited to about 5 to 10% of the area), as well as the effects of subsequent tectonism. Also, the limited economic importance of mineral deposits associated with these rocks has not spurred investigations. Nonetheless, a generalized picture is starting to emerge from radiometric dating.

There are two major age provinces in the crystalline basement of the western United States, an Archean province (> 2500 Ma) in the north, and an early to middle Proterozoic province (> 1000 Ma) in the south (figure 20). The extent of these provinces has been complicated by overprinting by younger Precambrian and Phanerozoic igneous and metamorphic events. No Archean radiometric ages have been found south of a major structural discontinuity, the Mullen Creek - Nash Fork shear zone (figure 20),

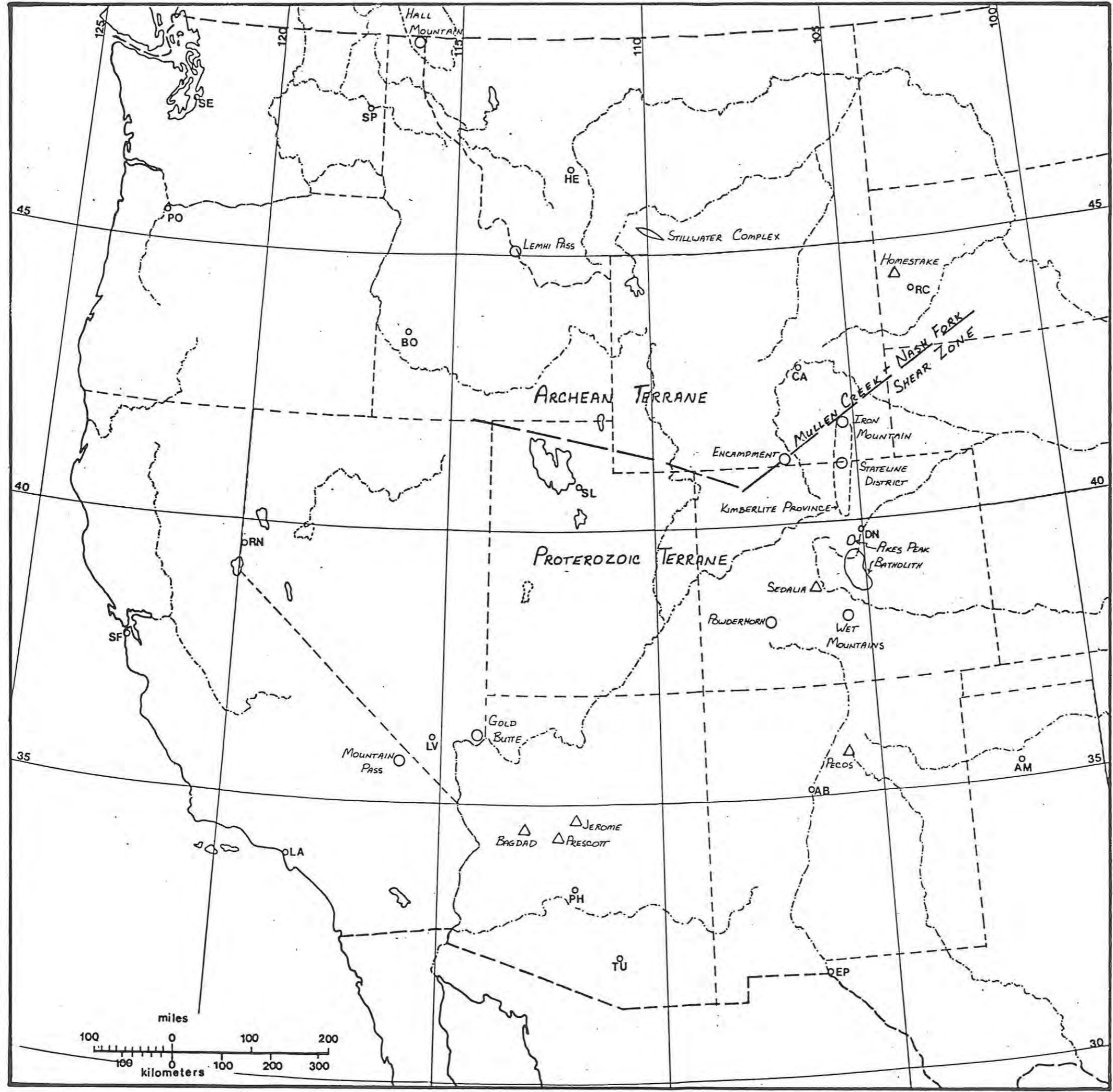


Figure 20. Precambrian and Paleozoic Magmatism in the Craton.

- △ Volcanogenic deposits
- Magmatic or epigenetic deposits

- Homestake - Au
- Sedalia - Cu, Zn, Ag, Pb
- Pecos - Zn, Pb, Ag, Cu, Au
- Jerome - Cu, Zn, Ag, Au
- Prescott - Zn, Pb, Au, Ag, Cu
- Bagdad - Zn, Cu, Au
- Stillwater Complex - Cr, PGM, Ni, Cu
- Encampment - Cu, Au, Ni, Co, PGM
- Iron Mountain - Ti, V, Fe
- Pikes Peak Batholith - Be, Fl (Sn, W, Mo, U)
- Gold Butte - REE
- Mountain Pass - REE, Th
- Powderhorn - Nb, REE, Th, Ti
- Wet Mountains - REE, Th, Nb
- Lemhi Pass - Th
- Hall Mountain - Th
- Stateline District - diamonds

References

King, 1976
 McCallum and Mabarak, 1976
 Staatz, 1974
 Volborth, 1962
 Warner, 1979

suggesting this marks the southern limit of the Archean continent (King, 1976).

Archean Magmatism

Archean terrane (Precambrian W of the United States Geological Survey classification) in Wyoming and Montana mostly is composed of paragneiss, orthogneiss, and granite intrusions with a complex history of deformation. Some infolded belts of supracrustal rocks, including metasediments and metavolcanics which resemble the greenstone belts in the Superior province of the Canadian Shield, also are present (King, 1976). The entire sequence has been intruded by post-tectonic tonalitic to granodioritic plutons and diabase dikes with ages of 2760-2500 Ma (Burchfiel, 1979).

The Stillwater Complex (figure 20), a unique igneous feature in the Archean terrane, is a major layered mafic-ultramafic intrusive which intrudes and overlies Archean gneiss. Its age is estimated to be between 2700 and 2500 Ma (Proffett, 1979). The complex consists of three series of layered rocks with a preserved thickness of 5500 m and an exposed strike length of 48 km (King, 1976). According to Todd and others (1981), a basal series with highly variable thickness (averaging about 50 m) is composed of norite and bronzitite zones. The overlying ultramafic series, 800 to 1200 m thick, contains a lower peridotite zone and an upper bronzitite zone. The peridotite zone consists of up to 15 cycles of interlayered harzburgite and bronzitite with thinner chromitite, while the bronzitite zone mostly consists of massive pyroxenite. The uppermost banded series is at least 4500 m thick, with the top covered by Cambrian sediments. This series is a complicated succession of norite, two pyroxene-gabbro, and anorthosite with subordinate gabbro, troctolite and feldspathic peridotite. The J-M reef, a 1-3 m thick layer that is grossly comparable to the Merensky reef, occurs 400-450 m above the base of the banded series.

Proterozoic Magmatism

Lower Proterozoic (Precambrian X) crystalline basement is found in the Black Hills, south of the Mullen Creek - Nash Fork shear zone in Wyoming and Colorado, and throughout New Mexico, Arizona and southern California. A few scattered outcrops are found in Nevada, Utah, Texas, Montana and Idaho, while supracrustal Precambrian X units are found immediately north of the Mullen Creek - Nash Fork shear in Wyoming. Rock types include a wide assortment of metavolcanics, metasediments, and syn- to post-tectonic intrusives.

Metavolcanic and metasedimentary sequences similar to those found in Archean greenstone belts are located in the Precambrian X terrane of the Black Hills, Colorado, New Mexico, and Arizona. These belts have ages ranging from 1650-1850 Ma (King, 1976), and have experienced strong deformation and greenstone to amphibolite grades of metamorphism. In Arizona, where the belts are best exposed and have been studied in the greatest detail, there are three major subdivisions; (1) a northwest region with high-grade metamorphosed paragneisses containing minor volcanic accumulations; (2) a central region of dominantly metavolcanic and metavolcaniclastic strata, and (3) a southeastern region of paraschist with minor volcanic intercalations (Anderson and Guilbert, 1979). Like the Canadian Shield greenstone belts, mafic to felsic volcanic sequences with associated exhalite horizons and volcanoclastic sediments are found in these greenstone terranes, but they seldom achieve the magnitude of the Canadian greenstone piles.

The lower Proterozoic terrane has been intruded during at least three major periods of granite plutonism, with the younger groups emplaced at progressively shallower levels in the crust (King, 1976). The first phase is represented by a group of syntectonic, generally concordant granodioritic batholiths. These include the Boulder Creek Granite in the Colorado Front Range and many of the granitic intrusives in Arizona. Intrusion took place during the last major phase of folding of the Precambrian crystalline basement and the granites usually show some foliation. The second, most widespread magmatic episode occurred from 1470 to 1390 Ma. It includes late syntectonic to post-tectonic, concordant to discordant granitic batholiths and small plutons. Examples include the Sherman and Silver Plume Granites in Colorado, the Embudo Granite in New Mexico, and the Oracle Granite in Arizona. This magmatic event is not associated with any major tectonism, but it is broadly contemporaneous with the final cataclastic deformation of the basement and intrusives show local foliation (King, 1976). Several anorogenic anorthosite-syenite complexes in California and Wyoming (eg. Iron Mountain, figure 20) were also intruded during this period. The last phase of magmatism is the least extensive, but is the most unusual and of some economic importance. These post-tectonic intrusives include the Pikes Peak Granite in the Colorado Front Range (1040 Ma), Rapakivi-type granites near Gold Butte, Nevada (1060-1090 Ma), and the Mountain Pass alkaline complex in California (900-1000 Ma), all shown on figure 20.

The Pikes Peak batholith is an elongate (100 km N-S by 50 km E-W), composite, subalkalic to alkalic intrusive that was emplaced at shallow depths (Barker and others, 1975). The predominant phases are biotite granite and biotite-hornblende granite with minor amounts of quartz syenite, fayalite granite and riebeckite granite. Seven small sodic and late potassic plutons, including the Redskin stock, intruded along linear zones within and on the margin of the batholith (figure 21; Wobus and Anderson, 1978). Local facies of the batholith, as well as the Redskin granite, are enriched enough in rare elements such as Be, Sn, F, Li, Rb, W, U, and Mo, to be called "tin granites" (Hawley and others, 1977). The entire Pikes Peak complex averages 0.35% F. The batholith is thought to have been generated by a reaction melting system in which a basaltic magma of mantle origin reacted with, and partially melted, the lower to intermediate crust (Barker and others, 1975).

The Rapakivi-type granites of Gold Butte are chemically similar, but more mafic than the Pikes Peak batholith (Volborth, 1962). These granites and associated pegmatites also show enrichment in fluorine and the rare earth elements. At Mountain Pass, carbonatites are associated with a potash-rich igneous complex including shonkinite, syenite, and granite. The entire complex, especially the carbonatites, are enriched in rare earth elements, barium and uranium.

This period of magmatism (1000 Ma) occurred during deposition of the Belt Supergroup and associated sediments as well as the Grenville event. The Belt sedimentation may be related to rifting along the western continental margin (Burchfiel and Davis, 1975), while the Grenville Province, extending in a linear belt from Newfoundland to Texas, shows similarities with Phanerozoic orogenic belts (King, 1976). However, the rifting event is based more on conjecture than fact, while the Grenville belt has limited exposures in the southwestern United States but is not well understood. Therefore, there is no obvious correlation of the 1000 Ma magmatic event with either of these tectonic events.

Paleozoic Magmatism

Paleozoic magmatism within the craton of the western United States is extremely limited, being confined to a few alkalic complexes in the Powderhorn and Wet Mountain districts of Colorado, and numerous kimberlitic diatremes in the Front Range of Colorado and Wyoming (figure 20).

The alkalic complexes at Powderhorn and in the Wet Mountains have been

dated at 570 and 520 Ma, respectively (Olson and Hedlund, 1981; Armbrustmacher, 1979). At Powderhorn, a sequence of pyroxenite, uncomphagrite, ijolite, and nepheline syenite has been intruded by late stage massive carbonatite and carbonate dikes (Armbrustmacher, 1980; Olson and Hedlund, 1981). The perimeter of the complex shows fenitization. The complex shows enrichment in Th, Ba, Nb, P, Sr, U, and rare earth elements, with the greatest concentrations usually associated with carbonatite. The three small alkalic complexes in the Wet Mountains contain similar rock types and rare element enrichment (Armbrustmacher, 1979).

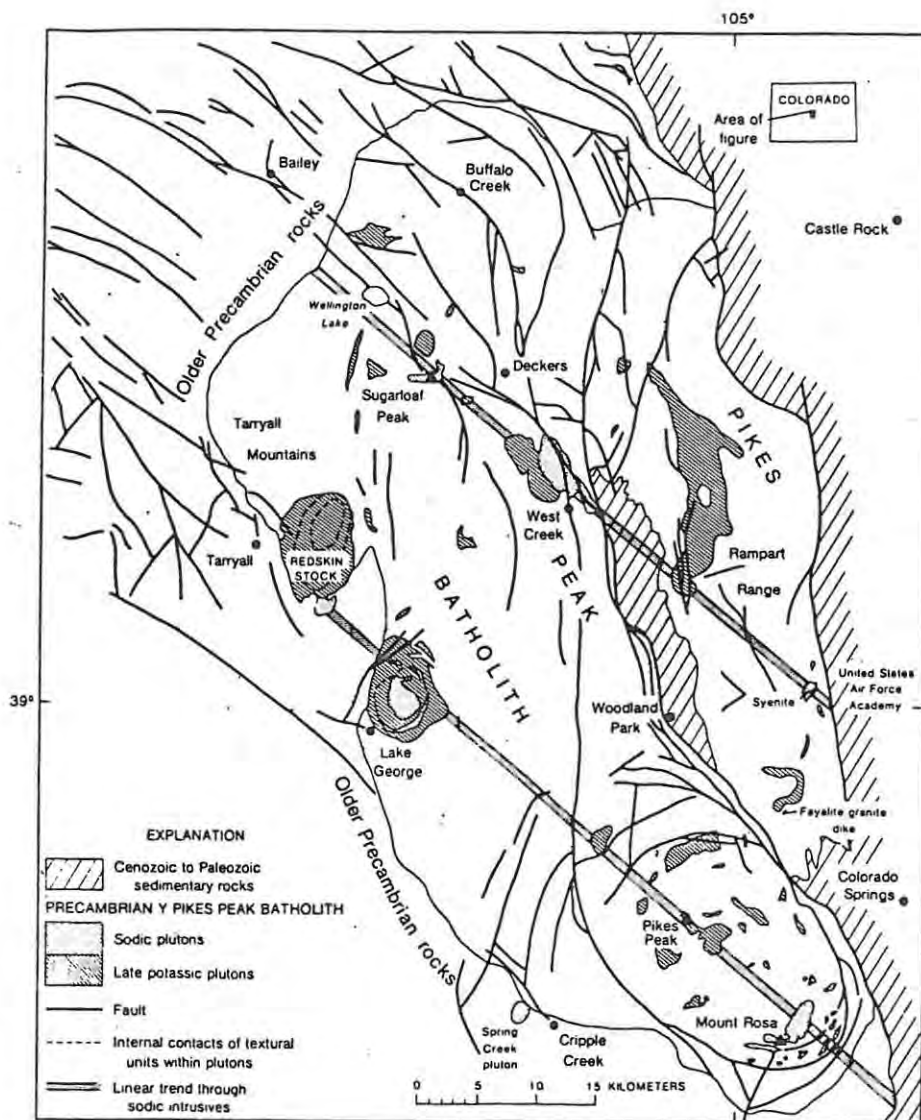


Figure 21: Geologic index map of the Pikes Peak batholith showing locations of sodic and late potassic plutons and linear trends through sodic intrusive centers. From Wobus and Anderson (1978).

In excess of 90 kimberlite localities have been discovered in the Colorado - Wyoming State Line district, while several other kimberlitic diatremes have been found at Iron Mountain, Wyoming and Boulder, Colorado (Hansel and others, 1979). The kimberlites in the State Line district usually show an intrusive breccia texture, and are mineralogically and chemically similar to kimberlite occurrences in South Africa (Meyer, 1976). The largest kimberlitic diatreme has dimensions of 100 m by 600 m. Fossiliferous xenoliths suggest a late Silurian - early Devonian age (McCallum and Mabarak, 1976). Several of the kimberlites in the State Line district recently (1975) were discovered to be diamondiferous.

Magmatism in Accreted Terranes

Approximately 500 km or more of terrane has been accreted to the western United States since late Precambrian time. Figure 22 shows several indicators used to estimate the original extent of Precambrian crystalline basement in the western United States. The eastern limit of the Cordilleran miogeosyncline, marked by the 300 m isopach, is postulated to represent the western extent of Precambrian crystalline crust of normal thickness. The western limit of miogeosynclinal facies, possibly representing the platform edge of the Cordilleran geosyncline, is postulated to represent the western limit of Precambrian crystalline basement.

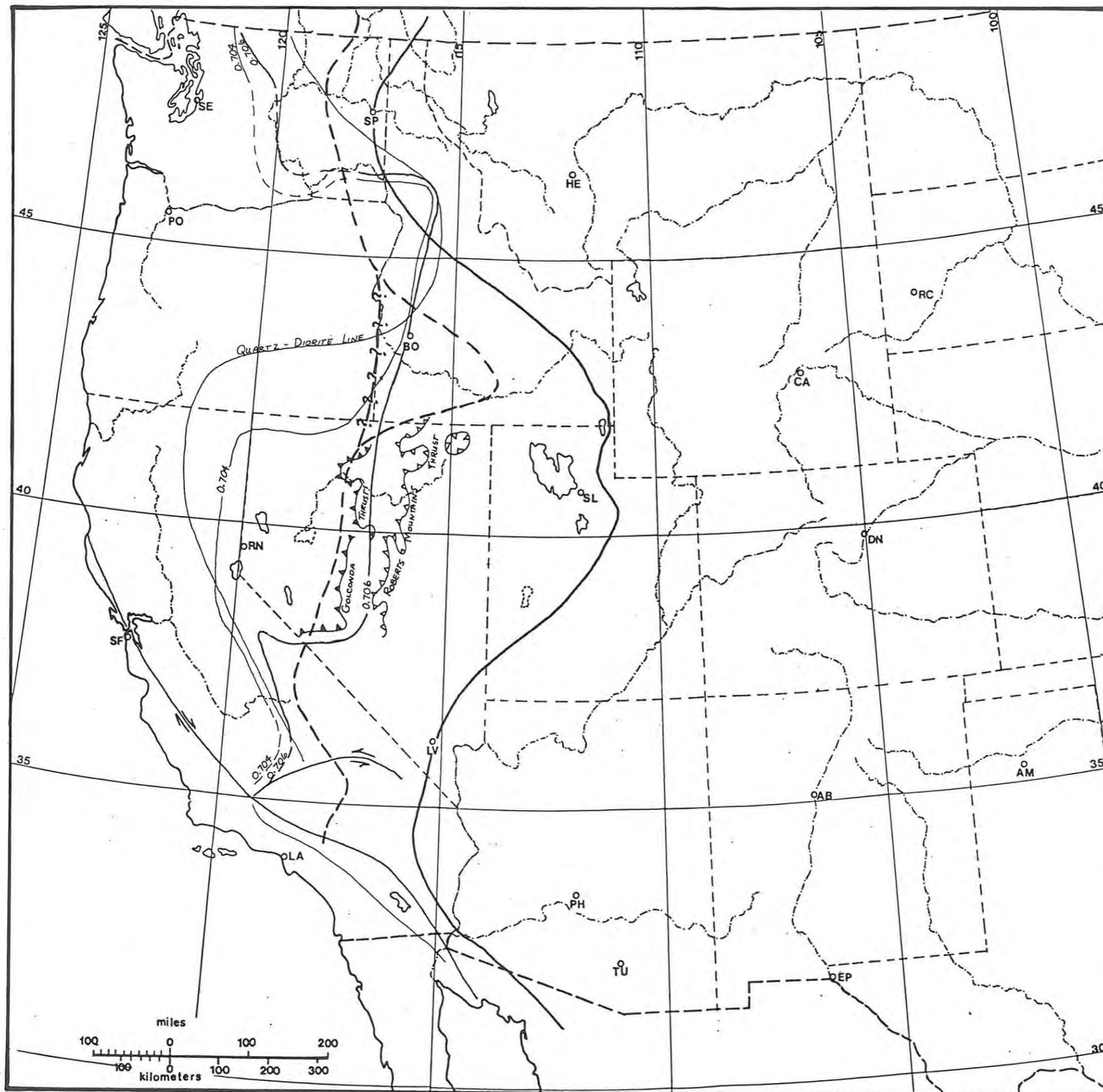
Other indicators of Precambrian basement are derived from chemical analysis of Mesozoic and Cenozoic intrusives. Moore (1959) was the first to quantify the observation that Mesozoic and Cenozoic intrusives tend to become more felsic towards the east, by defining the eastern limits of occurrence of quartz diorite (figure 22). This line could be considerably refined by including more recent data and would probably correspond closely with the 0.704 Sr isotope line. Kistler and Peterman (1973) and Armstrong and others (1977) found that intrusives in miogeosynclinal rocks have initial Sr isotope ratios > 0.706 while intrusives in eugeosynclinal rocks have initial Sr isotope ratios < 0.704 . The high Sr isotope ratio is thought to be due to contamination or partial derivation of the plutons by the crust that contains them (Armstrong and others, 1977). These observations permit construction of a postulated Precambrian margin through areas with extensive Tertiary cover and through the major Mesozoic batholiths. For these reasons, the 0.706 Sr isotope line may be the best indicator of the extent of Precambrian crystalline basement. Thus, all of Oregon, most of California, western Nevada, and a considerable portion of Washington are postulated to have no Precambrian basement.

Figure 22. Indicators for the craton margin in the western United States.

- Eastern limits of upper Precambrian and lower Cambrian quartzite, siltstone, and carbonate facies
- - - Western limits of upper Precambrian and lower Cambrian quartzite, siltstone, and carbonate facies
- · - · - Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.704$
- - - Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$
- Quartz diorite line (eastern limit of quartz diorite)

References

- Armstrong and others, 1977
- Kistler and Peterman, 1973
- Kistler and Peterman, 1978
- Moore, 1959
- Speed, 1979
- Stewart, 1978



The geophysical data reviewed earlier shows that the area between the Pacific coast and the western margin of the Precambrian basement is now composed of continental crust. The method of formation of this new terrane has not been resolved satisfactorily. There are two major theories to account for the accretion of this large area: (1) the terrane may be a product of Paleozoic and Mesozoic island arcs that developed along a subduction zone along the Pacific coast (Burchfiel and Davis, 1972, 1975), or (2) the area may be the product of numerous collisions of the North American craton with small fragments of continental, island arc, and oceanic crust, mostly during Mesozoic and early Cenozoic time (Coney and others, 1980). The expected location and types of mineral deposits found in the accreted terrane is influenced by which of these two processes is envisioned.

Field work in Nevada led to the concept that the Cordilleran geosyncline is composed of a miogeosynclinal and eugeosynclinal facies. Roberts and others (1958) noted that rocks older than upper Mississippian age in eastern Nevada are mostly limestone and dolomite with minor amounts of shale and quartzite, while correlative strata in central and western Nevada are predominantly clastic sediments and chert, with intercalated volcanic and pyroclastic rocks, generally with mafic compositions. From this work, they divided the geosyncline into an eastern, carbonate, miogeosynclinal assemblage and a western, siliceous, eugeosynclinal assemblage separated by a transitional zone with shale, chert, and limestone. In plate tectonic terminology, the miogeosynclinal assemblage represents a continental shelf environment, while the eugeosynclinal assemblage represents deeper water deposits on a continental slope and rise, or in a marginal basin behind an island arc (figure 23).

Paleozoic island arc terranes have been found to the west in the Klamath Mountains and northern Sierra Nevada of California (figure 24), while fragments are present in the Blue Mountains of Oregon and the northern Cascade Mountains in Washington. Burchfiel and Davis (1972, 1975) envision these areas as representing a Paleozoic island arc separated from the North American craton by an oceanic margin basin represented by the eugeosynclinal facies in Nevada. Active subduction resulted in development of a backarc fold thrust belt, represented by the Antler orogeny (Roberts Mountains thrust fault, figure 22), while total closure of the basin and accretion of the arc onto the craton is represented by the thrusting in the Sonoma orogeny (Golconda thrust fault, figure 22). This event extended the North

American continent 200-300 km to the west (Burchfiel and Davis, 1972, 1975).

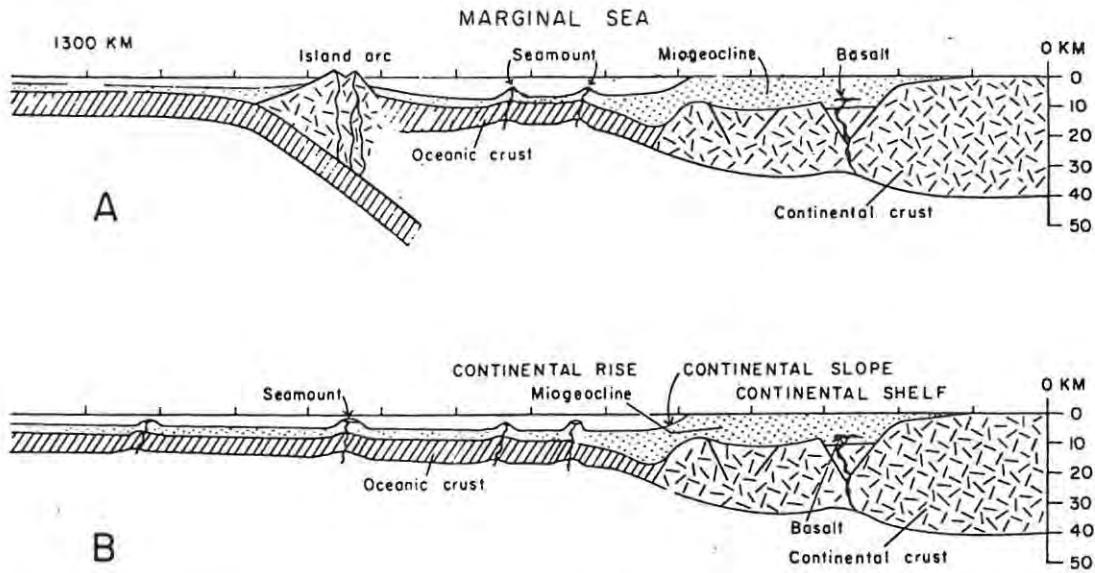
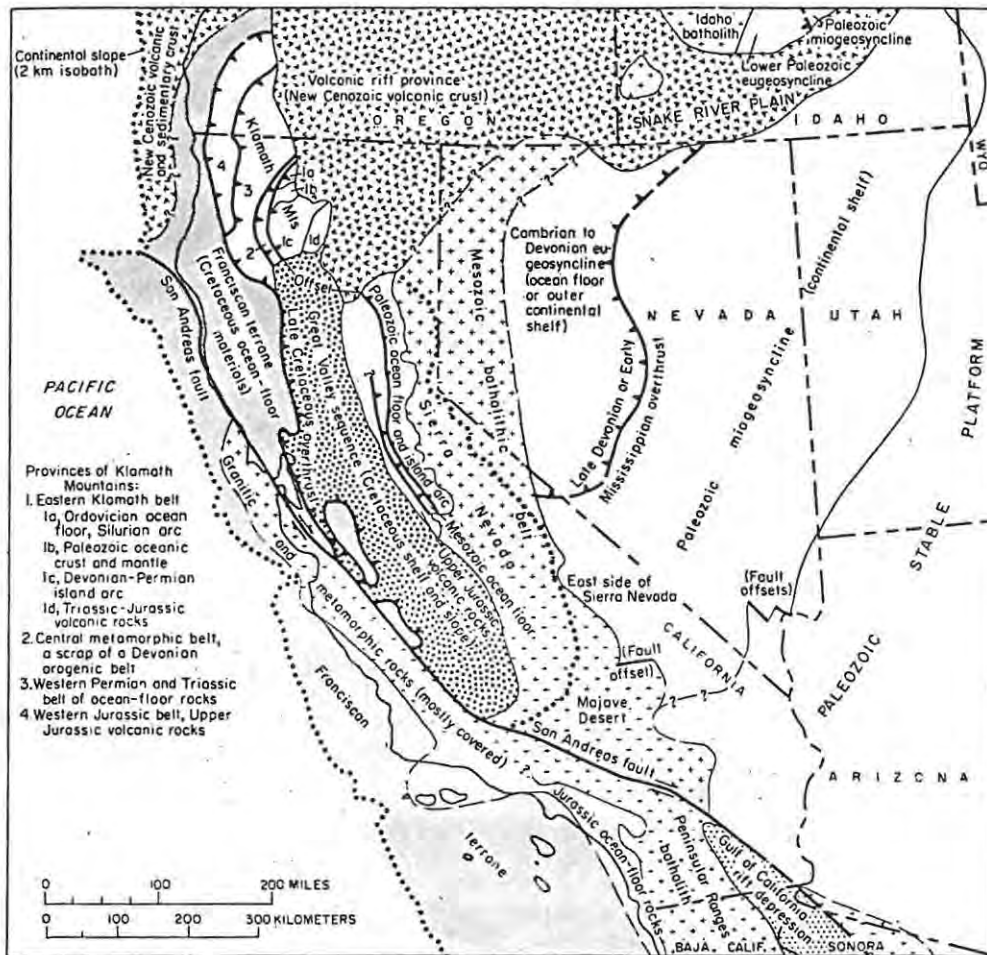


Figure 23: Models of lower Paleozoic and uppermost Precambrian Cordilleran geosyncline. From Stewart and Poole (1974).

Figure 24: Tectonic elements of California, Nevada and neighboring regions. From Hamilton (1969).



Island arc magmatism continued during lower Mesozoic time, in association with subduction beneath the North American craton. In the western Sierra Nevada, a complexly deformed assemblage of Jurassic and Triassic greenstones and ophiolites has been intruded by the Sierra Nevada batholith. This island arc assemblage may be the precursor of an Andean-type magmatic arc, but the exact relationship is not clear. Elsewhere, lower Mesozoic island arc sequences, also intruded by later Mesozoic plutons, are found in the Klamath Mountains and Blue Mountains. The Franciscan assemblage, located to the west of the island arc assemblage, is a *mélange* of graywacke, shale, mudstone, and siltstone with lesser amounts of pelagic chert and shale, ocean floor pillow basalts, blue schist, eclogite, serpentinite, and limestone (Albers, 1981). This terrane appears to represent oceanic crust and trench sediments that have been accreted to the continent during Mesozoic and early Cenozoic plate subduction. Figure 25 is a schematic geological cross section showing the general structure of the Paleozoic and Mesozoic accreted terrane.

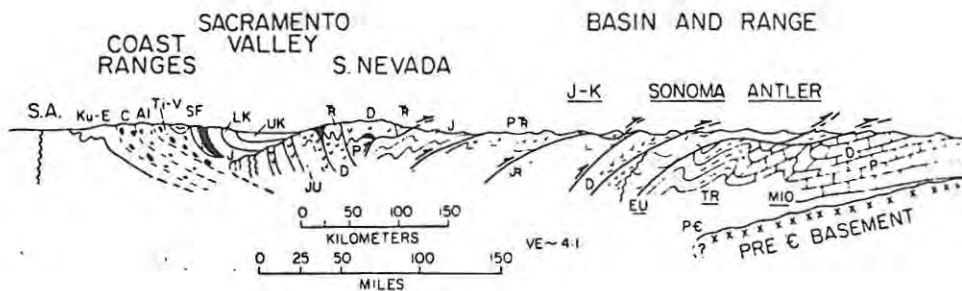


Figure 25: Schematic geological cross section, coast of northern California eastward to the foreland of the Antler orogen. Notation, west to east: S.A., trace of San Andreas fault; Ku-E, upper Cretaceous-Eocene; C, Cenomanian; Al, Albian; Ti-V, Tithonian-Valaginian; SF, South Fork Mountain Schist; LK, UK, Lower, Upper Cretaceous; TR, Triassic; D, mid-Paleozoic; J, Jurassic; PTR, Permo-Triassic; J-k, Jurassic-Cretaceous orogenic belt. From Maxwell (1974).

There are several significant problems with this tectonic model for Paleozoic accretion. First, the eugeosynclinal facies in Nevada of Roberts and others (1958) is only found in the upper plates of thrust faults, so there is no firm evidence that it is laterally continuous with miogeosynclinal facies. Likewise, there is no direct connection between the eugeosynclinal sequence and the Paleozoic island arc terranes (figure 24), while correlation between nearby segments of the island arcs, such as between the Klamath and northern Sierra Nevada fragments, is nebulous. Also, the age of volcanism in the island arcs does not correlate with the Antler and Sonoma orogenies. In fact, there is virtually no magmatism associated with these two major orogenic events.

Likewise, Mesozoic and early Cenozoic accretion may be considerably more complex than envisioned. There is no clear relationship between the island arc assemblages and the subsequent Mesozoic batholiths. Also, paleomagnetic evidence indicates that a portion or all of the basal Eocene sequence of the Oregon and Washington coast ranges has rotated 50-70° with respect to the North American craton (Simpson and Cox, 1977). This sequence is composed largely of oceanic ridge tholeiites, with the segment in the Olympic Peninsula possibly representing a seamount (Cady, 1975). These data suggest the basal portions of the Oregon and Washington coast ranges are completely unrelated to the North American continent. Thus, the Franciscan assemblage is the only Mesozoic terrane that appears to have been formed along the continental margin.

Coney and others (1980) postulate that all of the geologic terranes west of the Paleozoic miogeosyncline are "suspect" because their paleogeographic setting with respect to North America during much of Phanerozoic time cannot be ascertained. They state that most of these terranes (over 50 in number, that cover 70% of the North American Cordillera, figure 26) are allochthonous and seem to have collided and accreted to the North American cratonic margin, mostly during Mesozoic and early Cenozoic times. According to this concept, the Antler and Sonoma orogenies are products of these collisions, and there was no subduction beneath the Pacific margin until the early Triassic (as earlier collisions were with west dipping subduction zones). The suspect terranes are characterized by internal homogeneity and continuity of stratigraphy, tectonic style, and geologic history. In a few cases, faunas with Asiatic affinity are present. The terranes may include pieces of oceanic crust, oceanic arcs, and continental basement, although most display sedimentary and volcanic sequences that are

of oceanic affinity.

The boundaries between terranes are fundamental discontinuities in stratigraphy that cannot be explained easily by conventional facies changes or unconformities. Most boundaries separate distinct rock sequences and many juxtapose different faunal assemblages. Some terranes have paleomagnetic records that differ strongly from those of the North American craton.

These data suggest large displacements and/or rotations between the terranes themselves and between the terranes and the craton (Coney and others, 1980). Most of the boundaries between terranes are known or suspected faults that usually display a complex history of recurrent movement. These postulated suture zones sometimes contain ultramafic rocks which are thought to represent ophiolite sequences (Maxwell, 1974). The ages of ultramafic rocks show a complex distribution pattern which supports multiple accretion events, especially where younger ultramafics are found inland from older ultramafics (figure 27).

Some support for the concepts of Coney and others (1980) is provided by the data shown in figure 22. The irregular trend of the postulated margin of Precambrian crystalline basement contrasts sharply with the present smooth margin of the Pacific coast. These irregularities have been accounted for by transform faulting, possibly during Precambrian rifting that initiated the Cordilleran geosyncline. However, evidence for major transform faulting of several hundred kilometers is lacking, and the eastern margin of the geosyncline does not show any effects of such faulting. Major transform faulting does appear to have occurred in southern California and Mexico, where the Precambrian craton margin approaches the Pacific coast and the Cordilleran geosyncline is thinned or absent. Silver and Anderson (1974) suggest that up to 800 km of left-lateral shear, probably during Triassic time, has shifted the geosynclinal terrane into Mexico.

The sharp protuberances in the Precambrian crust may be caused by fragments of continental crust that were accreted to the craton. One of these protuberances, in northeastern Washington, corresponds with one of the suspect terranes of Coney and others (1980). Alternatively, the irregularities in the Precambrian crust may indicate an originally complex continental margin, or, the assumptions used to define the edge of the craton may be incorrect.

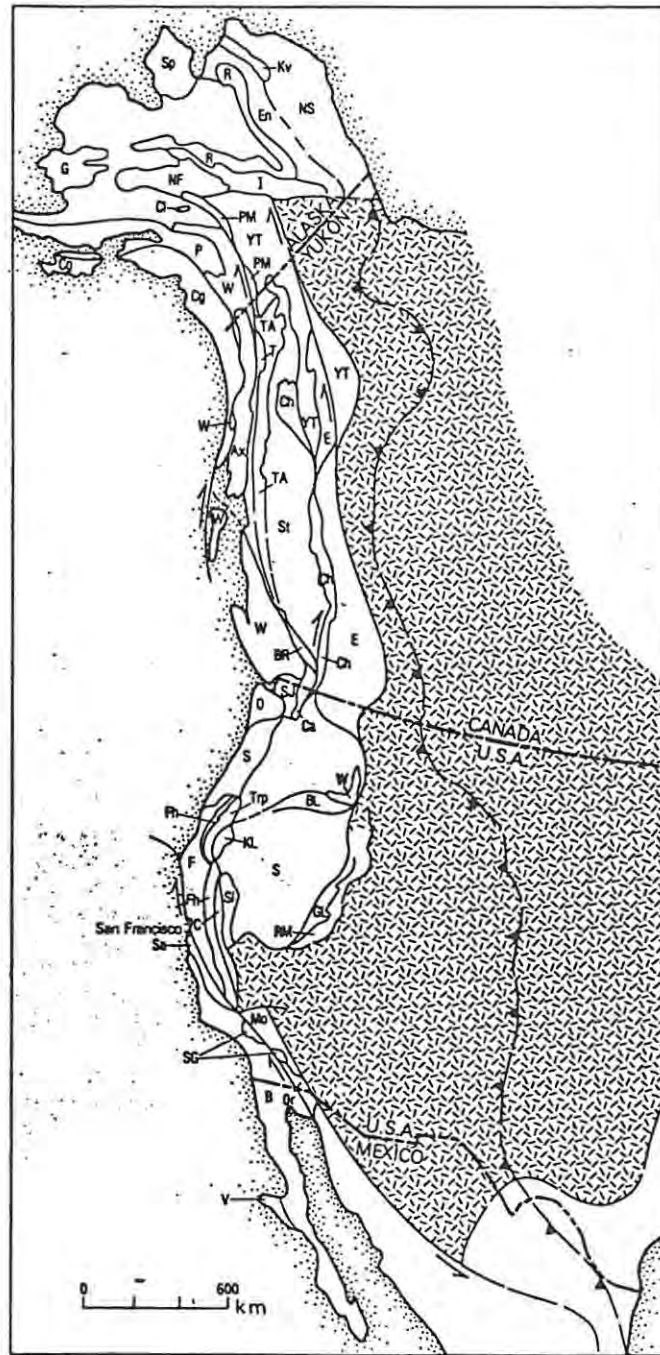


Figure 26: Generalized map of Cordilleran Suspect Terranes. Dashed pattern, North American autochthonous cratonic basement. Barbed line, eastern limit of Cordilleran Mesozoic-Cenozoic deformation. Barbed arrows, direction of major strike-slip movements. Descriptions of the terranes follow.

Figure 26, continued:

Washington and Oregon

- SJ, San Juan (composite) - includes highly deformed Mesozoic chert, argillite, graywacke, and volcanic rocks, partly in melanges, with blocks of lower Paleozoic plutonic rocks, Paleozoic chert, carbonates, and volcanic rocks. Permian limestone blocks contain Tethyan fusulinids.
- Ca, Northern Cascades (composite) - includes crystalline and pelitic gneisses, and thrust sheets composed of: (1) Upper Paleozoic andesitic volcanics and associated sedimentary rocks; (2) green schist and blue schist, and (3) Jurassic ophiolite.
- O, Olympic - Lower Cenozoic volcanic rocks and associated deep and shallow water sedimentary rocks. Basement unknown, but presumed to be oceanic.
- S, Lower Cenozoic volcanic and sedimentary rocks lying west of the Cascade Range. Paleomagnetic data imply post-Eocene clockwise rotation of 70°.
- BL, Blue Mountains (composite) - includes melange with blocks of Paleozoic ophiolite, limestone, and chert, and Mesozoic chert and sandstone, structurally overlain by Triassic and Jurassic volcanic sandstone, conglomerate, and argillite.

California

- Fh, Foothills - Upper Jurassic andesitic volcanic and volcanoclastic rocks associated with phyllite, slate, and graywacke, and Upper Jurassic ophiolite.
- Trp, Triassic and Paleozoic of Klamath Mountains (composite) - includes a structurally complex assemblage of Lower Mesozoic ophiolite, chert, basalt, Jurassic andesitic rocks, and associated sedimentary rocks.
- KL, Eastern Klamath Mountains - Middle to Upper Paleozoic clastic, volcanic, and carbonate rocks, overlain by Triassic and Jurassic volcanics and minor limestone.
- Si, Northern Sierra - Lower Paleozoic clastic sedimentary rocks, Upper Paleozoic and Lower Mesozoic volcanic and associated sedimentary rocks.
- C, Calaveras (composite) - including a western belt of melange with ophiolite and Mesozoic chert, and an eastern belt of quartzose clastic rocks, argillite, and minor Permian limestone.
- F, Franciscan (composite) - includes Upper Mesozoic Great Valley sequence with ophiolite at base, and structurally underlying disrupted and

Figure 26, continued:

partially metamorphosed rocks of the Franciscan Complex.

Sa, Salinia - includes metamorphosed pelitic rocks, marble, and graywacke of unknown ages, intruded by Cretaceous granite plutons.

SG, San Gabriel (composite) - two structurally complex and juxtaposed Precambrian crystalline terranes intruded by Mesozoic plutons.

OR, Orocochia - metagraywacke and mudstone and minor chert and basic volcanic rocks, age unknown. No known basement.

Mo, Mojave (composite) - juxtaposed and disrupted Paleozoic sedimentary sequences, Lower Mesozoic sedimentary and volcanic rocks intruded by Mesozoic plutons.

Nevada

S, Sonomia (composite) - includes Upper Paleozoic volcanics in the south, and Lower Mesozoic volcanics in the north. Si and KL terranes originally included in Sonomia.

GL, Golconda - structurally deformed assemblage of chert, argillite, minor limestone, and volcanics of Mississippian to Permian age.

RM, Roberts Mountains - structurally complex assemblage of chert, argillite, sandstone, basalt, and minor limestone of Cambrian to latest Devonian or early Mississippian ages.

From Coney and others (1980).

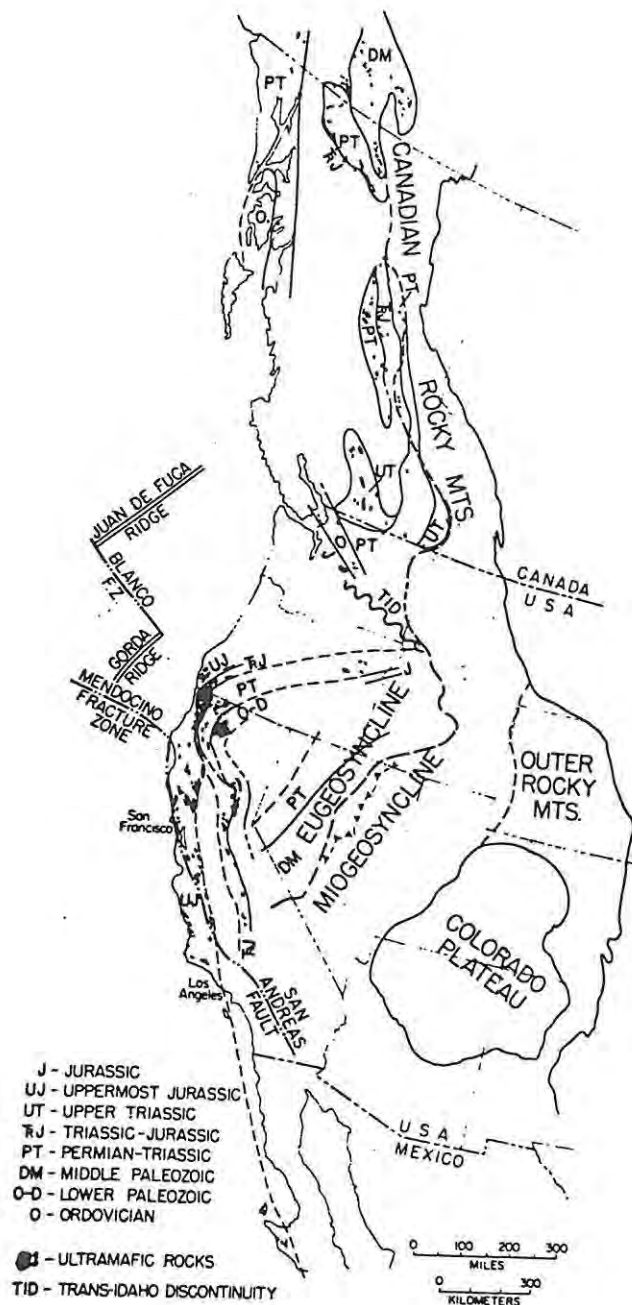


Figure 27: Apparent ages of ultramafic rocks. From Maxwell (1974).

The concept of suspect terranes has important implications bearing on the distribution of magmatism and mineralization in the accreted terrane. First, the different terranes may have early histories of tectonism and magmatism that are unrelated to adjacent terrane or the western United States in general. Likewise, mineralization associated with these events may be unique to that particular terrane. Second, the original tectonic environments of these terranes may be partially obscured due to accretion and subsequent subduction along the Pacific coast. However, the original characteristics of the terrane, such as thickness and composition of the crust, may influence later magmatic and tectonic events. For example, the unusually thick crust in northwestern Washington (figure 10), may be a result of accretion of a fragment of continental crust. This in turn may be related to the later development of porphyry molybdenum deposits such as those found in northwestern British Columbia, and at Quartz Hill in southeast Alaska. Third, the terranes largely are composed of oceanic crust and oceanic volcanic arcs. Thus, deposits most typical of these environments are expected to occur, even though the terrane now may be located a considerable distance within the continental interior.

Mesozoic Magmatism

The emplacement of major granitic batholiths and associated volcanic rocks along the western margin of North America during the Mesozoic was the first major magmatic event in the Cordillera since the middle Proterozoic granitic intrusive episode. Late Proterozoic and Paleozoic magmatic activity within the craton and the Cordilleran miogeosyncline was minor, while the limited island arc volcanism in Paleozoic suspect terranes is probably allochthonous. The oldest radiometric dates for Mesozoic intrusive rocks are about 220 Ma. Magmatism was more or less continuous until about 75 Ma, when a change in tectonic and magmatic style heralded the Laramide orogeny.

Mesozoic magmatism was immediately preceded by two tectonic events, the Sonoma orogeny and postulated left-lateral strike faulting, which altered the continental margin of the western United States. The Sonoma orogeny (approximately 280 to 200 Ma) is postulated to represent a major accretion event as previously discussed. This caused an abrupt westward shift of the continental margin. Evidence for left-lateral faulting in southern California (Silver and Anderson, 1974) is largely circumstantial. Mesozoic magmatic belts cut diagonally across the Cordilleran miogeosyncline into the Precambrian craton, suggesting the miogeosyncline was truncated by

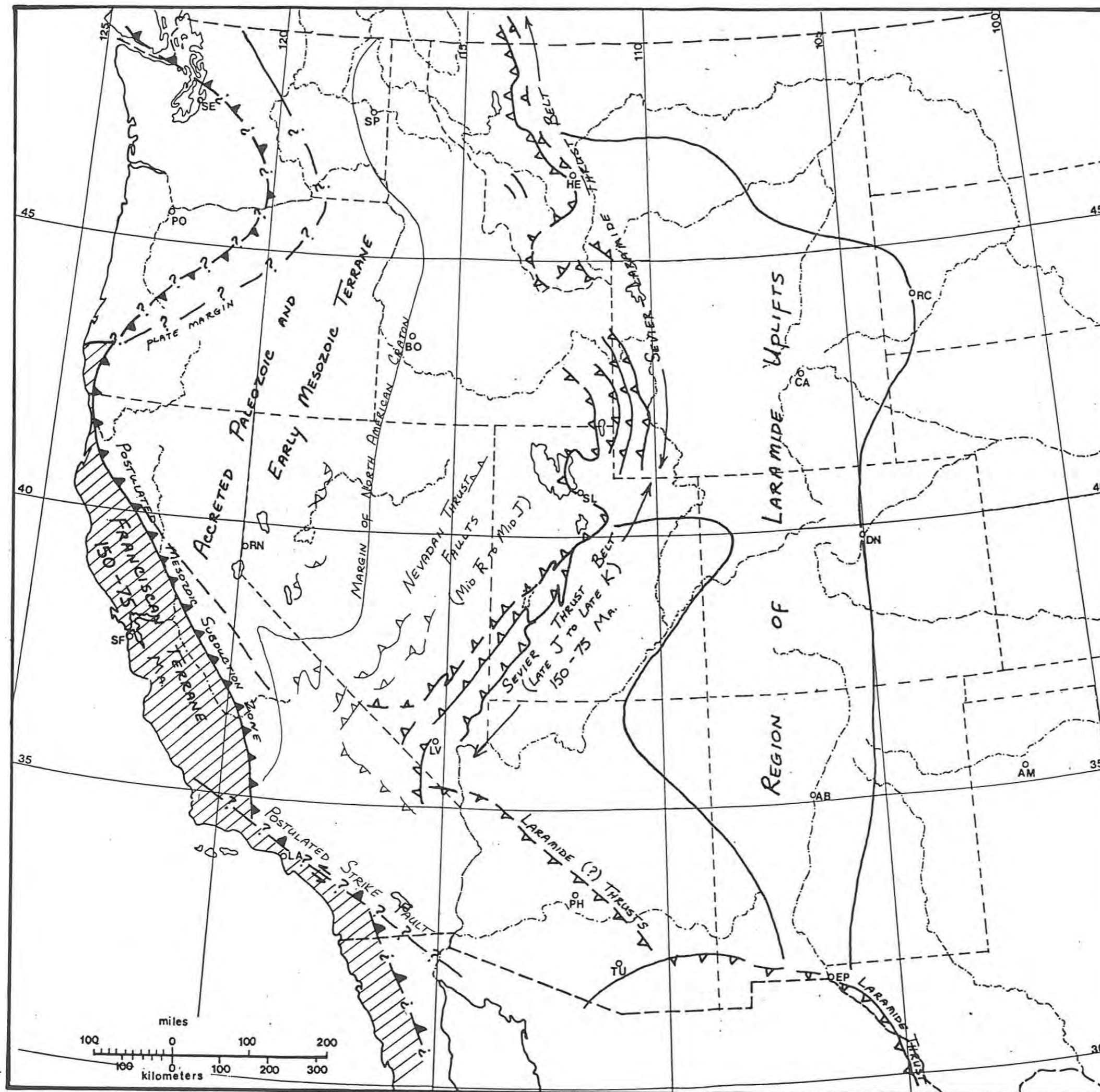
rifting or left-lateral faulting (figure 28). A model postulating movement beginning in Triassic time fits available radiometric data for intrusive activity. The resultant continental margin is shown in figure 28.








The tectonic environment in which large volumes of granitic rocks were emplaced along the western margin of North America during Mesozoic time is thought to be analogous to that which exists today in Japan and the Andes; plate subduction along a continental margin. Several important tectonic and structural features developed in the western North American plate during the Mesozoic appear to be related to this model. These are: (1) the Franciscan terrane, thought to have formed by accretion of oceanic and trench sediments as well as oceanic crust onto the continental margin by eastward subduction of oceanic rocks beneath the North American plate (figure 28), (2) west-directed thrust faults along the continental margin, thought to have been produced by the eastward subduction (figure 28), (3) a volcanic-plutonic arc of Andean-type along the modified western margin of the North American plate (figure 29), (4) east-directed thrust faults that developed east of the arc and affected rocks of the Paleozoic miogeosyncline as far east as its transition to the craton and in southern areas, rocks of the craton (figure 28), and (5) a region of basement uplifts that developed within the craton at the termination of arc magmatism (figure 28; Burchfiel and Davis, 1975). During Mesozoic subduction, the zone of west-directed thrusting generally migrated westward due to the progressive accretion of oceanic, island arc, and continental sediments to the margin (not shown). Also, the eastern zone of thrusting moved progressively eastward to the Sevier thrust belt (figure 28).

The strongest aspect of the plate tectonic model for Mesozoic magmatism lies in the close petrologic similarity between Mesozoic granitic plutons and present day arc-type magmas. Also, most radiometric dates in the Cordilleran batholith belt are essentially coeval with metamorphism in the high pressure, low temperature Franciscan belt (Armstrong and Suppe, 1973). However, the source of the granitic magmas and associated mineral deposits is more enigmatic. Some of the problems for determining the source of subduction zone-related magmas are brought out by a review of the characteristics of Mesozoic magmatism.

Mesozoic intrusives, for the most part of batholithic dimensions, are concentrated in an S-shaped arc that is approximately 200 km wide and more or less parallel to the Mesozoic continental border (figure 29).

Figure 28. Tectonic features of the western United States during the Mesozoic and Laramide orogenies.



-  Franciscan terrane
-  Postulated Mesozoic subduction zone
-  Plate margin
-  Margin of North American craton
-  Nevadan thrust faults
-  Sevier, Sevier-Laramide and Laramide thrust faults
-  Region of Laramide uplifts

Note
 Craton margin is delineated based on initial $^{86}\text{Sr}/^{87}\text{Sr} = 0.706$ and on the margin of miogeosynclinal facies.

References

Burchfiel, 1979
 Burchfiel and Davis, 1975
 King and Beikman, 1974
 Stewart, 1978

Figure 29. Mesozoic and Laramide Magmatism.

Regions with closely spaced Mesozoic batholiths

Laramide intrusives

Laramide volcanic rocks

Age boundaries (Ages given as Ma)

References

Albers, 1981

Armstrong, 1978

Armstrong and others, 1977

Armstrong and Suppe, 1973

Bennett, 1980

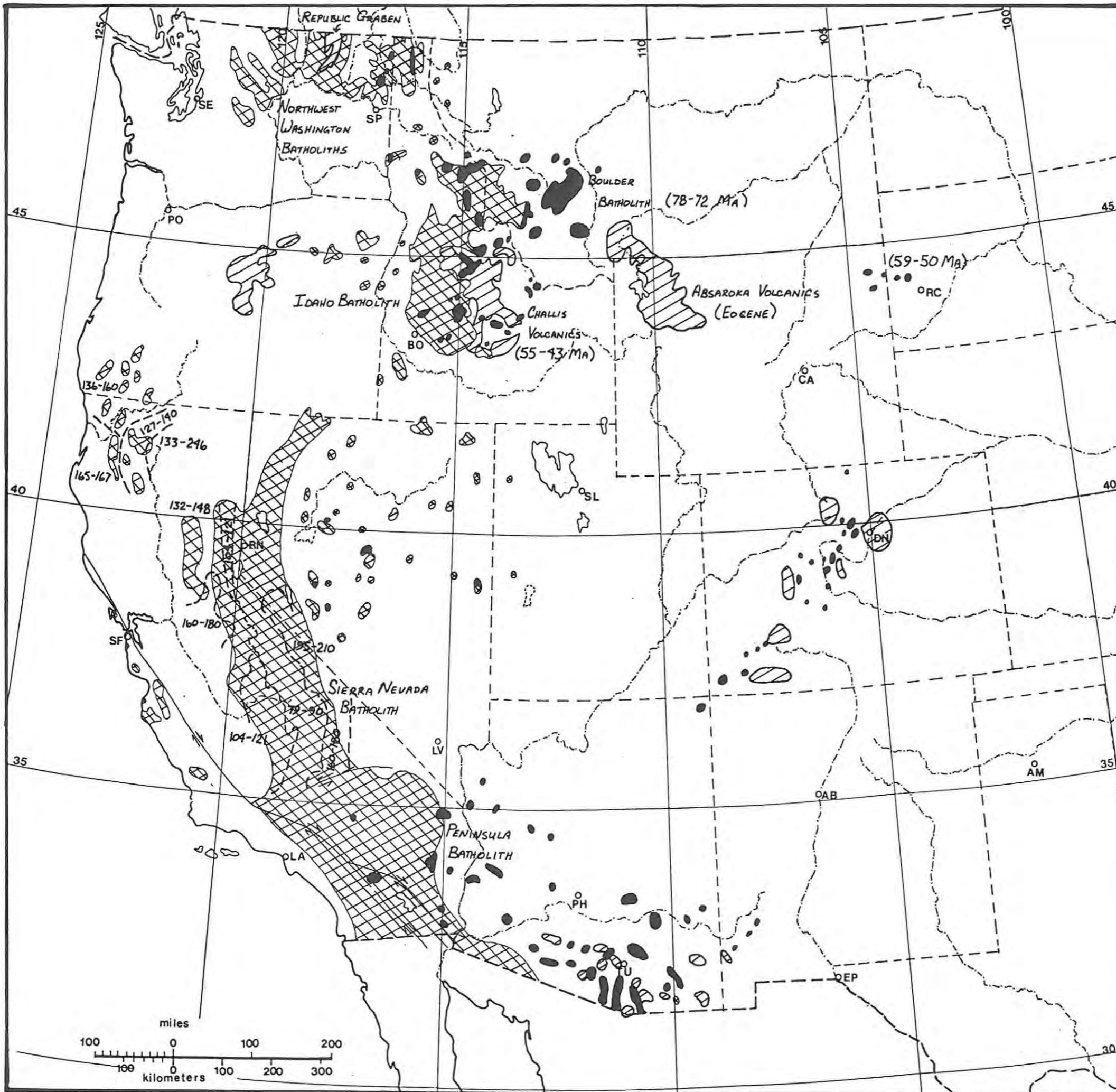
Drewes, 1981

Evernden and Kistler, 1970

King and Beikman, 1974

Proffett, 1979

Tweto, 1975



Smaller, essentially synchronous bodies were intruded to the east, across a width of more than 600 km. The major intrusives are the Peninsula batholith in southern California, the Sierra Nevada batholith in California and western Nevada, the Idaho batholith, and a complex assemblage of batholiths in northwestern Washington. Of this group, the Sierra Nevada have been the most thoroughly studied, and will be used for most examples of Mesozoic magmatism characteristics.

The Sierra Nevada batholith is composite in nature, being made up of many plutonic bodies of granitic rock of Mesozoic age, together with scattered remnants of metamorphosed country rock and small masses of darker, generally older, mafic igneous rocks. The plutons of granitic rocks differ in texture and composition, and are in sharp contact with one another or are separated by thin septa of metamorphosed rocks, mafic igneous rocks, or late aplite dikes. Individual plutons vary in size from less than 2.5 square km to several hundred square km. All of the large plutons, and many of the smaller ones, are elongated NW, parallel to the long axis of the batholith (Bateman and Dodge, 1970). The southern portion of the batholith occurs within the transition zone between miogeosynclinal and eugeosynclinal sequences of the Cordillera geosyncline, while the northern portion extends into accreted terrane.

The degree of continuity of Mesozoic magmatism is controversial. Kistler (1974) identified five epochs of granitic rock emplacement in the Sierra Nevada, each of 10-15 million years duration, separated by intervals of 15-20 million years with very little magmatism. The major areas of magmatism in each epoch generally occur in the belts shown in figure 28. The pattern is generally one of decreasing age from west to east, except for the first magmatic event on the east side of the batholith. Kistler believes this pattern can be applied throughout the North American Cordillera, with major magmatic pulses during Cretaceous (121 to 75 Ma), Jurassic (180 to 136 Ma), and a more poorly defined event in middle to late Triassic times. Armstrong and others (1973, 1977) and Lanphere and Reed (1973) recognize the episodic nature of Mesozoic magmatism, but do not believe it to be periodic. Furthermore, the timing of magmatic episodes varied from place to place within the Cordillera. Armstrong and others (1977) found that Mesozoic magmatism showed a shifting pattern of activity that cannot be simplified as a few narrow belts, each characteristic of a distinct magmatic episode. Nor is there an eastward progression of magmatism with time. The

conflict between these viewpoints remains unresolved, largely due to the limitations of K-Ar dating, and the relative scarcity of dates determined by other methods. Over large areas of the Mesozoic magmatic belt, especially in Idaho and Washington, K-Ar ages have been reset by younger tectonic and thermal events. In these areas, a few U-Pb dates for zircons are the only reliable data. These data are insufficient for resolving the igneous history, due to the multiple episodes of magmatism.

The Sierra Nevada batholith exhibits chemical zonation on several scales. Individual plutons show gradational zonation, with more mafic peripheral zones and more felsic interiors (Albers, 1981). Plutons which can be grouped together in a comagmatic sequence show a similar trend, with the oldest phases most mafic, and successively younger plutons progressively more felsic (Bateman and Dodge, 1979). However, the most important zonation is on a regional scale, in which the comagmatic sequences are progressively more felsic to the east. In the western foothills, the comagmatic sequences grade from abundant granodiorite or tonalite, through leucotonalite and leucogranodiorite, to sparse granite. All rock types are equigranular. Within the medial portion of the batholith, the sequences grade from equigranular granodiorite, through porphyritic granodiorite and granite to equigranular granite. In the east, the sequence is equigranular monzodiorite, through equigranular monzonite to porphyritic quartz monzonite and granite, to equigranular granite (Dodge and Bateman, 1977). Likewise, potassium, rubidium, uranium, thorium, beryllium, rare earth elements, and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ increase from west to east, while calcium decreases (Albers, 1981). These changes correlate with the quartz diorite line of Moore (1959) and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ contours of Kistler and Peterman (1973; figure 22). The regional compositional changes are independent of the ages of the rocks, but they do correlate with a change from a eugeosynclinal sequence to the west and a miogeosynclinal sequence to the east. However, this pattern may not be applicable to the entire Mesozoic magmatic belt, as Armstrong and others (1977) found no obvious changes in chemistry or petrology of plutonic rocks in the vicinity of the isotopic discontinuity in the Idaho batholith. Also, Kistler (1974) reported there was no systematic pattern of potassium enrichment in the Klamath Mountains.

Origin of Granite Batholiths

The variety of tectonic environments of occurrence, as well as the variable geochemical characteristics of granite, suggest granitic magmas

can be formed by several processes. However, granitic rocks occur predominantly in association with continental crust, and in batholithic volumes only within mobile belts marginal to or within such crust (Pitcher, 1979). In the western United States, the granitic batholiths are products of calcic to calc-alkaline magmatism that can reasonably be inferred to be related to a paleosubduction zone. A variety of methods have been proposed for generation of subduction-related magmas. These include: (1) fractional crystallization of high- Al_2O_3 tholeiitic magma, (2) partial or complete melting of sialic crustal rocks, (3) partial melting of wet ultramafic rocks in the upper mantle, perhaps followed by fractional crystallization, (4) mixing of mantle-derived basaltic magma with siliceous magmas, and (5) partial melting of upper mantle and crustal rocks in subduction zones (Condie, 1976). Melting in and/or above subduction zones is thought to result chiefly from water liberated by dehydration of descending oceanic crust, and perhaps from frictional heating along the top of the descending slab. Various models based on melting in descending slabs (eg. Ringwood, 1974; Burnham, 1979) account for most of the geochemical and isotopic distribution in calc-alkaline magmas. However, all of the above methods may be operative to some extent. In particular, melting of sialic crust may be related to the formation of large calc-alkaline batholiths (Condie, 1976).

Several features of the Mesozoic batholiths in the western United States suggest possible sources for the magmas, but the evidence is by no means unequivocal. The most important feature is the relationship between granite composition and the type of crust intruded. In the Sierra Nevada batholith, there is a distinct change in composition and trace element content between rocks intruded into the eugeosynclinal and the miogeosynclinal sequences. In the western portion of the batholith, the plutons are depleted in alkali and rare earth elements. In this respect, they are similar to oceanic tholeiite and alkali basalts. Also, the Sr and Pb isotopic compositions are similar to oceanic tholeiite (Kistler, 1974). To the east, plutons show a gradational increase in alkali abundance, more fractionated rare earth elements, greater initial $^{87}\text{Sr}/^{86}\text{Sr}$ values and more radiogenic Pb isotopic compositions (Kistler, 1974). Kistler (1974) interprets this data as indicative of two chemically distinct parental materials for the plutons; oceanic lithosphere and continental lithosphere. He favors derivation of the magmas from depths of 30 to 50 km, rather than from along subduction zones. Armstrong and others (1977) conclude that Sr isotope variations indicate the plutons are contaminated with, or partially derived from the

crust that contains them, and that initial Sr isotopic ratios, as well as other isotopic and trace element characteristics of many rocks are better indicators of the nature of the enclosing crust, rather than the magma source at depth. Both views are divergent from those expressed by Dickinson (1975) and Keith (1977), who contend that potash content is directly related to the depth of magma generation along subduction zones. This latter concept is not supported by data from the Sierra Nevada batholiths, where potash content variations are dependent of geographic rather than temporal factors; unless, of course, the paleosubduction zone maintained a constant dip for 145 million years -- a concept that is apparently an anathema to recent plate tectonic models. (See, for example, Coney and Reynolds, 1977; Keith, 1978; Westra and Keith, 1981.)

The source of granite magmas in the Mesozoic batholiths remains unresolved. Subduction zones are an important mechanism for generating the magmas, but it is not clear whether or not the magmas originate in the subduction zones. However, the influence of crustal composition on granite composition indicated there is some crustal component in the magma. This suggests some of the mineral deposits associated with the batholith also may be related to crustal composition.

Magmatism During the Laramide Orogeny

The Laramide orogeny began between 80 and 70 Ma and continued until 50 to 40 Ma. In this dissertation, the orogeny limits are placed at 75 to 40 Ma, although it is recognized that initiation and termination of the orogeny are not synchronous throughout the western United States. The Laramide orogeny is characterized by a unique style of tectonism and distribution of magmatism, as well as by a change in the distribution and an increase in the intensity of mineralization from that of earlier periods.

Laramide Tectonism

The major tectonic features of the Laramide orogeny are the large, monoclinical folds developed within the Colorado Plateau and the very large fault-bounded, Precambrian crystalline massifs developed within the Rocky Mountains and adjacent areas. Figures 1 and 30 show the distribution of these basement-cored uplifts, which lie almost wholly within the Paleozoic and Mesozoic craton. Recent work by Davis (1979) indicates that similar features of Laramide age may be present in southern Arizona, but they now are largely indistinguishable due to subsequent basin-range faulting. Almost all of the uplifts are assymmetric, elongate, sometimes

sinuous, doubly plunging antiforms with draped covers of Paleozoic and Mesozoic sedimentary rocks (Burchfiel and Davis, 1975; Coney, 1976). They are characterized by up to 15,000 m of differential vertical displacements of the Precambrian basement rocks. The uplifts are bounded by low to high angle reverse faults that steepen at depth (Burchfiel and Davis, 1975).

Folding and thrusting continued along the Sevier belt in the northwestern and southwestern United States during the Laramide orogeny, but ceased from central Utah to southern California before the end of Cretaceous time (figures 28 and 30). Thrust faults developed during Laramide deformation have a structural style similar to those developed in the earlier Sevier orogenic event, but they generally lie slightly east of the Sevier structures. This deformation continued until middle to late Eocene time (Burchfiel and Davis, 1975). The location of much of the province of basement uplift opposite from the sector of the thrust belt that became inactive at the end of the Sevier orogeny has important implications for analysing Laramide tectonism.



Figure 30: Major structural and magmatic elements developed during the Laramide orogeny (70-50 Ma). MTB, Montana thrust belt; MFTB, Mexican fold and thrust belt; WL, Wasatch line. Shaded areas are Precambrian rock outcrops in basement-cored uplifts. From Burchfiel (1979).

Laramide Magmatism

The Mesozoic magmatic arc began to break up at about the same time as the Laramide orogeny began. Compared with the Mesozoic, subsequent igneous activity was uncommonly sparse. Laramide igneous rocks are rare in central and northern California, Nevada and western Utah; the area of the Laramide igneous gap. Most igneous activity is confined to three areas: (1) northwestern Washington, central Idaho, and southwestern Montana, (2) southwestern and central Colorado, and (3) southern Arizona and southwestern New Mexico (figures 28 and 30). There is a general spatial coincidence of Laramide igneous activity with the province of basement uplift, particularly if this province is extended into southern Arizona. However, there are large areas in the region of basement uplift where igneous rocks of Laramide age are unknown. Another important feature is the location of magmatism in Colorado, directly east from the gap in Laramide magmatism and thrusting. The character and age of magmatism in the three regions show important variations which are summarized below.

Magmatism in the northwestern United States

Much of the early Laramide magmatism in the northwestern United States is associated spatially, and perhaps temporally with the waning stages of emplacement of the Idaho batholith. However, precise radiometric dating throughout northwestern Washington, Idaho and, to a lesser extent, western Montana, has been difficult because much of the area was affected by a vigorous episode of Eocene volcanic-plutonic activity that disturbed the K-Ar and Rb-Sr isotopic systems (Armstrong and others, 1977). For this reason, the distribution of late Mesozoic and early Laramide magmatism is imprecisely known. Armstrong and others (1977) estimate that the southern (Atlantic) lobe of the Idaho batholith was emplaced from 100 to 75 Ma, while the northern (Bitterroot) lobe was emplaced from 80 to 70 Ma. Intrusive outliers in southwestern Montana (eg. the Boulder batholith), which are largely unaffected by the Eocene event, have radiometric ages ranging from 82 to 70 Ma. This suggests a genetic relationship between these outliers and the imprecisely dated Idaho batholith, particularly since this magmatism was followed by a lull in activity until 55 Ma. Thus, this early Laramide magmatism might be more properly classified with Mesozoic magmatism. However, mineralization at Butte, which is intimately associated with the Boulder batholith (78 to 72 Ma) is dated at 63 to 58 Ma (Proffett, 1979).

This example demonstrates some of the drawbacks of attempting to establish the distribution of magmatism and mineralization using radiometric

age dates. First, the radiometric dates can be affected by subsequent tectonism. Also, radiometric dates of intrusives are cooling dates rather than emplacement dates. Likewise, the age of associated mineralization may not correspond with the cooling dates of associated intrusives. The resulting inconsistencies merely are indicators that major magmatic centers are long-lived features and that radiometric dates from these centers may reflect a local magmatic event rather than a major tectonic event. Nevertheless, maps with radiometric age distributions are useful for indicating changing patterns of magmatic activity, so they are included in this dissertation. However, their limitations should not be overlooked.

For most of the Paleocene, igneous activity was exceedingly restricted in volume and extent in the northwestern United States. However, thrusting and folding still proceeded vigorously, especially in western Montana and Wyoming and in eastern Idaho (Armstrong, 1978). A unique, geographically restricted, isolated igneous episode in the Black Hills (figure 29) is represented by phonolite laccoliths and volcanic necks (eg. Devils Tower). These intrusives are aligned WNW, suggesting control by a linear zone of weakness in the crust. They also are spatially associated with the Homestake Mine, but there does not appear to be a genetic relationship.

Beginning about 55 Ma, volcanic-plutonic activity spread southward across the Canadian border and became widespread over the entire northwest by 50 Ma (Armstrong, 1978; figures 31 and 32). This magmatic event, known as the Challis or Absaroka episode, is marked by widespread accumulation of volcanic rocks and associated sediments (figure 29), development of fault-bounded basins (Republic Graben, figure 29), intrusion of dike swarms and plutons ranging in size up to mesozonal batholiths, extensive resetting of K-Ar dates, and local development of metamorphic fabrics in gneiss domes largely composed of older igneous rocks (Armstrong, 1978). Initiation of this event approximately coincides with the termination of thrusting and basement uplift in areas to the east in Montana and Wyoming (Armstrong, 1978), which, in a strict sense, marks the end of Laramide style deformation. Magmatism migrated southward with time, and gradually faded out in the northwest between 43 and 36 Ma (Armstrong, 1978, figures 32 and 33).

The chemical composition of Challis-Absaroka episode rocks ranges from a varied calc-alkaline assemblage of intermediate average silica content over central Oregon, northern Washington, Idaho, southwestern Montana, and northwestern Wyoming, to unusual alkalic volcanic associations in many of the smaller igneous centers on the stable craton in Montana and Wyoming (Lipman

and others, 1972). Many of the Tertiary stocks and plutons within the vicinity of the Idaho batholith, ranging in age from 51 to 38 Ma, have a remarkably similar alkalic nature (Bennett, 1980). The intrusives have a quartz monzonitic to granitic composition, are pink, and are marked by the presence of microlitic cavities containing smoky quartz crystals. They have a background radiation that is twice that of the batholith and are associated with Mo, W, Sn, and Be, as well as Cu, Au, Pb, Zn, and Ag mineralization (Bennett, 1980).

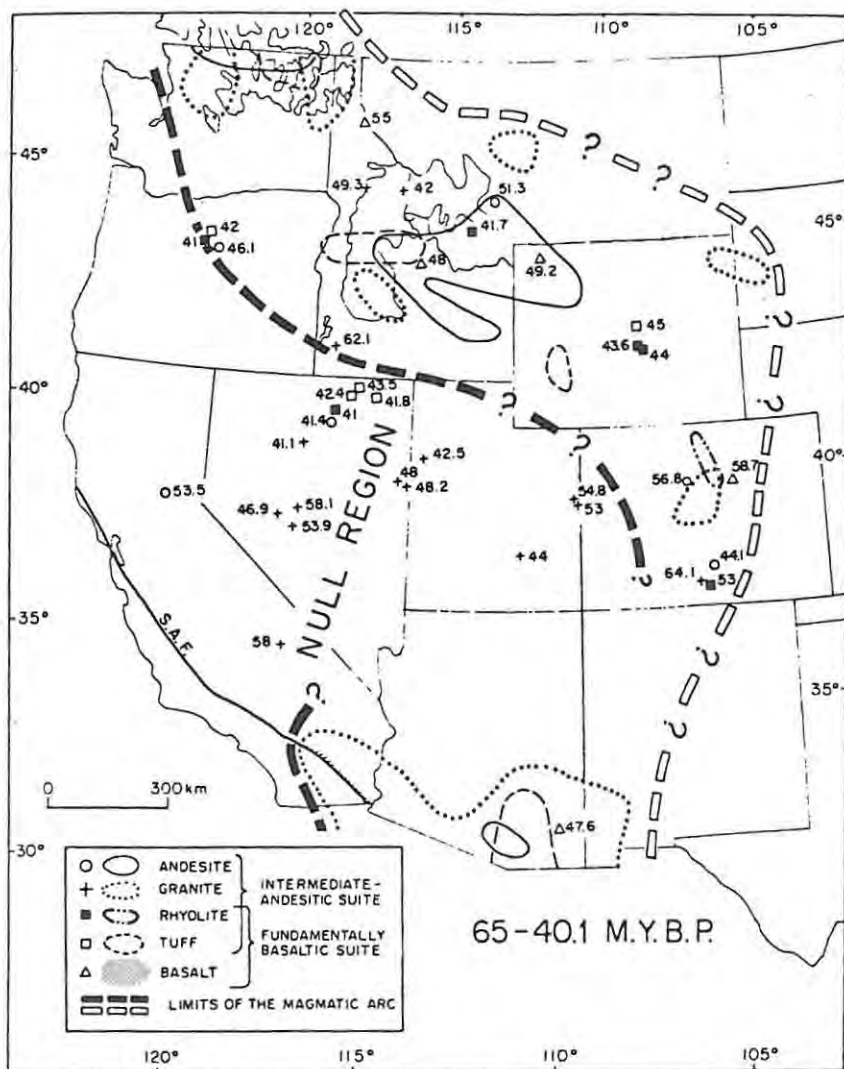


Figure 31: Distribution of igneous activity from 65 to 40.1 Ma based on 260 radiometric age dates. Distribution of Cenozoic batholiths shown by subdued outlines. Note that all igneous activity ceased in the southern Basin and Range province from approximately 47.5 to 39 Ma. From Snyder and others (1976).

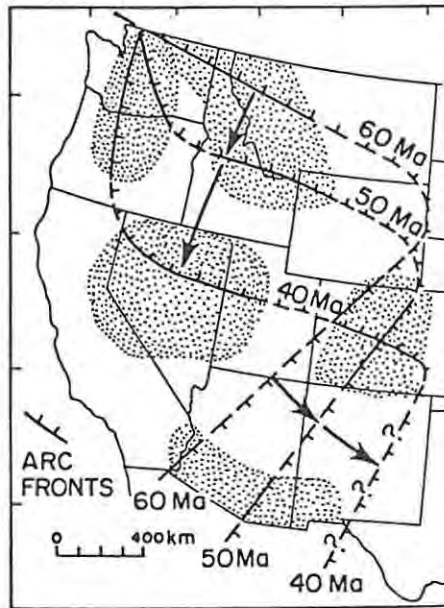
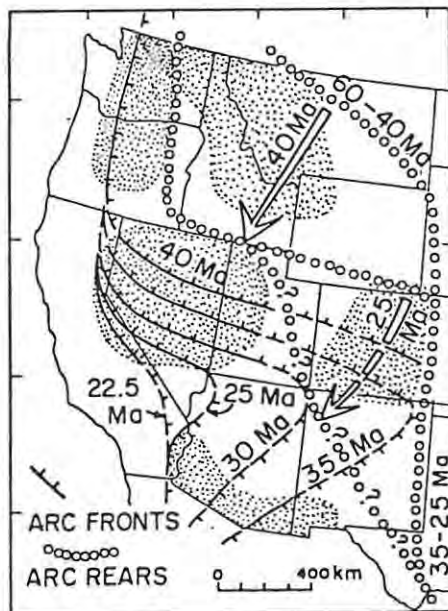


Figure 32: Diagrammatic map showing Paleogene migration of arc volcanism in the western United States. From Dickinson and Snyder (1978).

Figure 33: Diagrammatic map showing mid-Cenozoic migration of arc volcanism in the western United States. From Dickinson and Snyder (1978).



Magmatism in Colorado

Laramide magmatism in the Colorado region apparently was continuous throughout the orogeny (figure 32) but the greatest activity occurred in early Laramide time (Tweto, 1975). The development of basement-cored uplifts was concurrent with magmatic activity. Laramide intrusive stocks and associated sills and dikes are concentrated in a narrow, northeast-trending zone that coincides with the Colorado mineral belt (figure 29). Associated volcanic sediments, mostly of andesitic composition, are found in the lowest portions of Laramide basins adjacent to the mineral belt. Actual volcanic rocks are comparatively minor (Tweto, 1975).

Geologic and gravity data suggest the numerous stocks and other hypabyssal porphyritic bodies are expressions of an underlying, northeast-trending batholith, or string of batholiths (Tweto, 1975). Emplacement appears to have been controlled by a northeast-trending belt of Precambrian shear zones that were reactivated in Laramide time (Warner, 1978). The limited amount of chemical data on the intrusives indicates most belong to a high potassic calc-alkaline suite. However, a small area of alkaline magmatism is located in the Front Range (Keith, 1978). Carbonate replacement deposits of Pb-Zn-Ag and veins with Au and Ag are the predominant mineral deposits associated with Laramide magmatism (Tweto, 1968).

Magmatism in the southwestern United States

Laramide magmatism is widespread throughout southern Arizona, southwestern New Mexico, and to a lesser extent, in western Arizona and southeastern California (figure 30). The western part of this region experienced a limited amount of magmatic activity during Jurassic and Triassic times, including the economically important igneous center at Bisbee. Following a mid-Cretaceous pause, andesite, dacite and rhyodacite volcanism became widespread over the region by 72 Ma, accompanied and followed by emplacement of numerous epizonal stocks (Drewes, 1981). This magmatism was accompanied by regional and differential local uplift, thrust faulting, and folding. The amount of movement on the regional thrust faults (figure 28) is believed to be large, at least 15 km and probably more than 30 km. The actual amount of tectonic transport on one or two major thrust faults may be 100 km (Drewes, 1981). A second pulse of emplacement of many small stocks, plugs, and dikes may have peaked at about 54 to 56 Ma. Tectonic activity during this episode is characterized by left-lateral strike-slip movement on northwest trending faults (Drewes, 1981). Many of the porphyry copper deposits are associated with this younger magmatic pulse.

The northwest-trending regional fault system has had a recurring and major influence on the movement of magmatic and mineralizing fluids in this region. All of the large- and most of the medium-sized mining districts are located within a few km of one of the northwest-trending faults. Many of the Laramide stocks are elongated in a northwest direction (Drewes, 1981). The faults have a complex history of movement that can be traced back to Precambrian time. This broad zone of apparent en echelon faults has been the basis for projecting the Texas lineament through southeastern Arizona and southwestern New Mexico (Drewes, 1981). However, the continuity of the lineament has not been established conclusively. In any event, the faults very likely are surface expressions of an ancient system of flaws in the crystalline basement that were reactivated at various times and in response to various stresses, to produce a complex array of field relations (Drewes, 1981).

Most of the Laramide intrusive and associated volcanic rocks are members of the calc-alkaline suite (Keith, 1978). The most common rock types are granodiorite and quartz monzonite, or their fine-grained and porphyritic equivalents (Drewes, 1981). Individual magmatic centers often show a differentiation sequence from dioritic to monzonitic plutonic rocks, usually with late latitic, rhyolitic, or quartz porphyry hypabyssal rocks (Lowell and Guilbert, 1970). There is no apparent difference in composition and differentiation trends between mineralized and unmineralized plutons (Creasey, 1977). Individual plutons show a decrease in age from northwest to southeast (Lowell, 1974; figures 32 and 34), a pattern of migrating magmatic fronts that is similar to that shown by magmatism in the northwestern United States.

Tectonic Models for the Laramide Orogeny

During the Laramide orogeny, there appears to have been a close relationship between the development of basement-cored uplifts, thrust faulting, and magmatism. Tectonic models for the Laramide orogeny must account for the following features:

- (1) the development of basement-cored uplifts, largely confined to cratonic areas. These are a unique tectonic feature in the Cordillera.
- (2) the continuation of eastward-directed thrust faulting in the Canadian Cordillera and along the western margin in the Montana--Idaho portion of the region of basement-cored uplifts; and in the Mexican Cordillera, and along the western margin in the Arizona - New Mexico portion of the region of basement-cored uplifts.

- (3) the absence of thrust faulting and magmatism west of the central portion of the region of basement-cored uplifts. The termination of faulting and magmatism roughly coincides with the initiation of basement-cored uplifts.
- (4) the general correlation of magmatism with the region of basement-cored uplifts.
- (5) the migration of magmatic fronts; one advancing southward across Idaho and Montana that correlates with termination of Laramide deformation and another advancing southeastward across Arizona and New Mexico.

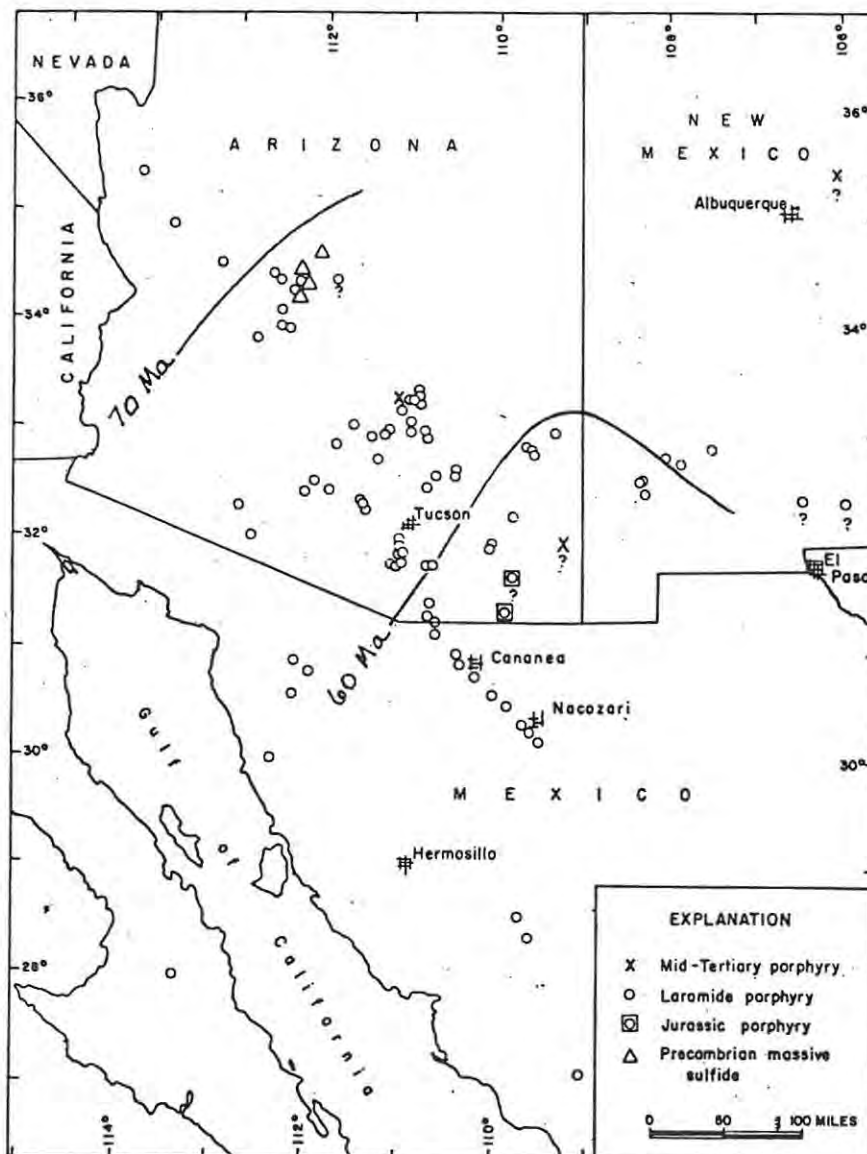


Figure 34: Map showing the distribution of porphyry occurrences in the Southwest province. Deposits shown have porphyry type alteration and contain at least 20,000,000 tons of 0.1% Cu. Modified from Lowell (1974).

The origin of the basement-cored uplifts is unclear, and several hypotheses have been proposed: (1) vertical uplift, (2) uplift due to thrusting, (3) fold-thrust uplift of basement, and (4) wrench or strike-slip faulting (Burchfiel and Davis, 1975). The critical factor for evaluating these proposals is whether or not the uplifts require crustal shortening. The first and last do not, while the second and third do. Since the region of basement uplifts forms a connecting link between regions with shortening by thrust faulting in Idaho - Montana - Canada and Arizona - Mexico, it seems likely that some crustal shortening has occurred (Burchfiel and Davis, 1975). The second and third hypotheses are also supported by structural analysis and detailed mapping of the uplifts. However, these models require no more than 5-10% shortening (8-17 km to 15-33 km), while estimates for Laramide shortening in Canada are on the order of 100 km (Burchfiel and Davis, 1975). Additional Laramide shortening could be distributed along other zones within the central portion of the Cordillera, but no structures of this type are known. This suggests the central region may not have experienced as much compressive stress as regions to the north and south. An explanation for the transfer of this stress from the Sevier thrust belt to a region well within the craton is not apparent.

The cause for the localization of basement uplifts within the craton, further east of the subductive plate margin than basement yielding in any other part of the Cordillera, is not obvious (Burchfiel and Davis, 1975). However, the uplifts in Colorado approximately coincide with the Pennsylvanian - Permian uplifts of the Ancestral Rockies; the eastern margin of the Front Range correlates with a zone of Precambrian and Paleozoic alkaline magmatism; and the uplifts in northwestern Wyoming and southwestern Montana are parallel to and project along the southeastern extension of the Lewis and Clark structural zone. These associations suggest the uplifts are at least partially controlled by reactivation of Precambrian basement structures.

The general correlation of magmatism with the region of basement-cored uplift suggests there is a genetic relationship between the two. Heating of the lower crust and upper mantle could have generated magmas as well as caused thermal expansion to form the uplifts. The region of basement-cored uplifts also experienced a regional uplift, as post-Cretaceous marine sediments are rare. However, this uplift was minor (perhaps a few hundred meters) compared with the late Tertiary uplift (King, 1976). Both uplifts and magmatism were at least partially controlled by reactivated Precambrian

structures, but, peculiarly, not always by the same structures. For example, the Colorado mineral belt is controlled by NE-trending structures while the basement uplifts are controlled by NNW- and N-S - trending structures. In southern Arizona, however, the margins of Laramide uplifts have localized some igneous rocks (figure 35).

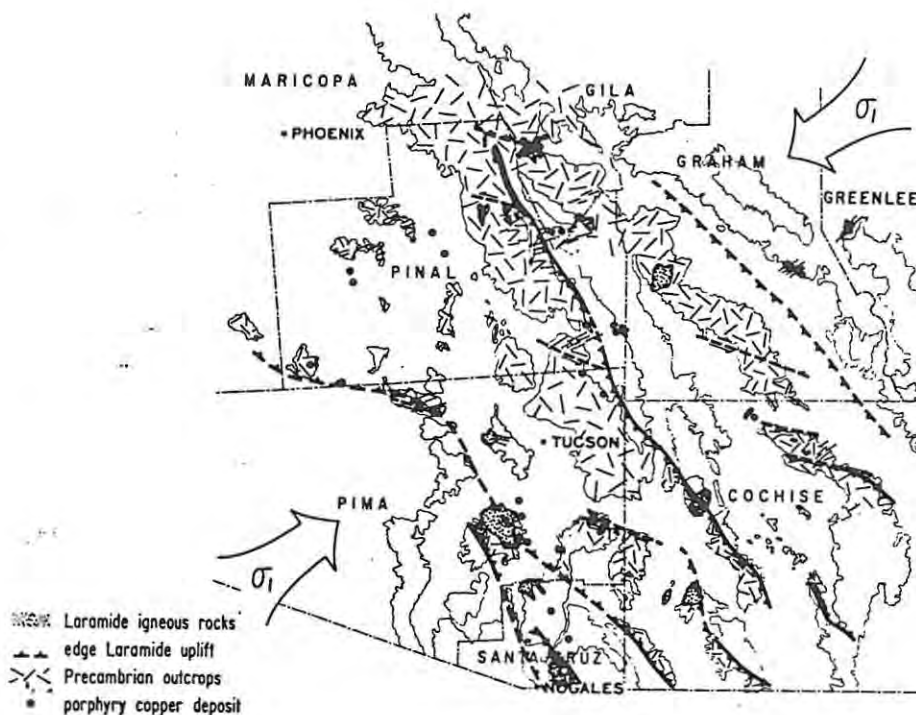


Figure 35: Location of crystalline basement-cored uplifts of Laramide age, southeastern Arizona. Outlined areas are principal mountain ranges and outcrops restored to inferred pre-Basin-Range location. Heavy dashed lines are left-lateral strike-slip faults of the Texas zone, thought to be active during Laramide time. Large arrows show the orientation of principal compressive regional stress. From Nielson (1979).

A variety of plate tectonic models have been proposed to account for the distribution and migration of Laramide magmatism. Dickinson and Snyder (1978) propose that the general eastward shift in magmatism is due

to a flattening of the angle of plate descent, while the southward advancing magmatic front in Idaho and Montana is caused by a south-migrating flexure between a steeply dipping plate to the north and a shallowly dipping plate to the south. Lipman and others (1972) used K_2O contents to form a model with two eastward dipping subduction zones, one along the continental margin and a second, sub-crustal zone further to the east. Coney (1976) postulated that the pattern may be related to the northward migration of a triple junction along the North American plate margin during Laramide time. Keith (1978) relates the type of magmatism to the depth of the descending slab. Alkaline magmatism is generated when the slab is greater than 400 km deep, etc.. A presentation of some of the complex geometries involved in these proposals is beyond the scope of this report.

It is difficult to prove or disprove these proposals because the data available is insufficient to construct a unique tectonic model (Coney, 1976). In any case, they generally are unsatisfactory because they are based on generalizations which are suspect when examined in detail. For example, the igneous suite theory of Keith (1978) does not explain high potassic calc-alkaline magmatism in the Silver Bell Mountains of Arizona that is concurrent with calc-alkaline magmatism in the Patagonia Mountains to the east and calcic magmatism at Morenci, even further east. Nor does it explain coincident calc-alkaline and alkaline magmatism in the Colorado Frong Range. Furthermore, the concept that magmatism moves away from the trench as the subduction zone flattens is open to question. Areas with flat subduction zones in the Andes may or may not be associated with Quaternary volcanism (Megard and Philip, 1976). When one considers that these discrepancies occur in western North America, which is the site of relatively detailed geologic mapping and intensive plate tectonic research, it casts doubt on the generalities assumed regarding the association between magmatism and subduction zones in the relatively lightly studied areas of the Pacific and South America (Lowell, 1974).

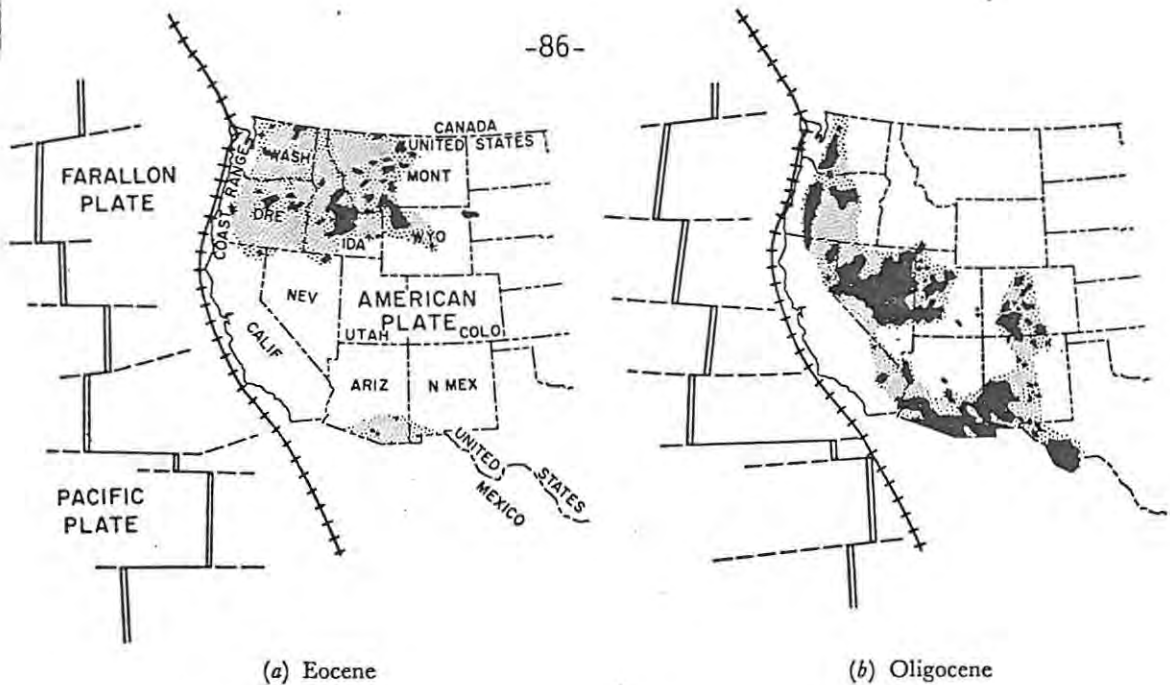
Post - Laramide Magmatism

The Pattern of Magmatic Activity

Because geologic events can be read within narrow time intervals due to increased accuracy of radiometric dating, more rapid shifts in geologic activity can be discerned during middle to late Tertiary time. As a result, it is possible to construct maps showing the changes in the distribution and nature of magmatism over short intervals of time, and relate these changes to variations in the tectonic environment.

Toward the end of Laramide time, magmatism had virtually ceased in Colorado and was greatly diminished in intensity and extent in the southwestern United States. In the northwest, however, the late Laramide pulse of magmatism was expanding southward. Unlike Laramide igneous activity, this magmatism was dominated by volcanic rather than intrusive rocks. Figures 32 and 33 show the southward advance of magmatism across the western United States from middle Laramide time (60 Ma) to the end of Oligocene time (22.5 Ma). This southward advance was accompanied by a westward advance across the southwestern United States during the Oligocene (figure 33). As magmatic fronts were moving across these areas, magmatism was dying out in areas behind the fronts, resulting in major changes in its aerial extent. The contrast in the distribution of magmatism during Eocene time (55 to 40 Ma) and Oligocene time (40 to 25 Ma) is shown in figure 36. Oligocene magmatism is confined to the Cascade Mountains, the Basin and Range province, and the northern extension of the Rio Grande rift in Colorado, while the Colorado Plateau, which was largely bypassed by Laramide tectonism and magmatism, was also bypassed by later Cenozoic magmatism (Burchfiel, 1979). The spatial coincidence of volcanism with the Basin and Range province is especially noteworthy, since this volcanism predates basin-range faulting (initiated about 17 Ma) and most faulting in the Rio Grande rift (initiated about 27 Ma in the north and 32 Ma in the south). This relationship is largely overlooked in the literature on the Basin and Range province.

There are two distinct suites of volcanic rocks and associated intrusives that are predominant during post-Laramide time (Lipman and others, 1972; Christiansen and Lipman, 1972). A largely intermediate-composition calc-alkaline suite is related temporally to subduction along the western margin of the North American plate. The predominant rock types are andesites to rhyodacites, commonly associated with more silicic differentiates (quartz latites to low silica rhyolites) that form ash-flow tuffs. There is a general tendency for this suite to become more alkaline toward the continental interior (Lipman and others, 1972). This suite was succeeded by fundamentally basaltic volcanism which accompanied regional normal and strike-slip faulting in an extensional tectonic environment. Volcanic fields that are regarded as fundamentally basaltic include: (1) tholeiitic or high-alumina basaltic fields (eg. Columbia River Plateau, parts of the Malheur Plateaus, and the Snake River Plains). (2) differentiated basaltic and alkalic fields (eg. San Francisco volcanic field of Arizona), and (3) bimodal basalt and high silica rhyolite fields (eg. Modoc Plateau, Yellowstone). The location of these fields are shown in figure 37.



(a) Eocene

(b) Oligocene

Figure 36: Approximate distribution of Eocene (40 to 55 Ma) and Oligocene (25 to 40 Ma) igneous rocks in the western United States. Present distribution is shown in black, while the inferred original extent is shown by the stippled pattern. From Lipman and others (1972).

Figure 37: Ages of transition from predominantly andesitic to fundamentally basaltic volcanism and of initial basin-range faulting in various Miocene and younger volcanic fields of the western United States. The Oregon Plateaus province shown in this figure is the same area as the Malheur Plateaus. From Christiansen and Lipman (1972).



Fundamentally basaltic volcanism frequently overlies earlier calc-alkaline volcanism in middle to late Tertiary magmatic centers such as the San Juan Mountains of Colorado, the Datil-Mogollon volcanic field of New Mexico and Arizona, and the Virginia City region in Nevada (Christiansen and Lipman, 1972). The transition from predominantly andesitic to fundamentally basaltic volcanism did not occur simultaneously throughout the western United States. Rather, the transition generally occurred earlier in the eastern and southeastern portions of the Cordillera than in those areas to the west (figure 37).

The Characteristics of Magmatic Activity

In the San Juan volcanic field (Lipman and others, 1978), mid-Tertiary volcanic activity began with the eruption of voluminous intermediate-composition lavas and breccias from widely scattered central volcanoes between about 35 and 40 Ma. Beginning about 30 Ma, pyroclastic eruptions of ash-flow tuff, generally associated with calderas, became dominant. These ash-flow tuffs are more silicic than the early intermediate-composition rocks, but geological and petrological features indicate they probably represent the more fractionated upper parts of bodies of intermediate-composition magmas. About 25 Ma, volcanic activity changed from the association of intermediate-composition lavas and related silicic rocks to widespread eruptions of basaltic lavas and local rhyolite flows and tuffs (figures 38, 39, and 40). The basaltic lavas are primarily silicic alkalic types, while the rhyolites are more silicic and alkalic than earlier rhyolites (Lipman and others, 1978).

Events in the Datil-Mogollon volcanic field were similar, but slightly different in character and timing (Elston and Bornhorst, 1979). An early period, from 40 to 29 Ma, of calc-alkaline volcanism became progressively more felsic with time, culminating in eruptions of quartz latite ash-flows from cauldrons. During late-stage resurgent magma pulses, bodies of monzonite or quartz monzonite invaded some of the cauldrons. About 30 Ma, basalt-like rocks became abundant. Basaltic andesite predominates in this calc-alkalic to sub-alkalic assemblage, but compositions range from basalt to quartz latite. Silicic ash-flow tuff and lava continued to erupt from large calderas, but the rocks changed to high-silica rhyolites. The eruptive centers of basaltic andesite and high-silica rhyolite seem to be mutually exclusive. Rhyolite volcanism became nearly extinct by 21 Ma, waning during the initiation of basin-range faulting. Basaltic andesite volcanism continued for somewhat longer, until about 18 Ma. Following a volcanic hiatus of about 3 million years, tholeiitic and alkalic basalt

erupted in the New Mexico portion of the Colorado Plateau and the southern Great Plains (Elston and Bornhorst, 1979; figures 38, 39, and 40).

In the Great Basin, andesitic and some rhyolitic lava flows with limited silicic ash-flow tuffs were dominant from 43 to 34 Ma (Stewart and others, 1977; figure 41). About 34 Ma, silicic tuffs became dominant as the volcanic front moved southwards across Nevada and Utah. Basalt and bimodal assemblages of basalt and rhyolite predominate after 17 Ma, and silicic tuffs are rare after 6 Ma. However, calc-alkaline dominantly andesitic volcanism persisted along the Walker Lane and adjacent areas in the Sierra Nevada (figure 42).

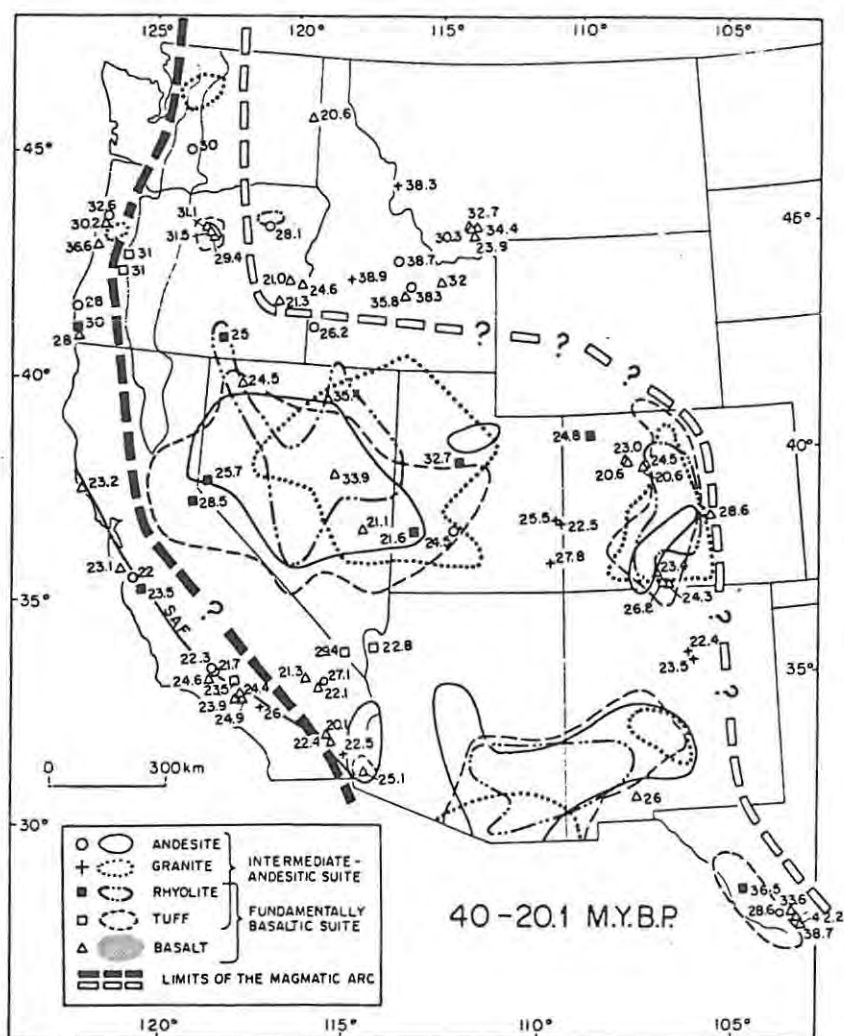


Figure 38: Distribution of igneous activity from 40 to 20.1 Ma based on 717 radiometric age dates. The inner limit of magmatic activity across southern Idaho represents the inferred boundary for 37.5 to 20 Ma. From Snyder and others (1976).

As in the Datil-Mogollon volcanic field, the period of transition around 17 Ma was a time of sparse volcanism (Stewart and others, 1977). This period also marks the initiation of basin-range structures in the Great Basin.

The volcanic sequence in southwestern Arizona is not as well established due to lack of exposures, but a few generalizations can be made. Andesitic volcanism with associated silicic tuffs did not become widespread until 28-26 Ma, and continued until 20-17 Ma (Eberly and Stanley, 1978; figure 38). A major graben structure, the ENE-trending Gila trough, developed during or immediately before this volcanic event. The trough is 140 to 150 km in length and 15 to 25 km in width. There is insufficient data to adequately explain the Gila trough, but it may represent a reactivation of basement structural elements (Eberly and Stanley, 1978). The trend of the trough is roughly parallel with one of the trend directions of porphyry copper deposits. However, the region of the trough, termed the Gila River Gap by Jerome and Cook (1967), is noticeably deficient in mineralization. Following a 4 million year period of diminished volcanism basalt and differentiated alkalic volcanism became dominant in southern Arizona after 13 Ma, about the same time as initial basin-range faulting (figures 39 and 40).

In the northwestern United States, only weak volcanism persisted in the interior during Oligocene time, as magmatic activity shifted southward into Utah and Nevada (Armstrong, 1978; figure 38). However, a chain of basalt-andesite-rhyolite volcanic centers along the Cascade trend were initiated and became progressively more active during Miocene time. This calc-alkaline magmatic arc reached its maximum extent about 20 Ma (figure 39), before retreating northward to its present southern limit at Mt. Lassen (figure 40). Meanwhile, a major eruption of tholeiitic flood basalts formed the Columbia River Plateau between 16.5 and 13.4 Ma (McDougall, 1976; figures 37 and 39). In the Malheur Plateaus province, bimodal rhyolite and basalt volcanism became widespread during this same interval and has continued to Recent time. The ages of basaltic and especially rhyolitic eruptions generally are younger toward the west and northwest (Armstrong, 1978; figures 39 and 40). During the past 13 million years, bimodal volcanic activity, associated with regional uplift and block faulting, transgressed northeastward to form the Snake River Plain - Yellowstone volcanic field (figures 37 and 40). Within any particular area of the field, volcanism began with eruption of large volumes of rhyolitic ash-flows,

air-fall tuffs, and lava flows. This was followed by eruption of flood basalts associated with a few rhyolite domes and flows, and finally by basalt flows intercalated with large volumes of fine-grained tuffaceous sediments. Yellowstone Park currently is the site of the first facies. The second facies occurs in eastern Idaho, and the third facies occurs in the western part of Idaho.

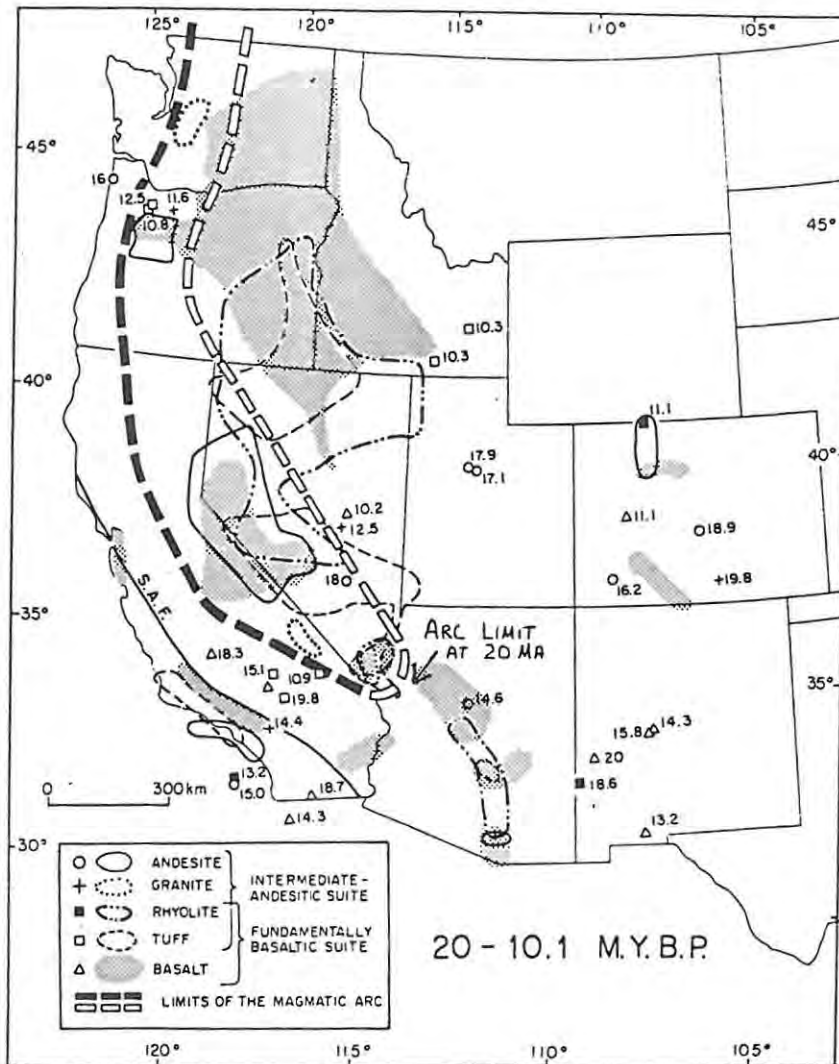


Figure 39: Distribution of igneous activity from 20 to 10.1 Ma based on 464 radiometric age dates. Modified from Snyder and others (1976).

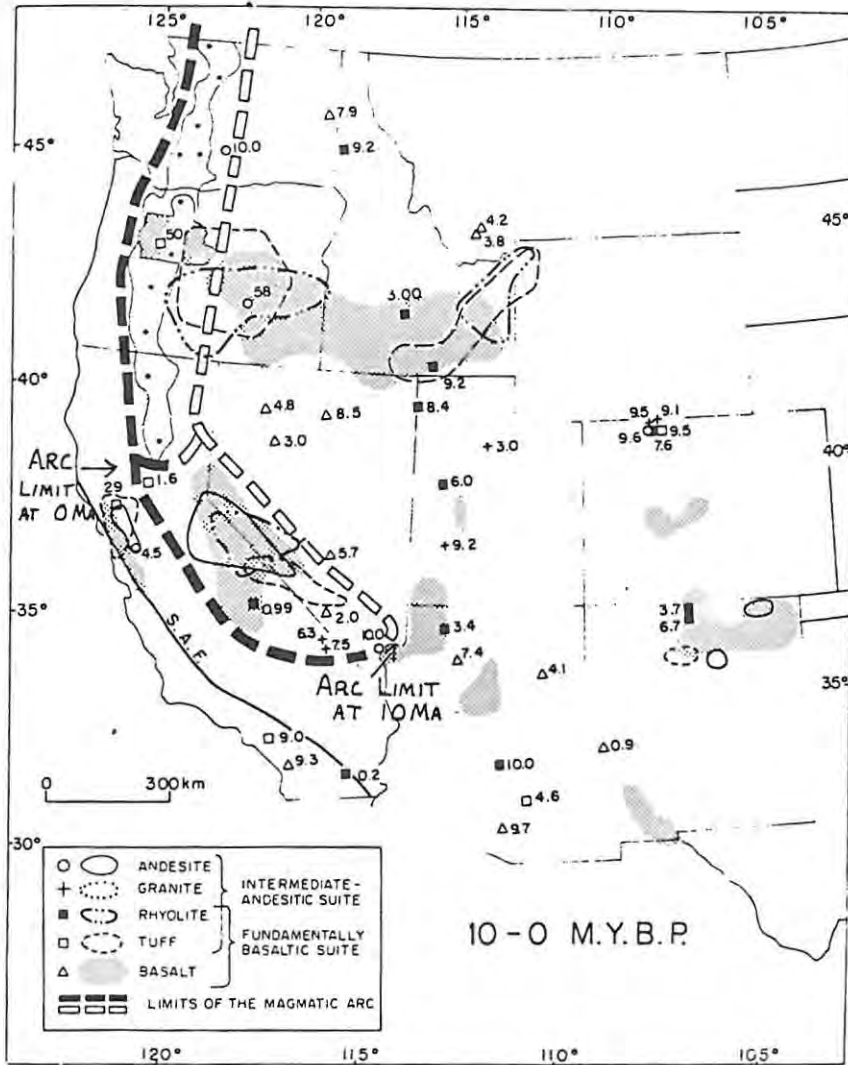


Figure 40: Distribution of igneous activity from 10 to 0 Ma based on 466 radiometric age dates. Modified from Snyder and others (1976).

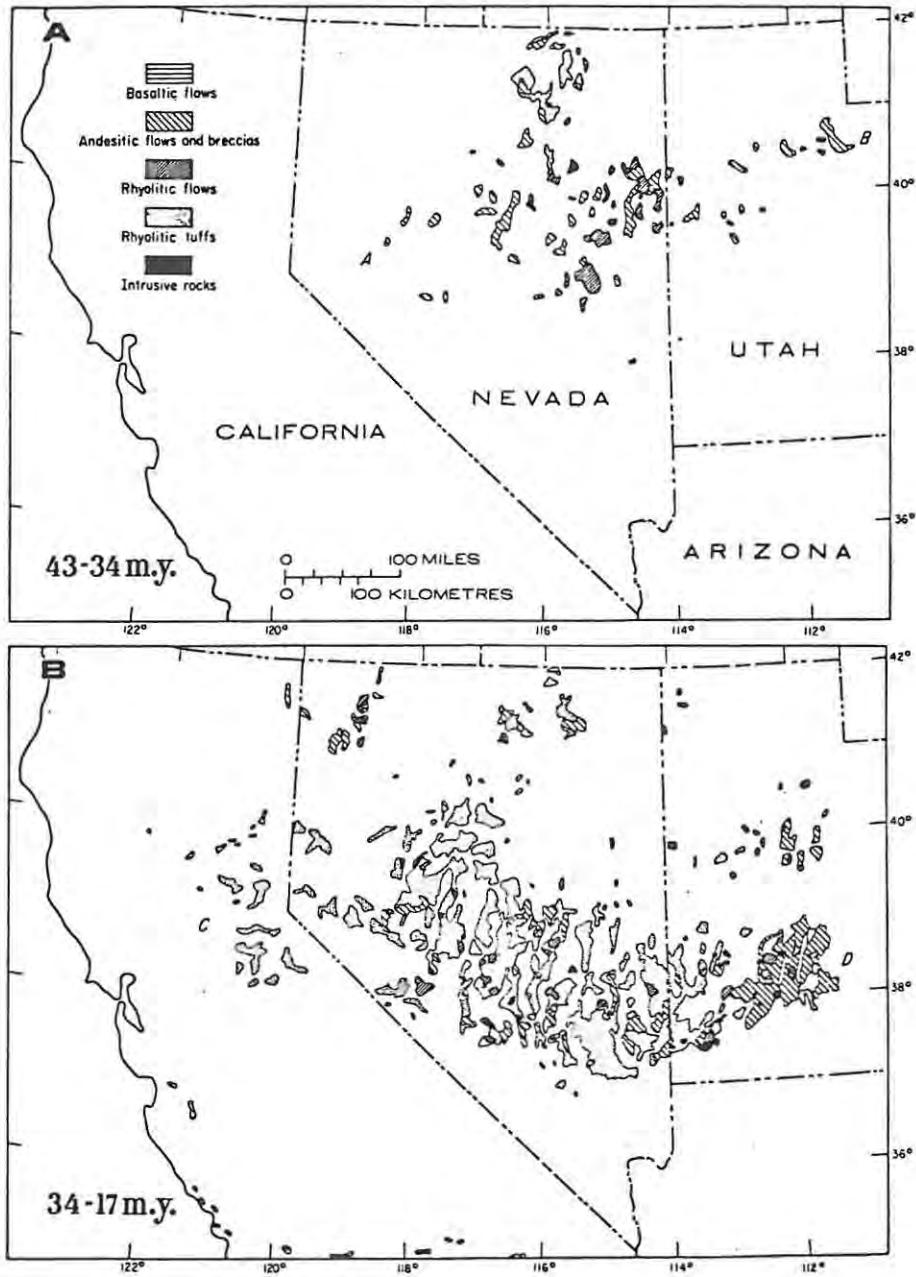


Figure 41: Generalized maps showing distribution of Cenozoic igneous rocks in Nevada, Utah and parts of adjacent states. From Stewart and others (1977).

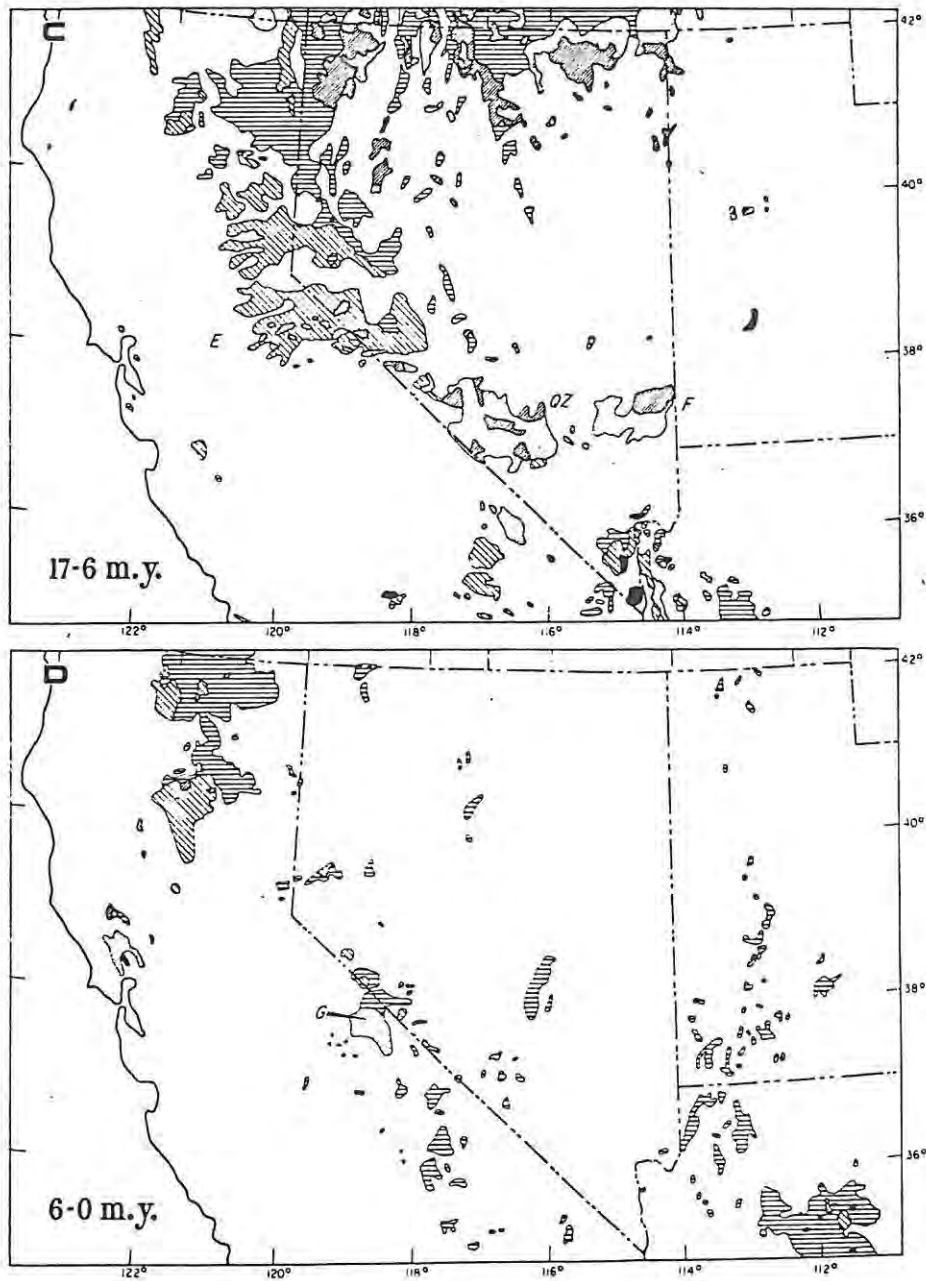


Figure 42: Generalized maps showing distribution of Cenozoic igneous rocks in Nevada, Utah and parts of adjacent states. Explanation and scale shown in figure 41A. From Stewart and others (1977).

Post - Laramide Tectonic History of the Western United States

The changes in igneous patterns during post-Laramide time correspond with changes in the tectonic environment in the western United States. Laramide-style deformation appears to have ended throughout the region by 40 Ma. The continuity of the southward advance of the magmatic front in the northwestern United States suggest the tectonic transition in this region was gradational over time, rather than related to a sudden change in plate motions as postulated by Coney (1978). Following the termination of Laramide deformation in the southern Cordillera, widespread erosion and beveling of the landscape became prominent (Epis and Chapin, 1975). The exact tectonic changes that accompanied the ignimbrite "flare-up" during Oligocene time are less certain, but the development of extensional tectonic features may be important. The Rio Grande rift was established from 32 to 27 Ma, while the Gila trough in Arizona also has a pre-Miocene age (Eberly and Stanley, 1978). The position of the Rio Grande rift is at least partially influenced by Mesozoic and Paleozoic crustal structures as it follows an axis of Laramide, Pennsylvanian, and possibly earlier uplifts (Chapin and Seager, 1975; Cordell, 1978).

The pattern of calc-alkaline volcanism, from intermediate-composition lavas to progressively more felsic ash-flows from cauldrons, may be related to changing tectonic conditions. In fact, the close spatial and temporal association of silicic and calc-alkaline cauldrons with the Rio Grande rift in the San Juan, Datil-Mogollon, and Trans-Pecos volcanic fields suggest the development of cauldrons may be related to an extensional tectonic environment. By analogy, many of the Oligocene cauldrons in the Great Basin may also have been related to rifts which subsequently have been obscured by basin-range faulting.

There is less direct evidence for an Oligocene-age extensional environment in the Great Basin. However, metamorphic core complexes, thought to be a product of regional extension and thermal incursion (Davis and Coney, 1979), are spatially and temporally associated with ignimbrites. These complexes occur from the Snake River plain south into Mexico (figure 43). Similar complexes are associated with the late Laramide magmatism in the northwestern United States (Armstrong and others, 1977). The regional lineation within the complexes strikes N60°E, suggesting an ENE-WSW direction of extension (Eaton, 1979).

Basin-range style faulting did not begin until 17 Ma in the Great Basin, and perhaps not until 13 Ma in southern Arizona. Most of these

Miocene faults trend NNW, as do dikes that fed the Columbia River Plateau basalts in Washington and Oregon, and the 16.5 to 13.8 million year old dikes of the Cortez rift in northern Nevada (figure 44; Eaton, 1979). Most basin-range faults in Arizona also trend NNW or NW. These trends suggest that middle to late Miocene and Pliocene crustal spreading was also ENE-WSW (Eaton, 1979).

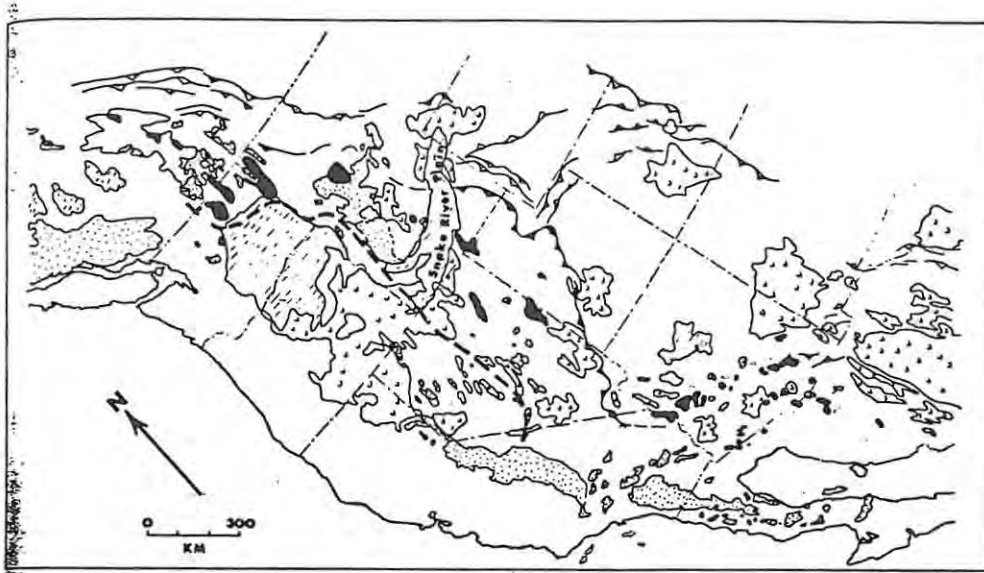


Figure 43: Distribution and general regional tectonic setting of Cordilleran metamorphic core complexes. Solid black, metamorphic core complexes; heavy stipple, major batholiths; dotted barbed lines, Sevier frontal thrust belt; V pattern, lower to middle Tertiary mainly ignimbrite volcanics; dashed line, $^{87}\text{Sr}/^{86}\text{Sr}=0.706$ line

From 10 Ma to the present, extensional deformation has continued in the Great Basin and the Rio Grande rift (figure 45). The trend of the present ranges indicated the direction of spreading has changed to E-W and WNW-ESE. In Arizona, where basin-range faulting terminated shortly before 10 Ma, the NW-trending ranges are still preserved.

Regional uplift of the entire western United States has occurred simultaneously with extensional deformation during the past 25 million years. In some areas, this uplift is partially controlled by major faults, but in most areas, it appears to be related to an upwarping of the entire crust. This uplift, faulting, and related erosion as well as recent volcanism is responsible for most of the present land forms of the western United States.

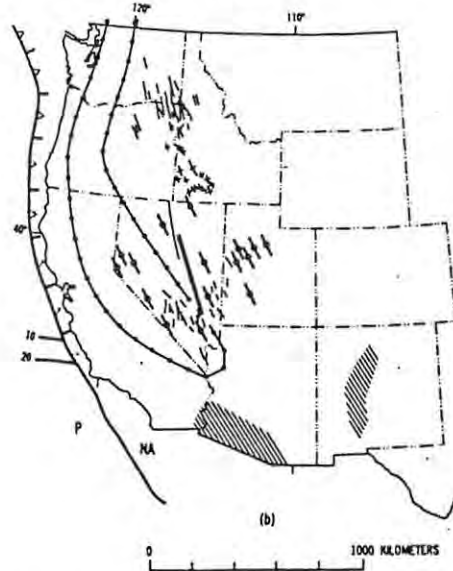


Figure 44: Cenozoic extensional features developed between 20 and 10 Ma. The cluster of fine lines on the north represents feeder dikes of the Columbia River Basalt Group. Area bordered by crossed lines is the middle Miocene western Snake River Plain and associated faults. Single line in north-central Nevada is dike swarm of the Cortez rift. Straight double line in eastern Nevada is symmetry axis of gravity anomalies of Eaton and others (1978). Short dashed lines in the south are normal faults of middle to late Tertiary age. Block faulting also occurred in areas with cross ruling. From Eaton (1979).

Figure 45: Cenozoic extensional features developed between 10 Ma and the present. Shaded areas indicate sedimentary rocks that accumulated in the Great Basin, Rio Grande rift, and their immediate environs in this period. From Eaton (1979).

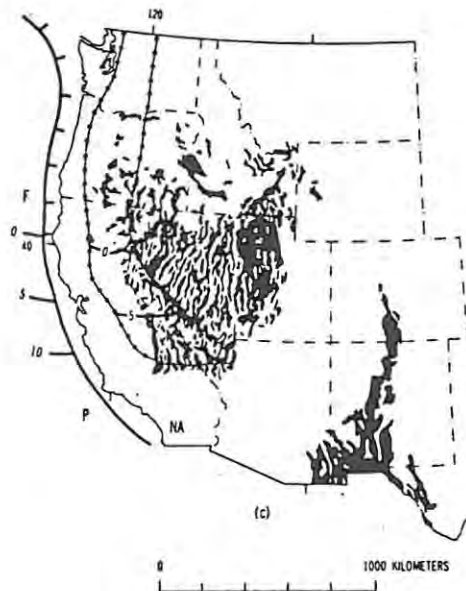
EXPLANATION

F, P, NA
Identifiers of the Farallon, Pacific, and North American plates

Site of trench at convergent plate boundary
Hachures between teeth mark section of trench still active at end of period represented by diagram. Numbered line (age in m.y.b.p.) marks position of Mendocino fracture zone

Boundary of calc-alkalic volcanic arc

Locations of Miocene normal faults with northwest strike (Loring, 1976)



Explanation for Figures 44 and 45:

Models for Post - Laramide Magmatism and Tectonism

The peculiar pattern of Oligocene magmatism, with magmatic fronts advancing in directions that are oblique to plate boundaries (figures 32 and 33), indicates that the interaction between converging plates can be considerably more complex than is usually implied in plate tectonic theory. The various models suggested for Laramide and post-Laramide tectonism and magmatism rely on features such as transform faults, warped plates, and fluctuations in the rate and angle of the dip of subduction to account for the complex patterns in the Cordillera. The preferred model is largely a matter of personal preference, since there is little factual data to support any of them. This is not to say that Oligocene magmatism is unrelated to plate tectonics. Rather, the relationship between the two is poorly understood, despite the large amount of geologic data on the Cordillera.

The relative motion of major lithospheric plates in the vicinity of the western United States during middle and late Cenozoic time has been established with reasonable accuracy from studies of ocean-floor magnetic anomalies (Atwater, 1970). Reconstruction of plate movements has shown that the spreading ridge between the Pacific and Farallon plate intersected the subduction zone along the western margin of North America approximately 29 Ma (figure 6). According to Atwater (1970), this led to the development of transform fault systems, including the San Andreas fault system, along parts of the western continental margin. Movement along the transform and related faults transmitted stress into the continental interior (Atwater, 1970). The lack of subduction at the transform plate boundary led to the growth of a slab-free region beneath that part of the continental block adjacent to the San Andreas system (Dickinson and Snyder, 1979; figures 46 and 47).

This model offers a plausible explanation for the development of Miocene magmatism and basin-range faulting about 17 Ma. This suggestion is supported by the present extent of the inferred slab-free region, which approximately coincides with the region of extensional faulting (figure 47). Also, the establishment of a tensional tectonic environment accounts for the transition from predominantly andesitic volcanism to fundamentally basaltic volcanism at about this same time. The model also shows that the northward retreat of the calc-alkaline magmatic arc along the Pacific coast is related to expansion of the slab-free region (figures 46 and 47), since arc magmatism and tectonism depend upon the presence of a subducted slab

of lithosphere beneath the arc-trench system (Dickinson and Snyder, 1979). The broad, epirogenic uplifts of the continent can also be related to the model. The tensile stress in the North American plate and consequent thinning of the lithosphere may have resulted in the passive rise of asthenospheric mantle and derivative magmas and resultant heating and uplift of the lithosphere (Eaton, 1979). Alternatively, Dickinson and Snyder (1979) suggest that regional uplift and extension may have been triggered by upwelling of asthenosphere through the gradually enlarging slab window.

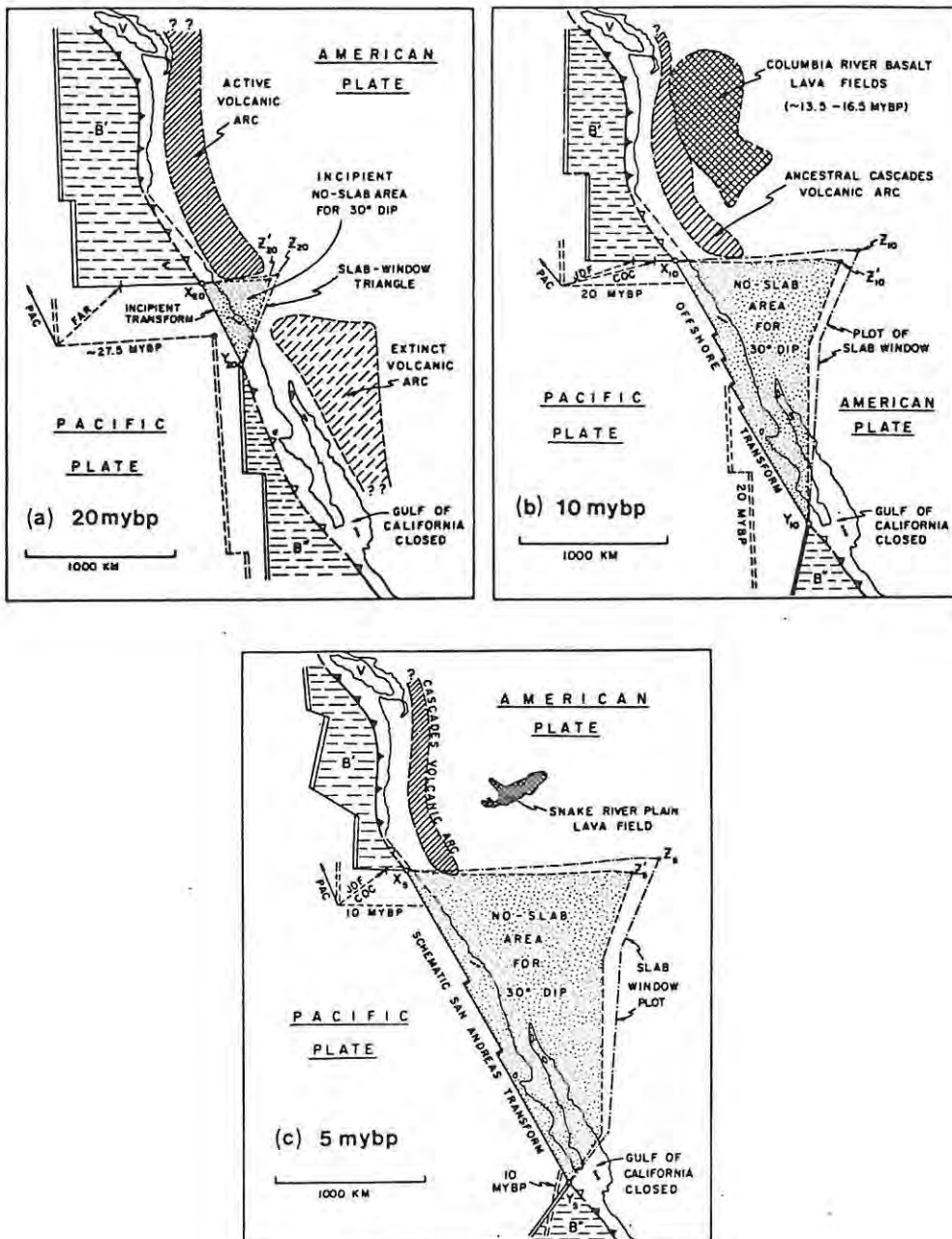


Figure 46: Inferred slab-free regions (stippled) adjacent to San Andreas transform at 20, 10, and 5 Ma. From Dickinson and Snyder (1979).

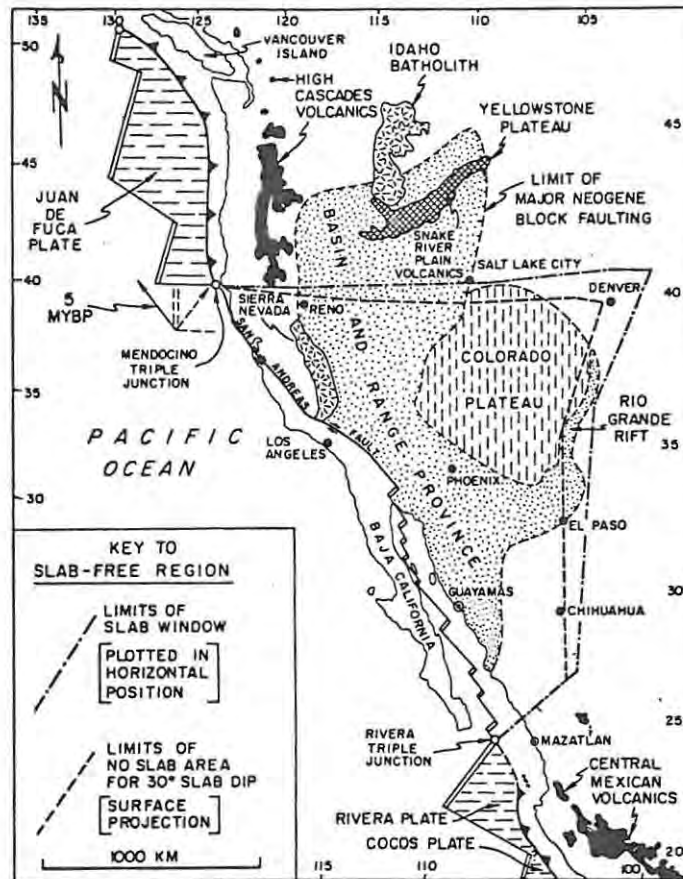


Figure 47: Inferred extent of present slab-free region adjacent to San Andreas transform. From Dickinson and Snyder (1979).

The model of Atwater (1970) and that of Dickinson and Snyder (1979) do not account for all of the variations in timing, location, and nature of late Cenozoic magmatism and tectonism. For example, previously cited evidence suggests that much of the Basin and Range province was in tensional stress prior to the extensive development of the transform system and the slab-free zone, and perhaps even before the intersection of the ridge and subduction zone. Likewise, volcanism was widespread throughout this province before the ridge-trench intersection. Also, although the transition from predominantly andesitic to fundamentally basaltic volcanism occurred around 17 Ma in the Great Basin and perhaps in southeastern Arizona, the transition was considerably earlier in volcanic fields on the margin of the Rio Grande rift (San Juan and Datil-Mogollon fields). These fields are more distal from the San Andreas transform system than is the Great Basin, and, theoretically, the transmission of stresses related to the transform should occur later than in the Great Basin. Other features that do not fit the model include the locations of areas with fundamentally basaltic volcanism (eg. the Columbia River, Malheur Plateaus, and Snake River

volcanic fields) outside of the slab-free region (figures 46 and 47). Likewise, the area of regional uplift includes a much more extensive area than the slab-free region.

A variety of other models have been proposed to explain these inconsistencies. Basically, these models regard mantle diapirism as the root cause of uplift and magmatism, with crustal extension an auxiliary effect (Scholz and others, 1971; Eaton, 1979). The diapirism commonly is viewed as a form of backarc spreading which forms an ensialic interarc basin within the continent. This model does not explain the northward retreat of the calc-alkaline magmatic arc, and the continuation of crustal extension despite the extinction of arc volcanism (Dickinson and Snyder, 1979). In conclusion, it seems likely that both models, development of a transform fault system and backarc spreading, have influenced late Cenozoic magmatism and tectonism.

Mid to late Cenozoic magmatism also appears to have been controlled by crustal structures. Widespread volcanism and a series of small intrusives are located within and adjacent to the Rio Grande rift in Colorado, New Mexico, and Texas. The Colorado lineament also was a focus of Cenozoic magmatism. Volcanism in the Great Basin tends to occur along discrete belts, especially in western Utah (figure 41). The northernmost belt lies along the westward projection of the Uinta uplift, suggesting magmatism has been localized by reactivation of basement structures. However, there is no surface expression of these structures. Other examples of structurally controlled magmatism are the Snake River - Yellowstone field, which appears to be propagating along a NE-trending basement zone of weakness (Eaton and others, 1975), and a NE-trending belt of recent volcanism from western Arizona across New Mexico. The Jemez Caldera is located at the intersection of this trend with the Rio Grande rift. Recent volcanism in the Great Basin has been confined mostly to the margins, especially along the Walker Lane (figure 42). Thus, like earlier episodes of magmatism, post-Laramide magmatism was partially localized along pre-existing zones of weakness in the crust.

MINERALIZATION ASSOCIATED WITH MAGMATIC ENVIRONMENTS

"Given an array of map points, linears can be drawn through any two of them. If two cannot be found, one will suffice. This rule is known to all prospectors who can prove their diggings lie on a straight line with the nearest mine." Donald U. Wise, 1976

The pattern of mineralization in the western United States is very similar to the pattern of magmatism, due to the close genetic relationship between mineralization and magmatism for most metallic mineral deposits. This relationship can be refined by several observations. For example, some types of mineral deposits are confined to a particular type or suite of igneous rocks. For these deposits, the processes for concentration of ore elements may be directly related to the original composition of associated magmas, or the path of differentiation of the magmas. Other mineral deposits occur within igneous rocks with a wide range in composition, suggesting concentration processes can occur under a wide range of geologic conditions.

Most types of mineral deposits in the western United States are restricted to certain time intervals, reflecting the limited periods of existence of favorable tectonic environments and associated magmatism. Mineral deposits show a very uneven distribution through geologic time, with most of the deposits being formed during a few short intervals. The time distribution of mineral deposits may also be controlled by long-term differentiation processes within the earth. This probably is not an important factor in the western United States, since the major period of magmatism (post-Permian) is a relatively short period of geologic time. However, a few ore elements, such as molybdenum, may be controlled by these processes.

Some types of mineral deposits are restricted to small areas within a larger region with favorable magmatism and tectonism. Frequently, the same element is concentrated in deposits of different types and of different ages in the same area. These relationships suggest the composition of the host rocks, or of the underlying crust and upper mantle, is an important factor controlling mineralization.

The following summary of mineralization in the western United States illustrates the importance of these factors for the various types of deposits.

Precambrian and Paleozoic Mineralization Associated with Magmatic Environments in the Craton

Precambrian and Paleozoic magmatic environments within the craton have had limited economic significance compared with younger environments in the Cordillera. Three major ore deposits have been discovered (Jerome, Homestake, and Mountain Pass), while two other areas are being evaluated at the present time (Stillwater and State Line). Also, several smaller deposits and numerous occurrences, as well as favorable geologic and tectonic environments, indicate there is a potential for several other types of mineral deposits. Due to lack of exposures, subsequent tectonism, and limited detailed investigations, there is no obvious relationship between tectonic environments of these deposits with subsequent tectonic events in the Cordillera.

Archean Mineralization

Compared with Archean terranes elsewhere in the world, the Archean of the western United States contains very little mineralization, partially due to the limited amounts of greenstone terrane exposed in the Archean crystalline basement. The only significant occurrence of mineralization, the Stillwater Complex, is not associated with greenstone terrane.

The Stillwater Complex (figures 48 and 49) contains mineralization that is similar to that found in the Bushveld Complex. Copper-nickel sulfide mineralization (mainly pyrrhotite-pentlandite-chalcopyrite) occurs in the chilled norite basal contact zone of the complex (Proffett, 1979). Layered chromite mineralization is found in the overlying peridotite zone (Jackson, 1968) and platinum group metals recently have been discovered in a layer similar to the Merensky Reef, in the lower banded series (Bow and others, 1981; Todd and others, 1981).

As many as thirteen tabular zones of chromite enrichment are found interlayered with harzburgite and bronzitite in the peridotite zone of the ultramafic series. Two of these, the G and H zones, were exploited during the Second World War. The G zone is up to 4 m thick and can be traced for 40 km. The overlying H zone is generally about half as thick as the G, but it has a higher grade. Upgraded ore from these zones runs about 43.5 to 46.9% Cr₂O₃ with Cr/Fe ranging from 1.61 to 2.33. These deposits contain nearly all of the chrome reserves of the United States (Jackson, 1968). Minor amounts of platinum group metals are found in the A, and, to a lesser extent, in the K chromite zone (Page and others, 1976).

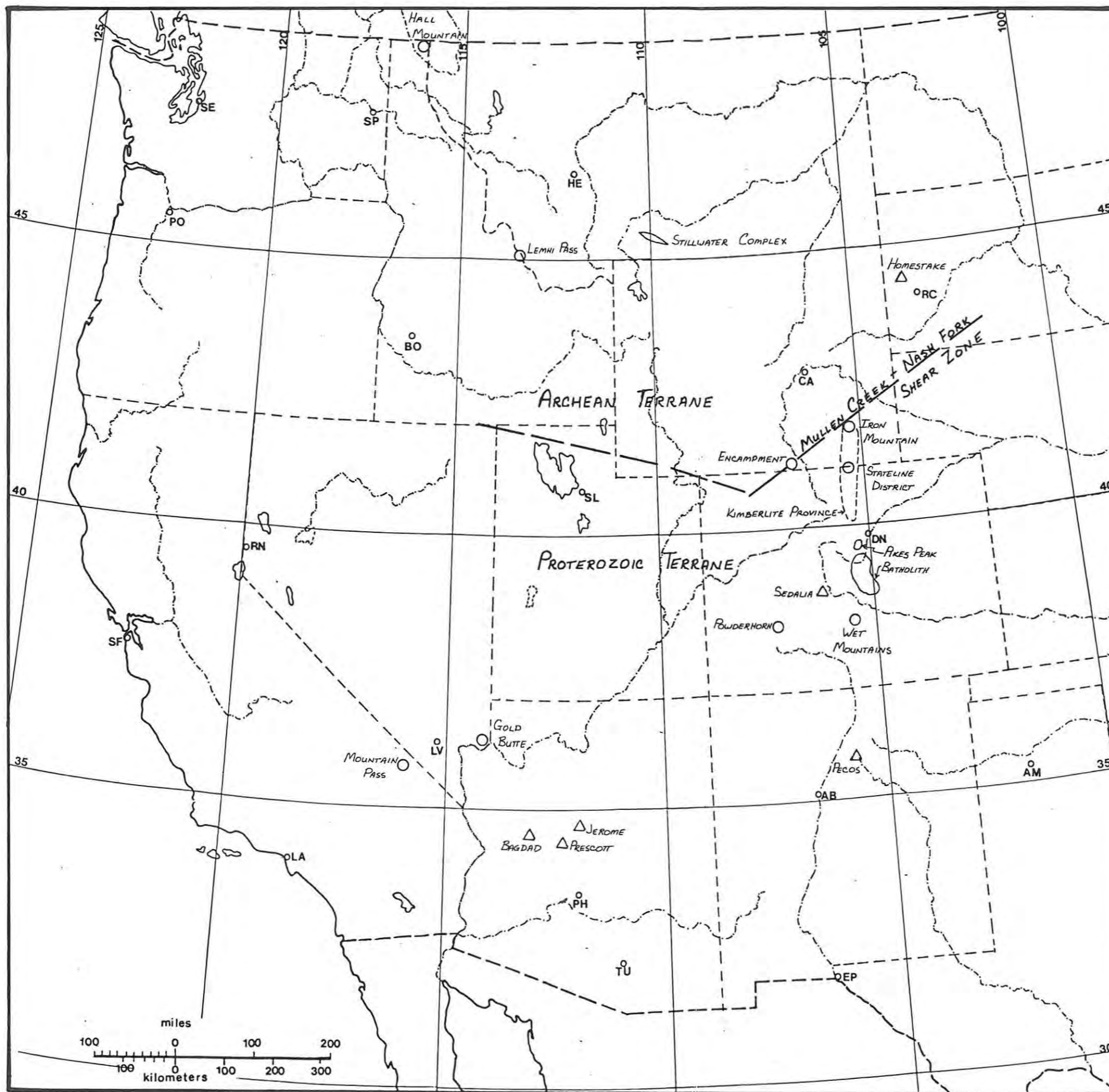


Figure 48. Mineralization associated with Precambrian and Paleozoic Magmatism in the craton.

- △ Volcanogenic deposits
- Magmatic or epigenetic deposits

- Homestake - Au
- Sedalia - Cu, Zn, Ag, Pb
- Pecos - Zn, Pb, Ag, Cu, Au
- Jerome - Cu, Zn, Ag, Au
- Prescott - Zn, Pb, Au, Ag, Cu
- Bagdad - Zn, Cu, Au
- Stillwater Complex - Cr, PGM, Ni, Cu
- Encampment - Cu, Au, Ni, Co, PGM
- Iron Mountain - Ti, V, Fe
- Pikes Peak Batholith - Be, Fl (Sn, W, Mo, U)
- Gold Butte - REE
- Mountain Pass - REE, Th
- Powderhorn - Nb, REE, Th, Ti
- Wet Mountains - REE, Th, Nb
- Lemhi Pass - Th
- Hall Mountain - Th
- Stateline District - diamonds

References

- King, 1976
- McCallum and Mabarak, 1976
- Staatz, 1974
- Volborth, 1962
- Warner, 1979

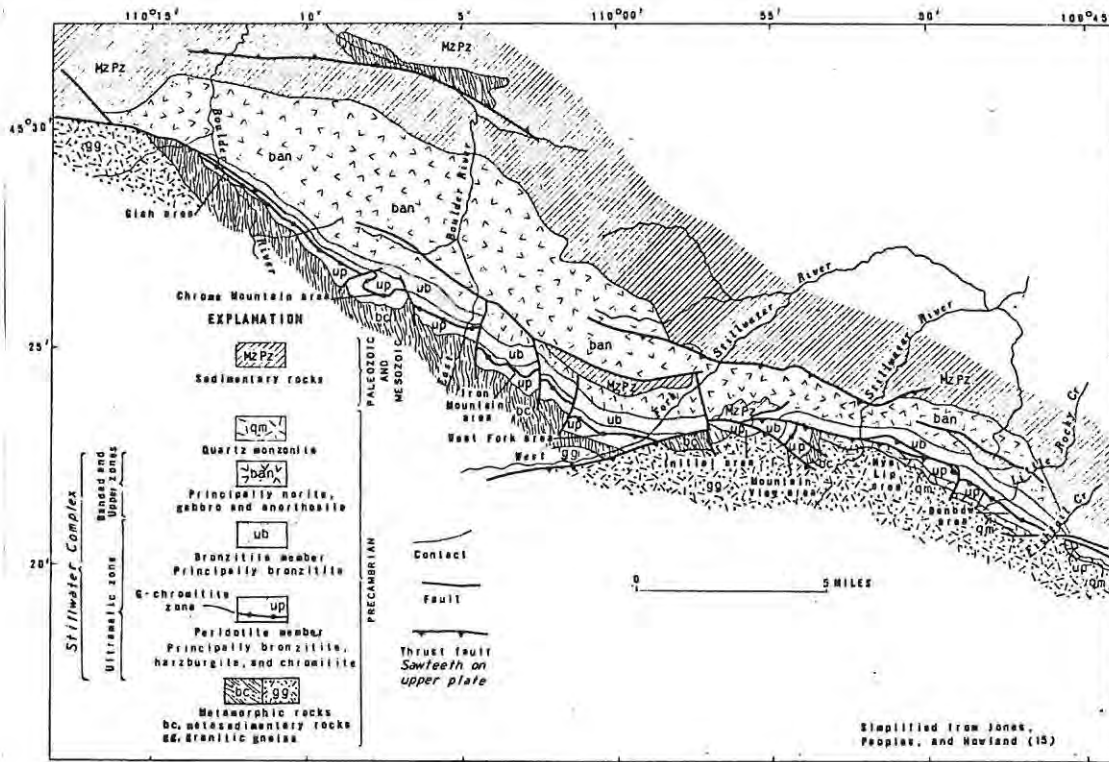


Figure 49: Geologic Map of the Stillwater Complex. From Jackson (1968).

Significant platinum-palladium mineralization with base metal sulfides is presently being evaluated by two mining companies. Mineralization occurs in the 1 to 3 m thick J-M reef, approximately 400 to 450 m above the base of the banded series (Todd and others, 1981). The J-M reef can be traced for 40 km, with a 5.5 km interval averaging 0.65 oz (22.3 gm) of Pt-Pd/short ton, over a thickness of 2.1 m (Todd and others, 1981). The Pd/Pt ratio typically runs 3.5:1, while sulfides average 1 to 2 volume percent. Mineralogy consists of Pt-Pd sulfides, arsenides, tellurides, and Pt-Fe alloys (Elliot and others, 1981). The mineralized zone dips steeply to the north. These grades and tonnages compare favorably with deposits in the Bushveld Complex.

Proterozoic Mineralization

In contrast to the Archean, the Proterozoic sequence in the western United States contains numerous small ore deposits and prospects as well as three major orebodies. Most mineralization is found in greenstone belts. However, there are several examples of mineralization related to intrusive activity.

Volcanogenic deposits

The greenstone belts in Arizona, New Mexico, and, to a lesser extent, in Colorado, contain numerous small volcanogenic Cu-Zn-Pb massive sulfide deposits. The major deposits (> 1 M tonnes production) of this type

include the United Verde and United Verde Extension Mines at Jerome, Arizona (Anderson and Creasey, 1958; Anderson and Nash, 1972), the Iron King Mine near Prescott, Arizona (Gilmour and Still, 1968), the Bruce/Old Dick Mine near Bagdad, Arizona (Baker and Clayton, 1968), and the Pecos Mine at Terrero, New Mexico (Krieger, 1932; figure 48). A more complete listing of other occurrences is found in Anderson and Guilbert (1979) and Giles (1976). The few deposits that have been dated have ages of 1800 to 1730 Ma. The deposits generally are similar to those found in the Abitibi greenstone belt, being closely associated with felsic volcanic centers near the top of mafic to felsic volcanic piles. Mineralization seems to have formed along time horizons marked by iron-rich chert exhalites near the termination of individual volcanic cycles. Examples of deposits formed in distal and proximal environments have been documented (Anderson and Guilbert, 1979).

At Jerome, Proffett (1979) states that the early Proterozoic section, up to 12,000 m thick, consists of mafic submarine volcanics and mudstones, graywackes, and sedimentary breccias, overlain by a submarine rhyolitic sequence, in turn overlain by various sedimentary units. The rhyolitic sequence includes flows, domes, breccias, and tuffs, with a unit of rhyolitic quartz porphyry tuff at the top. The United Verde orebody (figure 50) overlies a thickened portion of the quartz porphyry tuff, which probably represents an eruptive center. The deposit consists of stratiform pyrite-chalcopyrite ore overlain by bedded pyrite-sphalerite ore, in turn overlain by reddish ferruginous chert. Pyrite-chalcopyrite stringer ore and chloritic alteration occur in the quartz porphyry in the footwall of the deposit. The ore horizon is overlain by sediments. Thin interbeds of tuffaceous pebble conglomerate in the upper part of the orebody contain fragments of various types of sulfide ore, indicating that the stratiform ore was deposited at the same time as the enclosing host rocks. The sequence has been intruded by gabbro and tightly folded so that the massive sulfide lens is now a steeply plunging pipe-like mass along an anticlinal axis (Proffett, 1979).

The size and grade of the United Verde orebody is comparable to major Archean volcanogenic deposits. The deposit produced approximately 31 million tonnes with recovered grades of 4% Cu, 1.4 oz-ton Ag, 0.04 oz/ton Au, minor amounts of Zn, and small amounts of Pb (calculated from Anderson and Creasey, 1958). Due to metallurgical problems, an estimated 12 million tons of 7% Zn with Cu, Pb, Ag, and Au values, was never mined.

The production from the United Verde probably accounts for 75% or more of the total production from Proterozoic volcanogenic massive sulfide deposits in the western United States. This reflects the size of the volcanic pile at Jerome, which probably is an order of magnitude larger than any other known volcanic pile in the region.

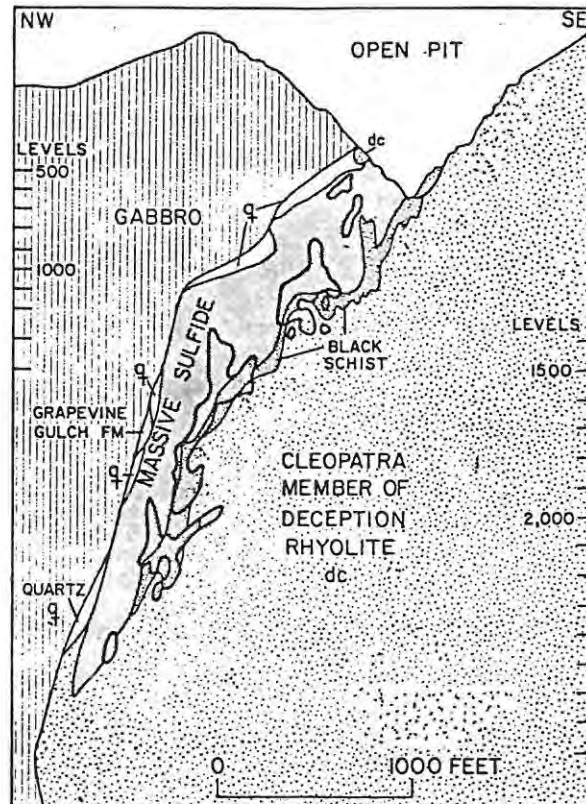


Figure 50: Vertical section through main ore body of the United Verde mine. Heavy black lines indicate the margins of stopes intersected by the plane of the section. Modified from Anderson and Nash (1972).

Numerous gold deposits associated with veins, shears, and exhalite horizons are found scattered throughout greenstone belts. The only major deposit in this group is the Homestake gold mine in the northern Black Hills (figure 48). Mineralization is found in a slightly graphitic, cherty, iron-rich carbonate unit (Homestake Formation) that was originally 60 to 90 m thick (figure 51). The Homestake Formation is part of a thick sequence of early Proterozoic metasediments and metavolcanics which have been tightly folded and locally metamorphosed to amphibolite grade (Slaughter, 1968). Orebodies are restricted to highly chloritized parts of cummingtonite or sideroplesite (Mg-rich siderite) schists containing abundant veins and masses of quartz, 7 to 8% disseminated pyrrhotite, pyrite and arsenopyrite, and a small amount of free gold. Gold is most closely associated with

arsenopyrite. Ore shoots have a pencil-like shape and are parallel to the plunge of enclosing folds. They tend to be localized in the vicinity of the intersections of cross folds with earlier isoclinal folds (Rye and Rye, 1974).

The Homestake deposit is similar to those at Morro Velho, Brazil and Kirkland-Larder Lakes in the Abitibi greenstone belt. The mineralization is postulated to have been formed by the introduction of Au, As, S, and Si into a chemical depositional environment by thermal spring processes. Mineralization was remobilized and concentrated into dilation zones during deformation. This concept is supported by isotopic evidence presented by Rye and Rye (1974). The mining district also is proximal to a WNW-trending belt of Tertiary granitic and syenitic intrusives (figure 29). However, there is no obvious genetic relationship between Tertiary magmatism and gold mineralization.

The Homestake mine consistently has been the largest gold producer in the United States for many years. Total production (continuous since 1878) exceeds 34 million troy oz of Au, with lesser amounts of Ag. Reserves have been maintained or gradually increased during the last few years and presently total over 17 million tons with 0.23 oz/ton Au (approximately 10 years of reserves). Several similar type deposits have been found in the Black Hills, but none are economically significant.

Magmatic deposits

Several types of magmatic mineral deposits are associated with Proterozoic intrusives. An anorthosite-syenite complex (between 1440 and 1385 Ma) intruded in the vicinity of the Mullen Creek - Nash Fork shear zone at Iron Mountain, Wyoming contains substantial, but uneconomic reserves of titaniferous and vanadiferous magnetite (Tweto, 1968). Another type, copper-nickel mineralization, is associated with a zone of mafic-ultramafic plutonic complexes and orthoamphibolites trending NE across the Sierra Madre, Medicine Bow, and Laramie ranges in Wyoming. These intrusives are broadly coincident with the trend and position of the Mullen Creek - Nash Fork shear zone (McCallum and others, 1976). High grade pockets of copper sulfides and, more rarely, nickel and cobalt sulfides with traces of platinum metals, as well as auriferous quartz veins, are found within the shear zone (eg. Encampment district, figure 48). Mineralization is not always directly related to the mafic intrusives, but this may be due to the strong deformation. The age of the intrusives is not known, but is probably lower

Proterozoic. The lack of information on these deposits is a reflection of their economic insignificance. However, their gross similarity with the Thompson nickel belt suggests they should be investigated in more detail.

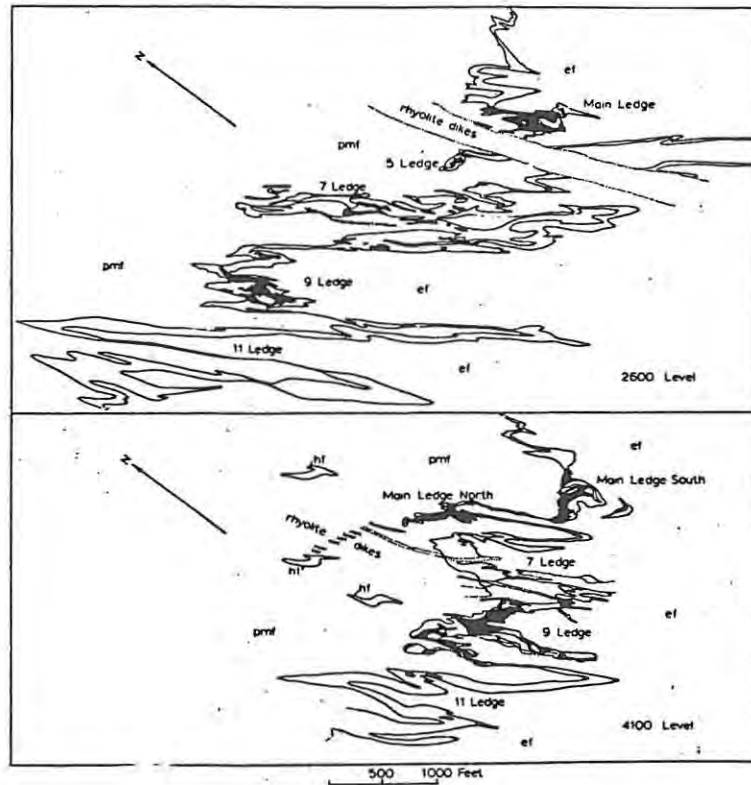


Figure 51: Relation of Ore Bodies to Structure. The outline of the Homestake Formation is shown on 2600 and 4100 levels. The changing relationship of the ore-bearing structures to each other brings about a marked shortening of total strike length of the whole group of folds. Ore is solid black, dikes are dotted, Poorman Formation, pmf, Ellison Formation, ef. From Slaughter (1968).

At Mountain Pass, California (figure 48), a major rare earth fluorocarbonate deposit is associated with a late phase carbonatite intrusive in a 900-1000 Ma potassic alkalic igneous complex (Olson and others, 1954). Mineralization occurs as bastnaesite in carbonate-rich veins with barite gangue. Thorium mineralization is found in veins on the outer margins of the district (Staat, 1974). The major products from Mountain Pass are cerium, lanthanum, neodymium, praseodymium, europium (Proffett, 1979), samarium, gadolinium, and yttrium. Present grades and tonnages are not available, but earlier studies indicated large zones averaging 5-15% rare earth oxides and

20% barite (Olson and others, 1954). The Mountain Pass deposit produces approximately one-half of the world's annual production of rare earth elements.

Substantial beryllium mineralization is associated with the Redskin stock of the Pikes Peak batholith at Lake George, Colorado (Hawley, 1969). Mineralization occurs in veins, pipes, pods, and other forms, generally encased in greisenized wallrock. Accessory minerals include quartz, muscovite, topaz, and fluorite. Trace amounts of Li, Sn, W, Mo, Pb, Zn, U, and Ag also are present. Most mineralization is confined to the porphyritic or granite-aplite facies of the Redskin stock, or is associated with small cupolas of more differentiated granite on the margin of the stock. The nature of this mineralization appears to be similar to the endogranitic mineralization found at Zaaipplaats, South Africa, except Sn is present in only trace amounts. The value of the Lake George Deposits has been abrogated by the discovery of a major bertrandite deposit in Pliocene tuffs at Spor Mountain, Utah.

Paleozoic Mineralization

The Powderhorn alkalic complex and the three alkalic complexes in the Wet Mountains contain several types of potentially economic mineralization. The massive carbonatites and carbonatite dikes contain significant amounts of niobium, rare earths, and thorium, as well as titanium and iron. Vermiculite is found in zones of fenitization. The Iron Hill carbonatite at Powderhorn is estimated to contain more than 419 million tons grading 12% TiO_2 (Arnbrustmacher, 1980) and a minimum of 100,000 tons with greater than 0.25% Nb_2O_3 (Temple and Grogan, 1965). Thorium-bearing veins with K feldspar, quartz, calcite, barite and thorite extend for considerable distances away from the alkalic intrusives. In the Powderhorn district, they are found throughout a NW elongated region, 32 km long by 10 km wide. The Wet Mountain district is of similar size and orientation. None of the deposits have been exploited on a large scale, but the Powderhorn area is being evaluated at the present time.

Thorium mineralization in the Lemhi Pass district of Idaho and Montana, and the Hall Mountain district of Idaho (figure 48), is similar to that in the Colorado districts (Staat, 1972a, 1972b, 1974). However, known alkalic magmatism is very minor, and the age of mineralization has not been established conclusively. Staat has postulated a mid Tertiary age for the Lemhi Pass district.

The other area of important Paleozoic mineralization is the kimberlite province along the foothills of the Front Range in Colorado and Wyoming (figure 48). This district has not had any production, but the diamond potential of the kimberlites is presently being evaluated.

Tectonic Controls on Mineralization

Mineralization associated with magmatism in the Archean and Proterozoic, as well as mineralization within the craton of Paleozoic age, is associated with greenstone belt-type volcanism, mafic-ultramafic magmatism, or alkalic-sub-alkalic magmatism. The Proterozoic greenstone belts of the western United States are similar to Archean greenstone belts and contain similar types of ore deposits. However, it may be misleading to make a direct comparison between the two, because there are significant differences. These include the rarity of ultramafic rocks, the small size of the volcanic piles, the lack of thick flysch sequences, and the absence of extensive granite-gneiss cratonic terrane with the Proterozoic greenstones. Thus, the nature of the tectonic environment during early to middle Proterozoic time remains problematic.

The location of intrusive activity during this period suggests crustal zones of weakness were important controls. The best example is the location of mafic-ultramafic and anorthosite-syenite intrusives in the vicinity of the Mullen Creek - Nash Fork shear zone, a crustal discontinuity that also controlled Tertiary magmatism (eg. Hahns Peak, figure 65). Another example is the north-south trend that includes Iron Mountain, Wyoming; the Colorado-Wyoming kimberlite province; the Pikes Peak batholith; and the Wet Mountains alkalic complexes (figure 48). This trend corresponds with the eastern margin of the Laramide uplift that formed the Front Range. Likewise, the northwest elongation of the Powderhorn and Wet Mountain districts correlates with northwest-trending Laramide faults as well as the Pennsylvanian age Ancestral Rockies uplifts. A more nebulous correlation is the location of the Stillwater complex at the intersection of the Humboldt structural zone with the postulated southeast extension of the Lewis and Clark lineament. Also, the Mountain Pass alkalic complex is located near the intersection of the Walker Lane with the Cordilleran miogeosyncline hinge line. These correlations suggest that many structural features within the craton that controlled sedimentation, magmatism and tectonism in the Phanerozoic also were in existence during Precambrian times.

The limited magmatism that occurred in the western United States from 1000 to 500 Ma is subalkalic to alkalic, suggesting the region was

experiencing tensional stress. This is in agreement with the theories that the Cordillera miogeosyncline was initiated by rifting along the margin of the craton during this same period. However, evidence for this rifting event remains sparse.

Mineralization Associated with Magmatism in Accreted Terranes

Early magmatism in the accreted terranes is most closely related to the tectonic processes that formed the crust prior to accretion, so that it usually has oceanic or island arc characteristics. Specific types of magmatism and mineralization are discontinuous between the different terranes, reflecting their possible separate origins or their dismemberment by subsequent tectonic events. Mineralization associated with the magmatic arc that developed during Mesozoic and early Cenozoic time, as well as mineralization associated with later Cenozoic magmatism, is superimposed on these terranes, but is not included here, since it is related to later magmatic events.

Barite Deposits

One of the most economically important deposit types in this group is the barite deposits found in a NNE-trending belt across central Nevada and adjacent parts of Idaho and California (figure 52). These deposits occur as stratiform horizons of massive barite over 30 m thick, interlayered with dark chert, shaly mudstone, and siliceous siltstone (Brobst, 1973). A sedimentary origin is indicated by the presence of sedimentary structures within the beds, such as intraformational conglomerate and graded bedding, as well as by the lateral continuity and conformity of the deposits (Shawe and others, 1969). The ore horizons commonly exceed 80% barite, with the remainder composed of silica and dark carbonaceous material. Only trace amounts of metals are present (Shawe and others, 1969).

The deposits are found in Ordovician and Devonian eugeosynclinal rocks of the upper plate of the Roberts Mountains thrust fault (Shawe and others, 1969), often near the facies change from miogeosynclinal rocks (Proffett, 1979). Even the ordinary siliceous rocks of the eugeosynclinal facies contain anomalously high barite. Although the deposits have no direct volcanic association, the size and grade of the layers suggest some sort of relationship to oceanic volcanism. This type of mineralization is confined to the Roberts Mountains terrane (RM in figure 26), suggesting a genetic relationship between mineralization and the early tectonic environment of this terrane.

Figure 52. Mineral deposits associated with magmatism in accreted terrane.

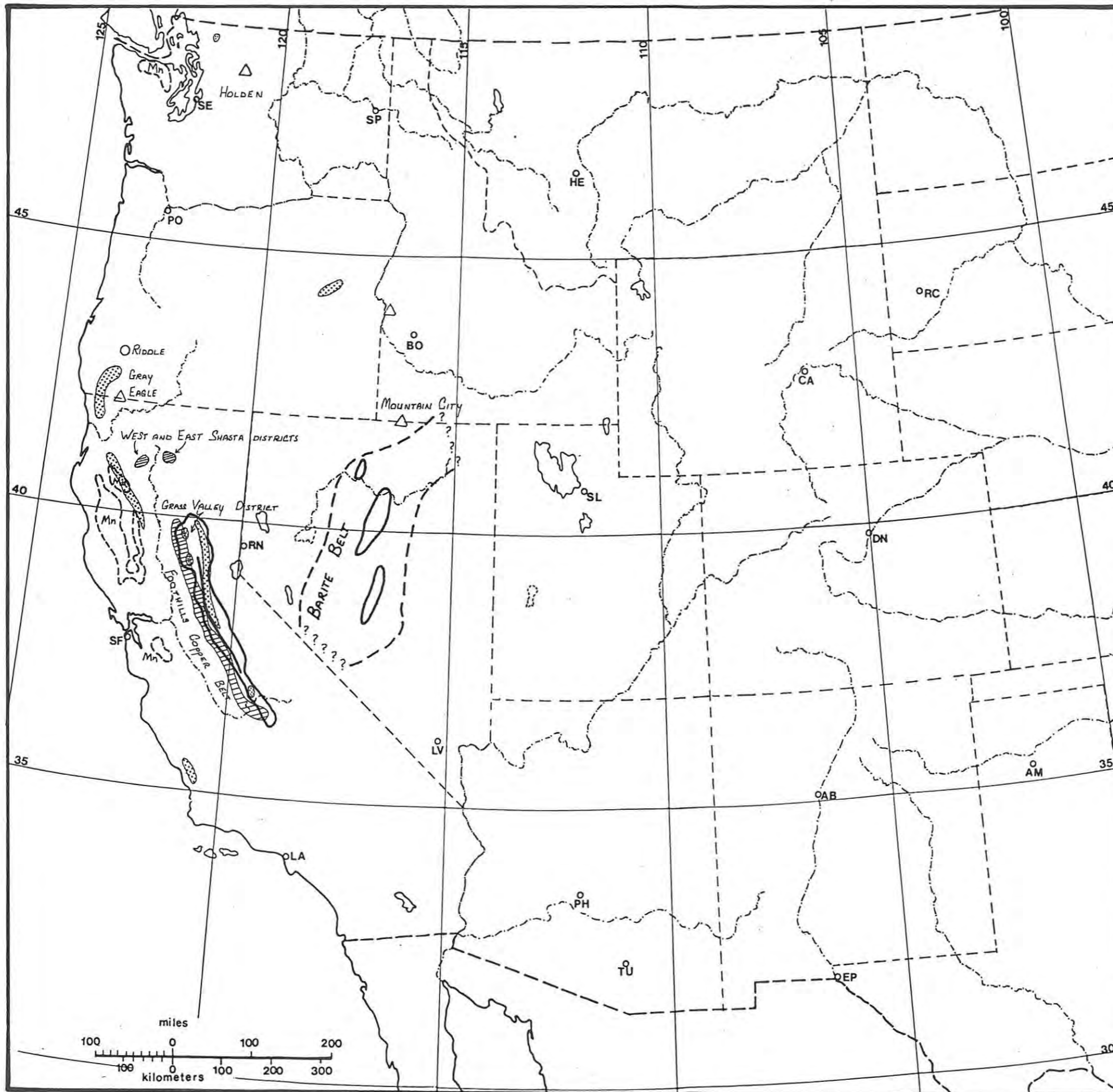
- △ Volcanogenic massive sulfide deposits
- Regions with podiform chromite deposits
- Barite belt with zones of numerous occurrences
- (Mn) Regions with layered manganese deposits
- Sierra Nevada gold belt and the Mother Lode
- Nickel laterite deposits

Volcanogenic Deposits

- West Shasta - Zn, Cu, Au, Ag
- East Shasta - Zn, Cu, Pb, Au, Ag
- Foothills Copper Belt - Cu, Zn, Au, Ag, Pb
- Gray Eagle - Cu, Zn, Pb
- Mountain City - Cu, Ag, Au
- Holden - Cu, Zn, Au, Ag, Pb

References

- Albers, 1981
- Guild, 1978
- Shawe and others, 1969
- Youngberg and Wilson, 1952



Volcanogenic Massive Sulfide Deposits

A variety of volcanogenic massive sulfide deposits are scattered throughout the accreted terrane of the western United States. The Mountain City copper mine in Nevada (figure 52), occurs in Ordovician eugeosynclinal rocks in the upper plate of the Roberts Mountains thrust fault (Coats and Stephens, 1968). A conformable lens of nearly massive pyrite-chalcopyrite-quartz ore is found in dark shales with minor quartzites and mafic volcanic rocks. This sequence may be the same or similar to the host rocks for the barite deposits. The Mountain City deposit appears to have been deposited in ocean floor sediments, and may be comparable to Besshi-type or Cyprus-type mineralization. Total production exceeded 1 million tons of ore averaging nearly 10% copper (some supergene enrichment) with minor gold and silver values. Similar deposits include the Gray Eagle mine, located in the Klamath Mountains of California, and the Big Mike mine, associated with upper Paleozoic pillow basalt and sediments in western Nevada.

The West Shasta district (figure 52) is the largest massive sulfide district within the accreted terrane. Mineralization occurs in lenticular stratiform bodies of massive pyrite with sphalerite, chalcopyrite, and minor gold and silver values with quartz and sericite gangue. The nine known ore deposits in the district occur at or near the top of a porphyritic rhyolite unit within a volcanic pile of rhyolite flows and pyroclastics of middle Devonian age. The rhyolites interfinger with and are underlain by intermediate to basic volcanic flows, breccias, and tuffs and overlain by black, siliceous shales and gray shales. The exposed volcanic sequence is up to 2100 m thick (Kinkel and others, 1956). The wedge shape of the rhyolite pile suggests that it represents a felsic volcanic center. Total production from the district is estimated to be 8 million tonnes with grades of 4-5% Cu, 8-9% Zn, 1-3 oz/ton Ag and 0.03 oz/ton Au.

The East Shasta district, immediately adjacent to the West Shasta district, also contains volcanogenic massive sulfides associated with an island arc sequence. Typical ore consists of lenticular to vein-like or tabular bodies of massive pyrite with sphalerite and chalcopyrite, smaller amounts of galena, tetrahedrite-tennantite, and bornite, and minor gold and silver values. Gangue minerals include barite, quartz, sericite, anhydrite, gypsum, and calcite. The concordant orebodies are found at or near the top of small pod-like bodies, 30 to 750 m thick, of rhyolite flows and pyro-

clastics of middle to late Triassic age. Mineralization sometimes extends into adjacent, overlying shale and mudstone (Albers and Robertson, 1961). The association of massive sulfide deposits with thickened, brecciated rhyolites suggests mineralization is related to explosive felsic volcanic centers. Total production from the three mines in the district is estimated at less than 1 million tons with 15-20% Zn, 3% Cu, 1-2% Pb, 5 oz/ton Ag, and 0.03 oz/ton Au.

The Foothills Copper Belt (figure 52), on the west flank of the Sierra Nevada, contains at least 40 copper-zinc mines in a narrow, 400 km long belt of interbedded felsic and mafic volcanics and related pyroclastic rocks of middle to late Jurassic age. Mineralization consists of lenticular or tabular bodies of massive pyrite with chalcopyrite, sphalerite, and small amounts of gold and silver. The sparse gangue minerals include quartz, barite, sericite, and chlorite (Kinkel and Kinkel, 1966). Some deposits grade into bedded barite and ferruginous chert outward along the ore horizon. Deposits may be associated with felsic or mafic volcanics (Proffett, 1979).

Other volcanogenic massive sulfide deposits are found in the Permian-Triassic volcanic sequence in the Blue Mountains in Idaho, and at the Holden Mine in an island arc sequence (Mesozoic or Paleozoic ?) in the northern Cascade Mountains of Washington (figure 52).

Gold Mineralization

Gold-bearing quartz veins are fairly common in oceanic or island arc-crustal terranes. However, with the exception of the Grass Valley and Mother Lode districts in California (figure 52), these deposits are small and of limited economic importance. The Mother Lode district is a NNW-trending belt of gold mineralization about 200 km long by 2 km wide in the western foothills of the Sierra Nevada (figure 53). The belt is near to, and essentially parallel with the Foothills Copper Belt. Gold mineralization is found in quartz veins and in bodies of pyritized mineralized schist and greenstone in a system of linked and anastomosing faults, fractures, and shear zones cutting a complex of Jurassic, Permian, and Carboniferous greenstones, serpentinites, slates, and schists, and Cretaceous (?) granodiorites. The fracture system is part of the Melones fault zone, a major east-dipping, reverse fault, thought to represent a Jurassic or Triassic subduction zone (Proffett, 1979). Similar, smaller deposits are found in reverse faults in belts to the east and west of the Mother Lode (figure 53).

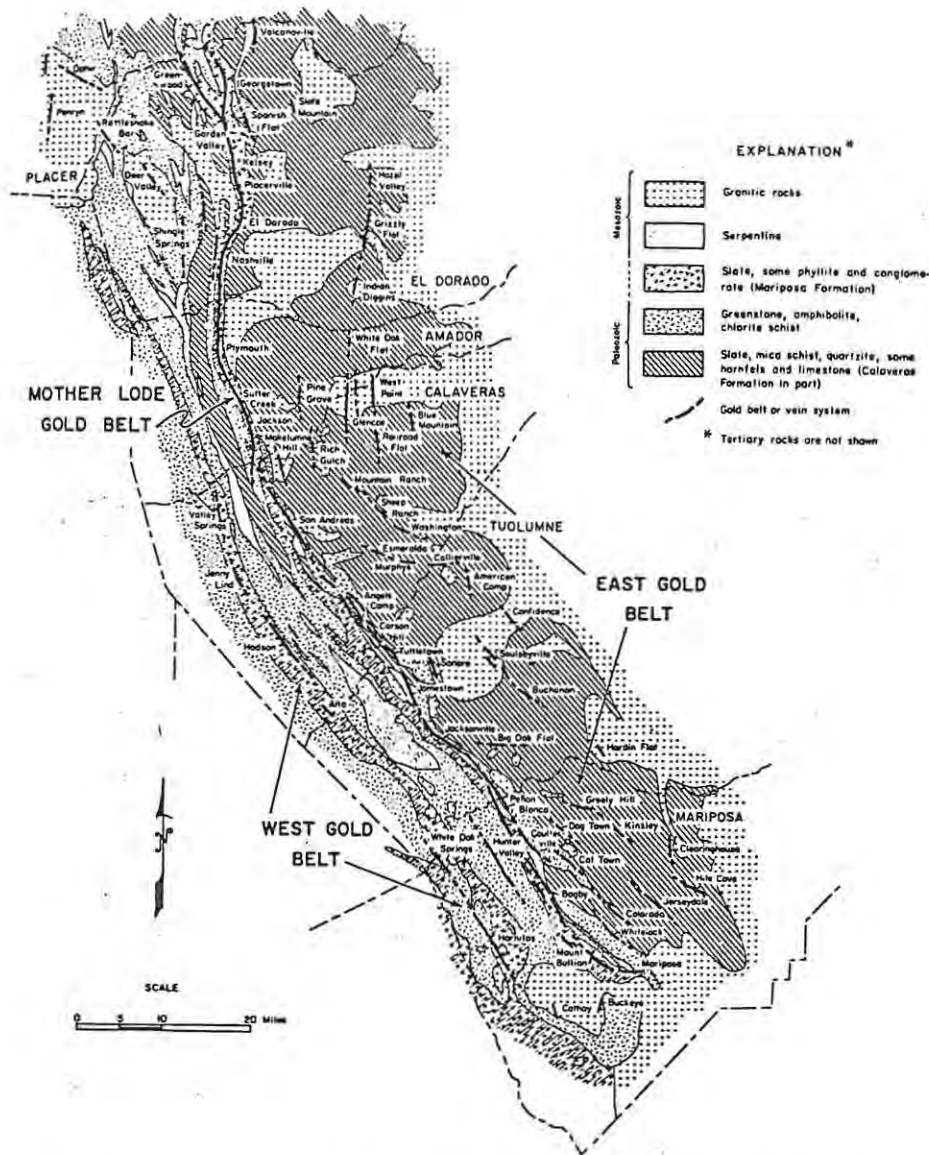


Figure 53: Map of major rock units and lode-gold belts, central Sierra Nevada. From Clark (1970).

The quartz veins are discontinuous, forming lenticular bodies as much as 17 m thick. Ore shoots occur generally where the veins are thickest, especially where veins intersect or branch. The shoots have short strike lengths, but pitch or rake lengths as long as 2200 m are known. Veins consistently dip to the east, with veins in slate generally steeper than veins in greenstones (Albers, 1981). Typical mineralogy consists of native gold in coarse-grained milky quartz with ankerite, calcite, pyrite, and mariposite (Cr-mica), with traces of disseminated arsenopyrite, galena, sphalerite, chalcopyrite, tetrahedrite, scheelite, molybdenite, and various other tellurides (Boyle, 1979). Common wall rocks are graphitic metasediments, mafic volcanics, mafic intrusives, and serpentinites (Proffett, 1979). The wall rocks show intense alteration, mainly carbonization (ankerization), pyritization, and sericitization (Boyle, 1979). Average grade of the

deposits was 0.3 oz/ton gold, with Au:Ag 10:1.

In the Grass Valley district immediately north of the Mother Lode, gold mineralization occurs in quartz veins and lodes, and in quartz stockworks and sheeted zones developed in faults, fracture zones, and breccia zones that cut Paleozoic and Mesozoic amphibolites (greenstones), slates, and schists, as well as a Mesozoic granodiorite stock that intrudes the sequence (Boyle, 1979). The mineral deposits are similar in morphology, mineralogy, and alteration to the Mother Lode deposits. The average grade of the deposits is about 0.5 oz/ton gold, with Au:Ag 3.7:1 (Boyle, 1979).

Although inactive at present, the Mother Lode, Grass Valley and adjacent districts have the largest historic production of gold of any area in the western United States. Total production from lode deposits is on the order of 40-50 million oz, with perhaps another 25-35 million oz produced from adjacent placer fields (data from Clark, 1970).

The source and genesis of mineralization has been enigmatic. Recently, K-Ar dating of mariposite, thought to be contemporaneous with mineralization, has given ages ranging from 108 to 127 Ma (Albers, 1981). These dates correlate with magmatism and deformation during the Nevadan orogeny. This evidence, along with the postulation that the Melones fault represents a paleosubduction zone, permits speculation that subduction, magmatism, and Mother Lode-type mineralization have a genetic relationship (Albers, 1981). Gold, silica, and other components may have been mobilized from the eugeosynclinal rocks and concentrated in favorable sites during metamorphism and deformation associated with plate subduction, or during the intrusion of granodiorite that closely followed (Proffett, 1979). Figure 54 is a hypothetical diagram of tectonic events that may be related to ore genesis of the Mother Lode. In a sense, this proposed method of ore formation is similar to those envisioned for many of the Archean greenstone deposits.

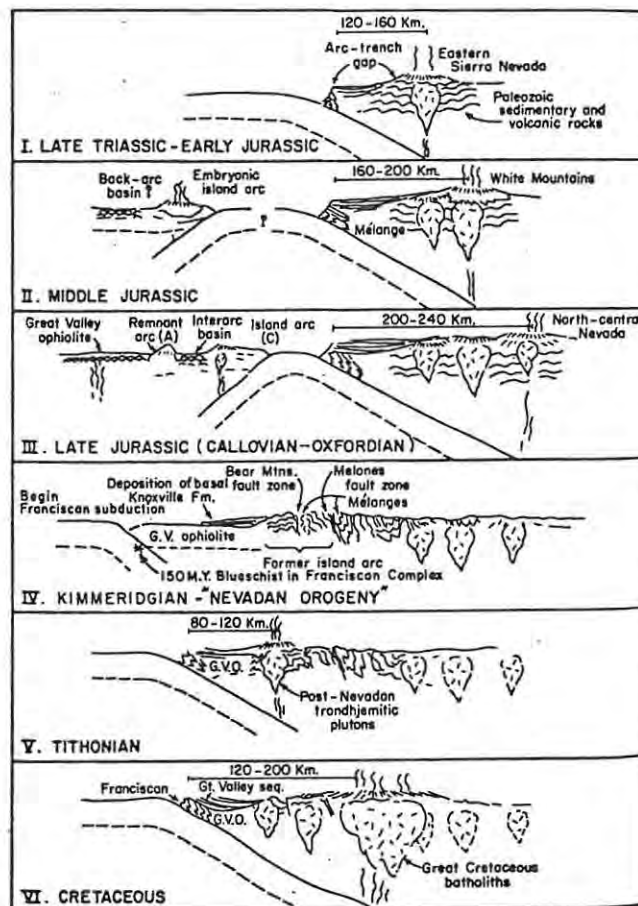


Figure 54: Hypothetical schematic sections showing postulated tectonic evolution of the Sierra Nevada during Mesozoic time. From Schweickert and Cowan (1975).

Podiform Chromite Deposits

Numerous small chromite deposits are associated with irregular peridotite masses or peridotite-gabbro complexes in oceanic crustal terrane or in mélangé complexes. The principal concentrations of these deposits are found in the Klamath Mountains of southwestern Oregon and northern California, along the western slope of the Sierra Nevada, in the Coast Ranges of California, and in eastern Oregon (figure 52). The chromite deposits occur as massive pods, deformed discontinuous layers, and disseminations in the ultramafic complexes, often near the contacts between peridotite and gabbro. The deposits appear to be formed by magmatic segregation and crystal settling processes and sometimes show settled textures. Thayer (1973) believes these deposits are formed in the upper mantle, and emplaced into the upper crust by solid flowage at high temperatures, possibly at or near oceanic spreading centers. The deposits subsequently have been incorporated into the continental crust by obduction

or other tectonic mechanisms. These deposits are generally small, very seldom exceeding 1 million tons, and are of limited economic importance. Secondary chromite deposits in raised beach sands have been found along the southwestern Oregon coast, but are too small to exploit.

Nickel Laterite Deposits

Nickel laterite deposits developed over serpentinites, peridotites, dunites, and, to a lesser degree, pyroxenites, are found in the same terranes as the podiform chromite deposits along the Pacific coast in northern California, Oregon, and Washington. There are two types of deposits, nickeliferous iron laterites formed by the weathering of serpentinites, and nickel silicate laterites formed by the weathering of fresh ultramafics (Cornwall, 1973). The only economic deposit of this group, which is also the only operating nickel mine in the United States, is the nickel silicate deposit at Riddle, Oregon (figure 52). The formation of the laterite is related to an early to mid-Tertiary subtropical erosion surface, possibly related to an arc-trench gap tectonic environment (Proffett, 1979). Total production from Riddle is estimated at over 20 million tons at 1.5% Ni.

Manganese Deposits

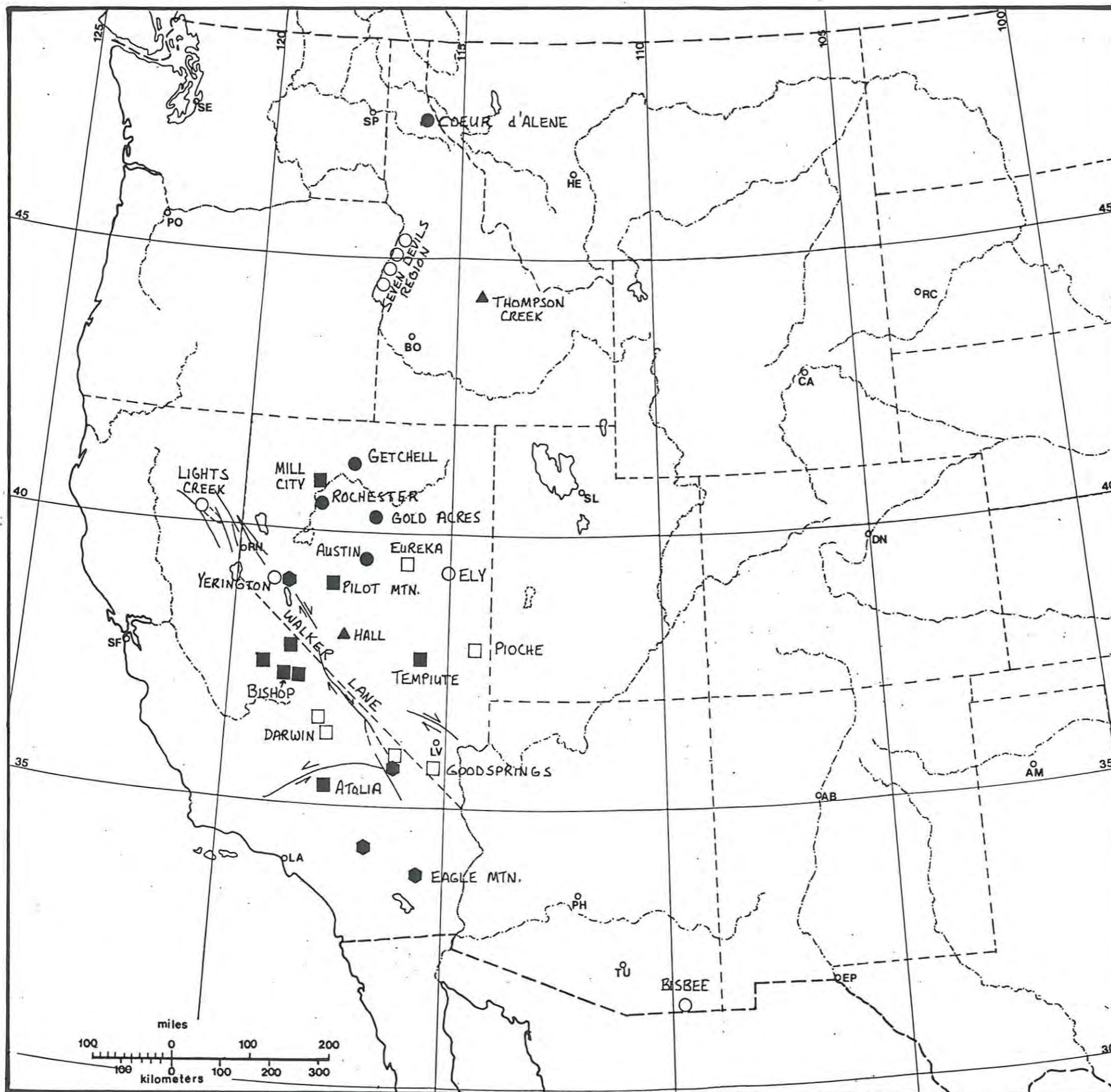
Lenticular manganese carbonate-silicate-oxide deposits are widely distributed in Paleozoic, Mesozoic, and Tertiary cherts and argillites in close association with massive mafic volcanic sequences (Guild, 1978). The principal occurrences are in the central mélangé belt of the Franciscan Complex and on the Olympic Peninsula in Washington (figure 52). Nearly all of the deposits are of negligible importance and none are presently in production.

Mineralization Associated with Mesozoic Magmatism

The advent of major calc-alkaline magmatism during Mesozoic time also marks the first appearance of the most important group of metallic ore deposits in the western United States -- hydrothermal sulfide deposits associated with granitic plutons. The major types of Mesozoic deposits include base- and precious-metal veins; mineralized breccia pipes; contact-metamorphic iron, copper, and tungsten orebodies; lead-zinc-silver replacement ores; and porphyry copper-molybdenum deposits (Proffett, 1979). The most important occurrences are shown in figure 55.

Figure 55. Mineral deposits associated with Mesozoic Magmatism.

Legend on following page.



Legend for Figure 55: Mineral deposits associated with Mesozoic magmatism.

p = prospect

○ Porphyry copper deposits

Bisbee	(163 Ma)		AZ
Ely	(111 Ma)		NV
Yerrington	(150 Ma)		NV
Lights Creek		p	CA
Seven Devils	(200-120 Ma)	p	ID

▲ Granodiorite Stockwork molybdenum deposits

Thompson Creek	(86 Ma)	p	ID
Hall	(77 Ma)		NV

□ Replacement deposits

Eureka		Ag, Au, Pb	NV
Pioche	(94 Ma)	Ag, Zn, Pb, Au	NV
Goodsprings		Zn, Pb, Ag	NV
Darwin		Pb, Zn, Ag	CA

■ Tungsten deposits

Bishop			CA
Mill City			NV
Pilot Mountain		p	NV
Tempiute			NV
Atolia			CA

◆ Iron deposits

Eagle Mountain			CA
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● Precious metal deposits

? Coeur d'Alene		Ag, Pb, Zn, Cu	ID
? Getchell		Au	NV
? Gold Acres		Au	NV
Rochester		Ag, Au	NV
Austin		Ag, Au, Pb	NV

References

Albers, 1981
 Field and others, 1974
 Guild, 1978
 Lemmon, 1966
 Proffett, 1979
 Roberts and others, 1971
 Schmidt and others, 1979
 Steward, 1966
 Storey, 1978

Porphyry Copper Deposits

Porphyry copper-type mineralization is associated with the early phases of Mesozoic magmatism (lower to middle Jurassic), especially in British Columbia. The deposits have been subdivided into two groups; diorite, and quartz monzonite granitic pluton types (Hollister, 1978). The diorite deposits (eg. Copper Mountain - Ingerbelle, Afton, Galore Creek) are associated with quartz-deficient, commonly zoned, diorite-monzonite-syenite plutons intruded into upper Paleozoic-lower Mesozoic marine volcanic rocks. The deposits are small, contain no significant molybdenum, but have above average copper grades and important gold and silver values (Drummond and Goodwin, 1976). There are no known examples of this deposit type in the United States. The quartz monzonite granitic pluton deposits (eg. Guichon batholith deposits, Gibraltar) are associated with quartz diorite-granodiorite-quartz monzonite intrusions of batholithic dimensions, with mineralization frequently occurring in the youngest phase (Hollister, 1978). All are intrusive into Triassic-Jurassic marine volcanic rocks. The deposits are very large tonnage, medium to low grade, and frequently contain significant molybdenum. Nearly all of the major deposits of British Columbia are members of this group. The only cited examples in the United States are four low-tonnage, low-grade prospects in the Seven Devils region of western Idaho (figure 55; Field and others, 1974), although the Yerrington deposit has many similarities with this group.

The Yerrington porphyry copper deposit occurs in a composite batholith 15-18 km in diameter, that was intruded 150 Ma into Triassic and early Jurassic sedimentary and volcanic rocks (Proffett, 1979). The batholith lies immediately east of the Sierra Nevada batholith in an area with initial $^{87}\text{Sr}/^{86}\text{Sr}$ values intermediate between oceanic and Precambrian crust (figure 22). Yerrington also is within the area of the Walker Lane shear zone, but it is not known if the zone was existent during Yerrington magmatism. However, Alters (1967) indicates that available evidence permits the interpretation that deformation along the Walker Lane began as early as late Early Jurassic. The batholith consists of an equigranular granodiorite phase, intruded by an equigranular hornblende quartz monzonite phase. These were intruded by a porphyritic quartz monzonite pluton which grades upward into swarms of dikes and small stocks of quartz monzonite porphyry (Proffett, 1979). In the Yerrington Mine, mineralization is associated with a complex of several quartz monzonite porphyry phases (figure 56), with the highest grades associated with the earliest phase and successively lower grades with later phases (Proffett, 1979). Since the Yerrington deposit has been tilted

nearly 90° by late Cenozoic listric faulting, it provides a unique example of an almost complete vertical exposure of a porphyry system.

Very few porphyry deposits are directly associated with the major pulse of batholith emplacement (late Jurassic to late Cretaceous) in both British Columbia and the United States. In fact, throughout the tectonic history of the North American Cordillera, there is no correlation between intensity of magmatism and intensity of mineralization. Although intrusives of Mesozoic age are by far the most voluminous, Noble (1974) estimated only 12% of the total value of metallic (Cu, Mo, Pb, Zn, Au, Ag, W, Hg) production in the western United States has come from Mesozoic deposits. In contrast, Laramide magmatism, which is represented by a few small batholiths, numerous small stocks, and limited areas of volcanism, is associated with 57% of metallic production. Tertiary age deposits contribute 28%, while pre-Mesozoic deposits contribute only 3% (Noble, 1974).

The Lights Creek stock is a differentiated satellite of the Sierra Nevada batholith with several small porphyry copper prospects (Storey, 1978). It may be the only example of significant porphyry copper mineralization associated with the late Jurassic to late Cretaceous magmatic pulse as the stock has been imprecisely dated between late Jurassic and early Eocene age. The nearby Sierra Nevada batholith has been dated at 97.4 to 101 million years (Evernden and Kistler, 1970). The zone with copper mineralization extends approximately 29 km in a northwesterly direction and is along the northwest extension of the Walker Lane (figure 55). The Lights Creek stock has intruded a Jurassic-Triassic volcanic and sedimentary rock sequence and is located just west of the 0.704 initial $^{87}\text{Sr}/^{86}\text{Sr}$ contour (figure 22). Mineralization within the stock is associated with quartz monzonite that shows a greater degree of fractionation than elsewhere (Storey, 1978). Three subeconomic deposits have been discovered to date: one with 250 million tons of 0.35% copper; the second with 100 million tons of 0.33% copper; and a third, poorly defined zone with large tonnages of greater than 0.25% copper (Storey, 1978). Molybdenum is not significant. Gold values are not reported, but the silver content is similar to that found in copper-gold porphyries. As the deposit is located on the northern margin of the Grass Valley - Alleghany gold region, gold content could be significant.

The other major porphyry copper deposits are located well within the Cordilleran miogeosyncline at Ely, Nevada and Bisbee, Arizona. At Ely, porphyry copper mineralization occurs within at least 6 bodies of quartz monzonite porphyry, elongates E-W and spatially associated with barren sills,

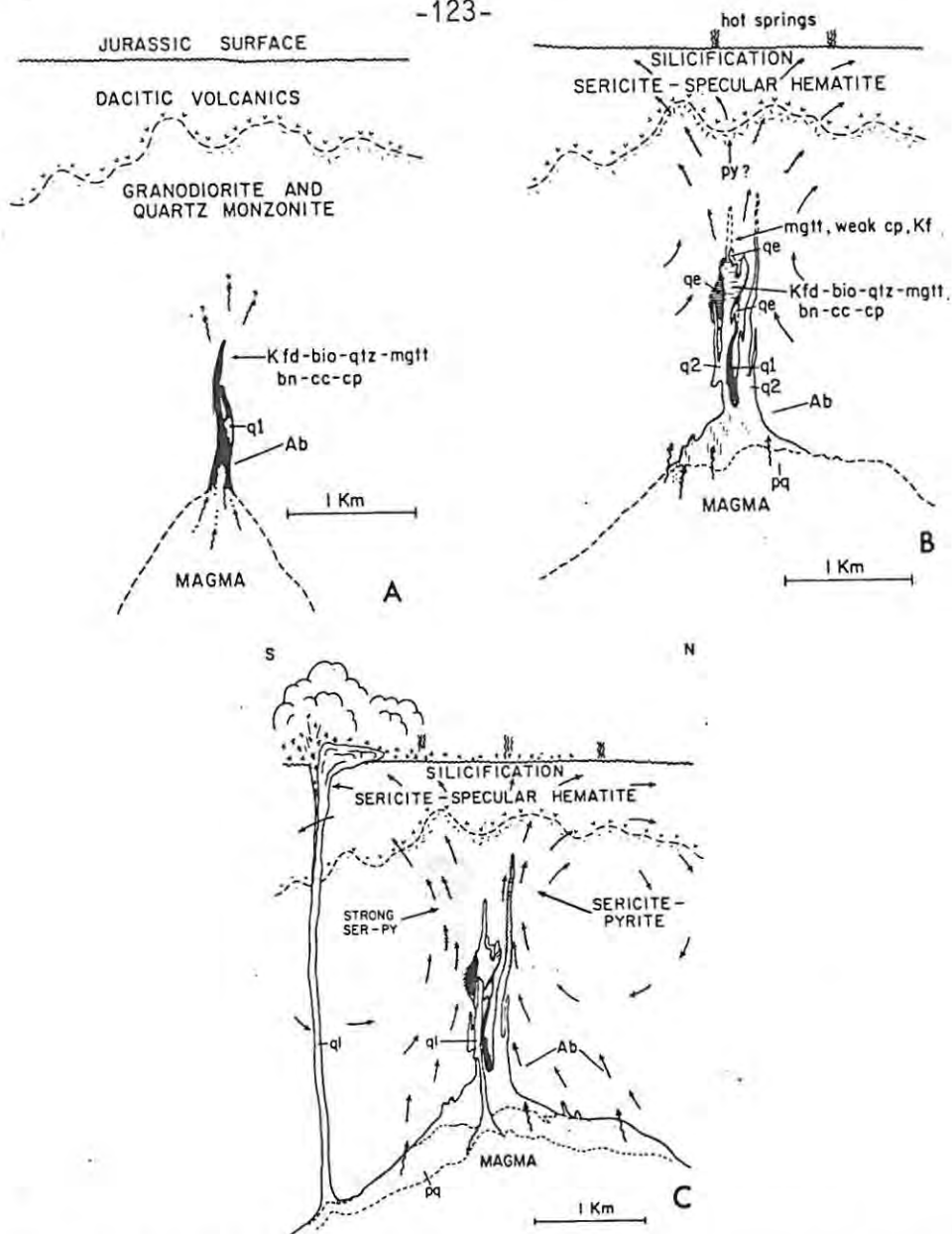


Figure 56: Pre-tilt north-south sections through the Yerrington Mine, Nevada, showing stages in the development of the porphyry copper deposit. A - Emplacement of earliest porphyries (generalized here as q1) above apex in the roof of porphyritic quartz monzonite magma chamber accompanied by strong primary copper mineralization and K-feldspar-biotite-magnetite alteration; B - several other porphyry phases have been emplaced (shown here as qe and main or southwest mass, q2), each followed by primary copper mineralization that is cut by the next younger porphyry. Porphyry phases lose their identity downward and grade into porphyritic quartz monzonite that evidently was the magmatic source of the porphyries during porphyry intrusion and copper mineralization. The earlier the porphyry phase in question, the stronger the copper mineralization associated with it. Albitization took place beneath K-feldspar alteration; C - Pyrite-quartz veinlets and sericite-quartz-pyrite alteration followed intrusion of porphyries that post-date copper mineralization (in the northernmost q2). Various late porphyries (q1) post-date some sericite-quartz-pyrite alteration and pre-date the remainder. The pyrite-quartz veinlets and its accompanying alteration appear to have been a separate and distinct event from the primary copper mineralization and may have been caused by a groundwater convection cell activated by the porphyries as a heat source. Albitization took place along the top of the crystallizing batholith. Porphyritic quartz latite was erupted on the surface, much of it following mineralization and alteration.

plugs, and a large stock of porphyritic quartz monzonite (figure 57; James, 1976). Total production prior to the recent closure of Ely, is estimated at 350 million tons of ore, with nearly 1% copper as well as molybdenum, silver, and gold values. Ely is one of several mid-Cretaceous igneous centers that occur along an E-W trend across Nevada (figure 53). However, apart from the E-W elongation of mineralization at Ely and Yerrington, and the alignment of intrusives, there is no geological or geophysical evidence for a lineament. At Bisbee, mineralization is found disseminated in granite porphyry and associated intrusive breccia, and in replacement deposits in adjacent limestone (Bryant, 1968). Total production (4.4 million tons of Cu) has been somewhat larger than that of Ely. The age of magmatism and mineralization at Bisbee (163 Ma) considerably predates the Laramide porphyry deposits in the southwest (71-54 Ma). There are no obvious structural or tectonic controls on mineralization, but the Paleozoic sedimentation pattern indicates WNW-trending structures were prevalent.

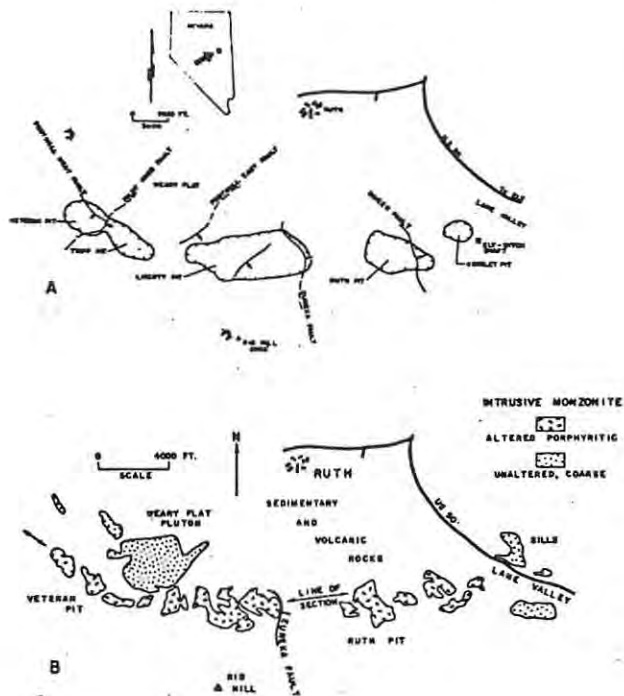


Figure 57: Map showing copper mines, major structures, and some geographic features of the Robinson mining district, east-central Nevada (A), and the same area showing Cretaceous intrusive rocks (B). From James (1976).

Stockwork Molybdenum Deposits

Stockwork molybdenum deposits at Thompson Creek, Idaho, and Hall, Nevada (figure 55), have late Cretaceous ages. Thompson Creek occurs in a late quartz monzonite within a granodiorite stock thought to be a late intrusive phase of the Idaho batholith (Schmidt and others, 1979). The deposit, presently under development, contains 105 million tons of 0.15% Mo. The Hall deposit is located along the margins of a small stock of granite, quartz monzonite, and alaskite porphyry (Proffett, 1979). The deposit, presently being brought into production, has reserves of 125 million tons of 0.125% MoS_2 and a supergene orebody with 40 million tons of 0.4% Cu. Both deposits are associated with calc-alkaline magmatism (Westra and Keith, 1981), rather than the more alkaline magmatism associated with Climax-type deposits. Hall is located near the margin of the Walker Lane structural zone (figure 55), while Thompson Creek is the earliest deposit in the Idaho-Montana porphyry belt (figure 59). Both deposits are located in areas thought to be underlain by Precambrian continental crust.

Tungsten Skarn Deposits

Scheelite-bearing skarns associated with granitic rocks in contact zones and roof pendants of the Sierra Nevada batholith and smaller plutons to the east and north (figure 55) have been the major source of tungsten in the United States. The largest deposits are found in the Bishop district of California, but significant skarn deposits are also located in the Mill City, Tempiute, and Pilot Mountain districts in Nevada. The quartz vein deposits in Atolia, California formerly were important producers.

In the Bishop district, skarn deposits are found in the Pine Creek pendant along the marble-Tungsten Hills quartz monzonite contact for a length of 4 km (Gray and others, 1968; figure 58). The size and shape of the orebodies is controlled by irregularities in the intrusive contact and by bedding and lithology of the carbonates. Composition of the intrusive appears to be important, as deposits are preferentially associated with the most silicic-potassic intrusives (Albers, 1981). In addition to scheelite, the deposits contain significant amounts of copper, molybdenum and fluorite, as well as gold and silver values. During the period 1961-1965, average grade from the district was 0.93% WO_3 , 0.10% Mo, and 0.29% Cu (Gray and others, 1968).

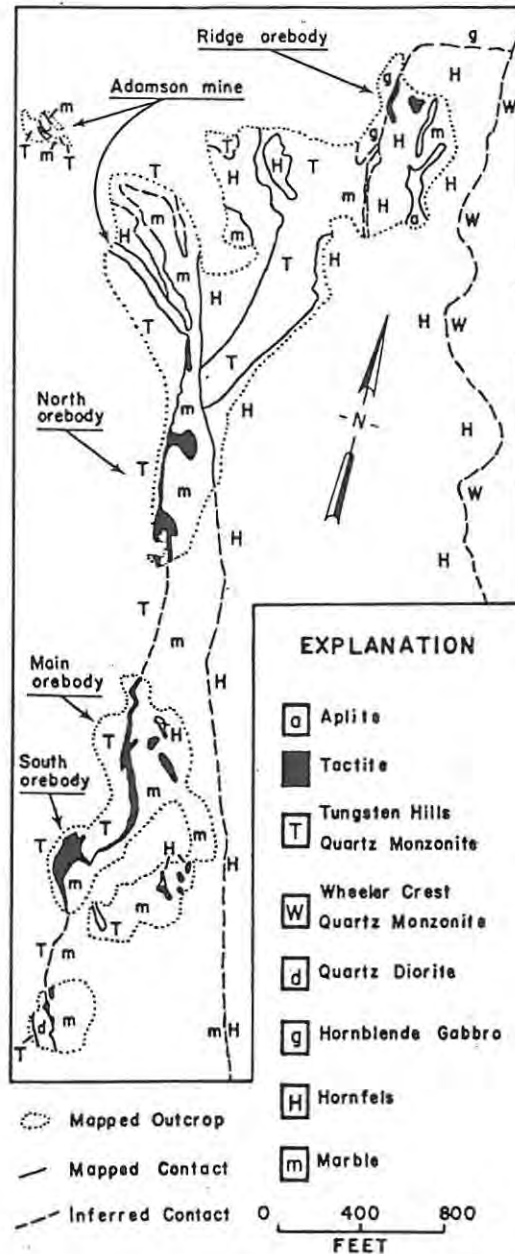


Figure 58: Surface geology of Pine Creek Mine and vicinity. From Gray and others (1968).

Elsewhere in the Sierra Nevada batholith, the distribution of contact metasomatic tungsten deposits is controlled mainly by the location and abundance of carbonate roof pendants and to some degree by the igneous lithology (Albers, 1981). Tungsten deposits occur in association with granitic rocks of all ages from 79 to 210 Ma (Albers, 1981), but Dodge and Bateman (1977) report there is a dearth of deposits associated with late Cretaceous granitic rocks. All of the tungsten deposits in California and Nevada are within the 0.706 initial Sr isotope contour (figure 22), suggesting the presence of Precambrian crust is an important control. However, the locations of mineralization also reflect the distribution of carbonate rocks.

Lead-Zinc-Silver Replacement and Vein Deposits

There are numerous districts throughout the western United States with replacement and vein deposits containing lead, zinc, and silver mineralization. The most important ones associated with Mesozoic intrusives are at Pioche (Gemmil, 1968), Eureka (Nolen and Hunt, 1968), Austin, and Goodsprings in Nevada, and Darwin, California (Hall and MacKevett, 1962; figure 55). Small stocks and dikes of quartz monzonite and granite porphyry are nearly always present in these districts, but the intrusives seldom show a direct spatial relationship with mineralization. Instead, lithologic and structural features are the most important controls. Mineralization may occur in carbonates as irregular replacement deposits forming pods, chimneys and pipes, and mantos, as well as bedded replacement, fault-zone replacement, disseminated, and contact-metasomatic deposits. Adjacent quartzites frequently host vein deposits. Mineralization typically consists of galena, sphalerite, and various silver minerals. Sometimes chalcopyrite, arsenopyrite, stibnite, and cinnabar are present (Hewitt, 1968). At Darwin, fluorite and scheelite are important accessory minerals.

The major proportion of production from these deposits has come from oxidized, enriched ores located within a few tens of meters of the surface. Table I shows the average grade from ore mined in the Eureka district. This is mostly oxidized ore, compared with sulfide ore discovered by deep drilling, suggesting a 2-3 fold order of enrichment for the oxidized ore. The size of individual orebodies within the carbonate replacement districts is small, generally a few tens of thousand to hundreds of thousand tons, and total district production was no more than a few million tons. Pioche, the largest, produced 6 million tons, while Eureka produced 2 million tons. Due to the high grades, the total value of individual district production was often hundreds of million dollars.

All of the lead-zinc-silver replacement deposits are associated with miogeosynclinal sediments underlain by Precambrian crust. The major districts also are spatially related to postulated lineaments. Goodsprings is associated with the Walker Lane, Austin and Eureka are associated with the Yerrington - Ely trend of mineralization, while Pioche is at the west end of the Wah Wah - Tushar lineament (figures 55 and 67).

Other Deposits

Several other important districts may be associated with Mesozoic magmatism, but the correlations are questionable. Small, late Cretaceous monzonite stocks, possible outliers of the Idaho batholith, are found in

the Coeur d'Alene district, but the main stage of mineralization apparently predates these (Hobbs and Fryklund, 1968). The disseminated Carlin-type gold deposits at Getchell and Gold Acres are reported to be related to small Cretaceous plutons (Proffett, 1979), but Dickson and others (1979) favor a middle to late Tertiary age for this type of mineralization.

Table I - Recorded production and new reserves in the Eureka District

<u>Years</u>	<u>Tons of Ore</u>	<u>Gold (oz)</u>	<u>Silver (oz)</u>	<u>Lead (%)</u>	<u>Zinc (%)</u>
1869 - 1901	1,317,338	1.1	27.0	17.0	-
1902 - 1959	666,981	0.27	4.6	4.75	-
Deep Sulfide Mineralization		0.15-0.2	7.0-9.0	5.0-7.0	9.0-12.0

From Nolan and Hunt (1968).

Summary of Tectonic Relationships

All of the major mineral deposits of Mesozoic age occur within the miogeosynclinal sequence of the Cordilleran geosyncline, and are thought to be underlain by Precambrian continental crust. Typically, the deposits are related to the most felsic, fractionated phase of the associated magmatic sequence. The two exceptions that occur in eugeosynclinal terrane, the Lights Creek and Seven Devils districts, contain subeconomic deposits. Contact-metasomatic and replacement deposits are common. Whether their distribution is controlled only by the presence of carbonate rocks, or by the characteristics of the underlying crust and mantle, is debateable.

The most typical deposit-type associated with the Sierra Nevada batholith is scheelite-bearing skarns. These deposits also are abundant to the east in Nevada, where they are associated with small granitic stocks.

Porphyry-type deposits may be associated with late phases or outliers of the major batholiths, such as at Thompson Creek, Lights Creek, or Yerrington, or they may be related to isolated stocks, such as Ely and Bisbee. Although production from these porphyries has been significant, particularly from Ely and Bisbee, they are not as large as Laramide and Tertiary deposits. Yerrington, Ely and Bisbee are the only major porphyries in the western United States that have terminated production due to exhaustion of ore reserves, while Thompson Creek and Hall have only recently been considered for production, due to the changing economics of the molybdenum market.

Many of the Mesozoic mineral deposits appear to be related to lineaments, although much of the evidence is circumstantial. Thompson Creek and Pioche are located on trends that are defined by Laramide and Tertiary magmatism. Although several deposits are spatially related to the Walker Lane, it remains to be proven whether or not the Walker Lane existed in Mesozoic time. The Yerrington - Ely mineral belt is defined by points on a map rather than by geological or geophysical evidence, and should be considered as a concept to be investigated, rather than an exploration guideline. The most important deposit in terms of total production, Bisbee, shows no obvious relationship with any tectonic features.

These remarks are meant to temper rather than castigate the use of lineaments, since there is a tendency in some quarters to promote lineaments to the point of exclusion of other geological evidence relating to the location of mineral deposits (eg. Kutina, 1976). However, lineaments, when used in conjunction with other geological and geophysical evidence, can be useful guidelines to understanding controls on the location of magmatism, sedimentation, and tectonism, which in turn are important controls on mineralization. Lineaments controlling recent geologic activity are the most obvious, while older lineaments which have not been reactivated, may be obscured by subsequent tectonic events. This may explain the poor definition of Mesozoic lineaments. Also, it is misleading to visualize lineaments as a single straight line on a map. Even a well defined lineament, like the San Andreas fault, frequently occurs in a zone of shearing several km across, while parallel to subparallel faults occur within a zone 80 or more km across (see King and Beikman, 1974). It is logical to infer that lineaments that are presently less active have a similar nature.

Mineralization Associated with Laramide Magmatism

Types and Distribution of Mineralization

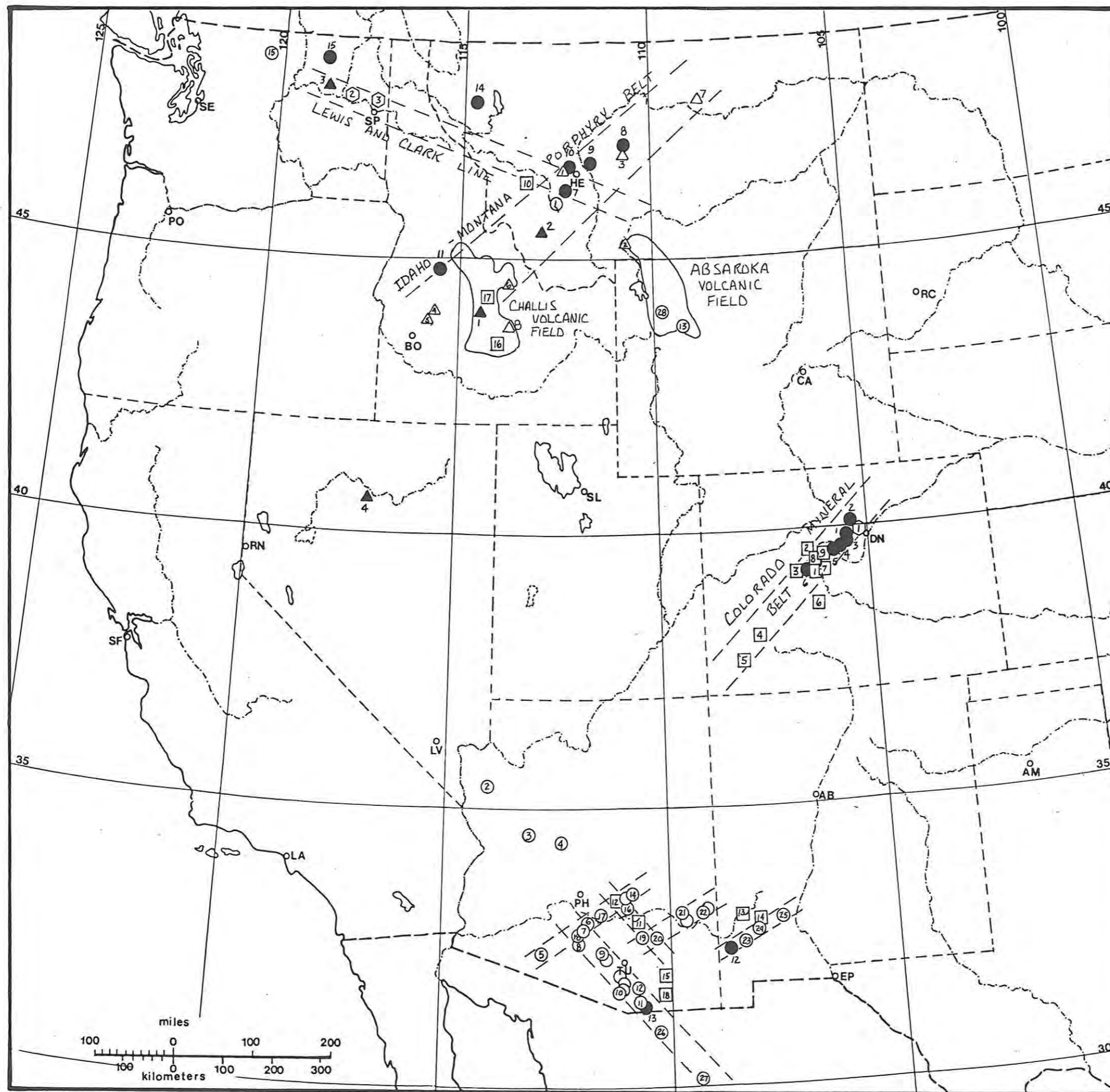
The types of mineral deposits associated with Laramide magmatism are much the same as the types associated with Mesozoic magmatism. These include porphyry copper deposits, stockwork molybdenum deposits, Pb-Zn-Ag replacement deposits, Au-Ag vein deposits, and U-sulfide vein deposits. However, the location (figure 59) and intensity of mineralization is considerably different from the Mesozoic deposits. Most of the Laramide deposits are confined to three areas: (1) southern Arizona - southwestern New Mexico, (2) the northeast-trending Colorado mineral belt, and (3) the somewhat vaguely defined, northeast-trending Idaho-Montana porphyry belt. Other areas with Laramide mineralization include the Absaroka volcanic

Figure 59. Laramide Mineral Deposits (75-40 Ma).

Legend on following pages.

References

- Anderson, 1968
- Bennett, 1980
- Hobbs, 1968
- Hollister, 1978
- Rich and others, 1977
- Rostad, 1978
- Tweto, 1968
- Watson, 1977
- Westra and Keith, 1981



Legend for Figure 59: Laramide Mineral Deposits (75-40 Ma).

○ Porphyry copper deposits

1	Butte	(63-58 Ma)	Pb, Zn, Ag, Au		MT
2	Mineral Park	(72 Ma)			AZ
3	Bagdad	(71 Ma)			AZ
4	Copper Basin	(64 Ma)			AZ
5	Ajo	(63 Ma)			AZ
6	Sacaton				AZ
7	Casa Grande West			p	AZ
8	Lakeshore				AZ
9	Silver Bell	(63 Ma)			AZ
10	Pima district				AZ
	San Xavier				
	Mission	(57 Ma)			
	Pima	(57 Ma)			
	Twin Buttes	(58 Ma)			
	Sierrita - Esperanza	(60 Ma)			
11	Red Mountain			p	AZ
12	Santa Rita district				AZ
	Helvetia			p	
	Rosemont			p	
13	Kerwin			p	WY
14	Globe - Miami district				AZ
	Pinto Valley				
	Inspiration	(60 Ma)			
	Copper Cities	(60 Ma)			
	Castle Dome	(60 Ma)			
15	Mazama	(70 Ma)		p	WA
16	Ray	(63 Ma)			AZ
17	Poston Butte			p	AZ
18	Vekal			p	AZ
19	San Manuel - Kalamazoo				AZ
20	Copper Creek	(52-53 Ma)		p	AZ
21	Safford district				AZ
	Sanchez			p	
	Phelps Dodge - Safford			p	
	Kennecott - Safford	(53 Ma)		p	
22	Morenci - Metcalf	(55 Ma)			AZ
23	Tyrone	(56 Ma)			NM
24	Santa Rita	(63 Ma)			NM
25	Hillsboro				NM
26	Cananea	(59 Ma)			MX
27	La Caridad	(53 Ma)			MX
28	Stinkingwater				WY

△ Granite Stockwork Molybdenum deposits

1	Bald Butte	(48 Ma)		p	MT
2	Emigrant Gulch	(Eocene)		p	MT
3	Big Ben	(50 Ma)		p	MT
4	Little Falls	(41-42 Ma)		p	ID
5	Cumo	(44 Ma)		p	ID
6	Ima	(41 Ma)		p	ID

Legend for figure 59, continued...

△ Molybdenum deposits - uncertain classification

7	Hawkeye	(58-66 Ma)	p	MT
8	Empire		p	ID

▲ Granodiorite Stockwork Molybdenum deposits

1	White Cloud (Little Boulder Creek)	(62 Ma)	p	ID
2	Cannivan Gulch	(62-59 Ma)	p	MT
3	Mt. Tolman	(58-59 Ma)	p	WA
4	Buckingham	(70 Ma)	p	NV

□ Replacement deposits

1	Leadville	Ag, Zn, Pb, Au, Cu		CO
2	Gilman	Zn, Ag, Cu, Pb, Au		CO
3	Aspen	Ag, Pb		CO
4	Ouray	Au, Ag, Pb, Cu		CO
5	Rico	Ag, Zn, Pb, Au, Cu		CO
6	Monarch - Tomichi	Zn, Ag, Pb, Cu		CO
7	Alma	Au, Ag, Pb		CO
8	Kokoma	Zn, Pb, Ag, Au		CO
9	Breckenridge	Au, Ag, Pb, Zn		CO
10	Phillipsburg	Ag, Zn, Pb, Mn		MT
11	Christmas	Cu, Pb, Zn, Ag, Au		AZ
12	Superior	Cu, Ag, Au, Zn		AZ
13	Pinos Altos	Cu, Zn, Ag, Pb	p	NM
14	Hanover - Fierro	Zn, Cu, Ag, Pb		NM
15	Johnson Camp	Cu, Zn, Ag, W		AZ
16	Wood River	Ag, Pb, Au, Zn		ID
17	Bayhorse	Ag, Pb, Zn		ID
18	Tombstone	Ag, Pb, Au, Zn		AZ

● Gold - Silver Vein deposits

1	Central City - Blackhawk	Au, Ag, Cu, Pb, U		CO
2	Gold Hill	Au, Ag		CO
3	Idaho Springs	Au, Ag, Zn, U		CO
4	Georgetown - Silver Plume	Ag, Pb		CO
5	Montezuma	Ag, Pb, Cu		CO
6	Sugar Loaf - St. Kevin	Ag, Pb		CO
7	Jefferson City	Ag, Pb, Zn, Au, Cu		MT
8	Barker	Ag, Pb, Zn, Au		MT
9	Elkhorn	Au, Ag		MT
10	Helena - Maryville	Au, Ag		MT
11	Yellowpine	Au, Sb, Ag, W		ID
12	Lordsburg	Cu, Au, Ag		NM
13	Hardshell	Ag, Pb		AZ
14	Hog Heaven (Eocene)	Ag, Pb, Zn		MT
15	Republic (Eocene)	Au, Ag		WA

○ Hydrothermal Uranium - sulfide vein deposits

1	Schwartzwalder (73-65 Ma)			CO
2	Mt. Spokane			WA
	Midnite			
	Sherwood			
3	Daybreak			WA

field and north-central and northeastern Washington. The major deposits in the latter area are on the western extension of the Lewis and Clark lineament, but this structure does not have an obvious surface expression in Washington.

The types of mineral deposits show an even more limited distribution. Nearly all of the porphyry copper deposits are confined to southern Arizona and southwestern New Mexico. In fact, with the exception of the Tombstone district, copper is the major metal in all of the major vein and replacement deposits in this region. The only major Laramide porphyry copper deposit outside of this region is at Butte, Montana. Like many exceptions to the rule, the Butte district is a very important exception, having accounted for 8% of the copper, 15% of the lead and zinc, and 15% of the silver production of the western United States (Noble, 1974).

Stockwork molybdenum deposits also show a limited distribution, with most Laramide deposits confined to the Idaho-Montana porphyry belt. However, the major exception, the Mt. Tolman prospect, contains 800 Mt grading 0.10% MoS₂ and 0.09% Cu, an amount that is larger than the known total resources in the Idaho - Montana porphyry belt (excluding Butte).

Individual mineralized regions may also show zonation of mineral deposit types. For example, most major Au-Ag veins are confined to the northeastern portion of the Colorado mineral belt, while the major replacement deposits are located in the central and southwestern portions.

Porphyry Copper Deposits

The Laramide porphyry copper deposits are the economically most important metallic mineral deposits in the western United States. Copper has accounted for 58.6% of the total metal values produced in the western United States, and the Laramide deposits have accounted for approximately 80% of this copper production (from data in Noble, 1974).

At least 88 porphyry copper deposits with at least 20 million tons of greater than 0.1% copper are known in the southwestern United States (figure 34). Of these, approximately 30 are economic (Lowell, 1974). The major mines and prospects are shown on figure 59. Nearly all of these contain several hundred million tons of mineralization with greater than 0.4% copper. Molybdenum is present in significant amounts in nearly all of the Laramide porphyry deposits, and is an important by-product in many of them. Gold and silver are relatively minor, but they are economically recoverable due to the scale of mining.

The characteristics of the southwestern porphyry copper deposits have been extensively reviewed (eg. Lowell and Guilbert, 1970; Lowell, 1974; Hollister, 1978) and only the most important features are mentioned here. Most of the deposits are closely associated spatially and temporally with small stocks (averaging about 2 sq. km) of calc-alkaline affinity. These stocks often show multiple phases of intrusion, with younger phases more felsic and differentiated. The youngest phases, with which mineralization is most frequently associated, usually are hypabyssal intrusives with porphyritic textures. Coeval volcanic rocks may be present, but they generally are not well preserved. The most abundant rock types are granodiorite and quartz monzonite, with mineralization most frequently associated with the latter.

Nearly all of the intrusives have been passively emplaced, suggesting a tensional tectonic environment was present. This is in agreement with geologic and radiometric age data which indicates most of the southwestern porphyry copper deposits post-date regional thrusting and coincide with strike-slip faulting (Drewes, 1981). Localized tensional tectonic environments might have been developed by uplift and doming (Lowell, 1974), or by reactivation of the complex Precambrian fault system (Neilson, 1979; figures 60 and 61).

Many of the porphyry copper deposits are located in northwest-trending belts that are parallel with Precambrian fracture directions. The best example is the belt extending from Sacaton to La Caridad and further south in Mexico (figures 59 and 62). Shorter belts with porphyry deposits are aligned ENE. The structures that control these belts may have little surface expression, usually no more than a few discontinuous parallel fracture zones. The predominant fracture orientations within individual porphyry copper deposits are approximately parallel with these two trends (Lowell, 1974; Rehrig and Heidrick, 1972), suggesting the trends are real geologic features.

Individual deposits show a broad zonation of alteration assemblages, sulfide mineralogy, and metal grades reflecting progressive changes in temperature, pressure, and chemical parameters in circulating hydrothermal fluids during mineral deposition. The general metal zonation from the core of the deposit outward is: Mo, Cu-Mo, Cu, Pb-Zn-Ag (figure 63). This pattern may become locally complex when multiple phases of mineralization are present (figure 64). Ore grade copper mineralization is confined to the potassic and/or phyllic alteration zones. Lead-zinc-silver mineralization

often is present in small, generally insignificant amounts on the margins of the porphyry system, but occasionally, major deposits are present (eg. Butte, Bingham, Santa Rita; figures 63 and 64).

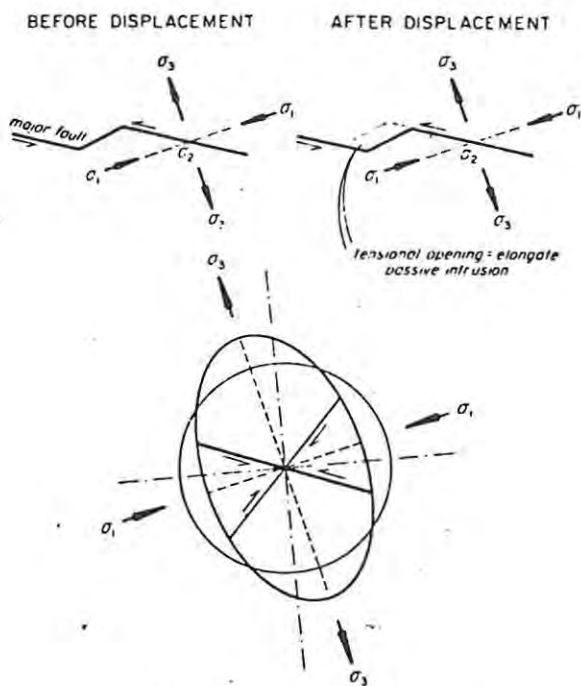
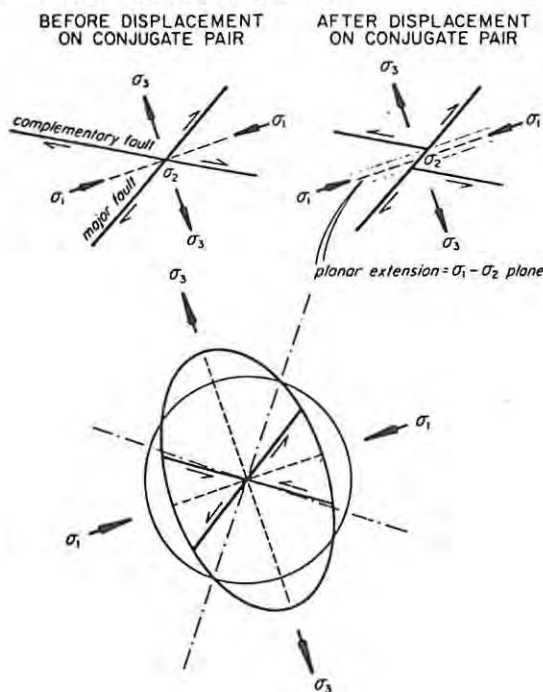


Figure 60: Plan view of tensional structure developed in a compressive stress field. Passive hypabyssal intrusions may be emplaced in tensional openings formed at a flexure in a fault surface. From Nielsen (1979).

Figure 61: Plan view of tensional structure developed in a compressive stress field. Hypabyssal intrusions and dikes emplaced in planar extensional fractures after displacement on a conjugate fault pair resulting from horizontal compression. From Nielsen (1979)



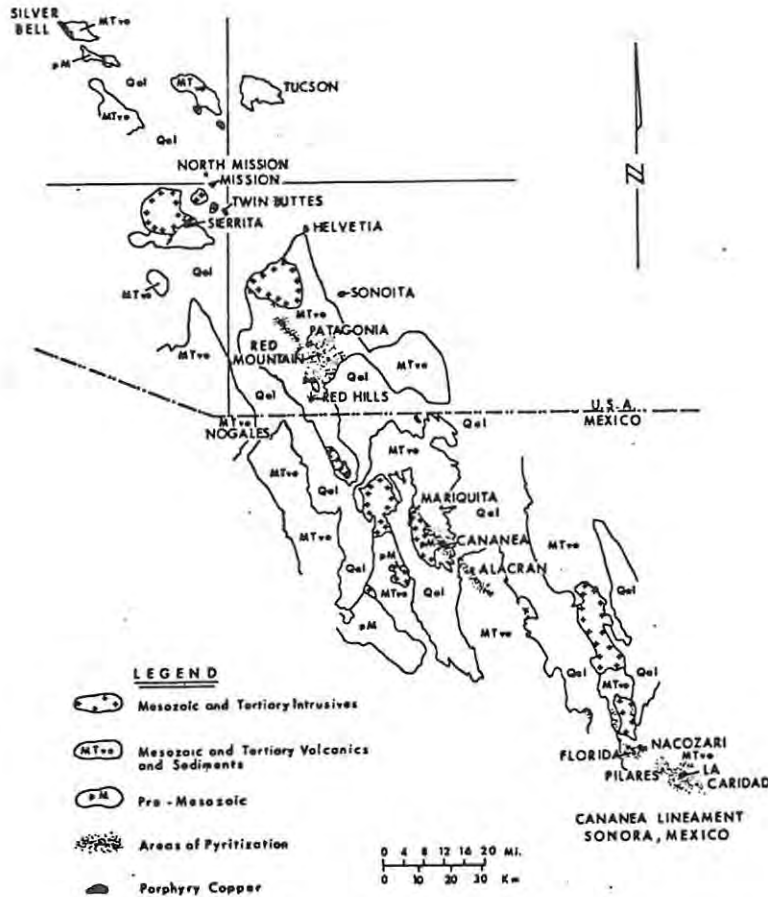


Figure 62: Cananea line. From La Caridad to the vicinity of Tucson, discontinuous zones of pyrite dissemination occur between known porphyry copper deposits. The zones are elongated parallel to the trend of the line of deposits and add to continuity from one porphyry occurrence to the next. Pyrite halos around each porphyry copper are elongate along the line of deposits, giving substance to Cananea line as a linear grouping of deposits from La Caridad northwest. From Hollister (1978).

Many of the southwestern porphyry deposits have been upgraded by supergene enrichment. For example, the protore of 0.1 to 0.15% Cu of the Morenci - Metcalf deposits (figure 65) has been enriched to 0.88% by two cycles of supergene enrichment (Langton, 1973). Enrichment is related to a cycle of erosion following regional uplift during the Laramide orogeny (pre-Miocene enrichment, figure 65), as well as to erosion associated with basin-range block faulting (post-Miocene enrichment, figure 65). Thus, the post-mineralization tectonic history of the southwestern United States has been an important factor for establishing the economic viability of many of the porphyry copper deposits.

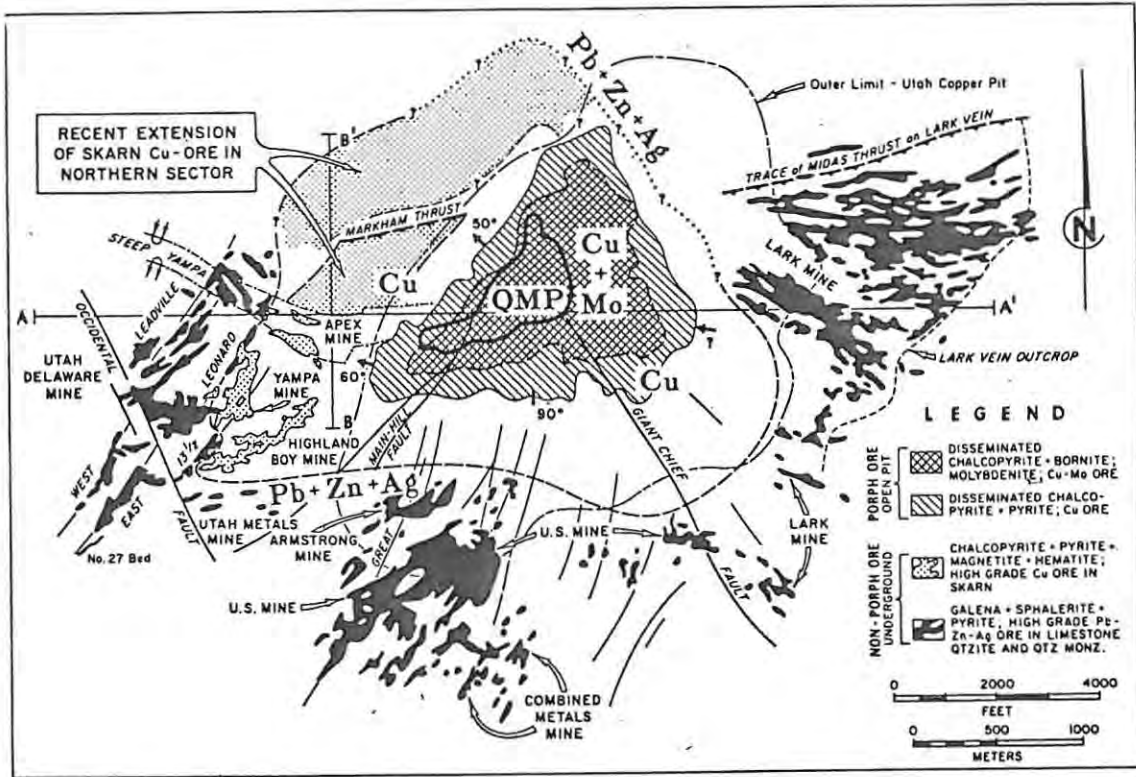
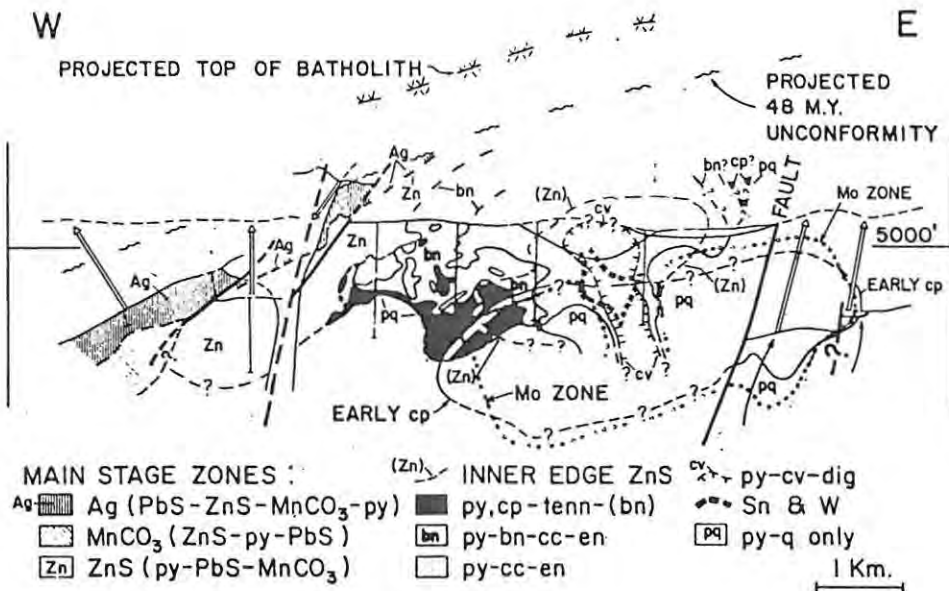


Figure 63: Principal mines, surface projection of composite stoping, and metal zoning in the Bingham district. QMP, quartz monzonite porphyry. From Atkinson and Einaudi (1978).

Figure 64: An interpretive east-west section through the Butte district, Montana, with main-stage vein-mineral assemblages of the east-west Anaconda vein and correlative veins and Minnie Healy horsetail zone projected on to it. The effects of post-ore faults have been removed. Open arrows point to where given blocks would have been moved by post-ore faulting. From Proffett (1979).



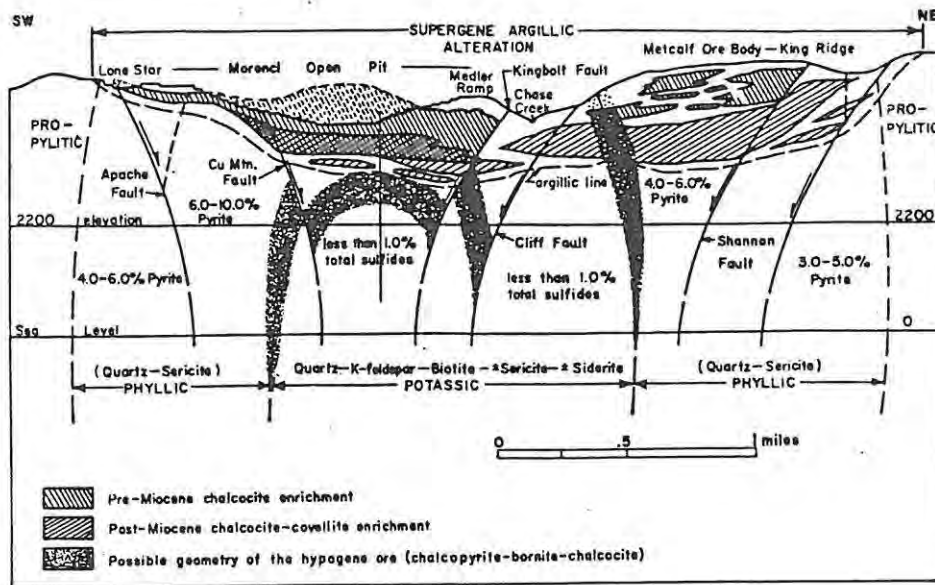


Figure 65: Diagrammatic cross-section through the Morenic and Metcalf ore deposits. From Langton (1973).

Stockwork Molybdenum Deposits

The stockwork molybdenum deposits in the western United States may be divided into two groups based on the chemistry of the source pluton: (1) granodiorite systems and, (2) granite, or Climax-type, systems. These two groups show significant differences in age, tectonic settings at the time of formation, and orebody geometry (Mutschler and others, 1981). Most of the early Laramide molybdenum deposits are associated with intrusive outliers or the waning phases of the Idaho, Boulder, or Sierra Nevada batholiths and are classified as granodiorite systems. These include the White Cloud (Little Boulder Creek), Cannivan Gulch, Buckingham, and Mt. Tolman deposits (figure 59), as well as the late Mesozoic Hall and Thompson Creek deposits. The late Laramide deposits are associated with small stocks and plutons within and to the east of the Idaho batholith. The intrusives tend to show alkaline characteristics and the deposits are classified as granitic systems. The Emigrant Gulch, Big Ben, Ima, Bald Butte, Little Falls, and Cumo deposits (figure 59) are examples of this group, which marks the first appearance of the important Climax-type deposits in the western United States.

The granodiorite molybdenite systems are associated with mesozonal calc-alkaline granodiorite and quartz monzonite composite stocks and batholiths (Mutschler and others, 1981; Westra and Keith, 1981). Usually, molybdenum mineralization is most closely associated with peraluminous silica-rich leucocratic granites, alaskites, and aplites which represent the final products of magma differentiation in the stocks (Westra and Keith, 1981).

Doming of wall rock, formation of sheeted contact zones, and the presence of breccia pipes suggest the magmas have been intruded forcefully (Westra and Keith, 1981), indicating a compressive crustal stress state during emplacement of the granodiorite molybdenite systems (Mutschler and others, 1981).

The orebodies occur as tabular bodies within the pluton (Thompson Creek), marginal annular bodies (Hall), and veined tactites adjacent to the pluton (White Cloud, Cannivan Gulch). (Mutschler and others, 1981). The central or annular zone of molybdenite sometimes is surrounded by a zone of chalcopyrite with grades locally exceeding 0.1% Cu (Mt. Tolman, Hall). Skarns associated with the deposits may contain economically significant scheelite concentrations (Cannivan Gulch, Thompson Creek). However, tin is present only in trace amounts and fluorine content is comparable to that in porphyry copper deposits (Westra and Keith, 1981). Barium and strontium contents are significantly higher than in granite molybdenite systems, while rubidium and uranium are lower. Also, the tenor of molybdenum mineralization tends to be significantly lower. In terms of source rock chemistry, orebody geometry, and trace element signature, the granodiorite molybdenite systems show closer similarities to Cordilleran porphyry copper deposits than to the granite molybdenite deposits (Mutschler and others, 1981).

Unlike the mid-Cenozoic granite molybdenite deposits, the late Laramide granite molybdenite deposits tend to be small and/or low grade. The known occurrences are prospects or recent discoveries about which little information is available. Therefore, discussion of this type of deposit will be deferred until the section on mid-Cenozoic mineralization.

Replacement Deposits

Major replacement deposits in carbonate rocks are found in all three major areas of Laramide mineralization. A significant proportion of the mineralization in some porphyry copper deposits occurs in replacement deposits (eg. Twin Buttes, Pima, Ray, Silver Bell) while other porphyry copper districts contain large replacement deposits on the margins of the district (eg. Butte, Santa Rita, Mineral Park). However, none of the replacement deposits shown in figure 59 are related to porphyry copper mineralization. Some of these districts (eg. Superior, Leadville) have had total productions that are comparable in value to porphyry copper deposits.

The major products from most replacement deposits are lead, zinc, and silver, although copper and gold have been important in several districts (eg. Christmas, Superior, Johnson Camp). Mineralization occurs in veins as well as mantos. The two types may or may not be directly connected (figure 66). Occasionally, mineralization in the veins is more significant than that found in replacement bodies. Usually, mineralization is spatially and temporally associated with intermediate to felsic calc-alkaline intrusives. Mineralization may occur directly on the margins or stocks or batholiths (eg. Christmas, Philipsburg, Pinos Altos), or be closely associated with sills, dikes, and small plugs (eg. Leadville, Superior). Occasionally, mineralization shows no direct relationship with magmatic activity (eg. Gilman). Mineralization also is controlled by structures and favorable host rocks. Some of the Colorado deposits have been controlled by a Paleozoic karst system (Tweto, 1968; Anderson, 1968; Hobbs, 1968).

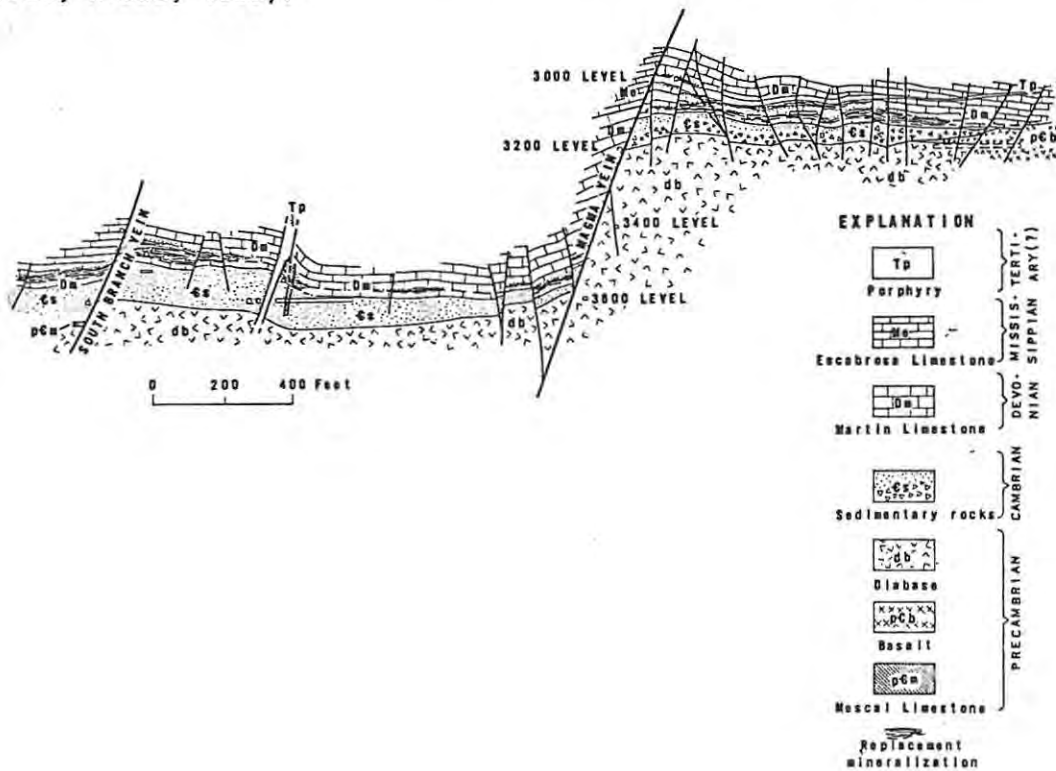


Figure 66: Vertical north-trending section through the limestone replacement deposit, Magma Mine (looking west). Some ore shoots show direct connection with veins, but others are isolated. From Hammer and Peterson (1968).

Gold - Silver Vein Deposits

Numerous vein deposits also are found in the three major areas of Laramide mineralization. This type of deposit may occur on the margins of porphyry copper deposits, in close association with replacement deposits, or as the major form of mineralization associated with some Laramide centers or magmatism. The more important districts and deposits that are predominantly vein-type mineralization are shown in figure 59. Individual vein deposits tend to be very small, generally no more than a few 10's to 100's of thousand tons. However, a few districts which contain numerous veins have had a significant total production. For example, the Central City district has produced more than 4.3 million oz of gold, 11.1 million oz of silver, 26 million pounds of copper, 37 million pounds of lead, and minor amounts of zinc and uranium from more than 500 mines (data from Sims and others, 1963).

Most of the Laramide vein deposits are spatially and temporally related to intermediate to felsic calc-alkaline plutons, dikes, or sills, rather than to volcanic rocks. The veins may be contained within intrusives or in adjacent wallrocks. Distribution of the veins, and mineralization within the veins is strongly controlled by structural features and wall rock compositions. Most veins were mined for the precious metal contents, but a few contained significant base metals (eg. Lordsburg).

Three of the deposits shown on figure 59, Hardshell, Hog Heaven, and Republic; are associated with volcanic rocks. The Hardshell deposit contains low grade silver mineralization disseminated in Mesozoic volcanic and volcanoclastic rocks (Watson, 1977) on the margin of the Red Mountain porphyry system. Mineralization and volcanism probably are related to porphyry copper-type mineralization. Hog Heaven and Republic appear to be related to late Laramide volcanism. The Hog Heaven deposit contains disseminated silver mineralization with pyrite, sphalerite, and barite in latite tuff breccia and volcanic conglomerates (Watson, 1977). Mineralization in the Republic district is found in fine-grained quartz veins containing electrum, stephanite, naumannite, and native silver associated with Eocene and Oligocene volcanic flows, breccias, proclastics, and tuffs and associated intrusives. The most extensive volcanism is confined to the Republic graben, a major structure that is from 10 to 16 km in width and more than 80 km in length (Full and Grantham, 1968). Thus, the Hog Heaven and Republic deposits are related to the late Laramide magmatic phase in the northwestern United States, and coincide temporally with granite stockwork molybdenum

mineralization. These deposits also are more similar to the mid-Tertiary precious metal deposits than are the earlier Laramide precious metal vein deposits.

Uranium - Sulfide Vein Deposits

Several pitchblende-sulfide vein deposits, apparently of hydrothermal origin, also are found in areas of Laramide magmatism (figure 59). The Schwartzwalder mine is located in the Colorado mineral belt, while the Mt. Spokane district and Daybreak mine are associated with Laramide magmatism in northeastern Washington. These deposits show features, such as hydrothermal alteration and structural control of mineralization, that are similar to other types of vein deposits. Mineralization consists of pitchblende; sometimes coffinite; small amounts of pyrite and marcasite; and minor amounts of pyrrhotite, molybdenite, arsenopyrite, chalcopyrite, and sphalerite. Typical gangue minerals include quartz, calcite, ankerite and adularia (Rich and others, 1977).

The Schwartzwalder deposit consists of mineralized fractures and breccia zones in Precambrian schists. Wall rock lithologies have also controlled mineralization (Rich and others, 1977). Although there are no igneous rocks in the vicinity, the age of the mineralization (73-65 Ma) and the presence of small amounts of uranium mineralization in the nearby Central City and Idaho Springs districts suggest the Schwartzwalder deposit is associated with Laramide magmatism. In the Mt. Spokane district, the Midnite deposit is associated with the contact zone of Precambrian pelitic and calcareous metasediments (Belt Supergroup?) and a Cretaceous porphyritic quartz monzonite pluton (Rich and others, 1977).

Tectonic Controls on Laramide Mineralization

Laramide mineral deposits show the same restricted distribution as Laramide magmatism, being confined mostly to southern Arizona - southwestern New Mexico, the Colorado mineral belt, and the Idaho - Montana mineral belt. Localization of mineral deposits in the southwest and in the Colorado mineral belt can be related to reactivation of Precambrian basement structures. Similar structures can be hypothesized in Idaho - Montana, since the porphyry belt cross-cuts tectonic and structural trends in the northern Rocky Mountains and extends out into the Great Plains. Mineralization in Idaho, Montana, and Wyoming also shows a relationship with intrusives within and adjacent to the Challis and Absaroka volcanic fields. However, most of these deposits -- stockwork molybdenum, porphyry copper-molybdenum, and related lead-zinc-silver-gold mineralization -- are relatively small and/or low grade.

The similarity in regional structural controls does not lead to a similarity in types of mineral deposits. Porphyry copper deposits are dominant in the southwest, while replacement and vein deposits in this region also tend to be copper-rich. The major Laramide deposits in the Colorado mineral belt are Pb-Zn-Ag replacement and Au-Ag vein deposits. In the northwest, there are two groups of deposit types associated with the two distinctly different phases of magmatism. The early Laramide group includes a major porphyry copper deposit, granodiorite stockwork molybdenum deposits, and most of the other basemetal deposits (Hobbs, 1968). The late Laramide group includes granite stockwork molybdenum deposits and precious metal deposits associated with volcanic rocks. Both of these latter types are characteristic of mid- to late Tertiary mineralization elsewhere in the western United States.

The spatial and temporal distribution of Laramide mineral deposits brings out two important features. During early Laramide time, compressional deformation was widespread throughout the western United States and calc-alkaline magmatism was predominant in the three areas of igneous activity. Yet, the mineral deposits in these three areas contain very different proportions of the major metals. This suggests that the source of metals for these deposits is partially controlled by factors other than the tectonic environment and the type of magmatism. The abundance of copper in the southwest, limited concentrations in the northwest, and rarity in Colorado, suggest the source areas of the associated magmas, probably in the lower crust or upper mantle, were more enriched in copper in the southwestern United States than elsewhere.

Also, the early termination of Laramide-style deformation in the northwest corresponds with the appearance of more alkaline-type magmatism, widespread volcanism, and limited amounts of rifting. It also marks a change in the types of mineral deposits, demonstrating the control of tectonism on mineralization. As previously outlined, this style of tectonism and magmatism moved southward across the western United States during mid-Tertiary times, resulting in changes in types and location of subsequent mineralization.

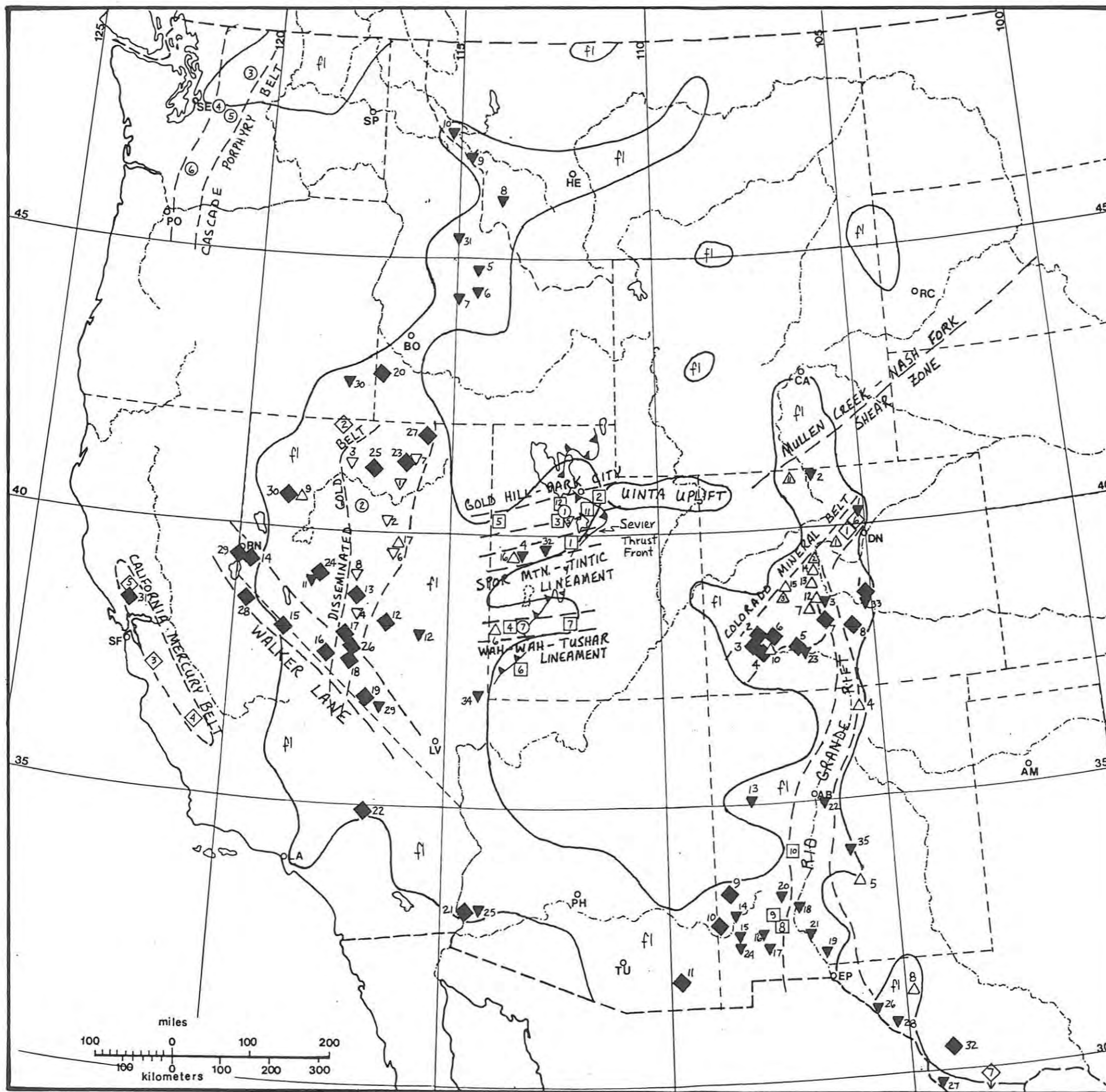
Mineralization Associated with Post - Laramide Magmatism

Types and Distribution of Mineralization

Most of the major types of post-Laramide mineral deposits are similar to those found with previous episodes of magmatism (figure 67). However,

Figure 67. Post - Laramide Mineral Deposits (< 40 Ma).

Legend on following pages.



Legend for Figure 67: Post - Laramide Mineral Deposits (< 40 Ma).

p = prospect d = development

Mineral belts

○ Porphyry Copper Deposits

1	Bingham Canyon	(36-39 Ma)	Mo, Au, Pb, Zn, Ag		UT
2	Battle Mountain	(37 Ma)	Au, Ag		NV
3	Glacier Peak	(22 Ma)		p	WA
4	North Fork	(10 Ma)		p	WA
5	Middle Fork	(18 Ma)		p	WA
6	Ryan Lake	(16 Ma)		p	WA
7	Rocky (Milford)	(25-30 Ma)	Ag	p	UT

△ Granite Stockwork Molybdenum Deposits

1	Urad - Henderson	(26-27 Ma)			CO
2	Climax	(29.5 Ma)			CO
3	Mt. Emmons - Redwell Basin	(17 Ma)		p	CO
4	Questa	(21-23 Ma)			NM
5	Nogal Peak	(26 Ma)		p	NM
6	Pine Grove	(20 Ma)		p	UT
7	Cumberland Pass			p	CO
8	Cave Peak	(32-36 Ma)		p	TX
9	Majuba Hill	(24 Ma)		p	NV
10	Chicago Basin - Horseshoe Bend	(9-10 Ma)		p	CO
11	hahns Peak	(10 Ma)		p	CO
12	Mount Antero	(31 Ma)		p	CO
13	Windfield	(37 Ma)		p	CO
14	Turquoise Lake			p	CO
15	Treasure Mountain	(12 Ma)		p	CO
16	Sand Pass			p	UT
17	Mount Hope	(30-36 Ma)		p	NV

◆ Base and Precious metal deposits associated with volcanic rocks


1	Cripple Creek	(30 Ma)	Au		CO
2	Ouray	(10.5 Ma)	Au, Ag, Pb, Cu		CO
3	Telluride	(17 Ma)	Au, Ag, Pb, Cu, Zn		CO
4	Silverton	(22-23 Ma)	Ag, Au, Pb, Zn, Cu		CO
5	Creede	(25 Ma)	Ag, Pb, Zn		CO
6	Lake City	(22 Ma)	Ag, Pb, Au		CO
7	Bonanza		Ag, Pb, Cu		CO
8	Westcliff - Silver Cliff		Ag, Au, Pb		CO
9	Mogollon	(24 Ma)	Ag, Au		NM
10	Steeple Rock	(35 Ma)	Ag, Au, Pb, Zn, fl		AZ-NM
11	Commonwealth		Ag, Au		AZ
12	Typo	(28-29 Ma)	Ag, Pb		NV
13	Round Mountain	(25 Ma)	Au, Ag		NV
14	Comstock	(13 Ma)	Ag, Au		NV
15	Aurora - Bodie	(10-7 Ma)	Au, Ag		CA-NV
16	Silver Peak	(5 Ma)	Ag, Au		NV
17	Tonopah	(19 Ma)	Ag, Au		NV
18	Goldfield	(20 Ma)	Au, Ag		NV
19	Bullfrog	(9 Ma)	Au, Ag		NV
20	Delamar		Ag, Au		ID
21	Silver		Ag, Pb		AZ
22	Calico		Ag, Ba		CA
23	Tuscarora	(38 Ma)	Ag, Au		NV
24	Wonder	(22 Ma)	Ag, Au		NV
25	Midas	(15 Ma)	Au, Ag		NV
26	Divide	(15 Ma)	Ag, Au		NV

Legend for figure 67, continued...

27	Jarbridge	(14 Ma)	Au, Ag		NV
28	Monitor	(5 Ma)	Ag, Au, Cu		CA
29	Steamboat Springs	(2.5-0 Ma)	Hg, Au, Ag	p	NV
30	Seven Troughs	14 Ma)	Au, Ag		NV
31	McLaughlin		Au	p	CA
32	Shafter		Ag, Pb	p	TX
<u>□ Replacement Deposits</u>					
1	Tintic - East Tintic	(31-33 Ma)	Ag, Pb, Au; Cu, Zn		UT
2	Park City	(33-36 Ma)	Ag, Pb, Zn, Au, Cu		UT
3	Ophir - Rush Valley		Ag, Pb, Au		UT
4	San Francisco		Ag, Pb, Au, Cu		UT
5	Gold Hill		Ag, Au, As		UT
6	Iron Springs	(25-30 Ma)	Fe		UT
7	Ohio - Mt. Baldy - Gold Mountain - Marysvale		Au, Ag, Pb, U, Mo		UT
8	Lake Valley	(33 Ma)	Ag, Pb, Au		NM
9	Kingston	(33 Ma)	Ag, Pb, Zn		NM
10	Magdalena	(28 Ma)	Ag, Pb, Zn, Au		NM
11	Cottonwood - American Fork		Ag, Cu, Pb, Au		UT
12	Carr Fork		Cu		UT
<u>▽ Disseminated Gold Deposits</u>					
1	Carlin - Bootstrap - Blue Star - Maggie Creek				NV
2	Cortez - Gold Acres - Buckhorn	(35-15 Ma)			NV
3	Getchell - Purison				NV
4	Manhattan	(16 Ma)			NV
5	Mercur		Hg, Th	d	UT
6	Alligator Ridge				NV
7	Jerritt Canyon			d	NV
8	Northumberland			d	
<u>◇ Mercury and other deposits</u>					
1	Nederland		W in veins		CO
2	McDermitt	(12 Ma)	U		NV-OR
3	New Almaden				CA
4	New Idria				CA
5	Maykamus				CA
6	Gold Hill		Au, Ag, W in veins		CO
7	Terlingua				TX
<u>▼ Fluorite deposits</u>					
1	Jamestown				CO
2	Northgate				CO
3	Browns Canyon - Poncha				CO
4	Spor Mountain - Thomas Range		Be		UT
5	Meyers Cove				ID
6	Bayhorse				ID
7	Stanley				ID
8	Crystal Mountain				MT
9	Snowbird				MT
10	Spar				MT
11	Broken Hills				NV
12	Quinn Canyon Range				NV
13	Zuni				NM
14	Gila				NM
15	Buno Mountains				NM
16	Cooks Peak				NM

Legend for figure 67, continued...

17	Fluorite Ridge		NM
18	Sierra Caballos		NM
19	Tortugas		NM
20	Sierra Cuchillo		NM
21	Tonuco		NM
22	Manzano		NM
23	Wagon Wheel Gap		CO
24	White Signal - Gold Hills		NM
25	Castle Dome		AZ
26	Quitman Mountains		TX
27	Chinati Mountains		TX
28	Eagle Mountains		TX
29	Fluorine		NV
30	Rome		OR
31	Big Squaw Creek		ID
32	Honey Comb Hills	Be, Cs, Li	UT
33	St. Peters Dome		CO
34	Wells Cargo		NV
35	Gallinas		NM

 Areas with fluorite deposits

Note: Some fluorite deposits may be Laramide age

several of these types are better developed during post-Laramide time. Granite stockwork molybdenum deposits and precious- base metal deposits associated with volcanism, types that first appeared during late-Laramide time in the northwestern United States, are more abundant and widespread than previously. The early examples are relatively small and scarce compared with their post-Laramide equivalents. Disseminated gold deposits also are an important type during post-Laramide time. It is uncertain whether or not this type made its first appearance during Mesozoic time. Porphyry copper deposits were still forming within the craton during mid-Tertiary time, although, significantly, the youngest known example is 36 Ma. Another belt of porphyry copper deposits associated with a magmatic arc developed in western Washington during Miocene time. Replacement deposits are limited to a few areas in western Utah and southwestern New Mexico. Vein deposits not associated with volcanism are rare. Most of the fluorite and mercury deposits in the western United States are thought to be of mid-Tertiary to late Tertiary age.

The distribution of mineral deposits is considerable different from that in Laramide time (figure 67). The Colorado lineament was reactivated, but the types of deposits are considerably different from those of Laramide age. The post-Laramide types include granite stockwork molybdenum deposits, precious metal deposits associated with volcanic rocks, and fluorite deposits. These types persist along the Rio Grande rift, with the greatest concentrations in the vicinity of volcanic fields. A few replacement deposits in southwestern New Mexico also are closely associated with the rift and the Datil - Mogollon volcanic field. Mineralization is rare in southern Arizona. The deposits in Arizona shown in figure 67 have not been dated, and may be Laramide.

Mineralization occurs along three belts in western Utah, corresponding with the belts of mid-Tertiary magmatism (figures 41 and 67). The areas with the most intense mineralization are located at the intersection of these belts with the north-trending Cordilleran hinge line - Sevier thrust belt - Great Basin margin. Deposit types include porphyry copper, replacement, disseminated gold, fluorite-beryllium, uranium, and granite stockwork molybdenum. The limited extent of these belts is not an accurate indication of the value of their production. The Bingham Canyon district has accounted for 10% of the copper production in the western United States, while the combined production from Bingham Canyon, Tintic, and Park City districts has accounted for 26% of the lead-zinc and 17% of the silver production

(Noble, 1974).

Western Nevada and adjacent parts of California, Oregon and Idaho contain numerous mid- to late Tertiary deposits. Most of these are disseminated gold and precious metal vein deposits associated with volcanic rocks. However, examples of porphyry copper, granite stockwork molybdenum, mercury, and fluorite deposits also are present. The Walker Lane appears to have a greater concentration of mineral deposits than other regions. However, the widespread occurrence of mineralization has suggested other mineral belts may be present (eg. Roberts and others, 1971). The disseminated gold belt closely corresponds with the Roberts Mountains suspect terrane (figure 26), suggesting a genetic relationship.

Although mid-Tertiary volcanism is widespread in eastern Nevada, mineral deposits are relatively sparse. This area corresponds with the magnetic quiet zone of Stewart and others (1977), figure 17. Mid- to late Tertiary mineralization may not have extended north of the Snake River, since the fluorite deposits shown in Idaho and Montana are thought to be late-Laramide.

A belt of mercury mineralization associated with volcanism along the San Andreas system in central California has accounted for most of the mercury production in the western United States. A major disseminated gold deposit recently has been discovered in this belt. The Cascade arc in Washington contains numerous porphyry copper prospects as well as small deposits of lead, zinc, gold, and silver. This belt may extend southward through Oregon into northern California. However, the southern Cascades have been less eroded than the northern Cascades, and potential mineral deposits may be deeply buried.

Porphyry Copper Deposits

Post- Laramide porphyry copper deposits can be subdivided into two groups: (1) those formed within the craton, and (2) those formed in the Cascade magmatic arc. The former group consists of the Battle Mountain and Bingham Canyon deposits. Both have late Eocene ages and may be more closely related to the terminal phase of Laramide tectonism rather than the extensional tectonic environment of mid- to late Tertiary time. Bingham Canyon is one of the world's largest porphyry deposits and is the most productive copper deposit in the United States. Mineralization is associated with a composite intrusive stock of monzonite to quartz monzonite composition. The suite of igneous rocks is significantly different from those associated with

the southwestern porphyry copper deposits in that they tend to be more potassic, and show a differentiation trend similar to that of Laramide stocks in Colorado and New Mexico (Creasy, 1977). Whether this difference reflects inhomogeneities in the continental crust (Creasy, 1977), or slightly different tectonic settings, is not clear. Battle Mountain also differs from the typical Laramide porphyry deposits by the occurrence of significant disseminated gold-silver mineralization immediately peripheral to the copper skarn mineralization (Blake and others, 1978). Ultimately, the value of gold will probably exceed that of copper produced in this district. The high gold content at Battle Mountain appears to be related to the location of the deposit within the disseminated gold belt (figure 67).

The porphyry copper deposits in the Cascade Range are similar in most respects to other North American porphyry deposits. The deposits are associated with differentiated granitic stocks and batholiths that have intruded the calc-alkaline, predominantly andesitic volcanic pile. The intrusives apparently are coeval with some of the volcanic rocks. Many of the porphyry copper prospects are spatially associated with northwest-trending regional faults with possible right-lateral strike-slip movement (Hollister, 1978). These faults appear to have formed in late Mesozoic - early Tertiary time, possibly in association with accretion of suspect terrane (Coney and others, 1980). Possible reactivation during the Miocene episode of magmatism may have controlled emplacement of the porphyry copper systems.

The Cascade deposits do show one unusual regional characteristic. Deposits in the northern Cascades contain minor amounts of scheelite as well as molybdenite, while southern Cascade deposits contain no tungsten and relatively insignificant molybdenite. This change in mineralogy roughly corresponds with the southern boundary of Cascade tungsten and molybdenum occurrences (W-Mo line, figure 67). Hollister (1978) suggests this line represents the southern limit of basement cratonic crustal conditions, with areas to the south underlain by oceanic crust. The W-Mo line correlates with a major change in the present crustal thickness shown in figure 10. This relationship implies that tungsten and molybdenum content in porphyry copper systems is related to crustal thickness and/or crustal composition.

The Cascade porphyry copper deposits show a close spatial relationship with an oceanic trench that runs parallel to the coast in the Pacific Northwest. However, no consensus has been reached on the question of whether

or not subduction is active now, or was a factor at the time these deposits were formed (Hollister, 1978). In any case, it seems reasonable to infer that the Cascade deposits are related to a plate subduction tectonic environment.

Granite Stockwork Molybdenum Deposits

The granite stockwork molybdenum deposits are one of the most important types of mineral deposits that formed in mid- to late Tertiary time. The greatest concentration and largest of these deposits is found in the central portion of the Colorado mineral belt, but occurrences are known along the Rio Grande rift from the Colorado - Wyoming state line (Hahns Peak) to west Texas (Cave Peak). Recent discoveries indicate this deposit type is present in the east-west-trending mineral belts of western Utah (Pine Grove and Sand Pass), and in the western Great Basin (Majuba Hill and Mount Hope).

Most of the deposits are associated with granite porphyry and/or rhyolite porphyry plugs which typically have a diameter of 0.5 to 1.5 km and a known vertical extent of 2 km or more. These plugs are thought to be cupolas extending above high level silicic plutons with batholithic dimensions (Mutschler and others, 1981). The composition of the plugs is that of metaluminous and peraluminous alkali granite with high silica and potassium (Westra and Keith, 1981). Compared to the average values for low-calcium granites, the granite porphyry plugs usually show enrichment in several of the following elements: Be, Cl, Cs, F, Li, Mo, Nb, Rb, Sn, Ta, Th, U, W, and Y (Mutschler and others, 1981; Westra and Keith, 1981). Ca, Sr, Ba, and Ti often are depleted in the granite porphyries (Westra and Keith, 1981). This pattern of enrichment is similar to that reported for tin-specialized granites (Tischendorf, 1977).

Many of the granite porphyries were implaced by forceful intrusion, indicated by doming of intruded country rocks and by the presence of ring dikes, cone sheets and radial dikes. Some of the deposits occur in a volcanic setting, and comagmatic ash flows occasionally are found (Westra and Keith, 1981).

The granite stockwork molybdenum deposits commonly have three mineralized zones: (1) a molybdenite zone consisting of a stockwork of quartz-molybdenite-fluorite veins, (2) a tungsten zone generally containing huebnerite in quartz-pyrite + molybdenite veins, and (3) a pyrite and base metal sulfide zone extending above the other zones (figure 68; Mutschler and others, 1981). The molybdenite zone usually forms a hemispherical shell in

or above the apex of the source porphyritic plug, while the tungsten zone immediately overlies or partially overlaps the molybdenite zone. This general pattern may be complicated by multiple events of intrusion and mineralization (eg. Wallace and others, 1968).

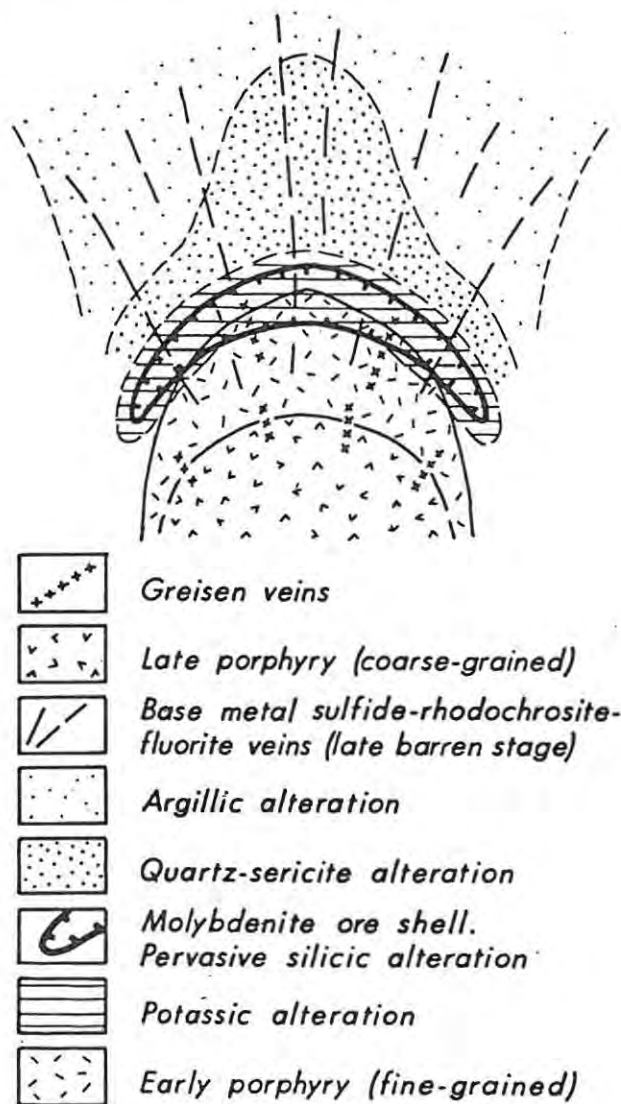


Figure 68: Generalized cross section of a granite molybdenite system. Not to scale. From Mutschler and others (1981).

The granite stockwork molybdenum deposits show a tendency to form just before or during regional crustal extension. The major deposits in Colorado - northern New Mexico (Urad - Henderson, Climax, Mt. Emmons, Questa) formed during the interval from 30 to 17 Ma, corresponding with the initiation of faulting in the northern portion of the Rio Grande rift around 29-28 Ma (Mutschler and others, 1981; Tweto, 1975). The slightly older Cave Peak

deposit in Texas (30-36 Ma) correlates with an earlier initiation of faulting in the southern Rio Grande rift (32 Ma; Chapin, 1979). Significantly, these dates also correspond to changes in the style and composition of volcanism, with silicic ash-flow tuffs dominant in the San Juan volcanic field and the Great Basin after 30 Ma and 34 Ma respectively, and bimodal volcanism dominant after 25 Ma and 17 Ma. Radiometrically dated Utah and Nevada prospects range from 18 to 25 Ma, spanning the onset of extensional basin-range plastic deformation and faulting about 20-17 Ma (Mutschler and others, 1981). These relationships provide strong evidence that the formation of granite stockwork molybdenum deposits and associated magmatism is controlled by a tensional tectonic environment.

Westra and Keith (1981) have proposed a more detailed classification of molybdenum deposits, based on magma series chemistry expressed as K_2O content at 57.5% SiO_2 . Their major categories are calc-alkalic, high K calc-alkalic, alkali-calcic, and alkalic molybdenum stockwork deposits. Calc-alkalic and some high K calc-alkalic deposits fall into the granodiorite category of Mutschler and others (1981), while the remaining high K calc-alkalic and more alkaline deposits are included in the granite category. Westra and Keith (1981) postulate that magma series chemistry is directly related to the depth to a paleosubduction zone.

This classification scheme is considered unsatisfactory for several reasons. First there is insufficient data on most deposits for them to be assigned with confidence to one of the categories. Second, the classification overlooks the spatial and temporal association of the two major deposit types with different tectonic environments. Finally, there are other factors besides the depth of a subduction zone which affect magma chemistry (eg. tectonic environment, and thickness, composition, and temperature gradient of the crust and upper mantle).

Replacement Deposits

Several major limestone-replacement deposits are associated with the east trending mineral belts in western Utah (figure 67). The major districts are located at Park City, Tintic, and on the periphery of the Bingham Canyon stock (figure 63). Mineralization is associated with 31-36 Ma calc-alkaline intrusives. These deposits have produced substantial amounts of lead, zinc, silver, gold, and copper.

Several smaller districts are found in carbonates on the margin of the Datil - Mogollon volcanic field in southwestern New Mexico (figure 67). These

deposits are spatially associated with intermediate calc-alkaline intrusives and volcanics that are part of the initial cycle of magmatism in the Datil - Mogollon volcanic field. The major products have been silver, lead, and zinc.

Base and Precious Metal Deposits Associated with Volcanic Rocks

Gold and silver deposits, sometimes associated with significant amounts of lead, zinc, and copper, are located in many areas of mid- to late Tertiary volcanism. Major occurrences are found in the San Juan volcanic field, the western Great Basin, and the Datil - Mogollon volcanic field (figure 67). Most deposits are spatially associated with volcanic centers which often occur as calderas. Mineralization occurs in veins, breccia pipes, disseminations, and veins in subvolcanic intrusives, and in a variety of other structural and igneous features related to the volcanic centers. Many of the deposits contained unusually high grades of precious metals, largely due to supergene enrichment. The deposits have a wide range in ages, but most are younger than 30 Ma. The type of associated magmatism is variable.

The mid-Tertiary ash-flow tuffs associated with calderas, belong to two overlapping magma suites: (1) an earlier suite of calc-alkaline, intermediate to felsic rocks, and (2) a later suite of high-silica, generally alkalic rhyolite. The source calderas for these ash-flow tuffs are interpreted as the surface expression of composite, near-surface granitic batholiths. Many calderas associated with mineral deposits are resurgent. These are defined as calderas in which the cauldron block, following subsidence, has been uplifted, usually in the form of a structural dome (Smith and Bailey, 1968). Doming of the cauldron block is most likely due to magma pressure rather than by stock or laccolithic intrusion, but the principal cause of doming is not known (Smith and Bailey, 1968). The stages in the formation of a resurgent caldera are shown in figure 69.

Ore deposits seem to be associated with calderas in several ways. The main stage of eviscerating ash-flow eruptions (figures 69 A and B) is likely to disperse metallic trace elements concentrated in the volatile-rich cupolas of the magma chambers, rather than concentrate them into ore deposits. However, volatile components may again be concentrated at the roof of the magma chamber during a resurgent magma pulse (figure 69 D) and mineral deposits may be formed by circulation of hydrothermal fluids during and after resurgence. Finally, structures associated with calderas may become conduits for later intrusions and mineralizing fluids (Elston, 1978).

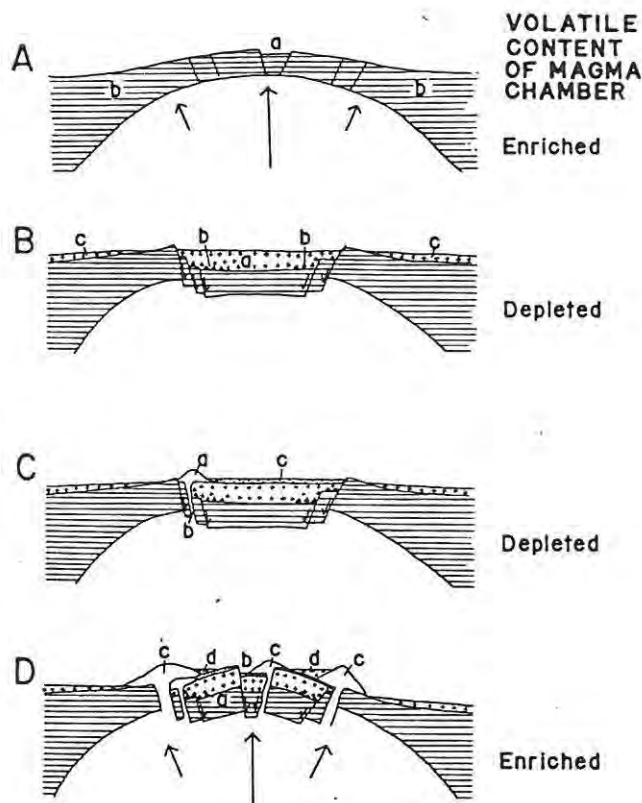


Figure 69: Stages in the formation of a resurgent cauldron.

- A. Tumescence stage. a, apical graben; b, country rock; arrows indicate magma pulse.
 - B. Main-stage eruption and caldera collapse. a, caldera fill of ash-flow tuff; b, caldera collapse breccia; c, outflow sheet of ash flow tuff.
 - C. Infilling of caldera. a, parasitic volcano, south of pyroclastic fill; b, feeder for volcano along ring fracture, which also may be site of magma caught during caldera collapse (early ring dike); c, sedimentary caldera fill.
 - D. Resurgent stage. a, disturbed caldera floor; b, graben apical to resurgent dome; c, ring-fracture dome above ring dike; d, moat deposits.
- From Elston (1978).

Mineral deposits in the Datil - Mogollon volcanic field

Almost all of the mining districts in southwestern New Mexico, of known or suspected mid-Tertiary age, lie in the ring fracture zone or on the central dome of resurgent calderas, or on the margin of the inferred Mogollon Plateau pluton (figure 70; Elston, 1978). Calc-alkalic calderas tend to be associated with copper, lead, and zinc mineralization, while

calderas with high-silica rhyolite tend to be associated with the lithophile metals: molybdenum, tin, and beryllium. Gold and silver and fluorite are ubiquitous and not tied to a specific magma type (Elston, 1978).

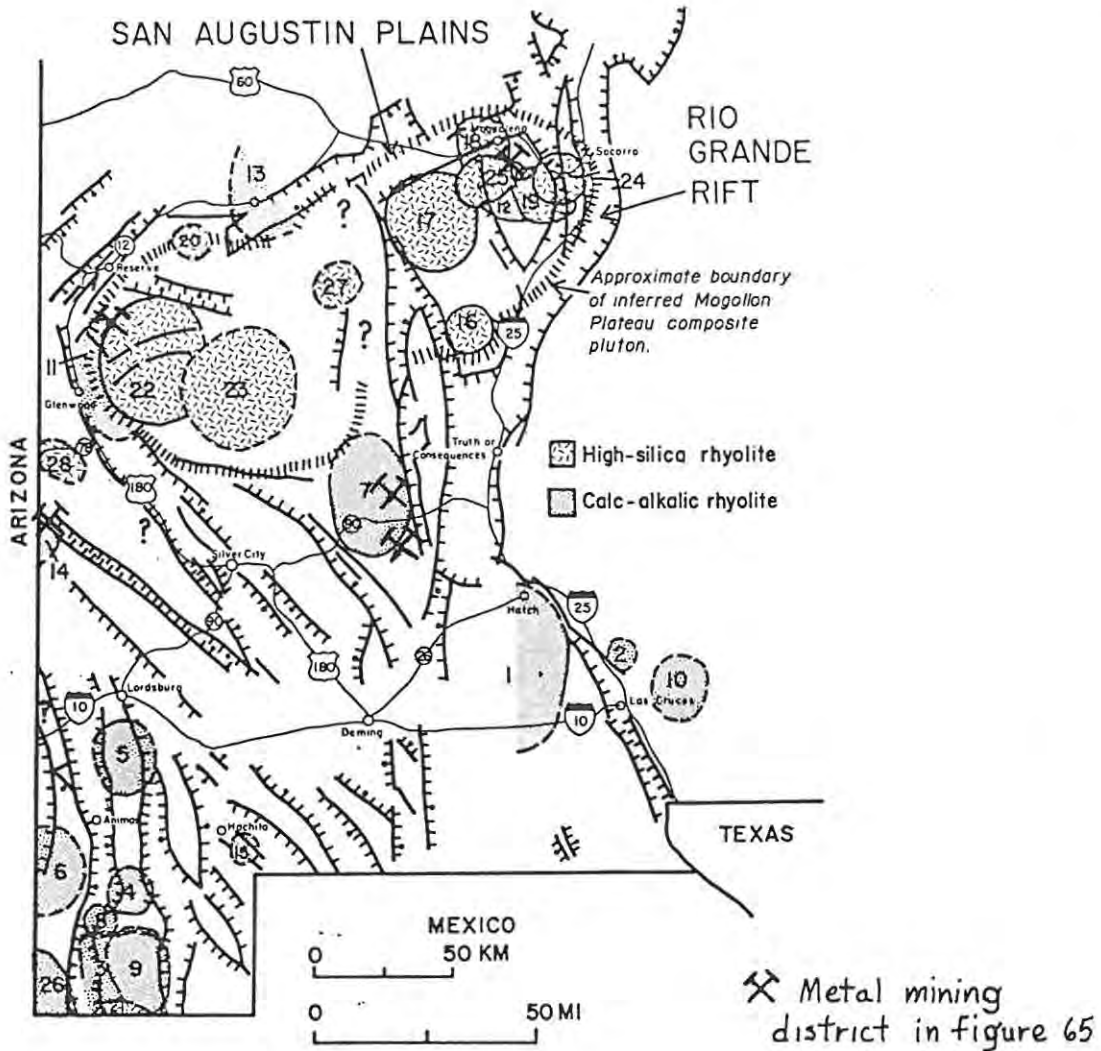


Figure 70: Mid-Tertiary ash-flow tuff cauldrons and mining districts of southwestern New Mexico. Modified from Elston (1978).

Mineral deposits in the San Juan volcanic field and adjacent areas

The major mining districts in the San Juan volcanic field and adjacent areas, from which significant amounts of silver, gold, lead, zinc, and copper have been produced, also are closely associated with large calderas. The geological setting of the deposits is similar to those in the Datil -

Mogollon volcanic field, except the deposits are considerably larger and contain more base metals. These differences may be related to the fact that deeper erosion in the San Juans has exposed deeper levels of mineralization.

Recent isotopic and fission-track age dating indicates that mineralization occurred intermittently from 30 to 10 Ma, generally late in the cycles of individual volcanic centers. However, the most valuable ores in the Silverton caldera, the host structure for the most important districts (Telluride, Ouray, and Silverton), were deposited 10 to 15 million years after caldera collapse and termination of major silicic caldera-related volcanism. These time relations seem to preclude any significant genetic tie between the major mineralization and emplacement of the caldera-forming magmas. Rather, the calderas seem to have served mainly as structural controls for subsequent mineralization (Lipman and others, 1976).

The major post-caldera mineralization in the Silverton area and at other locales is closely associated with distinctive quartz-bearing intrusions and flows of quartz latite and silicic, alkalic rhyolite. These rocks are part of the bimodal igneous suite that was emplaced intermittently throughout much of Miocene and Pliocene time. Quartz-bearing porphyries with similar composition are associated with the granite stockwork molybdenum deposits in Colorado and northern New Mexico (Lipman and others, 1976).

Gold telluride mineralization in the Cripple Creek district also is associated with alkali magmatism. The district is located in a small graben within the Pikes Peak batholith, which has been filled with water-lain sediments and latite-phonolite tuffs and breccias. The sequence has been intruded by 30 Ma phonolite, syenite, and other alkalic intrusives. Gold telluride mineralization is controlled by a vein system aligned parallel with the fault blocks. Small amounts of pyrite, sphalerite, galena, tetrahedrite, stibnite, cinnabar, molybdenite, and wolframite, occur as accessory minerals, while the gangue is composed of quartz, fluorite, carbonate, and roscoelite (V-mica). (Tweto, 1968). Although Cripple Creek is a small district, isolated from major Tertiary magmatic centers, it has accounted for 9% of the gold produced in the western United States (Noble, 1974).

Precious metal deposits associated with volcanic rocks in the Great Basin

Mid-Tertiary volcanism in the Great Basin differs from that in the San Juan and Datil - Mogollon volcanic fields in that volcanic centers are widespread throughout the entire region. More than 80 major Tertiary volcanic

centers have been identified in Nevada, of which, at least 17 are thought to be calderas (Albers and Kleinhampl, 1970). Mineralization, chiefly gold, silver, mercury, fluorite, and antimony, is associated with 35 or these centers. Typical geologic settings for mineralization are: (1) the rim fracture zones of calderas, (2) areas of local uplift that may reflect intrusion of an igneous body, and (3) groups of veins, breccia pipes, and breccia zones near the heart of a volcanic center (Albers and Kleinhampl, 1970).

The age of mineralization varies from 37 Ma to the present, but about two thirds of the dated deposits were formed during the interval from 17 to 5 Ma (Silberman and others, 1976). The deposits may be related to any of the three major volcanic suites: (1) calc-alkaline intermediate to silicic volcanic rocks (43 to 17 Ma), (2) silicic, peralkaline rhyolite and basalt of the bimodal assemblage (17 to 0 Ma), and (3) calc-alkaline andesitic volcanics along the Walker Lane and adjacent Sierra Nevada (23 to 0 Ma). However, the largest deposits (Comstock, Tonopah, Goldfield, Aurora - Bodie), with the major proportion of regional precious metal production (>80%) are associated with calc-alkaline andesitic volcanic centers along the Walker Lane (Silberman and others, 1976).

Disseminated Gold Deposits

Approximately 18 to 20 disseminated or Carlin-type gold deposits have been discovered in a north-south-trending belt across central Nevada (figure 67). This belt also contains the Goldfield district, the only major Tertiary volcanic precious metal district in the Great Basin which has produced more gold than silver. The disseminated deposits may contain up to several tens of millions of tons of ore with grades exceeding 5 gm/ton. With the development of several recently discovered deposits (Jerritt Canyon, Aligator Ridge, Mercur, Northumberland, Pinson and new orebodies near Carlin), this deposit-type may become the largest source of current gold production in the western United States.

The disseminated gold deposits characteristically occur as very fine-grained, disseminated, replacement-type mineralization in carbonaceous carbonate rocks. The deposits generally are sheet-like, conformable with bedding, and proximal to fault and fracture systems. Porphyritic intrusions often are present, but a genetic relationship is not clear. The deposits have a distinctive geochemical association of gold with Hg, As, Sb, and Te, which are dispersed in ore and in halos in the country rock. Trace amounts of Zn, Cu, Pb, W, Mo, and Ag also may be present. Gangue minerals usually

include pyrite, barite, fluorite, and calcite. Silicification and argillization are the most common alterations in host rocks (Dickinson and others, 1979).

The deposits are thought to be formed at shallow depths from hydrothermal fluids heated by volcanic energy. Most deposits are thought to be of Miocene age or younger, but Mesozoic ages have been obtained from Getchell and Gold Acres. Isotope data from the Carlin deposit indicates the hydrothermal fluids are meteoric in origin. The introduced sulfur is of sedimentary origin, and lead in galena and barite veins is similar to lead in the host rocks. Dickson and others (1979) suggest the gold also may be derived from underlying Paleozoic sediments.

The disseminated gold belt coincides with the lower Paleozoic eugeosynclinal sequence that contains major bedded barite deposits (figure 52). This sequence forms the upper plate of the Roberts Mountains thrust fault, and is the Roberts Mountains suspect terrane of Coney and others (1980). The genetic model postulated by Dickson and others (1979) suggests the eugeosynclinal sequence may be the source of the gold mineralization, and the limited extent of disseminated gold deposits reflects the limited extent of the Roberts Mountains terrane.

Mercury Deposits

Mercury mineralization is widely scattered throughout the western Cordillera. All of the deposits are of very young geological ages, mostly Pliocene or younger, almost certainly because their near-surface emplacement would cause older deposits to be removed by erosion (Bailey and others, 1973). The major deposits are restricted to two tectonic environments: (1) the Franciscan Mesozoic eugeosynclinal terrane of the California Coast Ranges, and (2) alkalic rhyolite volcanic centers in Nevada and Texas (figure 67).

The mercury deposits in California typically are spatially associated with serpentinites which have intruded sheared graywackes, sandstones, and shales of the Franciscan Formation. Cinnabar mineralization, usually with small amounts of stibnite, orpiment, and realgar, is found in fractures and veins, often with quartz-carbonate rock on the margins of the serpentinites. Pliocene to recent volcanic rocks often are present within the vicinity (White, 1967; Bailey and others, 1973). The deposits apparently formed by hot spring activity, with thermal energy derived from volcanic activity and mercury derived from the host rocks. The New Almaden and New

Idria districts have been the principal sources of mercury in the United States in the past. These deposits rank as the fifth and sixth most productive mercury districts in the world (Bailey and others, 1973). The discovery in 1980 of the McLaughlin gold deposit along the mercury belt adds a new dimension to exploration possibilities in this region.

The association of Hg-Sb-As-Au mineralization with quartz-carbonate alteration and mafic-ultramafic rocks is similar in many respects to Au and Sb mineralization in Archean greenstone terranes (eg. Barberton and Murchison greenstone belts in South Africa), implying genetic similarities between these two different ages of mineralization. Perhaps the present tectonic environment of the California Coast Ranges is partially analogous to the tectonic environment during deformation of Archean greenstone belts.

The recent discovery of low grade cinnabar mineralization in the McDermitt caldera complex in Nevada has established this area as the major current producer of mercury in the United States. The McDermitt complex is composed of at least five resurgent calderas (17.9-15.8 Ma) that overlap or are nested within one another. The associated ash-flow tuffs are peralkalic rhyolites. Five large mercury deposits occur along the ring fractures of the caldera, either in fracture zones within the volcanic rocks, or within moat-filling tuffaceous sediments. Mineralization consists of cinnabar and corderoite ($\text{Hg}_3\text{S}_2\text{Cl}_2$) with trace amounts of As, Mo, Be, Sb, and U. All of the volcanic rocks of the complex contain anomalous amounts of Hg, U, and Li, and small deposits of the latter two elements also are associated with the caldera. The mercury deposits are postulated to have been formed by hydrothermal systems along the ring fracture zones which removed mercury from country rock at depth and reconcentrated it in near-surface environments. Late stage ring domes and intrusive bodies provided a heat source (Rytuba and Glanzman, 1978).

The Steamboat Springs deposit is an active thermal spring system that presently is forming sinter with subeconomic Hg, As, Au, and Ag mineralization. The deposit is associated with Miocene and Pliocene calc-alkaline andesites along the Walker Lane (Silberman and others, 1976). Other small, poorly documented mercury deposits are scattered throughout the Great Basin and the Cascade Mountains. The moderate size Terlingua district is associated with alkalic magmatism in the Trans - Pecos volcanic field (Guild, 1978).

Fluorite Deposits

The region in the western United States that contains fluorite minerali-

zation, outlined in figure 67, appears to be related to several tectonic features. Most of the region is contained within the Precambrian craton or the Cordilleran miogeosyncline. Also, much of the region coincides with the Basin and Range province and the Rio Grande rift. Areas of fluorite mineralization outside of these two provinces tend to be regions with late Laramide or mid-Tertiary felsic, generally alkalic, magmatism. As most of the fluorite deposits are thought to be younger than 36 Ma, it is apparent that fluorine mineralization is closely associated with alkalic magmatism and extensional tectonic environments.

These generalizations are confirmed by features that control the location of individual fluorite districts and deposits. Regional structures, often large faults and subordinate fissures of a deep-seated regional tensional nature, control the location of most districts (Worl and others, 1973). Examples include the Jamestown district in the Colorado mineral belt, the Spor Mountain district in the Spor Mountain - Tintic east-west-trending lineament in western Utah, the Fluorine district in the Walker Lane, the numerous districts aligned along the Rio Grande rift, and the cluster of districts in southwestern New Mexico near the intersection of the rift with the "Texas Lineament". In addition, individual deposits frequently are associated with faults or fractures, especially in areas of tension along the margins of uplifts or structural basins (Shawe, 1976).

Many fluorite districts show a close spatial and genetic association with alkalic or silicic extrusives or intrusives, and the igneous rocks frequently are fluorine-rich. Fluorspar bodies in the Jamestown district are localized mainly in breccia zones and fissures that form radiating and ring fracture zones around a fluorite-bearing, alkalic granite-quartz monzonite stock. Pre- and post-mineralization dikes from the stock indicate mineralization is contemporaneous with igneous activity (Shawe, 1976). At Spor Mountain, fluorite deposits are in pipes and veins in Paleozoic carbonates which are locally overlain by a volcanic and volcanoclastic sequence which includes topaz-bearing rhyolites. Near the fluorite deposits, Tertiary volcanoclastic rocks contain very large beryllium deposits with about 5% fluorite (Shawe, 1976). However, some fluorite districts, such as in the Zuni Mountains, show no relationship with any kind of magmatism. Fluorine also shows a geochemical affinity with other elements (Be, Li, Nb, Sn, W, Mo, Y, and rare earths) that frequently are associated with alkalic magmatism.

Summary of the Tectonic Settings of Post-Laramide Mineral Deposits

The post-Laramide deposits show more variations in tectonic settings than do deposits of other eras, probably because the tectonic environment of the western United States was in transition during much of the period. Deposits related to calc-alkaline volcanism and plate subduction, such as porphyry copper and Pb-Zn-Ag replacement deposits, occur throughout the time interval, but in different geographic locations. Deposits related to tensile tectonic environments and alkalic magmatism, such as granite stockwork molybdenum and fluorite deposits, are more important during post-Laramide time than during any other period. Also, the occurrence of alkalic magmatism in Colorado is a repetition of alkalic magmatism in the same area during early Paleozoic and Proterozoic times. This pattern of repeated concentrations of lithophile elements apparently predates these earlier described events, since Precambrian fluoritic pegmatites are found throughout the southern Rocky Mountains. A Precambrian topaz-bearing gneiss has been noted in the Colorado Front Range (Shawe, 1976), molybdenum-enriched Precambrian rocks are found in the vicinity of the Climax and Henderson deposits (Wallace and others, 1978), and scheelite is rather widespread in occurrence in Precambrian calcic gneisses in Colorado and Wyoming (Tweto, 1960).

Several of the deposit types show no unique association with a particular magmatic suite. Precious and base metal deposits associated with volcanism are associated with alkalic felsic rocks as well as calc-alkaline volcanic rocks. In certain areas, such as the San Juan volcanic field, one volcanic suite may be the preferred source of mineralization. However, similar deposits are associated with both suites in the Great Basin. Other deposit types, such as the California mercury deposits, and the disseminated gold deposits, show no direct relationship with magmatism. Rather, these deposits may be formed by concentration of ore elements from the host rock by hydrothermal systems, driven by magmatic or tectonic energy.

Lineaments remain an important control on the localization of ore deposits during post-Laramide time. These may be reactivated basement structures, such as the Colorado lineament and possibly the Rio Grande rift, or the structures, such as the Walker Lane, may be related to plate motions.

Mineralization Not Directly Related to Magmatism

There are a few types of mineral deposits in the western United States that are not directly related to magmatism. Rather, the deposits are found in sedimentary environments. These environments include intracratonic basins, continental margin basins, forearc basins, and basin-range basins.

The intracratonic basins contain the most important mineral deposits, including sandstone uranium, red bed copper (figure 71), coal, oil shale, potash, trona, and sulfur. Basins on the former continental margin contain sulfide deposits in the Belt basin (figure 71), and phosphate deposits in the Permian Phosphoria basin. The carbonate host rocks for the Selkirk Zn-Pb Belt (figure 71) may have been deposited on the continental margin, or may have formed elsewhere and been accreted by subsequent tectonic events. Forearc basins, represented by the Great Valley in California, contain important placer gold deposits (figure 71). The closed drainage systems in many basin-range basins led to the development of thick lake beds, evaporites, and brines which contain borate mineralization.

The formation of most of the non-metallic deposits is controlled by sedimentary processes, which in turn, are directly related to tectonic and climatic conditions. These deposit types are not discussed further in this dissertation. However, this should not be interpreted as an indication that non-metallic mineral deposits lack importance. The potential value of the coal and oil shale deposits in the Colorado Plateau and Wyoming basins rivals that of the metallic resources for the entire western United States.

The sandstone uranium deposits of the Colorado Plateau and Wyoming are the most important type of metallic deposits found in sedimentary basins. Although these deposits are widespread geographically, they are restricted to a few stratigraphic zones containing beds of similar lithologies (Fischer, 1968). In the Colorado Plateau, uranium mineralization is concentrated in non-marine fluvial sandstone deposits of the upper Triassic Chinle Formation and the late upper Jurassic Morrison Formation (Fischer, 1968). The principal host rocks in the Wyoming basins are medium- to coarse-grained sandstones deposited in continental or brackish water environments. The ages of these sediments range from Cretaceous to Miocene, but greater than 95% of the mineralization is in Eocene sediments (Harshman, 1968). The host rocks for all of the sandstone uranium deposits contain, or are directly overlain by tuffaceous sediments (Fischer, 1968; Harshman, 1968).

The sediments in the Colorado Plateau and Wyoming basins were derived in large part from uplifts flanking the basins. In Wyoming, these were the Laramide basement-cored uplifts (Harshman, 1968), while in the Colorado Plateau, the uplifts may have been remnants of the Pennsylvanian - Permian Ancestral Rocky Mountains, or the uplifts may have been related to the synchronous Nevadan orogeny further to the west.

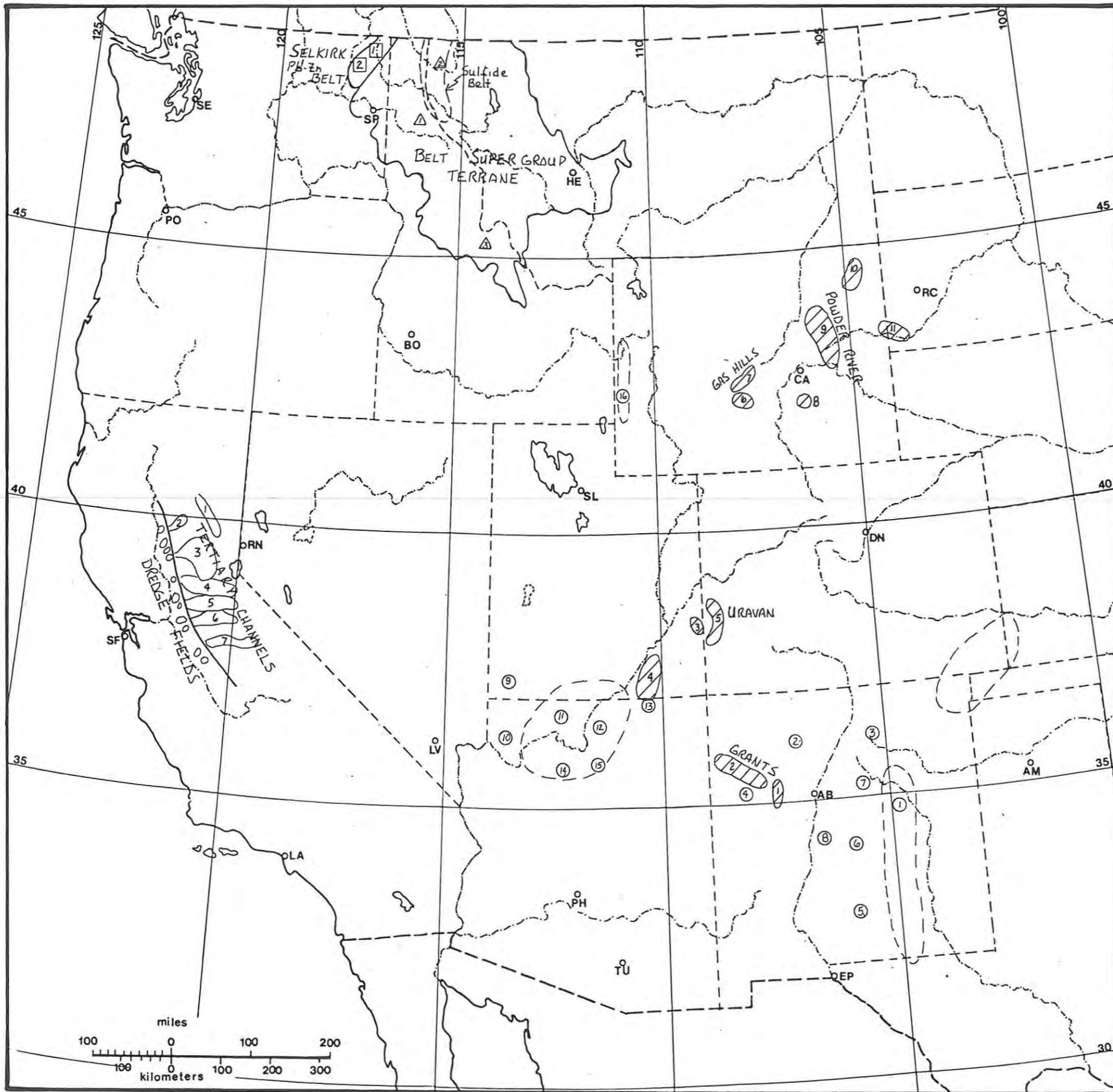


Figure 71. Metallic mineralization not directly associated with magmatism.

Legend on following page.

References

- Clark, 1969
- Clark, 1971
- Cox, 1968
- Fischer, 1968
- Harshman, 1968
- Harrison, 1972
- McConnel and Anderson, 1968
- Tourtlot and Vine, 1976

Legend for Figure 71: Metallic mineralization not directly associated with magmatism.

p = prospect

Mineral deposits in the Belt Supergroup

1	Coeur d'Alene	Ag, Pb, Zn	ID
2	Spar Lake	Cu, Ag	MT
3	Blackbird	Co, Cu, Bi	ID

Red bed copper deposits

1	Santa Rosa	(Triassic-Permian)	NM
2	Cuba	(Triassic)	NM
3	Coyote	(Pennsylvanian-Permian)	p NM
4	Zuni Mountains	(Permian)	p NM
5	Sacramento	(Pennsylvanian-Permian)	p NM
6	Estley	(Permian)	NM
7	Tecolote	(Permian)	NM
8	Scholle	(Permian)	NM
9	Silver Reef	(Triassic)	UT
10	Bentley		AZ
11	Warm Springs		AZ
12	White Mesa		AZ
13	Monument Valley		AZ
14	Francis		AZ
15	Cameron		AZ
16	Lake Alice	(Jurassic-Triassic?) Cu, Ag, Zn	WY

Sandstone uranium deposits

1	Laguna	(Jurassic)	NM
2	Grants	(Jurassic)	NM
3	Lisbon Valley	(Triassic)	UT
4	Monument Valley - White Canyon	(Triassic)	UT-AZ
5	Uravan	(Jurassic)	CO
6	Crooks Gap	(Eocene)	WY
7	Gas Hills	(Eocene)	WY
8	Shirley Basin	(Eocene)	WY
9	Powder River Basin	(Cretaceous-Paleocene-Eocene)	WY
10	Northern Black Hills	(Cretaceous)	WY
11	Southern Black Hills	(Cretaceous)	WY-SD

Carbonate lead-zinc deposits

1	Metalline	(Precambrian)	Zn, Pb	WA
2	Northern Stevens County	(Late Paleozoic)	Zn, Pb	WA

Placer gold deposits - California

<u>Tertiary Channels</u>		<u>Quaternary Dredge Fields (N to S)</u>	
1	Jura River	Butte Creek	
2	Magalia Channel	Oroville	
3	Yuba River	Honcut Creek	
4	American River	Hammonton	
5	Mokelumne River	Lincoln	
6	Calaveras River	Folsom	
7	Tuolumne River	Michigan Bar	
		Comanche	
		Jenny Lind	
		La Grange	
		Snelling	

The uranium deposits were formed after deposition of sediments, but whether mineralization is related to diagenetic or later ground water movements has not been established conclusively (Bailey and Childers, 1977). The resolution of this question will have an important bearing on the potential sources of uranium mineralization.

The uranium in the sandstone deposit most likely is derived by leaching trace amounts of uranium out of nearby rocks. The probable source rocks are the Precambrian basement in nearby uplifts, or the overlying tuffaceous sediments. If uranium mineralization was formed by diagenetic processes, the basement is the most likely source rock, while, if mineralization was formed by later ground water movements, the overlying volcanoclastic sediments could be the major source of uranium. Since uranium enrichment is most closely associated with alkalic magmatism, and since evidence for alkalic magmatism is found in both the Precambrian basement and the mid-Tertiary volcanics in Wyoming, the Wyoming uranium deposits appear to be an indirect product of magmatic activity. There is not much evidence on the nature of magmatism in the basement and in overlying volcanoclastics for the Colorado Plateau deposits. However, the ages of the host rocks (Triassic and Jurassic) correlate with the initiation and development of the Mesozoic batholiths.

Stratabound sulfide mineralization occurs throughout the Belt Supergroup. Important occurrences include the recently developed copper-silver deposit at Spar Lake, the cobalt-copper-bismuth deposits in the Blackbird district, and the Sullivan Pb-Zn-Ag deposits in British Columbia. The copper deposits show similarities with those in the Zambian - Zaire Copperbelt, while the Sullivan deposit is similar to volcanosedimentary deposits such as Broken Hill. Detailed sedimentological studies of the Belt Supergroup have been hindered by lack of exposures, so the relationship of mineralization to sedimentary facies has not been well established (Tourtelot and Vine, 1976). Volcanic rocks are not significant in the Belt sequence.

The Coeur d'Alene district, containing Pb-Zn-Ag sulfide mineralization in carbonate-barite-quartz veins, also is located in the Belt Supergroup. Since there is no obvious correlation of mineralization with magmatism, and because lead isotopes indicate an age of 1250 Ma, there is some speculation that the Coeur d'Alene mineralization was formed by remobilization of a Sullivan-type deposit. Alternatively, the Coeur d'Alene deposits may represent vein deposition of a Sullivan-type deposit. A comparison of

production data (Table II) brings out the similarities between the two districts. Coeur d'Alene is the second largest silver district in the world.

Table II: Production data from the Coeur d'Alene district and the Sullivan mine.

<u>Production interval</u>	<u>Coeur d'Alene</u> 1884 - 1979	<u>Sullivan</u> 1910 - 1972
Tonnes of ore mined	130 million (est.)	98 million
Ag (kg)	22.8 million	6.7 million
Pb (tonnes)	6.8 million	6.4 million
Zn (tonnes)	2.7 million	5.6 million
Cu (tonnes)	141 thousand	41 thousand
Other Products	Sb	Sb, Sn

Data from Jackson (1981), and Eithier and others (1976).

The Tertiary and Quaternary placer deposits in California (figure 71) are directly related to weathering of the Mother Lode and Grass Valley deposits. Erosion is related to uplift of the Sierra Nevada in late Tertiary and Quaternary times. Approximately 40% of the gold production in this region has come from placer deposits (Clark, 1969).

Other metallic mineral deposits in sediments are relatively small and unimportant. Red bed copper deposits are concentrated in Pennsylvanian, Permian, and Triassic sandstones and shales in northern Arizona and New Mexico (figure 71). Correlation of these deposits with tectonism is dependent on more detailed knowledge of the Paleozoic tectonic history of the southwestern United States. Likewise, the tectonic environment of the Metaline and Stevens County zinc-lead deposits in Washington is not understood.

CONCLUSIONS

Plate tectonics theory provides logical explanations for the major tectonic events in the western United States during Phanerozoic time. With the rapid accumulation of new data, principally radiometric age dates, the details of these tectonic events are becoming more apparent. When plate tectonic theory is applied to these more specific tectonic and magmatic events, the proposed models resort to speculative contrivances, such as complex plate motions, variations in dips of subduction zones, transform faulting, or migrating hot spots, for which there is no substantial evidence. In some cases, tectonic events are so remote from plate boundaries, that any association with them is based on faith, rather than on evidence.

The basic premise of these models is that plate tectonic processes virtually are the only factors affecting tectonism and magmatism. While this simplification may be valid for describing tectonic events on 1:100 million scale maps (see, for example, Coney, 1978), it becomes less tenable and outright misleading when applied to large scale maps. On the 1:8 million scale maps used in this report, plate tectonic features can be related only to the largest magmatic and tectonic features, and are of limited assistance for explaining the localization of mineral deposits. In this respect, the promulgation of plate tectonic models tends to obfuscate the tectonic and magmatic features which are important to the exploration geologist. These features are summarized below.

The overall tectonic environment is an important control on magmatism and related mineralization. Subduction and extensional environments in particular are favorable for the development of magmatism. The initiation of significant magmatism in the western United States appears to be related to the development of a subduction zone in early Mesozoic time, while the mid-Tertiary ignimbrite "flare-up" is related to the initiation of regional tensional stresses. The tectonic environment also influences the nature and composition of magmatism. Calc-alkaline magmatism is predominant in subduction environments along continental margins, while a bimodal basalt-rhyolite alkalic suite is important in extensional environments within the continent. The magmatic suites, in turn, influence the type of associated mineralization. Most base metal deposits are associated with calc-alkaline magmatism, while alkalic suites are more favorable for the development of Mo, W, Sn, Be, F, U, Th, and rare earths mineralization. There are numerous exceptions to these generalizations, however.

Much of the magmatism and associated mineralization in the western United States is localized by lineaments, which may or may not be related to plate tectonic activity. These lineaments may be expressed by surface features such as faults, fractures, or the elongation and alignment of magmatic centers and mining districts, as well as by regional geophysical surveys, especially magnetics. The lineaments usually have an appreciable width and frequently show evidence of repeated activation. Completely different types of mineralization may form concurrently or sequentially in close proximity along lineaments. The most important lineaments in the western United States include the Colorado mineral belt, the Texas lineament, the Walker Lane, the E-W-trending mineral belts in western Utah, the Idaho-Montana porphyry belt, the N-S trend along the Colorado Front Range (including the Rio Grande rift), and the Lewis and Clark line. The Walker Lane is the only one of these that may be related to plate tectonics. Most of the others appear to have originated in Precambrian time.

The composition of the crust influences the composition of magmatism and mineralization. The margin of the Cordilleran miogeosyncline is reflected by features such as the quartz diorite line and compositional zonation in the Sierra Nevada. Magmatism within the miogeosyncline and craton tends to be more felsic, and also shows a tendency to become more alkalic with increasing distance from the continental margin. Mineralizations show an even closer correlation with crustal compositions. For example, gold mineralization is best developed in eugeosynclinal terranes, particularly the lower Mesozoic sequence in the foothills of the Sierra Nevada and the Roberts Mountains terrane in Nevada. Major barite mineralization also is restricted to the latter. Major tungsten mineralization is restricted to those portions of the Sierra Nevada batholith and outliers in California and Nevada that have intruded miogeosynclinal terrane. Lead and zinc mineralization is widespread, but nearly all of the major deposits are located within the Cordilleran miogeosyncline or craton. Lead and zinc are relatively sparse in Arizona, but copper is much more abundant than elsewhere in the Cordillera. Molybdenum mineralization is widespread, but the three largest deposits are located in the central portion of the Colorado mineral belt. Likewise, the largest mercury deposits are located in Franciscan *mélange*.

These relationships suggest the crust or upper mantle may be the source of metals for many mineral deposits, and the distribution of mineralization reflects compositional inhomogeneities in the crust and upper mantle. This concept is supported by lead isotope studies, which show three major lead

provinces in the western United States that correspond with crustal composition (figure 72).

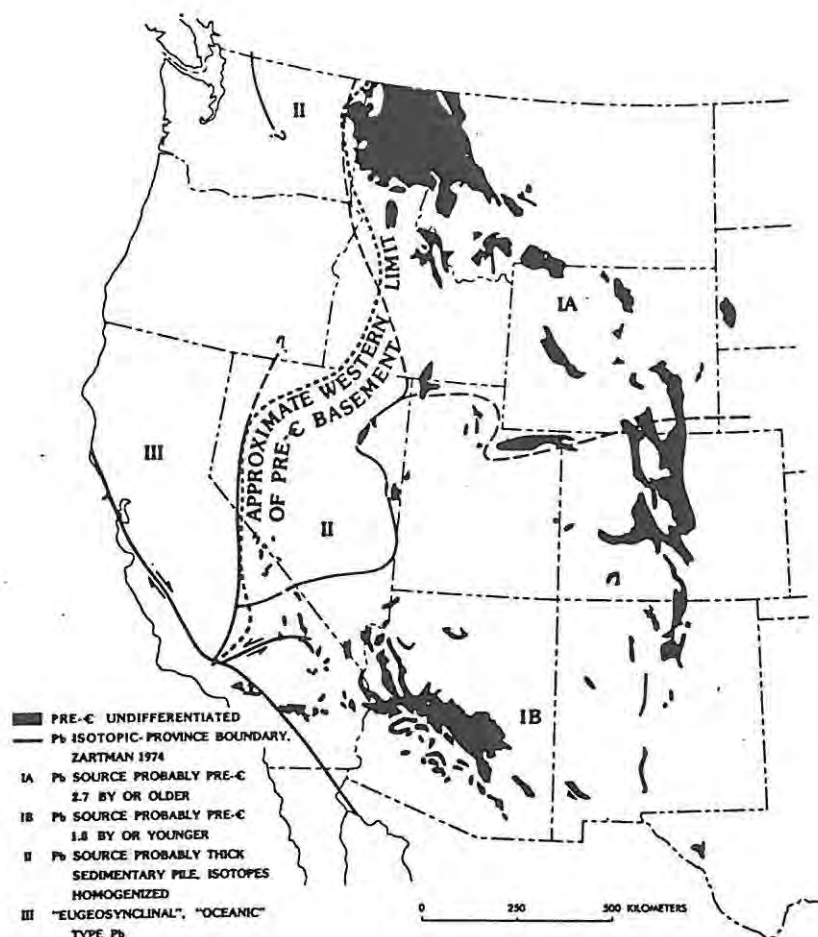


Figure 72: Outcrops of Precambrian rocks in the western United States, and lead-isotope provinces. From Guild (1978).

Regional zonation of metals in the western United States is not as clear-cut as is reported in most orogens. Although a very general west-to-east metal zonation of mercury, copper, gold-silver, tungsten, lead, and molybdenum exists, this sequence is in order of first appearance (in a geographic sense) and not in an order of concentration. If only the major deposits are considered, there is no significant zonation pattern (Noble, 1974). Since regional zonation of metals generally is attributed to plate subduction, this suggests: (1) plate subduction is not an important control on the distribution of mineralization in the western United States, or (2) the tectonic history has been too complex to preserve a zonation pattern.

In conclusion, although plate movements are the major control on the Phanerozoic tectonic history of the western United States, a variety of other factors including magma composition, crustal structures, and crustal composition, are more important controls for the localization of mineral deposits.

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