

**GEOLOGIC CONTROLS ON THE DISTRIBUTION  
OF RADON IN CALIFORNIA**

By

Ronald Churchill  
Associate Geochemist

For

The Department of Health Services

January 25, 1991

*Note: The website version of this report, prepared in December 2003, contains revised figures and minor revisions to the 1991 text—Ron Churchill*

## SUMMARY

The ultimate source of radon gas in buildings is the uranium naturally present in rock, water, and soil. Some rock types are known to contain more uranium than others. The geographic distribution of such rocks can be used to identify areas having an increased chance of elevated radon content in soil gas. Such information can be used to improve the efficiency of radon sampling programs, but it cannot be used to predict whether a particular building will have a radon problem. The following rock units contain uranium in concentrations above the crustal average: the Monterey Formation, asphaltic rocks, marine phosphatic rocks, granitic rocks, felsic volcanic rocks, and certain metamorphic rocks.

Radon anomalies can be associated with fault, fracture, and shear zones, particularly in rock units with above average uranium contents. These features facilitate the movement of radon to the surface by serving as conduits for radon produced at depth. When present, gases such as methane, ethane, propane, carbon dioxide, and helium can act as carriers for radon, sweeping radon along as they flow to the surface. Movement of such gases along faults is expected in areas containing oil and gas fields, geothermal activity, and along major zones of seismicity. Radon moving in this way can reach the surface from much greater depths than when moving by simple diffusion. Fractured rocks also provide pathways for aqueous solutions containing dissolved uranium, radium, or radon, allowing these solutions to move to the surface or close enough to the surface that radon gas can reach the surface by diffusion. Given the proper geochemical conditions, concentrations of uranium or radium can form by precipitation or adsorption in fractures in the near surface environment, and provide relatively large amounts of radon to the surface.

The highest probability of severe radon levels (>200 picocuries per liter<sup>1</sup>) in indoor air occurs in areas overlying uranium mineralization. In California, most uranium deposits are relatively small in areal extent and are located in rural areas. Consequently, the chance of severe radon levels occurring in buildings in California should be very low. The following types of uranium deposits occur in California: secondary mineral deposits along fractures; secondary mineral deposits in bedded sedimentary rocks; accessory mineral accumulations in granitic rock; uranium mineral accumulations in pegmatites, veins, contact metamorphic zones, in deposits in Precambrian schists and quartzites; and uranium accumulations in peat and coal.

---

<sup>1</sup> In the United States, radon levels in indoor air are reported in units of picocuries per liter, abbreviated as pCi/l.

## INTRODUCTION

Elevated radon gas levels in indoor air are a result of radon moving into buildings from the soil, either by diffusion or flow due to air pressure differences. The ultimate source of radon is the uranium that is naturally present in rock, soil, and water. Some types of rocks are known to have uranium concentrations greater than others and, consequently, there is an increased chance of elevated radon concentrations in soils and weathered bedrock where they are located. Such occurrences can produce elevated, but not usually severe, radon levels in indoor air (Otton, 1988). Areas down slope which receive sediments and/or surface and ground waters from rock units with above average uranium content also have an increased likelihood of elevated radon concentrations in soil, gas particularly if the uranium (or radium, a radioactive daughter element between uranium and radon) being transported becomes concentrated in a mineral deposit. The highest probability of severe radon levels in indoor air (i.e., greater than 200 pCi/l) occurs in areas overlying uranium mineralization (Otton, 1988). Luckily for California, at least with regard to the radon problem, most uranium deposits in the state are relatively small in areal extent and the majority are located in rural areas.

By mapping the distribution of uranium in rock, soil and water, broad areas can be generally identified as having an increased or a decreased chance of having elevated radon values in soil gas. However, the variable structural characteristics of buildings and the practical limits of geologic map scale, cost, and time make it virtually impossible to predict with certainty if a particular house will have a radon problem. If such precise predictions cannot be made then why bother with geological studies at all? There are several reasons. The knowledge that certain areas have above average or below average radon gas potential can be used to develop viable radon survey strategies for large areas at costs below those of saturation sampling, the money for the latter being seldom available (Schutz and Powell, 1987). Detailed information on the type of uranium occurrence in an area is needed for the proper design of sampling programs and the interpretation of data from large regional surveys. Such detailed information can also be important for decision making by individuals or municipalities that find themselves located within a broadly defined area of increased radon risk and are wondering they should do next (Schutz and Powell, 1987). For example, if uranium is evenly distributed in a given rock unit, then there will be an increased chance of having elevated indoor radon levels in all buildings overlying that rock unit. If uranium is concentrated along linear features, such as faults or veins, then only buildings along these features would be likely to have a radon problem (Modification of routine procedures for locating sample sites may be required for sampling in the latter situation or such features may be missed). The detailed definition of areas with increased radon risk may be improved with the use of additional information if it is available, such as: soil thickness, porosity, permeability, and moisture content data; fault locations; radon data from analyses of water well waters; and water table depth and fluctuation information.

The following report is an overview of the more significant uranium occurrences in California, and is based on a review of geologic literature published during and after

the 1950's. Its goals are: 1) to point out rock units and geologic settings in the state which may cause elevated radon levels in soil gas, and 2) to provide other geologic information that may be helpful in the design of radon sampling programs and the interpretation of data from such programs (For reference, a generalized geologic map of California is provided in Figure 1 at the end of the text). This report contains information on: rock units with above average uranium concentrations (greater than 2.6 parts per million uranium); structural controls on radon, radium, and uranium distribution; uranium mineral deposits; a list of the more common uranium bearing minerals occurring in California; and summaries of the geochemical behavior of uranium, radium, and radon.

## **ROCK UNITS WITH URANIUM CONTENTS GREATER THAN THE AVERAGE CRUSTAL ABUNDANCE**

### **MONTEREY FORMATION**

The Monterey Formation is a distinctive Miocene sedimentary formation occurring along coastal California from the vicinity of Drakes Bay southward to the Oceanside area (Figure 2). This formation is primarily composed of marine diatomaceous deposits, procelanite and porcelaneous shale, and chert and cherty shale, that were originally deposited as diatomite (Bramlette, 1946). The porcelaneous and cherty rocks are believed to have formed from the diatomaceous rocks by diagenetic processes during sediment compaction (Bramlette, 1946). Although sometimes referred to as a shale, much of the Monterey Formation contains smaller amounts of clay and is much more siliceous than is typical for normal shales. Large parts of the Monterey Formation are bituminous and are generally recognized as the source of hydrocarbons in many of California's oil fields (Bramlette, 1946). Dolomite (calcium-magnesium carbonate) beds and concretions occur throughout the formation and locally, the Monterey Formation contains beds of vitric tuff (siliceous volcanic ash), and pelletal phosphorite and phosphatic shale (Durham, 1987, and Dickert, 1966). Rocks of the Monterey Formation are often thin bedded and laminated. The thickness of the Monterey Formation is commonly between 2,600 and 5,200 feet, but it reaches a maximum of about 10,000 feet in the southern Salinas Valley (Durham, 1974, and Norris and Webb, 1990). Some of the best known exposures of the Monterey are at Newport Bay, Palos Verdes Hills, in the Santa Monica Mountains, near Santa Barbara, at Lompoc, near Santa Maria in the Salinas Valley area, and in the Temblor Range (Durham, 1987).

Durham (1987) has studied uranium content and geochemistry of the Monterey Formation and the following information is summarized from his work. Samples collected to be representative of various kinds of rocks in the Monterey Formation, without regard to their radioactivity in the field, ranged from 1.73 ppm (parts per million) to 83.4 ppm uranium, with average and median values of 11.1 and 6.77 ppm respectively. These values are considered to be representative of the formation overall, and show that the Monterey Formation is generally higher in uranium content than most other rock types in California (compare with typical values for granitic rocks of the Sierra Nevada and the Peninsular Ranges, which average between 2 and 4 ppm).

Unusually high uranium contents (up to 1854 ppm) found in the Temblor Range are not considered by Durham to be representative of the Monterey Formation as a whole.

Most of the uranium in the Monterey Formation is associated with organic material, either by adsorption or by incorporation in organic complexes. Samples from the Temblor Range, where Durham found the highest uranium contents in the Monterey Formation, contain only uranium minerals of secondary origin (autunite, meta-autunite, uranophane, and carnotite, which were deposited by vadose waters moving along fractures and bedding planes). However, these secondary minerals occur in quantities too small to account for the amount of uranium present in the rock. Radioluxographs of Temblor Range samples show diffuse background radiation with the only concentrations of radioactivity being related to cracks and areas of iron oxide discoloration. A scanning electron microscope study of the sample containing 1,854 ppm uranium, the highest concentration found by Durham, failed to identify the presence of any uranium bearing minerals, and supports the uranium-organic matter association. This association is further supported by Leventhal (1989), who found that uranium is statistically associated with the organic carbon content and, to a lesser extent, with sulfur content for Monterey Formation and related rocks from the Santa Maria basin. The presence of phosphatic material often results in locally elevated uranium values in the Monterey Formation, but it is not the principal agent for uranium enrichment in most of the formation. Durham analyzed only one sample of vitric tuff and it contained 9.45 ppm uranium, which is within the normal range for silicic volcanic rocks. If samples from the Temblor Range are omitted (i.e., those samples having undergone obvious secondary enrichment) there appears to be no systematic regional variation in uranium content in the Monterey Formation.

Within the Monterey Formation, cherty rocks, dolomitic rocks and rocks having a high percentage of terrigenous clastic material generally have the lowest uranium content. The lower uranium contents of the cherty rocks may be the result of the removal of uranium from these units during their conversion by diagenesis from porcelaneous rocks to chert. Uranium liberated in this way could move into and form deposits in other formations associated with the Monterey Formation. This is one possible explanation for the source of uranium in deposits in the Sespe Formation at Superior Ridge and Laguna Ridge, west of Ojai in Ventura County (Durham, 1987, also see Dickinson and Leventhal, 1988).

It is believed that the uranium in the Monterey Formation was derived chiefly from seawater, at or near the time the sediments were deposited. The accumulation of these diatomaceous sediments under anoxic conditions was probably an important factor in the control of uranium content in these sediments (Durham, 1987).

### **URANIUM IN ASPHALTIC ROCKS (and in crude oil)**

Rocks of the Monterey Formation and equivalent beds are generally considered to be the principal source for oil in California oil fields. Bell (1960) studied 11 crude oil

samples from Tertiary age rocks of California and found that their uranium content ranged from 0.1 parts per billion (ppb) to 37.7 ppb, averaged 5.04 ppb, and had a median value of 1.6 ppb. The uranium content for typical crude oils normally ranges from less than one ppb to a few tens of ppb and California crude oils do not appear to be abnormally high in uranium (Bell, 1960). However, some asphalt bearing rocks of California apparently contain more uranium than do most such rocks elsewhere (Hail et al., 1956, and Bell, 1960). California asphalt probably originated in the Monterey Formation.

Bell (1960) lists the uranium contents of 51 samples of rock asphalt from California Tertiary rocks. These samples were collected in the following counties: Kern, Mendocino, Monterey, San Benito, Santa Barbara, and Santa Cruz (Figure 3). The uranium content ranges from 0.17 ppm to 70.3 ppm, averages 5.22 ppm, and has a median value of 1.6 ppb. This range for asphalt is similar to that found for the overall Monterey Formation by Durham (1987), which is listed in the previous section. The highest uranium contents observed in Bell's study were found in samples from the following areas: Edna, San Luis Obispo County, in Pismo Formation, 70.3 ppm, 19.5 ppm, and 12.2 ppm; Chalone Creek, San Benito County, at the transition zone of the Monterey shale and the Santa Margarita Sandstone, 40.0 ppm; Los Alamos, Santa Barbara County, Sisquoc Formation, 27.4 ppm; and McKittrick, Kern County, Etchegoin Formation, 19.9 ppm. It must be emphasized that these are single sample values and may not be statistically representative of the overall uranium content at these sites. Most of the samples from these locales have uranium values that range from 0.1 ppm to 10.0 ppm.

### **MARINE SEDIMENTARY PHOSPHATIC ROCKS**

Phosphorite may occur in California in pelletal beds 1 to 4 inches thick, as nodules up to 8 inches across, or as thin argillaceous laminae (Gower and Madsen, 1964). Sedimentary phosphatic formations of marine origin often contain small amounts of uranium, generally less than 0.03 percent (300 ppm)  $U_3O_8$  (Heinrich, 1958). In these deposits, uranium is believed to substitute for calcium in the phosphate mineral apatite. Two phosphorite samples from the Monterey Formation analyzed by Durham (1987) contained 39.2 and 83.4 ppm uranium.

Most of the phosphate localities in California are Miocene in age and occur in the southern Coast Ranges (south of San Francisco), and along the west side of the San Joaquin Valley (Figure 4) (Gower and Madsen, 1964). Along with the Monterey Formation, some other units containing phosphatic rocks are: the Lomita Marl, the Modelo Formation, the Pancho Rico Formation, the Puente Formation, the Rincon Shale, the San Diego Formation, the San Lorenzo Formation, the Santa Margarita Formation, the Sisquoc Formation, the Temblor Formation, and the Vaqueros Formation. These units may or may not contain significant amounts of uranium and additional studies may be necessary to evaluate their uranium contents. The locations and descriptions of these and other more scattered occurrences are given in Gower and

Madsen (1964), Gower (1966), Dickert (1966), Evans (1976) and Roberts and Vercoutere (1986).

## **URANIUM IN GRANITIC ROCKS--AN OVERVIEW**

Granitic intrusive rocks, granites, granodiorites and quartz monzonites, are the dominant rock types in the Sierra Nevada and the Peninsular Ranges, and are common in parts of the Klamath Mountains, the Transverse Ranges, the Basin and Range, the Colorado Desert (Salton Trough), and the Coast Range geomorphic provinces of California (Figures 5 and 6). Granitic rocks often contain uranium in amounts above the crustal average and, consequently, are a potential source of elevated radon levels in soil gas and groundwater. The higher uranium content of granitic rocks is a result of a natural process called magmatic differentiation that occurs during magma cooling and results in the uranium content increasing from the first to the last formed rock (Klepper and Wyant, 1956). Silica, the alkali elements, and a number of rare elements like thorium, beryllium, and the rare earth elements also increase in this manner (Klepper and Wyant, 1956). As silicate magma cools, different minerals crystallize at different temperatures, and each mineral preferentially removes certain elements from the magma, causing the remaining magma to have a different chemical composition than the starting magma. The earliest (highest melting point) silicate minerals to crystallize are higher in magnesium, iron, calcium, than later formed silicate minerals, and these earlier minerals (e.g., olivine, pyroxene, and calcium plagioclase) cannot readily incorporate uranium atoms into their crystal structures. Consequently, rocks primarily composed of earlier minerals, such as peridotite and gabbro, generally contain less than 1-ppm uranium. Minerals crystallizing later, at lower temperatures from the residual magma, are higher in potassium, sodium, silica, and water (hydroxyl). Of these minerals, (e.g., biotite, muscovite, potassium feldspar, sodium feldspar, and quartz), the micas and certain accessory minerals<sup>2</sup> can incorporate from 10 ppm to several percent uranium into their crystal structures (Klepper and Wyant, 1956). Therefore, rocks principally composed of later minerals—granites, granodiorites, quartz monzonites, and syenites—typically have average uranium contents in the range of 2 to 6 ppm and less commonly in the 10 to 30 ppm range.

Pegmatites, coarse-grained rocks of granitic composition usually found as irregular dikes, lenses or veins at the margins of batholiths, represent the last and most hydrous portion of a magma to crystallize (Bates and Jackson, 1980). Pegmatites often contain high concentrations of minerals present in only trace amounts in granitic rocks, and are sometimes enriched in uranium (Klepper and Wyant, 1956, Buttler et al, 1956).

Studies of the uranium distribution in minerals contained in California granitic rocks show that major rock forming silicate minerals contain the bulk of the uranium present in these rocks (Larson and Gottfried, 1961). While the common accessory minerals, zircon, sphene, allanite and apatite, contain much more uranium than the

---

<sup>2</sup> Accessory minerals are minerals present in minor amounts whose presence does not affect a rock's classification, such as apatite, sphene, zircon, and monazite.

major silicates, these minerals are usually present in only small amounts (typically less than 0.2 weight percent of the rock). Consequently, accessory minerals typically only contribute about 10 to 30 percent of the total uranium in a granitic rock. Experimental acid treatments of southern California batholithic rocks (Larson and Gottfried, 1961) show that between 40 and 83 percent of the total uranium in these rocks can be removed by such treatments, with most of the uranium associated with quartz, feldspars, and major magnesium-iron silicates being readily dissolved. How this soluble uranium is held in these minerals is unknown. However, these experiments point out how granitic rocks can serve as uranium source rocks for secondary areas of uranium enrichment. Such secondary enrichment would occur by groundwater moving through fractures in granitic rocks, dissolving uranium, and then transporting it in solution to a site favorable for uranium precipitation, either in fractures within the granitic rocks, or in fractures or porous zones within rocks adjacent to the granitic rocks.

Some granitic rocks with average uranium contents in the tens of ppm have been documented in the northeastern United States (Larson et al., 1956, and Wathen, 1987), but this preliminary study found only one California granitic rock occurrence with average uranium contents that high—the quartz monzonite portion of the World Beater Complex (Death Valley area) which has a mean uranium content of 27.3 ppm with a range of 3.29 ppm to 215.85 ppm (Carlisle et al, 1980).

Not all uranium present in granitic rocks is incorporated in the crystal structures of silicate or accessory minerals. Primary uranium minerals may exist along the grain boundaries between silicate minerals or occur along microfractures formed at the last moments of crystallization, or uranium atoms may be absorbed on the surfaces of certain minerals, such as sericite. This uranium is usually more readily leached by ground water than uranium incorporated in the crystal structure of major silicate or accessory minerals, and is more subject to secondary concentration as described above. A particular type of granite termed “two-mica” granite may contain a higher percentage of loosely bound uranium than other kinds of granites. A study of groundwater from wells in two-mica granites and a biotite granite in New England (Wathen, 1987) has shown that groundwater from two-mica granites has higher uranium and radon contents than groundwater from biotite granite even though the latter had a higher average uranium content (25 ppm vs. 15 ppm).

Published studies have documented the presence of two-mica granitic rocks in the Peninsular Ranges (La Posta pluton), the Mojave Desert (Chemehuevi Mountains and the Whipple Mountains Core Complex), the Transverse Ranges (San Gabriel Mountains and the Pinto Mountains), the Sierra Nevada (Tharps Peak granodiorite), and the Klamath Mountains (Slinkard pluton) (Walawender et al., 1990, Anderson and Cullers, 1990, Barth, 1990, and Barnes et al., 1990). The limited published information on California two-mica granites suggests that they differ compositionally (in major elements and mineralogically), in depth of formation, and that they have lower average uranium contents than the New England two-mica granites described by Wathen (1987). If these differences are real, then California two-mica granites may be less likely to cause radon problems than the New England two-mica granites. However,

additional research is needed before any definite statement can be made on radon risk related to two-mica granites in California.

## **URANIUM IN CALIFORNIA GRANITIC ROCKS**

Larson and Gottfried (1961) studied the distribution of uranium in California granitic rocks and the following is a summary of their work.

### **Uranium in southern California Batholith**

The southern California batholith comprises the core of the Peninsular Range geomorphic province, beginning near Riverside, California, and extending southeastward nearly 1000 miles to the tip of Baja, California. These rocks underlie an area of about 8000 square miles within California. Based upon the analyses of 73 samples, Larson and Gottfried estimated an average uranium content for the batholith (within California) of 1.7 ppm. The uranium content of these samples ranged from 0.17 ppm (in a gabbro) to 6.6 ppm (in a quartz monzonite).

### **Uranium in Granitic Rocks of the southern California Desert (Mojave Desert, Transverse Ranges, and Salton Trough)**

Intrusive rocks in ranges east of the Peninsular Range occur in small scattered bodies that are separated by large masses of pre-batholithic rocks. The intrusive rocks are primarily granodiorites and quartz monzonites. From analyses of 16 samples, Larson and Gottfried estimated that the average uranium content for these rocks is probably in the range of 1.5 to 1.8 ppm. The overall range of the samples was from 1.0 to 3.0 ppm uranium. Recent studies of granitic rocks in the Chemehuevi Mountains plutonic suite (John and Wooden, 1990), and of Jurassic plutons on the South Bristol Mountains, South Providence Mountains, and the Colton Hills (Fox and Miller 1990), contain uranium analyses that ranged from 0.325 ppm to 13 ppm. Data from these newer studies suggest that the average uranium content is within the range of 1.5 ppm to 2.1 ppm--very similar to Larson and Gottfried's average of 1.7 ppm.

It should be noted that the quartz monzonites of the southern California desert may contain less uranium than do the quartz monzonites of the Peninsular Range (i.e., 1.7 ppm vs. 4.6 ppm, Larson and Gottfried, 1961).

### **Uranium in the Sierra Nevada Batholith**

Granitic rocks of the Sierra Nevada batholith underlie an area of about 17,000 square miles, and are similar in composition to rocks of the southern California batholith. Larson and Gottfried estimate the average uranium content for the Sierra Nevada batholith at 2.7 ppm, and found that their samples ranged from 0.50 ppm to 7.8 ppm uranium. These numbers are based on analyses of 48 samples. Three of these samples were from the Klamath Mountains rather than the Sierra Nevada, but their

inclusion does not affect the range or the average uranium estimated for the Sierra Nevada.

### Uranium in Sediments and Water Derived from Granitic Terrane

Because granitic rocks are generally slightly higher in uranium content than crustal average, sediments derived from them may also be higher in uranium than the crustal average, for example: arkosic and volcanoclastic sandstones and conglomerates, some Sierra Nevada glacial deposits, and alluvial fan deposits in granitic terranes (see Otton, 1987), and Ogden et al., 1988). Water moving through fractures in granitic rocks or through sediments derived from granitic rocks may contain elevated uranium contents. Wiegand et al. (1988) have contoured gross alpha radioactivity in well waters in the Raymond Basin (Los Angeles County) and the Santa Anna Plain (Orange County). Their study of Raymond Basin wells defined a radioactivity contour plume that points to the San Gabriel Mountains as a possible source for the Raymond Basin anomaly. The San Gabriel Mountains are composed of granitic rocks and the presence of unidentified secondary uranium mineralization in these mountains is also possible. A similar plume of radioactivity was found in Orange County, apparently related to low mountains to the east and north, and possibly to rocks traversed by the Santa Ana River. The maximum levels of gross alpha particle activity reported by Weigard et al. for the Raymond Basin and the Santa Ana Plain are relatively low, 44.2 and 30 pCi/l.

## **URANIUM IN FELSIC VOLCANIC ROCKS**

### General Information

The felsic volcanic rocks--rhyolite, rhyodacite, and dacite--are the extrusive equivalents of granite, granodiorite or quartz monzonite, and granodiorite respectively. They typically have uranium contents above the crustal average for the same reason as their intrusive counterparts (magmatic segregation). Klepper and Wyand (1956) cite a study showing that volcanic rocks are often 1.5 to 2 times higher in uranium content than their intrusive equivalents. A study of the uranium content for rhyolitic and dacitic volcanic rocks of Tertiary age in the western United States found an average uranium content of 5 ppm and a range of 0 to 30 ppm (Coats, 1956)

Uranium is present in volcanic rocks in the following forms: 1) as uraniferous accessory minerals (e.g., zircon, sphene, apatite), 2) in secondary oxides of iron, manganese, or titanium, 3) in volcanic glass, or 4) at mineral grain boundaries, crystal defects or cleavages (Zielinski, 1981). In rhyolitic composition volcanics, the largest share of whole-rock uranium is often contained in volcanic glass (Zielinski, 1981). The uranium in volcanic glass is readily removed by glass-water interactions, so such units can be good sources of uranium for secondary uranium mineralization. Such mineralization can occur along fractures, bedding planes, porous and permeable zones, or in clay, zeolite, or organic-rich units, either within the volcanics or in adjoining rock

units. The most favorable geologic settings for ground water leaching of uranium from felsic volcanics are intracaldera environments, and deposits of fluvial and lacustrine tuffaceous sediments. Lava flows and densely welded tuff ash flows are less favorable for uranium leaching because their low porosity and permeability restrict ground water penetration of these units (Zielinski, 1981).

### Uranium in California Felsic Volcanic Rocks

Only limited data on uranium in felsic volcanic rocks in California could be compiled in the time frame of this study, but these data suggest a probable range of 1-10 ppm for many of these rocks (Coats, 1956), and the following references). Durham (1987) analyzed a sample of vitric tuff from within the Monterey Formation (Coast Ranges) and it contained 9.45 ppm uranium. In the Sierra Nevada, studies of volcanic rocks in the Sonora Pass area show 6.01 ppm uranium for a tuff from the Miocene Relief Peak Formation (Durham and Felmlee, 1982) and uranium contents in the range of 7 to 14 ppm for the Table Mountain latite and the Eureka Valley tuff (Rapp and Short, 1980).

### **METAMORPHIC ROCKS**

Because metamorphic rocks can be derived from sedimentary or igneous rocks with widely different compositions, the range of uranium values for metamorphic rocks is quite large and some are above the crustal average. The effects of metamorphic processes on uranium concentrations in rocks are not well understood. Low-grade metamorphic processes probably do not affect uranium concentrations significantly, but high-grade metamorphic processes (high temperature and pressure) may permit certain minerals to form and concentrate uranium (Keppler, and Wyant, 1956).

Wedepol (1969) gives a range of 0.22 to 45 ppm uranium for 231 samples or metamorphic rocks collected worldwide. In California, gneiss associated with the World Beater Complex, Death Valley region, ranges from 1.53 to 5.83 ppm uranium, with a mean of 2.9 ppm (Carlisle et al, 1980).

## **THE EFFECT OF STRUCTURAL FEATURES ON THE MOVEMENT AND DISTRIBUTION OF RADON, RADIUM, AND URANIUM**

Faults, fractures, and shear zones are important controls on radon distribution at the earth's surface because they serve as conduits to the surface for radon produced at depth. Often radon surface anomalies are sharply bounded by the edges of these zones. Major fractures and associated microfractures are required in order to have significant quantities of radon escape from low porosity and permeability source rocks such as granites and felsic volcanics (Hall, et al., 1987, and Zielinski, 1981). The following is a brief summary of the geologic processes occurring in fracture systems that can affect surface radon concentrations.

Fractured rocks provide pathways for aqueous solutions containing dissolved uranium, radium or radon, allowing these solutions to move directly to the surface or close enough to the surface that radon gas can reach the surface by diffusion. If suitable chemical conditions exist in the near surface environment, uranium or radium can precipitate or be absorbed from solution and concentrated (forming secondary mineralization), providing relatively large amounts of radon to the surface. Even without uranium mineralization, fracture zones may enhance radon concentration in soil gas by a factor of three or more (Otton 1988, p.66).

Fractures can serve as conduits to the surface for other gasses at depth besides radon, for example light hydrocarbons (methane, ethane and propane), carbon dioxide, and helium. These gasses can serve as “carrier” gases for radon, sweeping radon along as they flow to the surface (Kristiansson and Malmqvist, 1984 and 1982, Fleischer and Turner, 1984, Jones and Drozd, 1983, and Irwin and Barns, 1980). Radon moving in this way can reach the surface from much greater depths than by simple diffusion. If the flux of a carrier gas is sufficiently high, then it is possible to deliver substantial quantities of radon to the ground surface from source rocks with only average quantities of radon (Otton, 1988).

Temporary increases in surface radon have been observed along faults at or near the time of earthquakes which could be the result of release of carrier gases at depth due to pressure buildup and rock movement at depth (King, 1980, Gaman and King, 1979, and Birchard and Libby, 1980).

Radon is known to be associated with geothermal fluids and sometimes soil-gas radon anomalies are present over geothermal reservoirs. A study by Lombardi and Reimer (1990) documents this type of anomaly in central Italy. They found a number of one to two kilometer sized radon anomalies (250-1500 pCi/liter in soil gas over the Phlegraean Fields geothermal area. The distribution of these anomalies is controlled mainly by local fracture and fault systems.

Because of the radon-rock fracture relationships just discussed, surveys and sampling programs to identify areas with increased probability of indoor radon problems should include the sampling of known faults, fractures, and shear zones, in the area being evaluated. This is especially important where these structural features are associated with: 1) rocks with above average crustal uranium content; 2) oil and gas fields (light hydrocarbons can serve as carrier gas for radon, and many oil and gas fields have associated microseeps of light hydrocarbons at the surface); 3) areas of currently active geothermal systems; and 4) secondary uranium mineralization

The surface expression of faults, fractures, and shear zones can be long (miles), but can also be quite narrow, often inches to tens of feet (Figures 7, 8, and 9). Consequently, these structural features can be missed by random or grid sampling programs because the distance between sample stations is often much greater than the width of these features. Sampling programs should require some radon detectors to be located on or immediately adjacent to known occurrences of these structural features in

the area under evaluation (especially in dwellings overlying or adjacent to such features). Obtaining detailed information on the location of faults and fracture zones at a given site is sometimes difficult and may require a site visit and subsurface drilling or trenching. Many small faults and fracture zones are not shown on geologic maps because of the map scale. These features can also be hidden by soil or other surface cover.

## **URANIUM DEPOSITS**

### **GENERAL INFORMATION**

Currently available published information on uranium mineral deposits in California is largely the result of work done in the late 1940's and 1950's (Walker, et al., 1956, Troxel et al., 1957, Walker and Butler, 1966, and parts of Finch, 1967, Walker and Osterwald, 1963, Heinrich, 1958, and Page et al., 1956). Recently, the U.S. Geological Survey has published several bulletins on uranium occurrences in the Monterey and Sespe formations (Durham, 1987, Leventhal, 1989, and Dickinson and Leventhal, 1988). The information on uranium deposits presented here is a brief summary of the information given in these publications.

The term "deposit" is used in slightly different ways by different geologists, but its connotation is an abnormal concentration of minerals, with the area of concentration containing noticeable greater amounts of a given mineral or minerals than the enclosing wall rocks (modified from Walker and Osterwald, 1963). This term does not imply anything about size of the occurrence or commercial potential.

Deposits of uranium-bearing minerals are widely scattered throughout California, but the majority occur in the southern Sierra Nevada and in the Mojave Desert geomorphic provinces (Figure 10). Clusters of uranium deposits occur: west of Ojai in Ventura County; in western Kern County in the Temblor Range area; in the Kern River Canyon northeast of Bakersfield; near the town of Mojave; in the Olancho area of Inyo County; and in eastern Plumas County and southeastern Lassen County.

The uranium deposits discussed in this section are categorized, in part, on the basis of the presence of primary or secondary uranium minerals. This approach is common because these two mineral groups form under significantly different geologic conditions. Primary minerals are those that form at the same time as the enclosing rock by igneous, hydrothermal or contact metamorphic processes. Secondary minerals are those that form later than the enclosing rock by weathering, metamorphic or solution processes (Bates and Jackson, 1980). A list of the more common uranium bearing minerals in California is given at the end of this section. Some uranium deposits in organic rich sediments where uranium minerals are absent or not obvious (because uranium is being absorbed by organics rather than precipitated as a mineral). These organic rich deposits are listed separately below.

## **Secondary Mineral Deposits Along Fractures**

The most common type of uranium deposit in California occurs in a wide variety of host rocks and consists of secondary mineral accumulations, erratically distributed along fractures, as fracture coatings and disseminated grains. The uranium minerals present in these deposits are usually one or more of the following: autunite, meta-autunite, carnotite, torbernite, meta-torbernite or uranophane. These deposits are usually small, rarely exceeding 100 feet in greatest dimension and commonly range from a few inches to 10 feet in width.

## **Secondary Mineral Deposits in Bedded Sedimentary Rocks**

Uranium deposits in bedded sedimentary rocks, sometimes called “sandstone-type deposits”, contain secondary uranium minerals that are associated with certain individual beds. These secondary minerals occur along bedding planes and are erratically distributed in porous portions of the rock adjacent to bedding planes. The host units may consist of arkosic sandstone, conglomerate, tuffaceous sandstone, siltstone, and shale, or sand clay. Selective deposition of uranium occurs in these beds as a result of the porosity and permeability of these units, which allows uraniferous aqueous solutions to migrate through them, and because local chemical conditions were favorable for the deposition of uranium. The deposition mechanism can be precipitation, or adsorption by organics, zeolites, clay, or iron oxides. In marine formations primary uranium may be associated with phosphate lenses, nodules, and pellets.

Sedimentary uranium deposits are usually flat lying and are lenticular in shape. In California, they rarely exceed 50 feet in their greatest dimension, and are often not more than a few feet thick. Finch (1963) lists the following as stratigraphic units in California that contain uranium deposits of this type: the Coso Formation, the Barstow Formation, the Monterey Formation, the Ricardo Formation, the Rosamond Formation, the Sespe Formation, the Tejon Formation—Coldwater Sandstone Member, and the Tropic Group. All of these are of Tertiary stratigraphic units.

## **Primary Mineral Deposits--accessory mineral accumulations, pegmatites, and veins**

Deposits of primary uranium minerals are less common and more widely scattered throughout the state than deposits of secondary minerals. These deposits include: 1) uranium minerals occurring as accessory minerals in granitic or metamorphic rocks of granitic composition, 2) uranium minerals as single crystals or small crystals or small crystal aggregates with other minerals in pegmatites in granitic rocks, and 3) clots of uranium minerals in quartz veins, often associated with base metal sulfides, and usually in granitic rocks. Uraninite is the most common uranium mineral in these deposits. Primary uranium deposits tend to be quite small in surface expression, usually no more than a few tens of feet in length and inches to feet in width (John Rapp, Division of Mines and Geology, verbal communication).

## **Primary Mineral Deposits in Contact Metamorphic (Metasomatic Zones)**

Uranium can occur with base-metal sulfides in limestone replacement and fracture filling deposits, which are associated with contact metamorphic zones around granitic intrusives. Examples of this type of deposit are at the Yerih prospect in San Bernardino County, and the Ubehebe mine in Inyo County (Walker et al, 1956).

## **Other Metamorphic Deposits**

Late Proterozoic age uranium deposits occur in metasedimentary, metavolcanic, and igneous rocks of the Kingston Peak Formation in the Death Valley region of California. These deposits appear in pyrite-bearing pelitic schist, quartz and quartzite-pebble conglomerates, and in the World Beater Complex, which consists of an 1800 m.y. old gneiss intruded by a 1350 m.y. old quartz monzonite. The deposits in this region have uranium contents that range from 0.003 percent to as high as 3.9 percent  $cU_3O_8$  (Carlisle et al., 1980).

## **Uranium Deposits In Peat and Coal**

Uranium deposits in unconsolidated peaty materials can occur in Pleistocene or Recent swamps, peat bogs, mountain meadows, and similar locations where plant debris can accumulate (Vine, 1962, p. 129). Examples of these deposits exist in the Sierra Nevada at Hoffman Meadow, Fresno County (Vine, 1962), in the Greenhorn Mountains east of Bakersfield, Kern County (Vine, 1962) (Figure 11), and in the Lake Tahoe-Carson Range area of Nevada and California (Otton et al., 1985). At Hoffman Meadow, samples of decomposed plant debris contain as much as 0.7 percent uranium. The Greenhorn Mountain deposit covers an area of about two acres. Both deposits are estimated to contain over 1000 tons of uranium ore (Vine, 1962).

Anomalous accumulations of more than 100 ppm (locally up to 0.6 percent) uranium occur in organic rich sediment as spring seeps, along valley bottoms, and in fens and marshes in the Carson Range, Nevada (Otton et al, 1985). These deposits may be several hundred meters in greatest dimension. Geologic and geomorphic settings similar to the Carson Range are common in the central Sierra Nevada and similar uranium occurrences are likely. Two springs west and south of Lake Tahoe, the Glen Alpine and the Rubicon Soda Spring, are known to contain anomalous values of uranium in their waters (54.7 ppb and 12.7 ppb), but sediments associated with these springs were not sampled as late as 1985 (Otton et al, 1985).

Humic type carbonaceous matter that has not been altered beyond the rank of subbituminous coal will readily extract and tenaciously hold uranyl ions from solution (Vine, 1962). Therefore, other peat and coal occurrences should be considered as possible "chemical sinks" for uranium and, consequently, potential radon sources (Figure 12). This is particularly true where granitic or felsic volcanic rocks occur nearby to provide uranium. A reconnaissance study of uranium-bearing coals made by Moore

and Stephens (1952), identified the following locations as principal occurrences in California (Figure 13): the Newhall prospect, Los Angeles County (0.020 percent uranium), the Fireflex mine, San Benito County (0.005 percent uranium), the American Lignite mine, Amador County (0.004 percent uranium), and the Tesla prospect, Alameda County (0.003 percent uranium). Forty-six other sites in California contained less than 0.003 percent uranium.

## **URANIUM MINERALS IN CALIFORNIA**

The following is a list of the more common uranium bearing minerals in California. Detailed mineralogical data and occurrence information for these minerals can be obtained from the references given at the end of the minerals list.

### **Primary and Accessory Minerals**

|              |  |
|--------------|--|
| allanite     | $\text{Ce,Ca,Fe}^{+2}\text{(Al,Fe}^{+3}\text{)}_3\text{Si}_3\text{O}_{12}\text{(OH)}$ , 0.02 % uranium |
| betafite     | $\text{(Ca,Na,U)}_2\text{(Ti,Nb,Ta)}_2\text{O}_6\text{(OH)}$ , 15-24 % uranium                         |
| brannerite   | $\text{(U,Ca,Ce)}\text{(Ti,Fe)}_2\text{O}_6$ , 26.5-43.6% uranium                                      |
| crytolite    | a variety of zircon  |
| davidite     | $\text{(La,Ce)}\text{(Y,U,Fe)}\text{(Ti,Fe}^{+3}\text{)}_{20}\text{(O,OH)}_{38}$ , 7-10 % uranium      |
| euxenite     | $\text{(Y,Ca,Ce,U,Th)}\text{(Nb,Ta,Ti)}_2\text{O}_6$ , 10-13 % uranium                                 |
| samarskite   | $\text{(Y,Ce,U,Fe}^{+3}\text{)}_3\text{(Nb,Ta,Ti)}_5\text{O}_{16}$ , 8.4-16.7 % uranium                |
| uraninite    | $\text{UO}_2$ 46-88 % uranium  |
| pitchblende  | massive uraninite, $\text{UO}_2$ to $\text{U}_3\text{O}_8$ , 55-88 % uranium                           |
| xenotime     | $\text{YPO}_4$ , <3.6 % uranium  |
| yttracrasite | $\text{(Y,Th,Ca,U)}\text{(Ti,Fe}^{+3}\text{)}_2\text{(O,OH)}_6$ 2.3% uranium                           |
| zircon       | $\text{ZrSiO}_4$ <2.7 % uranium  |

### **Secondary Minerals**

|                |   |
|----------------|---|
| autunite       | $\text{Ca(UO}_2\text{)}_2\text{(PO}_4\text{)}_2\text{10-12H}_2\text{O}$ , 45-48 % uranium         |
| meta-autunite  | $\text{Ca(UO}_2\text{)}_2\text{(PO}_4\text{)}_2\text{2-6H}_2\text{O}$ , 53-62 % uranium           |
| carnotite      | $\text{K}_2\text{(UO}_2\text{)}_2\text{(VO}_4\text{)}_2\text{3H}_2\text{O}$ , 52.8-55.0 % uranium |
| “gummite”      | generic name for gumlike secondary uranium minerals,<br>variable in composition                   |
| metazeunerite  | $\text{Cu(UO}_2\text{)}_2\text{(AsO}_4\text{)}_2\text{8H}_2\text{O}$ , 46.4-49.5 % uranium        |
| torbernite     | $\text{Cu(UO}_2\text{)}_2\text{(PO}_4\text{)}_2\text{8-12H}_2\text{O}$ 47.1-50.8 % uranium        |
| metatorbernite | $\text{Cu(UO}_2\text{)}_2\text{(PO}_4\text{)}_2\text{8H}_2\text{O}$ 50.8-55.0 % uranium           |
| uranophane     | $\text{CA(UO}_2\text{)SiO}_3\text{(OH)}_2\text{5H}_2\text{O}$ , 55.6 % uranium                    |

### **Mineralogy References**

Carlisle et al., 1980, Elevatorski, 1978, Frondel, 1958, Morton, 1979, Murdoch and Webb, 1966 Roberts et al., 1990, and Walker et al., 1956

## URANIUM GEOCHEMISTRY

Uranium consists of several isotopes, the principal one being uranium-238 (99.3% of all uranium). Uranium-238 is radioactive with a half-life of  $4.5 \times 10^9$  years. It ultimately decays to lead-206 with the longer lived intermediate daughter products being uranium-234, thorium-230, radium-226, radon-222, polonium-210, lead-210, and bismuth 210 (Figure 14). The natural abundance of uranium in the earth's crust is within the Range of 1 to 4 parts per million (ppm), and the average is probably about 2.6 ppm (Rogers and Adams, 1969, and Dyck, 1979).

Ocean waters contain a relatively uniform amount of uranium, with concentrations commonly in the 0.001 to 0.003 ppm range, and are usually saturated in uranium with respect to the local geochemical environments (Haglund, 1972). Continental waters are variable in uranium concentrations because of variations in the chemistry of rocks in drainage basins and local variations in the geochemical environment. Uranium concentrations for continental waters are usually in the 0.00X ppm range (where X = some number, 1 to 9), but concentrations on the order of 0.X ppm are possible in waters that are in contact with uranium mineral deposits (Haglund, 1972).

In aqueous solutions, the ionic species of uranium that are of importance in the natural environment are U (IV), U(V), and U (VI) (Langmuir, 1978). U (VI) as  $\text{UO}_2^{+2}$ , the uranyl ion, is quite soluble relative to the uranous ion,  $\text{U}^{+4}$ , which tends to form insoluble uraninite or coffinite (Rogers and Adams, 1978, and Langmuir, 1978). The carbonate ion strongly complexes with the uranyl ion and inhibits precipitation; the dissociation constant for the  $(\text{UO}_2)(\text{CO}_3)_3^{+4}$  complex is believed to be about  $10^{-10}$  (Rogers and Adams, 1978). U (V) as  $\text{UO}_2^+$  has an appreciable stability field in reduced water below pH 7 (Langmuir, 1978).

At typical ligand concentrations in groundwater, the most important uranyl complexes are fluoride, phosphate, and carbonate, under acid, near neutral and alkaline conditions respectively. Sulfate, silica, and hydroxyl complexes can also form under certain conditions. At a common groundwater  $\text{CO}_2$  pressure of  $10^{-2}$  atm and  $25^\circ\text{C}$ , uranyl carbonate complexes dominate down to about pH 5, and down to pH 5.8 at atmospheric  $\text{CO}_2$  pressure ( $10^{-3.5}$  atm). With increasing temperature, carbonate complexes decrease in importance relative to hydroxyl complexes (Langmuir, 1978).

Uranium is adsorbed from solution by organics (humic and sapropelic matter), iron oxides, and by clays (Haglund, 1972). At low temperatures, sorption is usually a more important control on concentrations of trace metals, such as uranium, than solubility equilibria (Langmuir, 1978). Mineral solubilities limit only the maximum uranyl concentration in solution, while sorption limits uranyl concentrations at all levels below saturation with the least soluble uranyl mineral (Langmuir, 1978). It should be noted that strong complexes with sulfate, fluoride, and carbonate can inhibit uranium sorption.

The enrichment factor<sup>3</sup>, E.F., is an indication of how strongly natural materials can absorb uranium from solution. E.F. values given as typical by Langmuir (1978) are : amorphous Ti (OH)<sub>4</sub>,  $8 \times 10^4$  to  $10^6$ ; amorphous Fe (III) oxyhydroxides,  $1.1 \times 10^6$  to  $2.7 \times 10^6$ ; peat,  $10^4$  to  $10^6$ ; fine grained goethite (FeOOH),  $4 \times 10^3$ ; phosphorites, 15; montmorillonite (clay), 6; and kaolinite (clay), 2. Note the relative efficiency of iron oxide compounds and peat as uranium collectors versus the clays. The above E.F. values were measured in the pH range of 5 to 8.5 and in the absence of strong uranyl sulfate, fluoride, and carbonate complexes.

In summary, uranium is mobile under oxidizing conditions, especially in acid or carbonate rich waters, but it is immobile under reducing conditions. Iron oxides and organic matter can be strong adsorbers of uranium, and sorption may be a strong control on uranium concentration in waters ambient temperatures.

## RADIUM GEOCHEMISTRY

There are four naturally occurring isotopes of radium; radium-224 and radium-228 (daughter products of thorium-232), radium-223 (a daughter of uranium-235), and radium-226 (a daughter of uranium-238). Radium-226 has a half-life of 1600 years, much longer than the other three radium isotopes, so it is of more importance in the natural environment.

Radium is an alkaline-earth metal and its chemical behavior is similar to barium. Its mobility in the surface environment is generally moderate to low, but it can be high in brines under reducing conditions because of chloride complexing and the absence of iron oxides (Rose, et al., 1979, Hem, 1985, Dyck, 1979, and Moore, 1972). Radium is adsorbed by iron oxides and organic matter, and coprecipitated with calcium carbonate, calcium sulfate, and barium sulfate (Rose, et al., 1979, and Dyck, 1979). The solubility of radium sulfate 25°C is apparently lower than the solubility of barium sulfate under similar conditions Hem, 1985). Because the existence of radium-226 is dependent upon its continuing production from uranium-238, and the strong immobility of thorium-234 and 230 in the environment, the mineralogical occurrence of radium is largely determined by the chemistry of uranium. This also means that uranium minerals will usually contain radium (Moore, 1972).

The natural abundance of radium in crustal rocks is extremely low, averaging about one part per trillion (Dyck, 1979). Typical concentrations of radium in water from an oxidation zone is about  $0.1 \times 10^{-12}$  gm/liter, or 0.1 picocuries per liter (Dyck, 1979). The most insoluble radium salt, radium sulfate, would support a Ra<sup>+2</sup> concentration in water of about 20 parts per billion (ppb)—about 5000 times the concentration of radium in a liter of rock (Dyck, 1979). Consequently, it is the low initial radium concentration in

---

<sup>3</sup> The enrichment factor is defined as the weight of sorbed uranium per weight of sorbent plus uranium, divided by the weight of dissolved uranium per weight of solution (Langmuir, 1978).

rock that is the major control on radium concentration in waters. However, enough radium does go into solution and its half-life is sufficiently long to allow radium to be transported over distances of several kilometers in the right geological setting (Dyck, 1979). During such migration, radium would be continually adsorbed and desorbed from mineral grains in the aquifer such that the majority of radium would be adsorbed on these surfaces at any given time (Dyck, 1979). Consequently, such radium movement would take place with radium concentrations in water that would be below analytical detection limits (this situation could give rise to radon anomalies that appear to be unsupported by radium or uranium).

Radium accumulations can be prominent in ground waters, which come from sufficient depths that reducing conditions prevail. Carbon dioxide escapes from these deep waters during their rise to the surface causing calcium and magnesium carbonate to precipitate, coprecipitating radium (e.g. radium enrichment around mineral springs). Radium can also be removed from water by cation exchange with clay minerals, where it exchanges with calcium (Dyck, 1979).

## **RADON GEOCHEMISTRY**

Radon is a noble gas and is produced by the radioactive decay of radium isotopes 223, 224, and 226. Radon-222 is the only radon nuclide that has a half-life long enough (3.8 days) to be of importance in the natural environment, the others have half-lives under one minute.

In a closed system, the presence of radon is entirely dependent upon the amount of radium present, and with no loss of radon, a sample of radium-226 will produce an equilibrium amount of radon-222 in about five radon half-lives, or 20 days (Moore, 1972). When radon is in radioactive equilibrium in this way it is said to be radium-supported. Being a gas, separation of radon from radium does occur in nature, but due to its short 3.8 day half-life, radon cannot travel far from radium by simple diffusion--probably no more than about six meters (Dyck, 1979). However, radon dissolved in flowing surface or ground waters, or being moved along with other subsurface gases (carrier gases, such as carbon dioxide and methane) can be transported much greater distances from its radium parent--10s to 100s of meters and possibly more (Kristiansson and Malmqvist, 1982, and 1984, Dyck, 1979).

In addition to the amount of radium-226 (and ultimately uranium-238) present, a second factor affecting radon in water and air is the emanation efficiency--the efficiency of radon escape from radium in minerals and rocks. Emanation efficiencies for typical igneous, metamorphic, and sedimentary rocks average about 9-10 percent, and are seldom higher than about 20 percent (Dyck, 1979). The emanation efficiency for different uraniumiferous minerals is quite variable (e.g., 0.1 percent for xenotime, 32 percent for carnotite, Dyck, 1979). Emanation efficiency has been found to be higher in the presence of water than in the presence of air (Dyck, 1979).

Averages and ranges of radon for various rock types and water have little significance because radon emanations vary so much, but the following information for Dyck (1979) can be used as a rough guide. Water and soil from granitic terrane will generally contain more radon than water and soil from sandstone terrane. Subsurface water contains more radon than does surface water. Continental waters have background levels of radon within these ranges: Lakes, 0 to 5 pCi/liter; streams, 5 to 100 pCi/liter; and wells and springs, 100 to 1000 pCi/liter. Calculations cited by Hem (1985) indicate that ground water in a porous aquifer containing 1 mg/kg (1 ppm) uranium in solids could have a radon activity of more than 800 pCi/liter (note that crustal rocks average about 2.6 ppm uranium).

Soil gas radon concentrations are typically about 100 pCi/liter, and air just above ground level usually contains about 0.1 pCi/liter radon (Dyck, 1979). Radon concentrations in soil gas are affected by the following: the type of underlying uranium mineralization, if any; the concentration of uranium and radium in the soil and underlying rock; the porosity of the soil; the soil moisture; and weather conditions—barometric pressure, wind, and rainfall (Dyck, 1979).

## REFERENCES

Anderson, J.L., and Cullers, R.L., 1990, Middle to upper crustal plutonic construction of a magmatic arc; An example from the Whipple Mountains metamorphic core complex: in Anderson, J.L., ed., *The Nature and Origin of Cordillerian Magmatism*, The Geological Society of America, Memoir 174, p. 47-70.

Barnes, C.G., Allen, C.M., Hoover, J.D., and Brigham, R.H., 1990, magmatic components of a tilted plutonic system, Klamath Mountains, California: in Anderson, J.L., ed., *The Nature and Origin of Cordilleran Magmatism*, The Geological Society of America, Memoir 174, p. 331-346.

Barth, A.P., 1990, Mid-crustal emplacement of Mesozoic plutons, San Gabriel Mountains, California, and implications for the Geologic history of the San Gabriel terrane: in Anderson, J.L., ed., *The Nature and Origin of Cordilleran Magmatism*, The Geological Society of America, Memoir 174, p. 33-46.

Bates, R.L., and Jackson, J.A., 1980, *Glossary of Geology*, second edition, American Geological Institute, Falls Church, Virginia, 749 p.

Bell, K.G., 1960, Uranium and other trace elements in petroleum and rock asphalts: U.S. Geological Survey Professional Paper 356-B, p. 45-65.

Birchard, G.F., and Libby, W.F., 1980, Soil radon concentration changes preceding and following four magnitude 4.2-4.7 earthquakes on the San Jacinto fault in southern California: *Journal of Geophysical Research*, v. 85, no. B6, p. 3100-3106.

Bramlette, M.N., 1946, The Monterey Formation of California and the origin of its siliceous rocks: U.S. Geological Survey Professional Paper 212, 57 p.

Butler, A.P., Jr., and Schnabel, R.W., 1956, Distribution and general features of uranium occurrences in the United States: in Page, L.R., Stocking, H.E., and Smith, H.B., eds., Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations international conference on peaceful uses of atomic energy, Geneva, Switzerland, 1955, U.S. Geological Survey Professional Paper 300, p. 27-40.

Carlisle, D., Kettler, R.M., and Swanson, S.C., 1980, Uranium- and thorium-bearing facies of the late Proterozoic Kingston Peak Formation, Death Valley Region, California: in Fife, D.L., and Brown, A.R., eds., Geology and Mineral Wealth of the California desert, South Coast Geological Society, Santa Anna, California, p. 379-386.

Coats, R.R., 1956, Uranium and certain other trace elements in felsic volcanic rocks of Cenozoic age in Western United States: in Page, L.R., Stocking, R.E., and Smith, H.B., eds., Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on peaceful uses of atomic energy, Geneva, Switzerland, 1955, U.S. Geological Survey Professional Paper 300, p. 75-78.

Dickinson, K.A., and Leventhal, J.S., 1988, The geology, carbonaceous materials, and origin of the epigenetic uranium deposits in the Tertiary Sespe Formation in Ventura County, California: U.S. Geological Survey Bulletin 1771, 18 p.

Dickert, P.F., 1966, Tertiary phosphatic facies of the Coast Ranges: in Bailey, E.H., ed., Geology of Northern California, California Division of Mines and Geology Bulletin 190, p. 289-304.

Durham, D.L., 1987, Uranium in the Monterey Formation of California: U.S. Geological Survey Bulletin 1581, 29 p.

Durham, D.L., 1974, Geology of the southern Salinas Valley area, California: U.S. Geological Survey Professional Paper 538, 121 p.

Durham, D.L., and Felmlee, J.K., 1982, National Uranium Resource Evaluation, Walker Lake Quadrangle, California and Nevada: U.S. Department of Energy report PGJ/F-010(82), Grand Junction, 43 p.

Dyck, W., 1979, The mobility and concentration of uranium and its decay products in temperate surficial environments: in Kimberley, M.M., ed., Uranium Deposits: Their Mineralogy and Origin, Mineralogical Association of Canada, Short Course Volume 3, University of Toronto Press, p. 57-100.

Evans, J.R., 1976, Economic evaluation of Pine Mountain phosphate deposit, Ventura County, California: *California Geology*, v. 29, no. 12, p. 275-279.

Elevatorski, E.A., 1978, Uranium Ores and Minerals, Minobras, Dana Point California, 93 p.

Finch, W.I., 1963, Geology of epigenetic uranium deposits in sandstone in the United States: U.S. Geological Survey Professional Paper 538, 121 p.

Fleischer, R.L., and Turner, L.G., 1984, Correlations of radon and carbon isotopic measurements with petroleum and natural gas at Cement, Oklahoma: *Geophysics*, v. 49, no. 6, p. 810-817.

Fox, L.K., and Miller, D.M., 1990, Jurassic granitoids and related rocks of the southern Bristol Mountains, southern Providence Mountains and Colton Hills, Mojave Desert, California: in Anderson, J.L., ed., *The Nature and Origin of Cordilleran Magmatism*, The Geological Society of America, Memoir 174, p. 111-132.

Fronzel, C., 1958, systematic mineralogy of uranium and thorium: U.S. Geological Survey Bulletin 1064, 400 p.

Gaman, W.A., and King, C., 1979, Catalog of soil-gas radon measurements in central California from May 1975 through December 1978: U.S. Geological Survey Open-File Report 79-547, 143 p.

Gower, H.D., 1966, Phosphate, in *Mineral Resources of California*: California Division of Mines and Geology Bulletin 191, p. 328-332.

Gower, H.D., and Madsen, B.M., 1964, The occurrence of phosphate rock in California: U.S. Geological Survey Professional Paper 501-D, p. D79-D85.

Haglund, D.S., 1972, Uranium: Element and Geochemistry: in Fairbridge, R.S., ed., *The Encyclopedia of Geochemistry and Environmental Sciences*, Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pennsylvania, p. 1215-1222.

Hail, W.J., Jr., Myers, A.T., and Horr, C.A., Uranium in asphalt-bearing rocks of Western United States: in Page, L.R., Stocking, H.E., and Smith, H.B., eds., *Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on peaceful uses of atomic energy*, Geneva, Switzerland, 1955, U.S. Geological Survey Professional Paper 300, pp. 521-526.

Hall, F.R., 1988, Geologic controls on radon gas in ground water: in Makofske, W.J., and Edelstine, M.R., eds., *Radon and the Environment*, Noyes Publications, Park Ridge, New Jersey, p. 48-55.

Hall, F.R., Boudette, E.L., and Olszewski, W.J., Jr., 1987, Geologic controls on radon occurrence in New England: in Graves, B., ed., Radon, Radium and Other Radioactivity in Ground Water, Proceedings of the NWWA conference April 7-9, 1987, Somerset, New Jersey, Lewis Publishers, Inc., Chelsea, Michigan, p. 15-29.

Heinrich, E., Wm., 1958, Mineralogy and Geology of Radioactive Raw Materials, McGraw-Hill Book Company, Inc., New York, 654 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Irwin, W.P., and Barnes, I., 1980, Tectonic relations of carbon dioxide discharges and earthquakes: *Journal of Geophysical Research*, v. 85, no. B6, p. 3115-3121.

Jennings, C.W., 1957a Asphalt and Bituminous Rock: in Wright, L.A., ed., Mineral Commodities of California, Division of Mines Bulletin 176, p. 59-70.

John, B.E., and Wooden, J., 1990, Petrology and geochemistry of the metaluminous to peraluminous Chemehuevi Mountains Plutonic suite, southeastern California: in Anderson, J.L., The Nature and origin of Cordillerian Magmatism, The Geological Society of America, Memoir 174, p. 71-98.

Jones, V.T., and Drozd, R.J., 1983, Predictions of oil and gas potential by near-surface geochemistry: *American Association of Petroleum Geologists Bulletin*, v. 67, no. 6, p. 932-952.

King, C., 1980, Episodic radon changes in subsurface soil gas along active faults and possible relation to earthquakes: *Journal of Geophysical Research*, v. 85, no. B6, p. 3065-3078.

Klepper, M.R., and Wyant, D.G., 1956, Uranium provinces: in Page, L.R., Stocking, H.E., and Smith H.B., eds., Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations international Conference on peaceful uses of atomic energy, Geneva, Switzerland, 1955, U.S. Geological Survey Professional Paper 300, p. 17-26.

Kristiansson, K., and Malmqvist, L., 1984, The depth-dependence of the concentration of Rn in soil gas near the surface and its implication for exploration: *Geoexploration*, v. 22, p. 17-41.

Kristiansson, K., and Malmqvist, L., 1982, Evidence for the nondiffusive transport of Rn in the ground and a new physical model for the transport: *Geophysics*, v., 47, no. 10, p. 1444-1452.

Langmuir, D., 1978, Uranium solution-mineral equilibria at low temperatures with applications to sedimentary ore deposits: in Kimberley, M.M., ed., Uranium Deposits:

Their Mineralogy and Origin, Mineralogical Association of Canada, Short Course Volume 3, University of Toronto Press, p. 17-56.

Larson, E.S., and Gottfried, D., 1961, Distribution of uranium in rocks and minerals of Mesozoic batholiths in western United States: U.S. Geological Survey Bulletin 1070-C, p. 63-103.

Larson, E.S., Jr., Phair, G., Gottfried, D., and Smith, W.L., 1956, Uranium in magmatic differentiation: in Page, L.R., Stocking, H.E., and Smith, H.B., eds., Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations international Conference on peaceful uses of atomic energy, Geneva, Switzerland, 1955, U.S. Geological Survey Professional Paper 300, p. 65-74.

Leventhal, J.S., 1989, Geochemistry of minor and trace elements of 22 core samples from the Monterey Formation and related rocks in the Santa Maria Basin, California: U.S. Geological Survey Bulletin 1581-B, 11 p.

Lombardi, and Reimer, G.M., 1990, Radon and helium in soil gasses in the Phlegraean Fields, central Italy: Geophysical Research Letters, v. 17, no. 6, p. 849-852.

Moore, W.S., 1972a, Radium: Element and Geochemistry: in Fairbridge, R.S., ed., The Encyclopedia of Geochemistry and Environmental Sciences, Cowden, Hutchinson and Ross, Inc., Stroudsburg, Pennsylvania, p. 1006-1007.

Moore, W.S., 1972a, Radon: Element and Geochemistry: in Fairbridge, R.S., ed., The Encyclopedia of Geochemistry and Environmental Sciences, Cowden, Hutchinson and Ross, Inc., Stroudsburg, Pennsylvania, p. 1014-1015.

Moore, G.W., and Stephens, J.G., 1952, Reconnaissance for uranium-bearing carbonaceous rocks in California and adjacent parts of Oregon and Nevada: U.S. Geological Survey Circular 313, 8 p.

Morton, R.D., 1979, The identification of uraniferous minerals: in Kimberley, M.M., ed., Uranium deposits: Their mineralogy and Origin: Mineralogical Association of Canada, Short Course Volume 3, University of Toronto Press, p. 141-183.

Morton, P.K., and Anderson T.PI, 1982, Mineral deposits of the transverse Ranges Province—an overview: in Fife, D.L., and Minch, J.A., eds., Geology and Mineral Wealth of the California Transverse Ranges, South Coast Geological society, Inc., Santa Ana, California, p. 190-197.

Murdoch, J., and Webb, R.W., 1966, Minerals of California: California Division of Mines and Geology Bulletin 189, 559 p.

Norris, R.M., and Webb, R.W., 1990, *Geology of California*, John Wiley and Sons, Inc., New York, 541 p.

Ogden, A.E., Welling, W.B., Funderburg, R.D., and Boschult, L.C., 1987, A preliminary assessment of factors affecting radon levels in Idaho: in Graves, B., ed., *Radon, Radium, and Other Radioactivity in Ground Water*, Proceedings of the NWWA Conference, April 7-9, 1987, Somerset, New Jersey, Lewis Publishers, Inc., Chelsea, Michigan, p. 83-96.

Otton, J.K., 1988, Potential for indoor radon hazards: A first geologic estimate: in Makofske, W.J., and Edelstine, M.R., eds., *Radon and the Environment*, Noyes Publications, Park Ridge, New Jersey, p. 29-34.

Otton, J.K., Aielinski, R.A., and Been, J.M., 1985, Uranium in Holocene valley-fill sediments, and uranium, radon, and helium in waters, Lake Tahoe-Carson Range area, Nevada and California: U.S. Geological Survey Open-File Report 85-389, 30 p.

Page, L.R., Stocking, H.E., and Smith, H.B., 1956, eds., *Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations international Conference on peaceful uses of atomic energy*, Geneva, Switzerland, 1955, U.S. Geological Survey Professional Paper 300, 739 p.

Pisciotta, K.A., and Garrison, R.E., 1981, Lithofacies and depositional environments of the Monterey Formation, California: in Garrison, R.E., ed., *The Monterey Formation and related siliceous rocks in California*, Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, California, p. 97-122.

Rapp, J.S., and Short, W.O., 1980, *Geology and uranium favorability of the Sonora Pass region alpine and Tuolumne Counties, California*: U.S. Department of Energy, National Uranium Resource Evaluation, report GJBX-132(81), Grand Junction, Colorado, 145 p.

Roberts, W.L., Camble, T.J., and Rapp, G.R., Jr., 1990, *Encyclopedia of Minerals*, second edition, Van Nostrand Reinhold Company, New York, 979 p.

Roberts, A.E., and Vercootere, T.L., 1986, *Geology and geochemistry of the upper Miocene phosphate deposit near New Cuyama, Santa Barbara County, California*: U.S. Geological Survey Bulletin 1635, 30 p.

Rogers, J.J.W., and Adams, J.A.S., 1969, Uranium: in Wedpohl, K.H., ed., *Handbook of Geochemistry*, v. II/5, Springer-Verlag, Berlin Germany, p. 92-D-1 to 92-N-1.

Rose, A.W., Hawkes, H.E., and Webb, J.S., 1979, *Geochemistry in Mineral Exploration*, second edition, Academic Press Inc., New York, 657 p.

Saucedo, G.J., Bedford, D.R., Raines, G.L., Miller, R.J., and Wentworth, C.M., 2000, GIS Data for the Geologic Map of California, DMG CD 2000-007, California Department of Conservation, Division of Mines and Geology.

Schutz, D.F., and Powell, J.A., 1988, The influence of geologic environment on the distribution of uranium/radon in New Jersey: in Makofske, W.J., and Edelstine, M.R., eds., *Radon and the Environment*, Noyes publications, Park Ridge, New Jersey, p. 35-47.

Troxel, B.W., Stinson, M.C., and Chesterman, C.W., 1957, Uranium, in Wright, L.A., ed., *Mineral Commodities of California: Division of Mines Bulletin 176*, p. 669-687.

Vine, J.D., 1962, *Geology of uranium in coaly carbonaceous rocks: U.S. Geological Survey Professional Paper 356-D*, p. 113-170.

Wagner, D.L., 2000, *Digital Database of Faults from the Fault Activity Map of California and Adjacent Areas, DMG CD 2000-006*, California Department of Conservation, Division of Mines and Geology.

Walawender, M.J., Gastil, R.G., Clinkenbeard, J.P., McCormick, W.V., Eastman, B.G., Wernicke, R.S., Wardlaw, M.S., Gunn, S.H., and Smith, B.M., 1990, Origin and evolution of the Zoned La Posta-type plutons, eastern Peninsular Ranges batholith, southern and Baja California: in Anderson, J.L., ed., *the Nature and Origin of Cordilleran Magmatism*, The Geological Society of America, *Memoir 174*, p. 1-18.

Walker, G.W., and Butler, A.P., Jr., 1966, Uranium, in *Mineral Resources of California: California Division of Mines and Geology Bulletin 191*, p. 436-439.

Walker, G.W., and Osterwald, F.W., 1963, *Introduction to the geology of uranium-bearing veins in the conterminous United States: U.S. Geological Survey Professional Paper 455-A*, 28 p.

Walker, G.W., Lovering, T.G., and Stephens, H.G., 1956, *Radioactive Deposits in California: Division of Mines, Special Report 49*, 38 p.

Wathen, J.B., 1987, The effect of uranium siting in two-mica granites on uranium concentrations and radon activity in ground water: in Graves, B., ed., *Radon, Radium, and Other Radioactivity in Ground Water, Proceedings of the NWWA Conference, April 7-9, 1987*, Somerset, New Jersey, Lewis Publishers Inc., Chelsea, Michigan, p. 31-45.

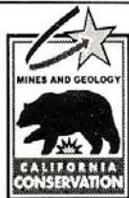
Wedepohl, K.H., 1969, *Handbook of Geochemistry*, v. II/9, Springer Verlag, Berlin, Germany, p. 92-D-1 to 19-N-1.

Wiegand, J., Yamamoto, G., and Gaston, W., 1987, Elevated levels of radioactivity in water wells in Los Angeles and Orange Counties, California: in Graves, B., ed., *Radon, Radium, and Other Radioactivity in Ground Water, Proceedings of the NWWA*

Conference April 7-9, 1987, Somerset, New Jersey, Lewis Publishers Inc., Chelsea, Michigan, p. 71-96.

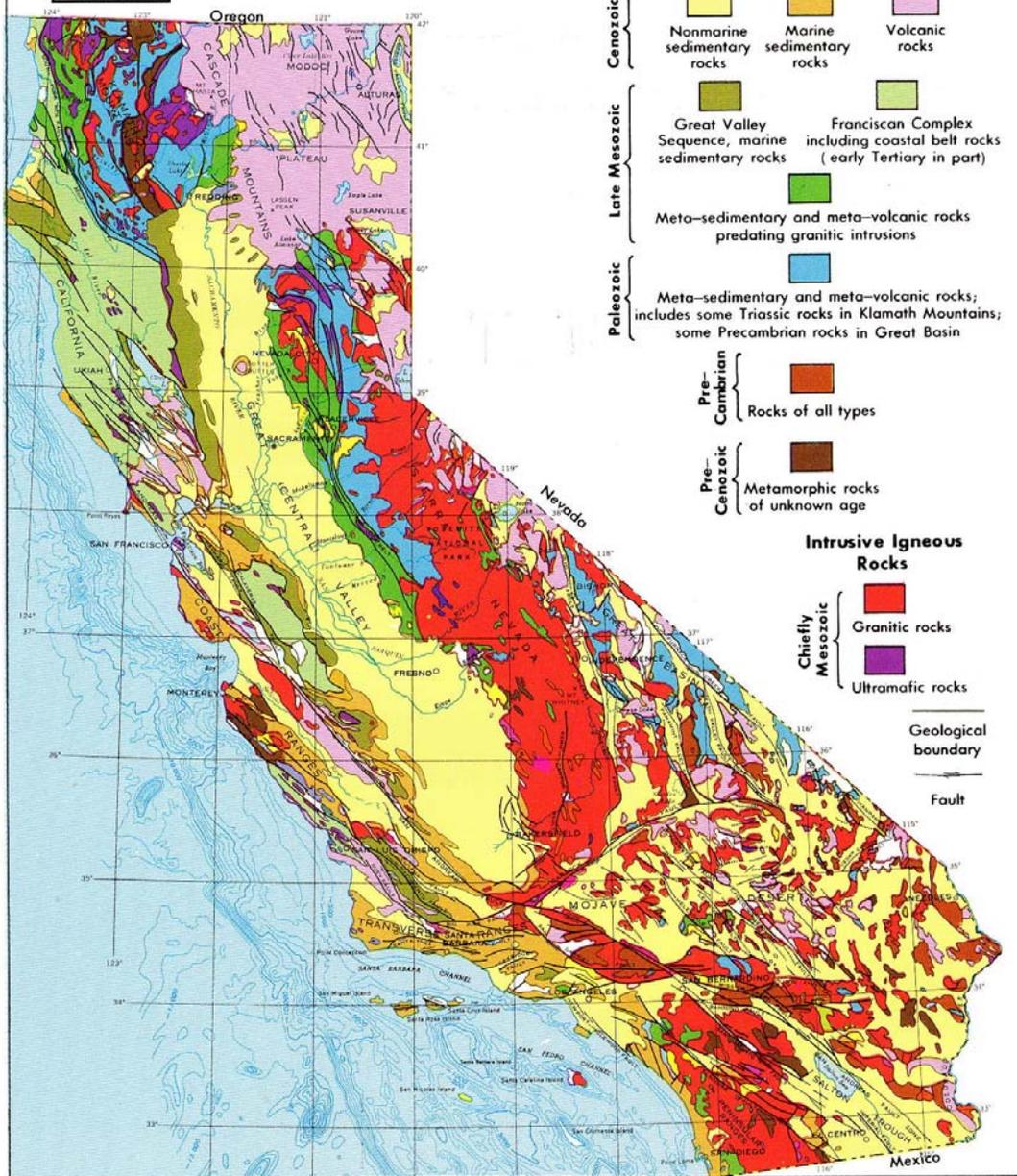
Zielinski, R.A., 1981, Experimental leaching of volcanic glass: Implications for evaluation of glassy volcanic rocks as sources of uranium: in Goodell, P.C., and Waters, A.C., eds., Uranium in Volcanic and Volcaniclastic Rocks, American Association of Petroleum Geologists, Studies in Geology No. 13, p. 1-12.

## FIGURES



California Department of Conservation  
Division of Mines and Geology

Simplified Geologic Map  
of California



**EXPLANATION**

**Sedimentary and Volcanic Rocks**

- Cenozoic**
  - Nonmarine sedimentary rocks
  - Marine sedimentary rocks
  - Volcanic rocks
- Late Mesozoic**
  - Great Valley Sequence, marine sedimentary rocks
  - Franciscan Complex including coastal belt rocks (early Tertiary in part)
  - Meta-sedimentary and meta-volcanic rocks predating granitic intrusions
- Paleozoic**
  - Meta-sedimentary and meta-volcanic rocks; includes some Triassic rocks in Klamath Mountains; some Precambrian rocks in Great Basin
- Pre-Cambrian**
  - Rocks of all types
- Pre-Cenozoic**
  - Metamorphic rocks of unknown age

**Intrusive Igneous Rocks**

- Chiefly Mesozoic**
  - Granitic rocks
  - Ultramafic rocks

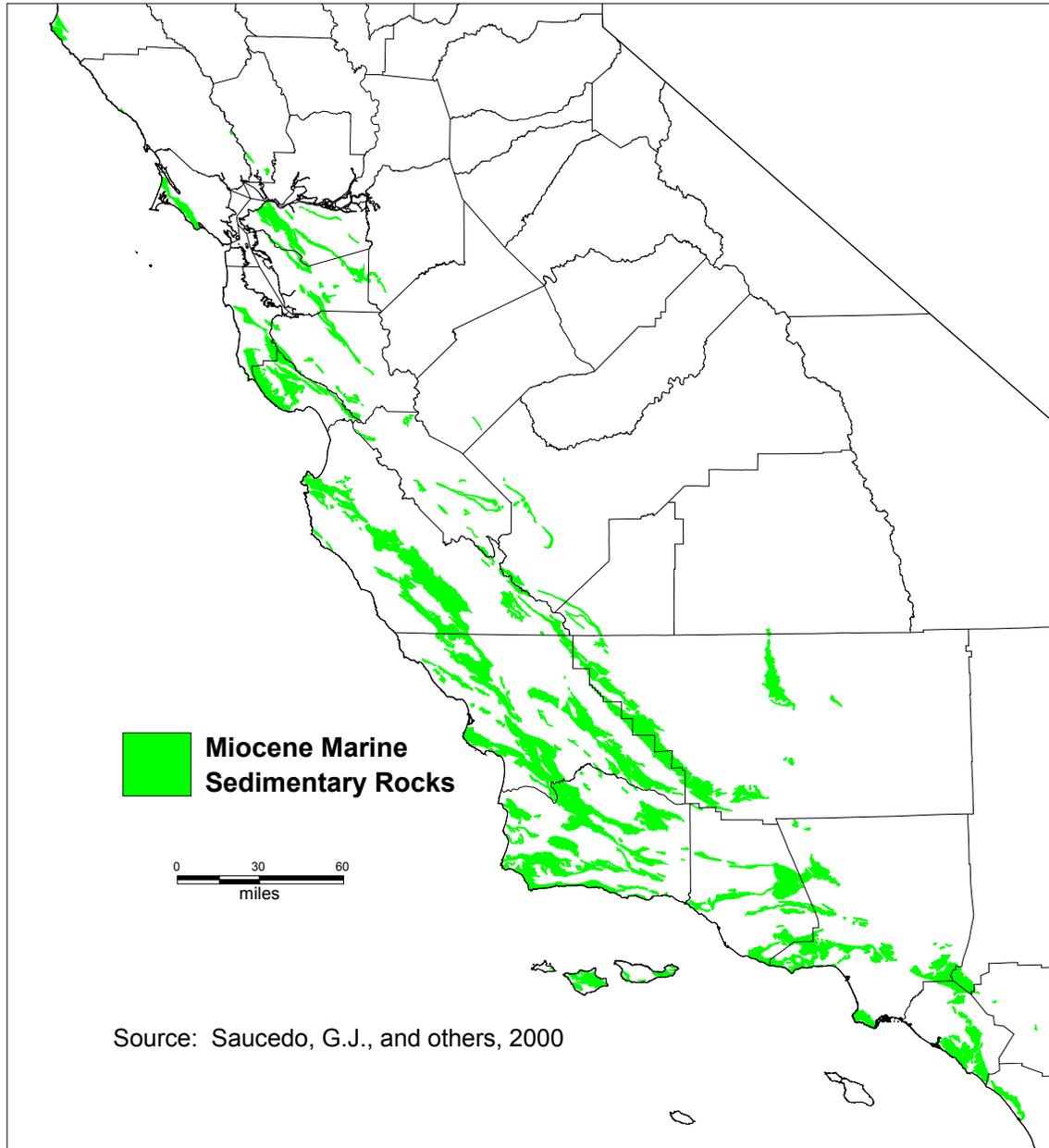
Geological boundary

Fault

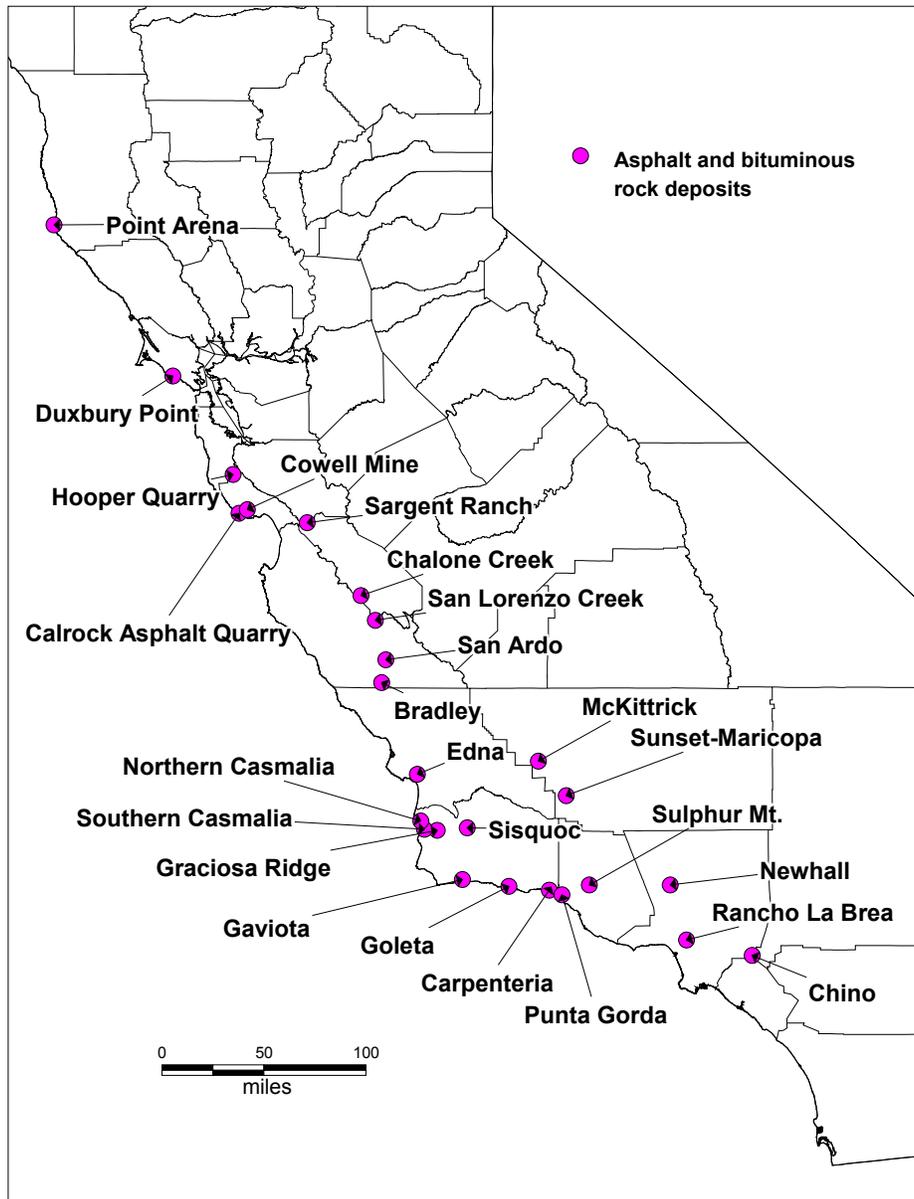
Compiled by USGS and CDMG, 1965.

Figure 1. Generalized Geologic Map of California

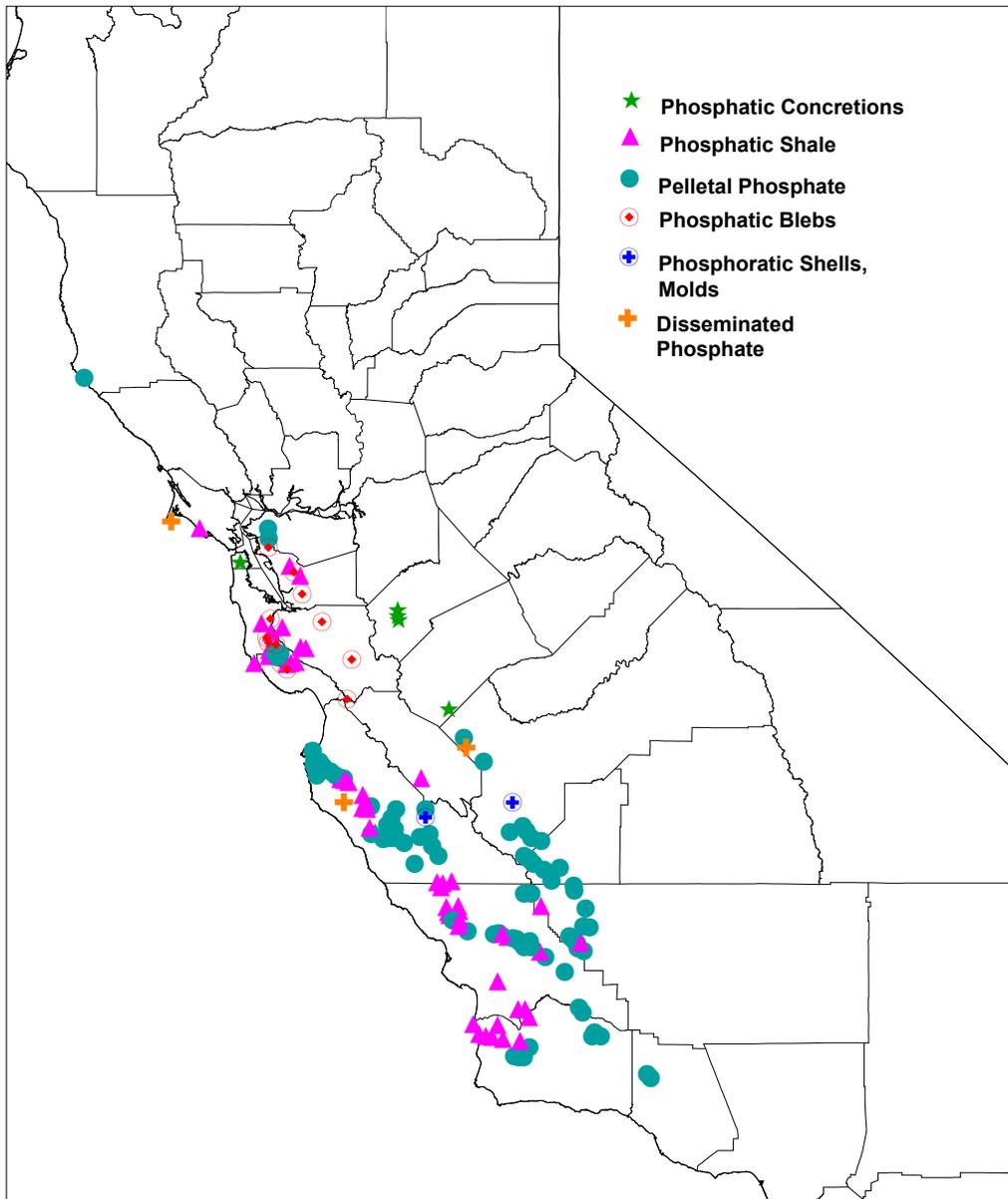
**Figure 2. Miocene Marine Sedimentary Rocks  
(The Monterey Formation is present in some of these areas)**



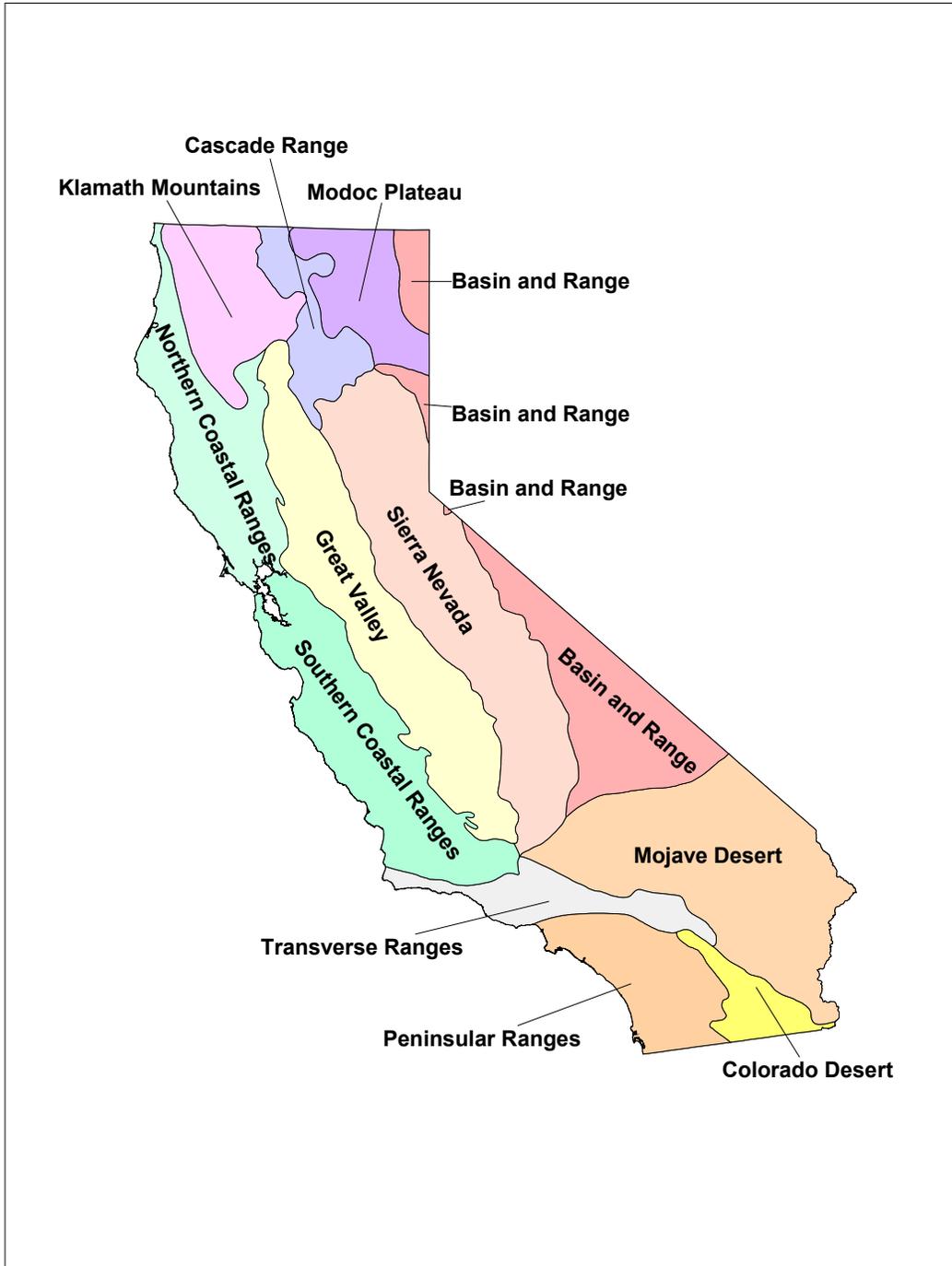
**Figure 3. Location of More Noteworthy Asphalt and Bituminous Rock Deposits in California (Modified from Jennings, 1957a)**



**Figure 4. Map of Phosphate-bearing Localities in the Central and Southern Coast Ranges (Modified from Dickert, 1966)**



**Figure 5. Geomorphic Provinces of California**



**Figure 6. Distribution of Granitic Rocks in California**

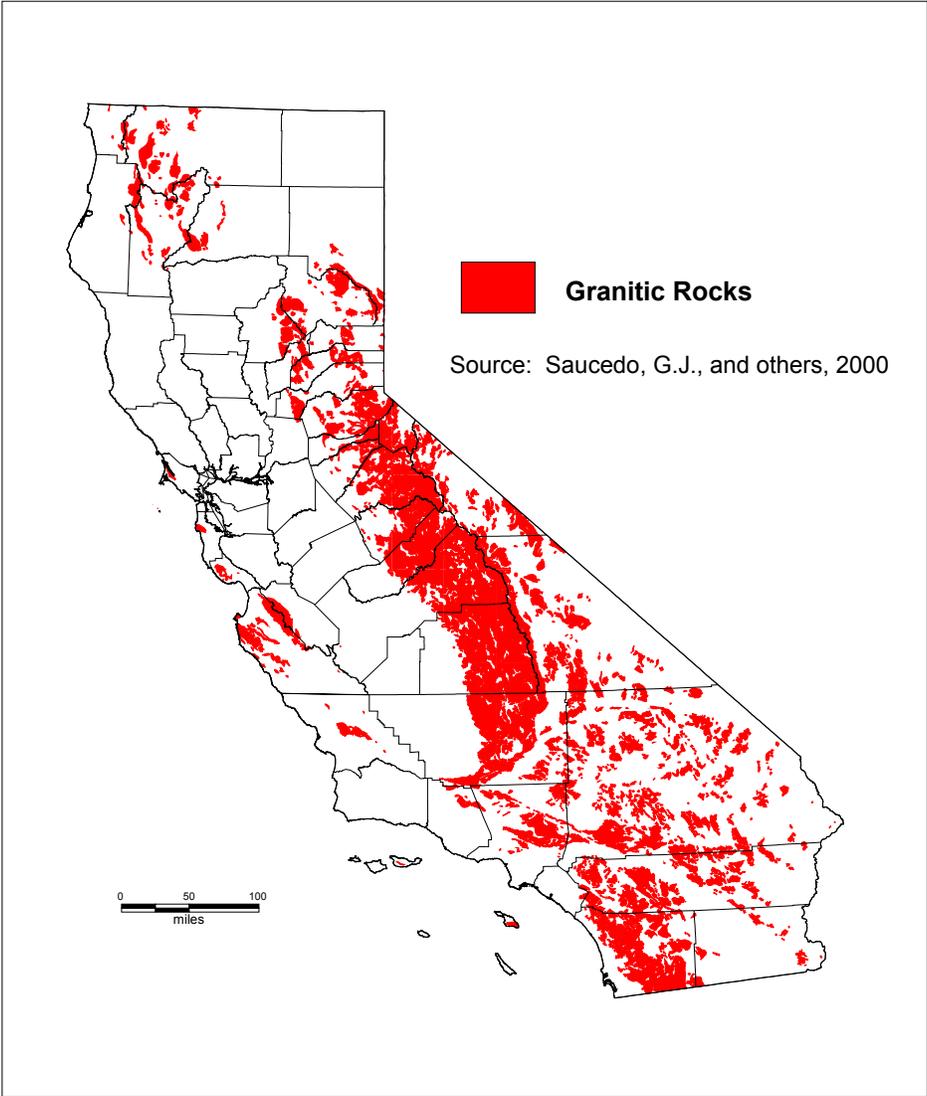


Figure 7. Faults in Southern California (Source: Wagner, 2000)

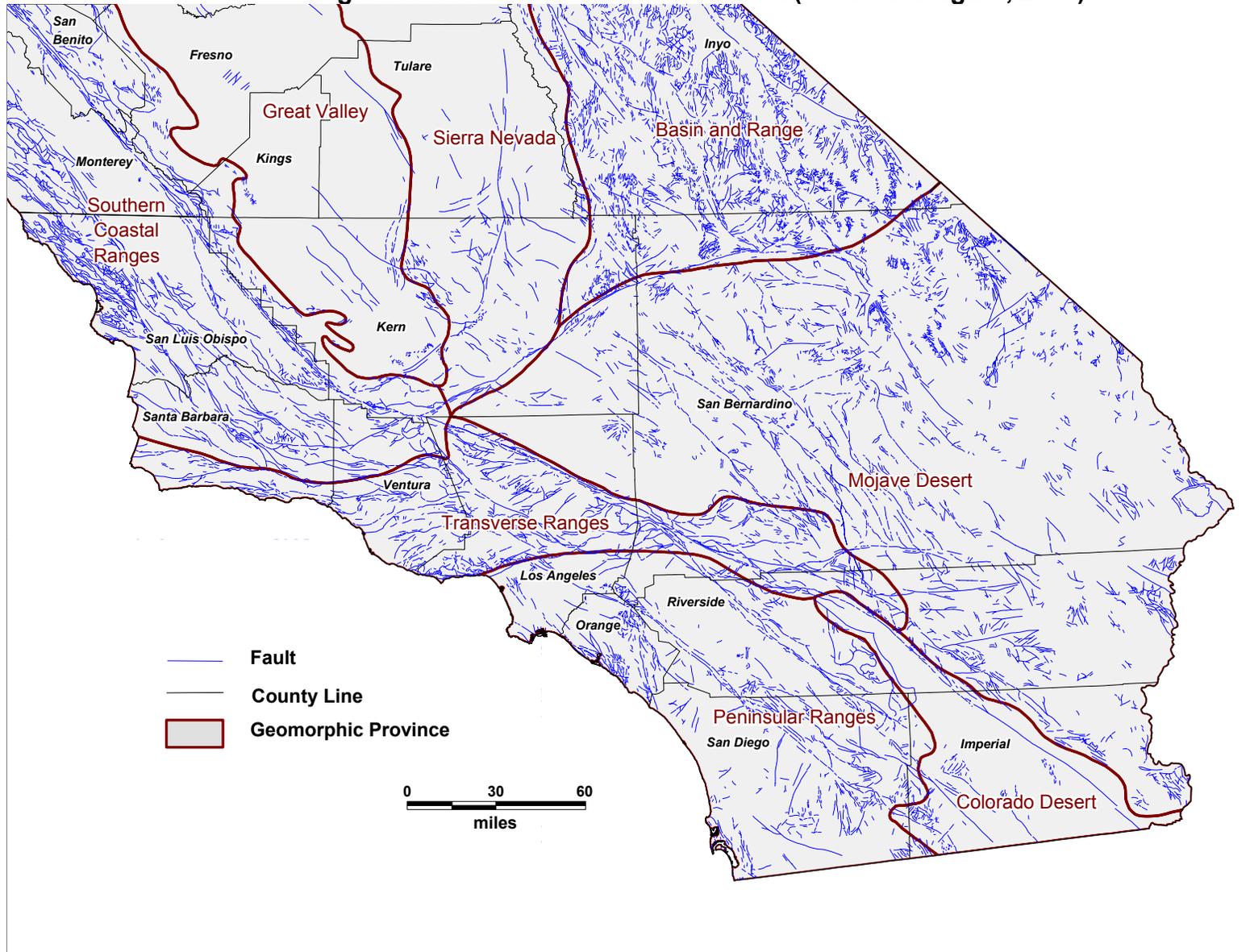


Figure 8. Faults in Central California (Source: Wagner, 2000)

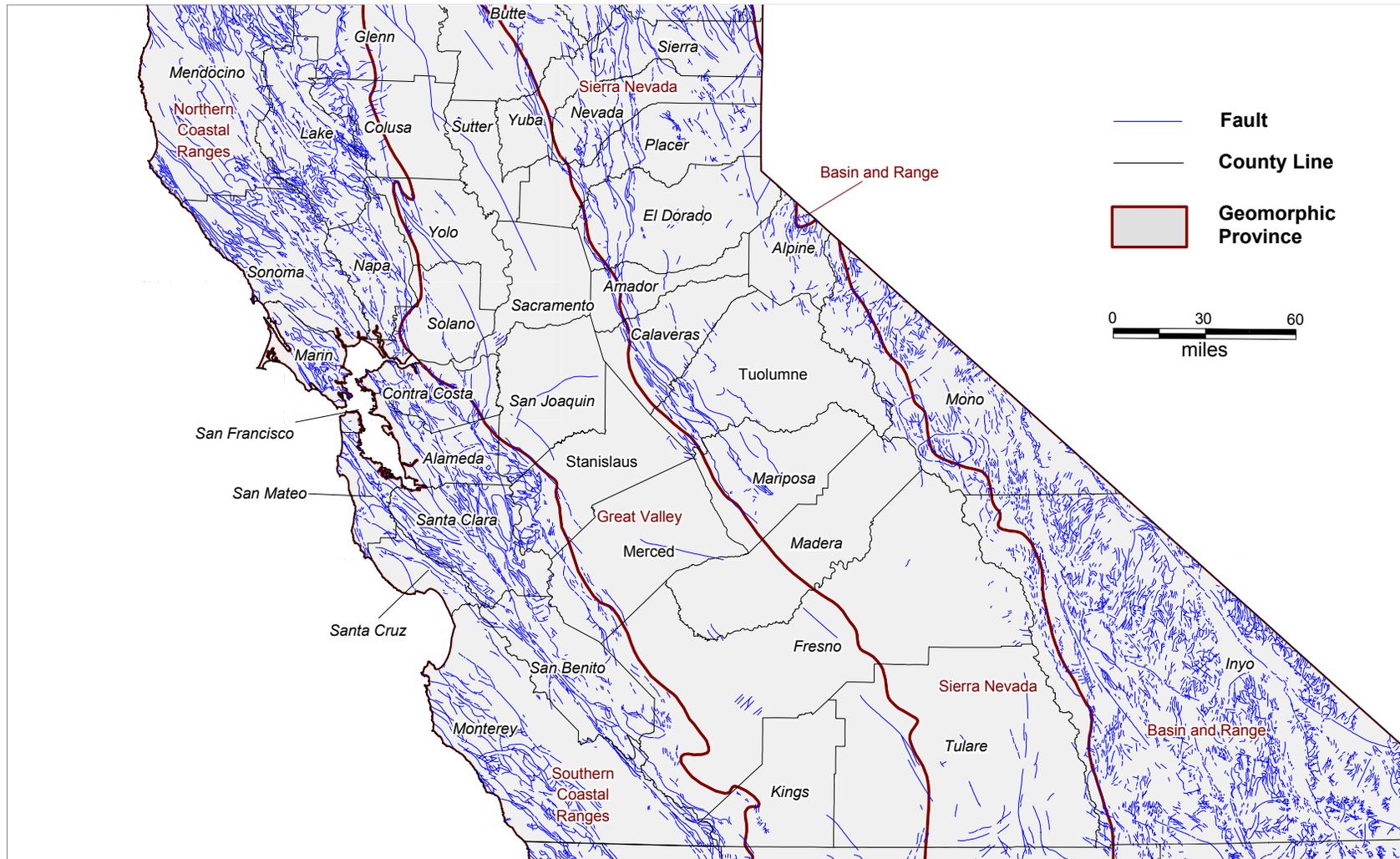
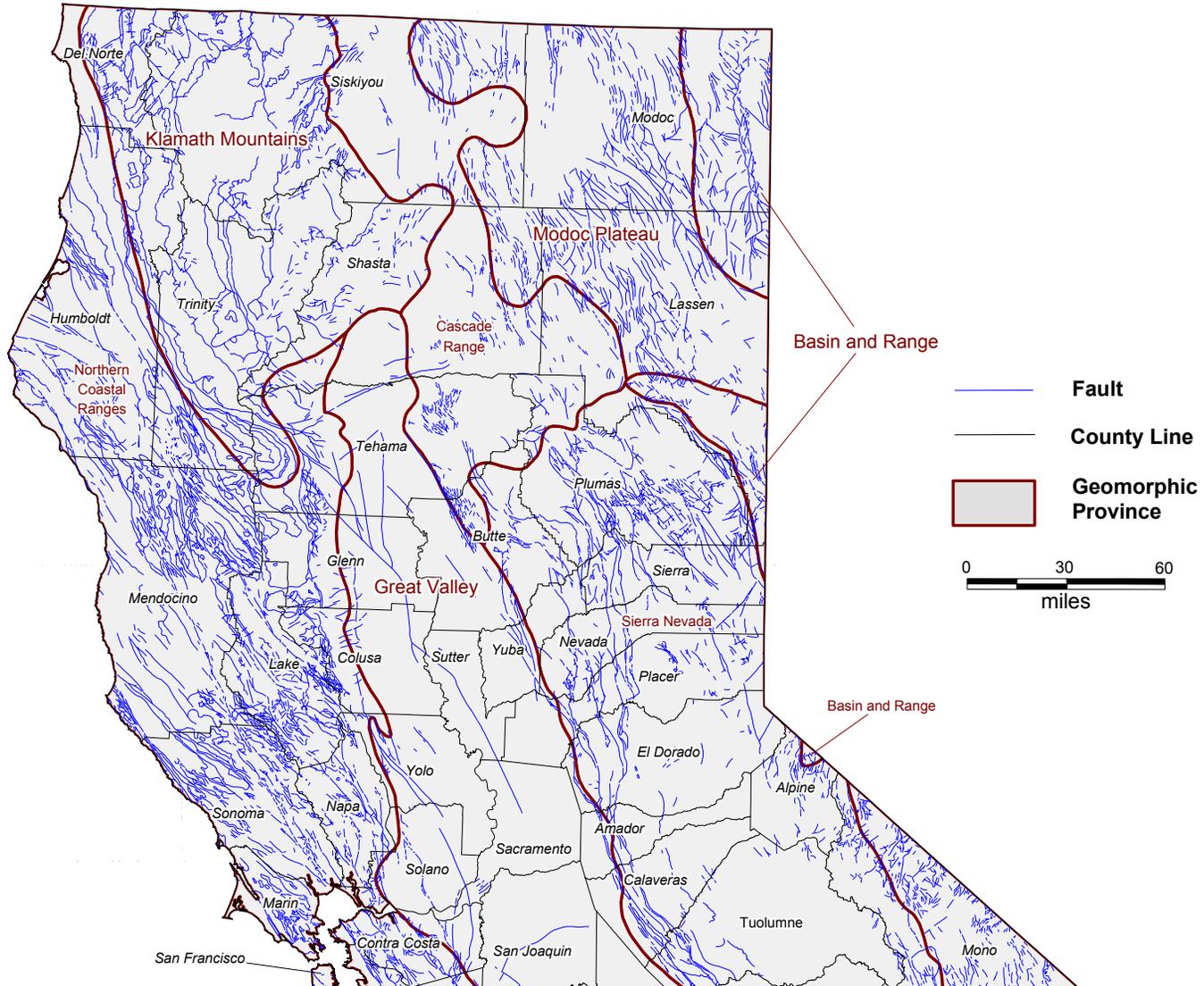
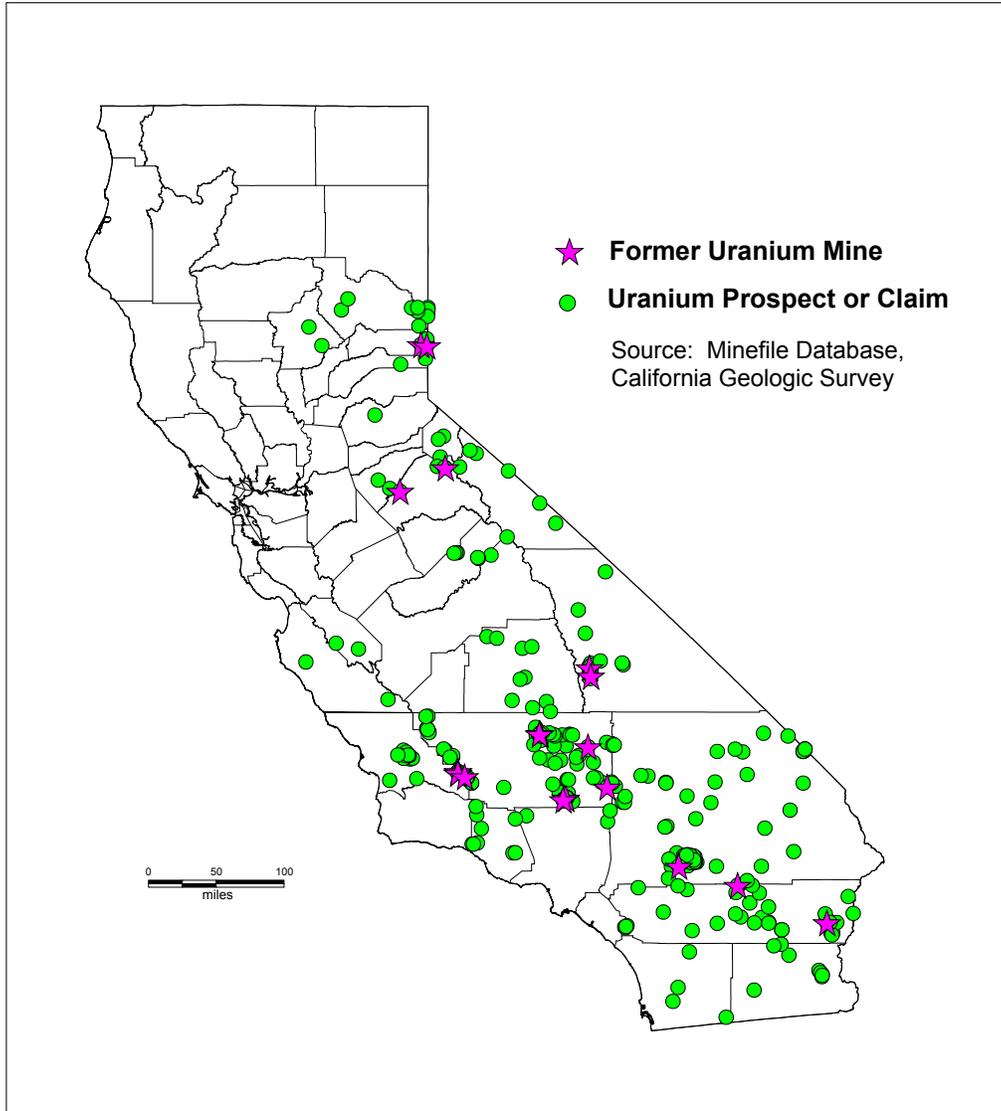


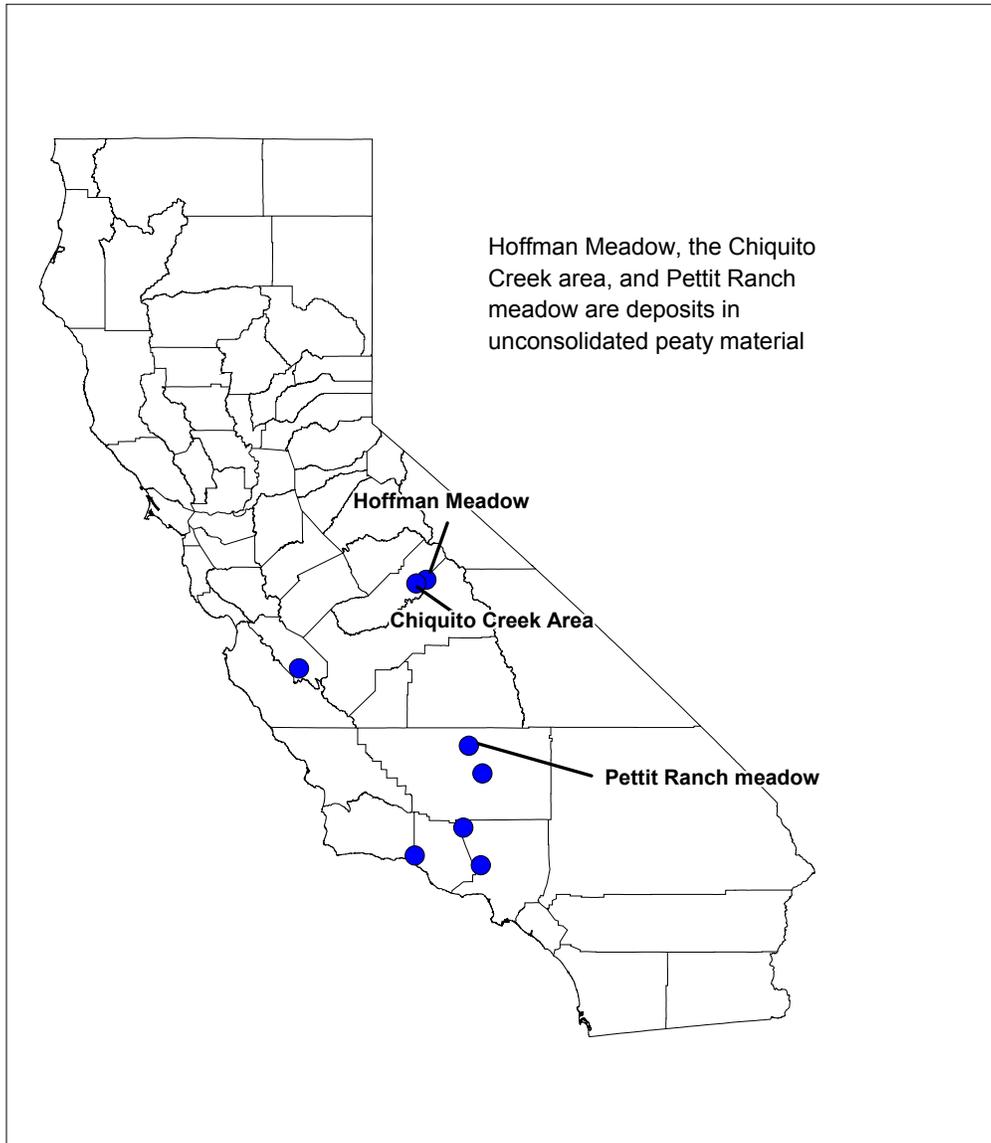
Figure 9. Faults in Northern California (Source: Wagner, 2000)



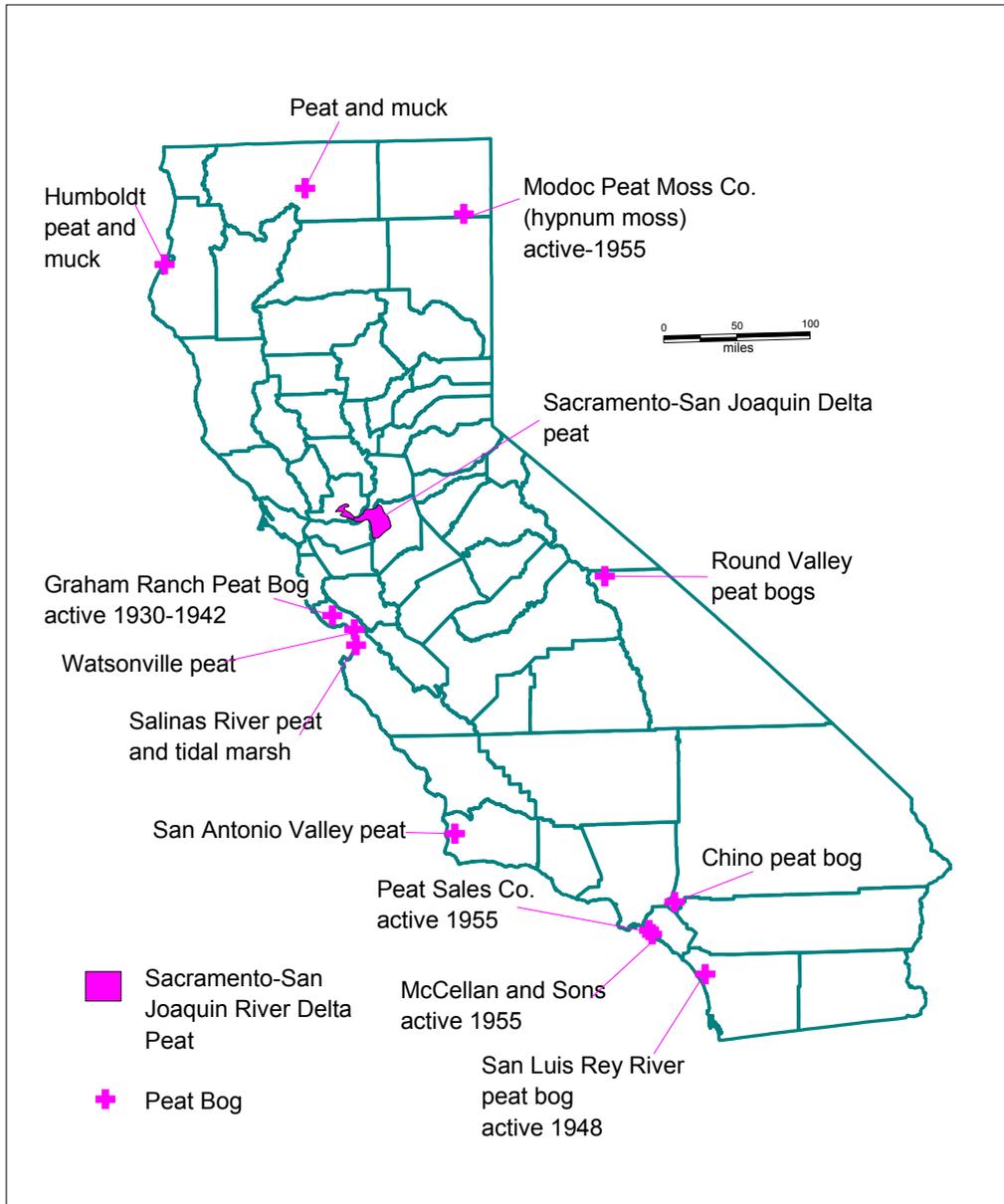
**Figure 10. Uranium Mines and Prospects in California**



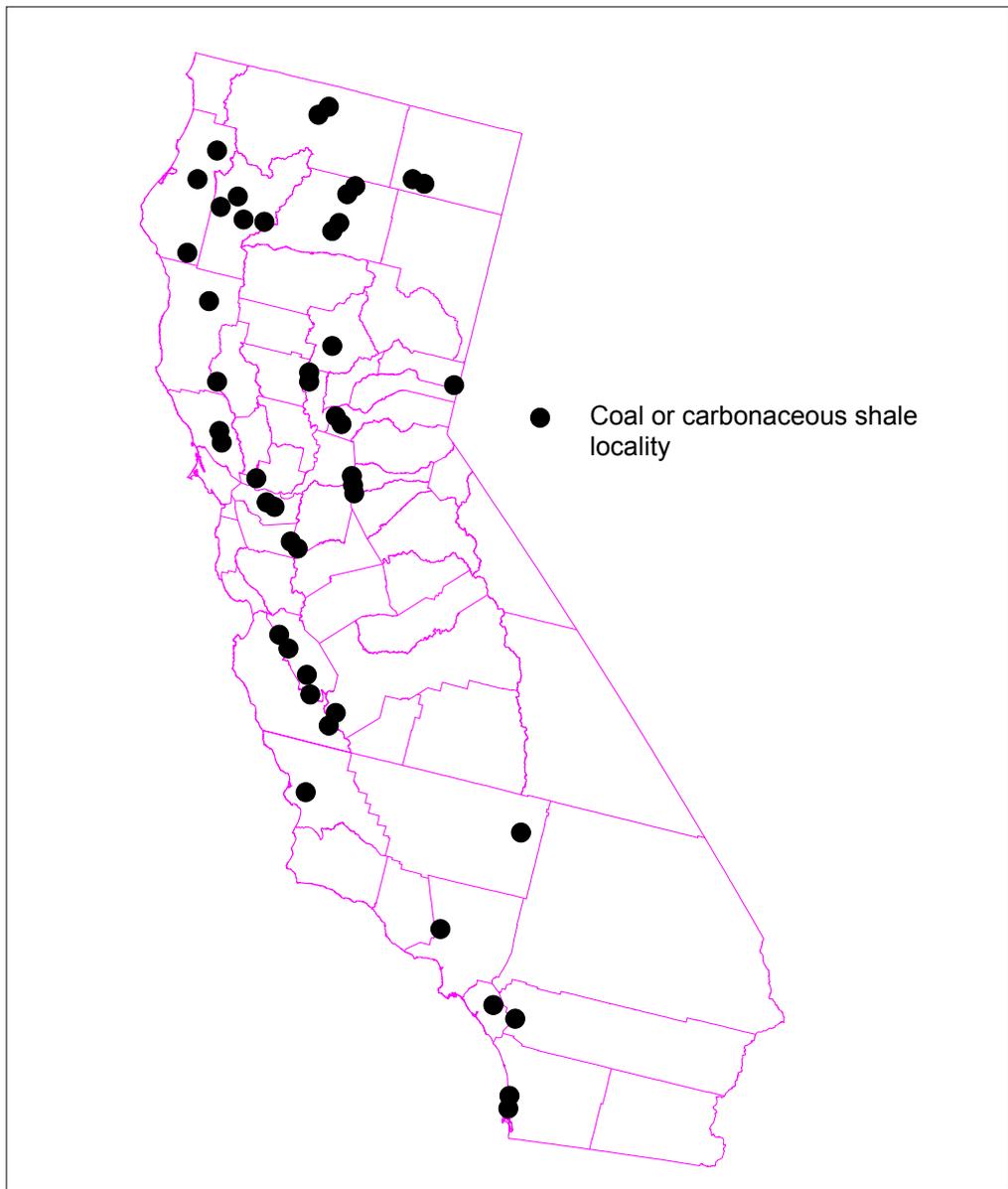
**Figure 11. Locations of Deposits of Coaly Carbonaceous Rocks with Uranium (modified from Vine, 1962)**



**Figure 12. The Distribution of Peat in California  
(Modified from Jennings, 1957)**



**Figure 13. Localities examined for uranium-bearing carbonaceous rocks, 1952. (Modified from Moore and Stephens, 1952)**



**Figure 14. Uranium-238 Decay Series**

