A GEOLOGIC MAPPING APPROACH TO IDENTIFY RADON HOT-SPOTS IN CALIFORNIA AND RAMIFICATIONS FOR THE STATE'S RADON RISK PICTURE

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Abstract

The California Geological Survey (CGS), in cooperation with the California Department of Public Health--Radon Program, has completed seven detailed radon potential maps at 1:100,000 or 1:48,000 scales since 2005. The CGS mapping process uses: 1) geologic maps; 2) short-term indoor-radon data; 3) sediment, soil and rock uranium data; and 4) soil data. CGS maps depict up to 5 radon potential categories, defined by percentages of homes exceeding 4 pCi/L: very high, high, moderate, low or unknown. CGS mapped high radon potential areas in western Los Angeles County correlate well with high radon potential Zip Code areas identified by a 1991 study using year-long house radon measurements. The CGS maps show California has significant high radon areas but many are too small for detection by the 1990 statewide radon survey and, consequently, are not represented by the US EPA Radon Zones or the Lawrence Berkeley National Laboratory (LBNL) High Radon Project maps.

Introduction

The California Geological Survey (CGS) has had annual cooperative agreements with the California Department of Public Health (CDPH)--Radon Program since 2003 to prepare radon potential maps and assist with radon surveys[1]. During this period CGS completed detailed radon potential maps for the southern half of Los Angeles County, Ventura County (revision of a 1995 CGS map), San Luis Obispo County, Monterey County, Santa Cruz County, the Palos Verdes area of Los Angeles County, and the Lake Tahoe area (Figure 1). A radon potential map was prepared for Santa Barbara County in 1995 under an earlier cooperative agreement. All CGS maps completed thus far are within US EPA Radon Map Zone 1 and Zone 2 counties (Figure 2). Approximately 10.7 million individuals, 28 percent of the state's population, reside within the CGS mapped areas. The mapping priority for California coastal counties relates to the presence of Miocene age organic-rich siliceous marine shale and mudstone geologic units such as the Monterey Formation and the Rincon shale (Figure 3). Association of these units with elevated radon homes has been known since the late 1980s (Churchill, 1997). Reports accompanying CGS radon potential maps document procedures, data utilized, and contain estimates for the number of residents exposed to ≥ 4 picocuries per liter (pCi/L) indoor -radon concentration. The maps and reports are available for viewing and downloading on the CGS radon webpage at: http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/radon/Pages/Index.aspx

1 CGS radon mapping activities were partially funded through CDPH-Radon Program annual US EPA State Indoor-Radon Grants (SIRG) and partially through match funds provided by CGS.

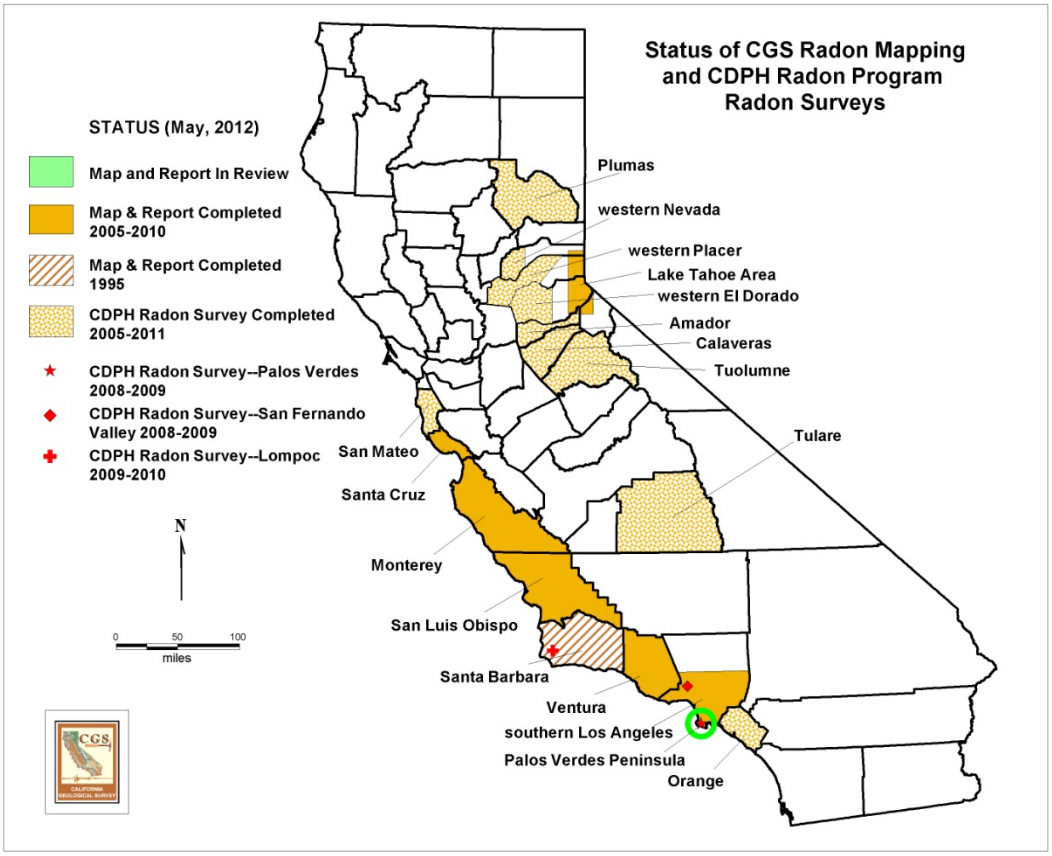


Figure 1. Status of CDPH--Radon Program Indoor-Radon Surveys and CGS Radon Mapping

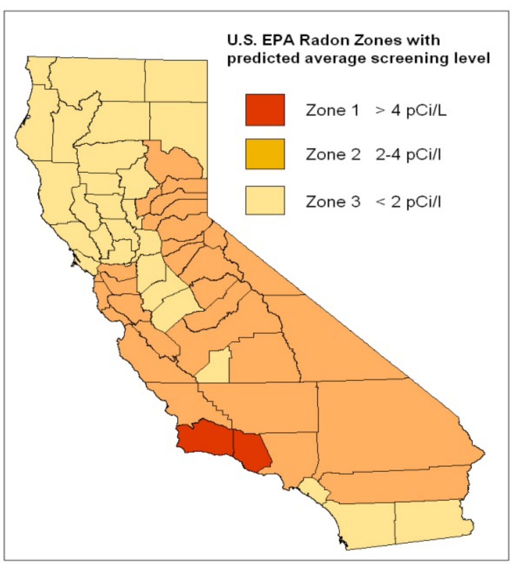


Figure 2. Map showing 1993 US EPA Radon Zone Classifications for California Counties

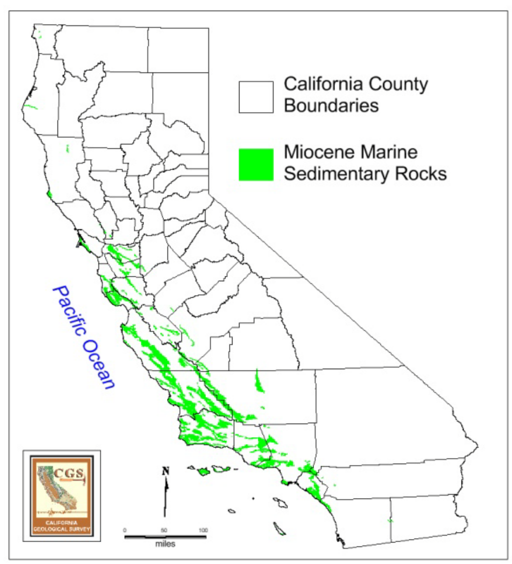


Figure 3. Map showing Miocene Marine Sedimentary Rocks in California
Geology source: Saucedo and others, 2000

CGS radon potential mapping overview

The CGS radon mapping goal is to identify the portions of a county or study area most likely to contain homes with indoor-radon concentrations at or above the US EPA recommended radon action level of 4 pCi/L. The CGS uses a geologically based mapping approach. This means that the location of one or more geologic units belonging to a given radon potential category defines the distribution of that radon potential category within the map. Many others have proposed this radon mapping approach and it has been successfully used in the United Kingdom (Appleton, 2005). For a discussion of the advantages of this approach for radon potential mapping over a simple random sampling of homes approach see Carlisle and Azzouz (1993).

CGS radon potential categories are based on short-term home radon test data and are defined as follows:

Very High: 50 percent or more home tests equal or exceed 4.0 pCi/L

High: 20 to 49.9 percent of home tests equal or exceed 4.0 pCi/L

Moderate: 5 to 19.9 percent of home tests equal or exceed 4.0 pCi/L

Low: 0 to 4.9 percent of home tests equal or exceed 4.0 pCi/L

Unknown: insufficient data are available to assign a radon potential.

All counties and areas mapped so far by CGS contain at least one high radon potential area (see Figure 4 map example). To date, the "Very High" radon potential category has only been required for the Lake Tahoe Area (see Figure 4). Maps completed since 2008 include the "Unknown" radon potential category where geologic units lack sufficient data for radon potential determination. These areas may be targets for future indoor-radon surveys, surface gamma-ray surveys or other radon evaluation work.

Geologic unit radon potentials are determined using indoor-radon measurements, uranium abundance data for soil, sediment and rock, and soil permeability and shrink-swell data. Except for indoor-radon measurements, data used for mapping are "off the shelf" from a variety of sources. California counties commonly contain more than 50 geologic units and some have more than 100 units[2]. Map preparation utilizes a Geographic Information System (GIS) which greatly facilitates data compilation, management and analysis for these large numbers of geologic units. GIS also allows the visual display of data distribution and values relative to individual geologic units. Visual inspection of such displayed data may reveal geographic trends within a geologic unit occurrence. If such a trend is observed the geologic unit occurrence may be subdivided and the subareas assigned different radon potentials to reflect the data trend.

Short-term, 2-3 day indoor-radon data from recent home surveys conducted by CDPH (described below) are used for geologic unit evaluations. When available, indoor-radon data from older

2 Information on 770 geologic units was compiled for developing the California Geological Survey's 1:750,000-scale Map of California Geology.

surveys and other CDPH compilations are examined but are primarily used for unit evaluations only if recent survey data are unavailable. For the CGS maps the number of indoor-radon tests available has ranged from 443 to 1,729. Experience has shown that about 25 short-term indoor-radon measurements are required to reliably categorize the radon potential of a geologic unit. This amount is consistent with the minimum number of samples required to reliably define sample population standard deviation (e.g., Noether, G., 1971, pp. 169-170) and for testing population normality (Razali and Wah, 2011). Interestingly, the British Geological Survey has found that 10-15 short-term measurements are the minimum required to reliably characterize soil radon gas at a site or a geologic unit (Appleton, 2005). Geologic units with less than 25 radon measurements may be assigned a "provisional" high or moderate rank if they have at least 10-15 measurements with a significant percentage exceeding 4 pCi/L, or if they have several measurements exceeding 10 pCi/L. Review of geologic unit data from adjacent completed radon potential maps may also result in provisional high or moderate radon potential rankings for units with few radon measurements in a current mapping area.

Uranium data sources commonly used for radon potential mapping are: National Uranium Resource Evaluation project (NURE) airborne equivalent uranium (eU) data and soil, sediment and rock sample uranium data; rock, soil and sediment sample uranium data from various published and unpublished geochemical research projects; and surface gamma-ray spectral eU measurements from research projects. Large amounts of data may be available for some counties but not others. For example, 1,347 miles of NURE project flight-lines containing approximately 54,800 gamma-ray spectral measurements were flown on a grid pattern with lines 2-4 miles apart north-south and 12 miles apart east-west in San Luis Obispo County. Additionally, 120 soil and 405 stream sediment uranium analyses are available from the NURE project for San Luis Obispo County. In contrast, no NURE airborne eU measurements or soil or stream sediment uranium data are available for metropolitan Los Angeles County, including the Palos Verdes Peninsula.

All uranium data types for a geologic unit are compared to the average crustal uranium abundance of about 2.5 parts per million (ppm) to qualitatively evaluate the unit's likely radon potential. Geologic units containing $\geq$ 5 ppm uranium (twice average crustal background) are generally considered anomalously high in uranium content, suggesting increased radon availability in rock and associated soil and sediment. Consequently, geologic units with the highest percentages of $\geq$ 5 ppm in a county or area are considered candidates for inclusion in the high or moderate radon potential categories. For example, if a geologic unit had only 12 indoor-radon measurements, but 3 (25%) exceeded 4 pCi/L and it had 10 soil uranium analyses with 6 exceeding 5 ppm uranium it would likely receive a provisional high radon potential classification. For NURE airborne eU data, geologic units containing the highest percentages of $\geq$ 5 ppm measurements may also be given provisional high or moderate radon potential classifications. Occasionally, much of the NURE eU data in a county exceeds 5.0 ppm (perhaps because of detector calibration issues when the data were collected). In these instances, 3 times crustal uranium abundance, 7.5 ppm uranium, is used for sample screening. Surface gamma-ray eU data are evaluated similarly, in reference to the $\geq$ 5 or $\geq$ 7.5 ppm thresholds. The purpose of this activity is to quickly identify those geologic units that often contain anomalous background uranium concentrations so they can be considered for inclusion in either the high radon potential or moderate potential groups of geologic units. This is an important step in assigning radon potentials to geologic units that have few or no indoor-radon data.

Soil permeability and shrink-swell data for soils associated with geologic units are obtained from Natural Resource Conservation Service (NRCS) soil reports. Unfortunately, these data are based on type soil locations considered representative of the soil unit as a whole rather than from specific sites near indoor-radon test homes; but they are still useful. Previous work at elementary school sites (Churchill, 1993a and 1993b) has shown California soils with: 1) moderate permeability and low shrink-swell character, or 2) low permeability and high shrink-swell character, are often associated with higher radon potential areas. Soils with either high permeability, or low permeability and low shrink-swell character, are often associated with lower radon potential areas. Consequently, these soil characteristics are also considered, along with uranium data and indoor-radon data, in making provisional assignments of geologic units to radon potential categories. However, provisional high or moderate radon potential assignments are not made based upon soil data alone (i.e., if indoor-radon or uranium data are unavailable).

The data evaluation steps just described result in groupings of very high, high, moderate, low and unknown radon potential geologic units. Each group typically contains a mix of geologic units, some units with 25 or more indoor-radon measurements and some with fewer and occasionally a unit with no associated indoor-radon measurements. The resulting aggregate indoor-radon populations for each group are compared statistically to confirm they significantly differ from each other. This comparison is usually done using the Mann-Whitney nonparametric test because these aggregate population distributions are typically non-normal and non-lognormal in character. While indoor-radon population distributions for single geologic units are often lognormal, the resulting indoor-radon data population distributions for groups of geologic units are often non-lognormal, mandating the use of non-parametric statistical comparison tests. If testing shows that each group is statistically unique, radon potential group boundaries are developed based upon the boundaries of the geologic units making up each group. If two or more radon potential groups are not statistically distinct, then the group assignments of provisional geologic units will be re-evaluated and possibly changed or a radon potential group may be eliminated and its geologic units and indoor-radon data assigned to another radon potential group. Another option is to slightly adjust the radon potential group boundaries to achieve statistical separation of radon potential group populations. However, such adjustments should be small because the different radon potential categories should be similar from map to map.

Final CGS radon potential maps are produced at 1:100,000-scale for which 1 inch represents 1.58 miles (or 1 cm represents 1 km). Less commonly more detailed scales such as 1:48,000 are used. At 1:100,000-scale city blocks can be depicted and prominent highways and roads can be shown and labeled on the map base, assisting the map user in identifying specific locations of interest. Figure 4 is reproduced at approximately 1:100,000-scale and shows highway and street details and different radon potential areas.

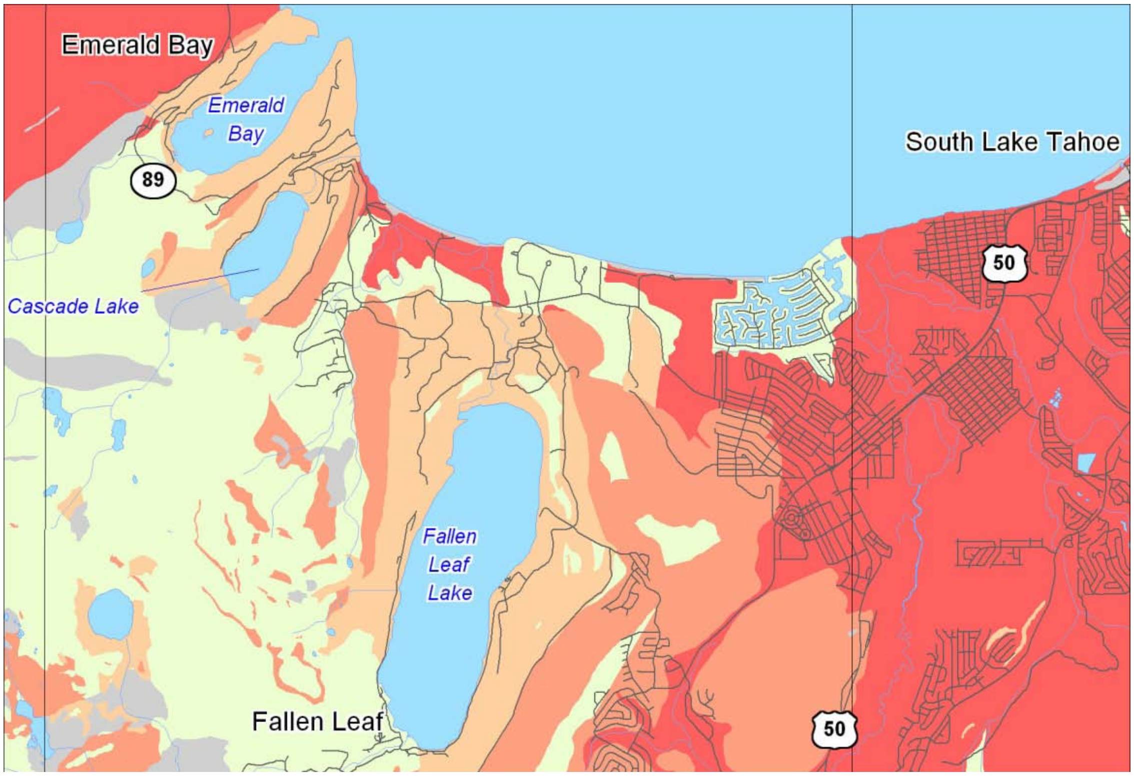


Figure 4. Part of the CGS Lake Tahoe Radon Potential Map.
The radon potential area categories are color coded as follows: red = very high radon potential; dark orange = high radon potential; light orange = moderate radon potential, pale green = low radon potential, and gray = unknown radon potential.

Geologic maps for radon potential mapping—requirements and limitations

Not every geologic map is suitable for radon potential mapping. In California, geologic maps at 1:100,000-scale (1 inch = 1.58 miles, or 1 cm = 1 km) or more detailed scale geologic maps such as 1:62,500-scale or 1:24,000-scale should be utilized for this purpose. At more detailed scales geologic map units often represent individual geologic formations, which generally have a predominant lithology and somewhat limited range of chemical composition (e.g., variation in uranium or radium concentration). Less detailed scale geologic maps (e.g., 1:250,000-scale or 1:750,000-scale) use more generalized map units defined by geologic time and origin (e.g., Miocene marine sediments). Less detailed scale geologic units typically consist of multiple geologic formations which may differ significantly from each other in lithology, chemistry, physical properties such as permeability and, consequently, in radon potentials. Table 1 provides examples illustrating differences in numbers of map units related to map scale for geologic maps.

If preexisting 1:100,000-scale geologic maps are not available for a county or map area, spatial geologic unit data must be compiled from multiple smaller scale maps such as 1:62,500-scale or 1:24,000-scale. This can be a time consuming process, particularly if the geologic map units are defined or mapped differently on different maps. Figure 5 shows geologic mapping for a small portion of the Lake Tahoe area at three different map scales 1:750,000, 1:250,000 and 1:100,000.

	Number of Geologic Units Shown on Geologic Maps at Different Map Scales		
Examples	**1:750,000 (1 inch=11.8 miles)**	**1:250,000 (1 inch=3.9 miles)**	**1:100,000 (1 inch=1.6 miles)**
Santa Cruz County	13	17	65
Lake Tahoe Area	11	36	141

Table 1. Comparison of a group of related geologic map units from California geologic maps at different map scales

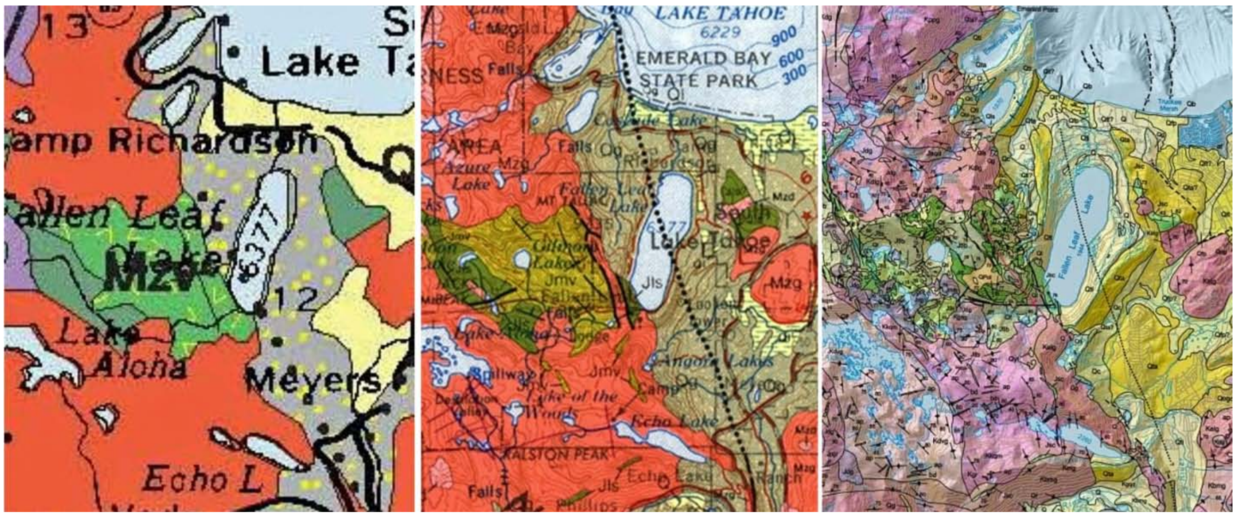


Figure 5. Geologic units from geologic maps developed at different map scales showing increase in geologic units and detail from left to right. The maps from left to right: 1:750:000-scale, 1:250,000-scale and 1:100,000-scale (the maps are not shown at their original scales). The area shown is at the south end of Lake Tahoe and each map is approximately 8.3 miles wide (E-W) and 10.7 miles long (N-S). The map references for these images are: Jennings, 1977; Wagner and others, 1981; and Saucedo, 2005.

Another geologic map issue is accuracy. At more detailed map scales geologic unit boundary locations are generally more accurately located because they require more field work than less detailed geologic maps. For 1:100,000-scale California geologic maps, geologic unit boundaries will often be accurate to better than plus or minus 1000 feet. Also, the size of map features that can be depicted should be kept in mind when using maps at various scales. A 1/16 inch wide line on a 1:250,000-scale map represents 1,302 feet. A 1/16 inch wide line on a 1:100,000-scale map represents 520 feet. A typical home lot parcel that appears to be located just inside a radon potential boundary on a 1:100,000-scale radon potential map is probably within the uncertainty of geologic unit boundary mapping. It may actually be underlain by an adjacent geologic unit with a different radon potential.

Public reception of CGS radon potential maps

CGS radon maps and accompanying reports are available for viewing and downloading on the CGS Radon webpage. CGS radon potential maps are advisory and non-regulatory in status. Recently, CGS radon webpage visits total about 5,800 per year and average about 480 per month. Several counties have placed the maps on their county websites. An iPhone app is now available for displaying CGS radon maps (Hobbs and Hobbs, 2012). CGS is receiving requests from property disclosure companies for its digital map radon potential area layers and recently has been able to start fulfilling those requests. Finally, detailed radon potential maps draw people to radon informational displays in public areas, particularly if the map covers the area where they reside. People want to find out what the radon potential is where they live.

CDPH indoor-radon surveys

In order to generate indoor-radon data for radon potential mapping, CGS assists CDPH-Radon Program indoor-radon survey efforts in reviewing address lists of owner occupied homes and preparing address lists for survey mail solicitations. The goal for solicitation mailing lists is to obtain a minimum of 25 to 30 indoor measurements for geologic units known or suspected to be associated with higher percentages of ≥ 4 pCi/L homes. With survey participation rates typically between 3 and 8 percent of solicitation letters, at least 600 addresses are randomly chosen for each likely radon-problem geologic unit if possible. If fewer than 600 addresses are available for a priority geologic unit all addresses related to that unit received a survey solicitation. After addresses for priority geologic units are assigned, the remaining addresses for the survey solicitation mailing list are assigned in an attempt to obtain some indoor-radon data for most or all of the remaining geologic units in the county or study area. Survey sampling generally starts between late November and early January and is completed by early May. Surveys utilize charcoal detectors exposed for 2-3 days and test results are provided directly to participants by CDPH contract radon laboratories within a few weeks after laboratory receipt of a detector. Once the CDPH-Radon Program obtains the survey test results from the laboratory they are incorporated into the online Radon Zip Code database for California and are made available to CGS for radon mapping projects. Survey participant names and addresses are proprietary and not available for public disclosure. Since 2003 all or portions of 14 counties have had indoor-radon surveys.

Does the CGS radon mapping approach using short-term home radon tests have merit?

Given the general consensus that short-term indoor-radon test data are less reliable than long-term test data, it is reasonable to question the reliability of CGS radon potential maps based on short-term test data. To check the mapping reliability, CGS maps for southern Los Angeles and Ventura counties were compared to a 1991 California Department of Health Services (DHS[3]) Indoor Air Quality study of 862 homes in 49 Zip Codes areas. Year-long alpha track measurements were conducted in the homes (Lui and others, 1991). If the DHS study high and medium radon potential Zip Code locations are similar to CGS high and moderate radon

3 California Department of Public Health was formerly named Department of Health Services.

potential area locations and if DHS and CGS ≥ 4 pCi/L home percentages are similar, it would be strong evidence supporting the CGS radon mapping approach.

Comparison of CGS mapping and DHS study results was done as follows:

1) Using GIS, DHS high and moderate radon potential Zip Code area locations were compared with CGS high and moderate radon potential area locations, and

2) Estimates of the average percentage of homes ≥ 4 pCi/L were prepared for DHS high and medium radon potential Zip Codes using CGS radon potential maps and compared with the averages reported in the DHS study.

For the first comparison, digital map layers for CGS radon potential areas and DHS high and medium radon potential Zip Code areas were compared. Figure 6 shows this comparison. The

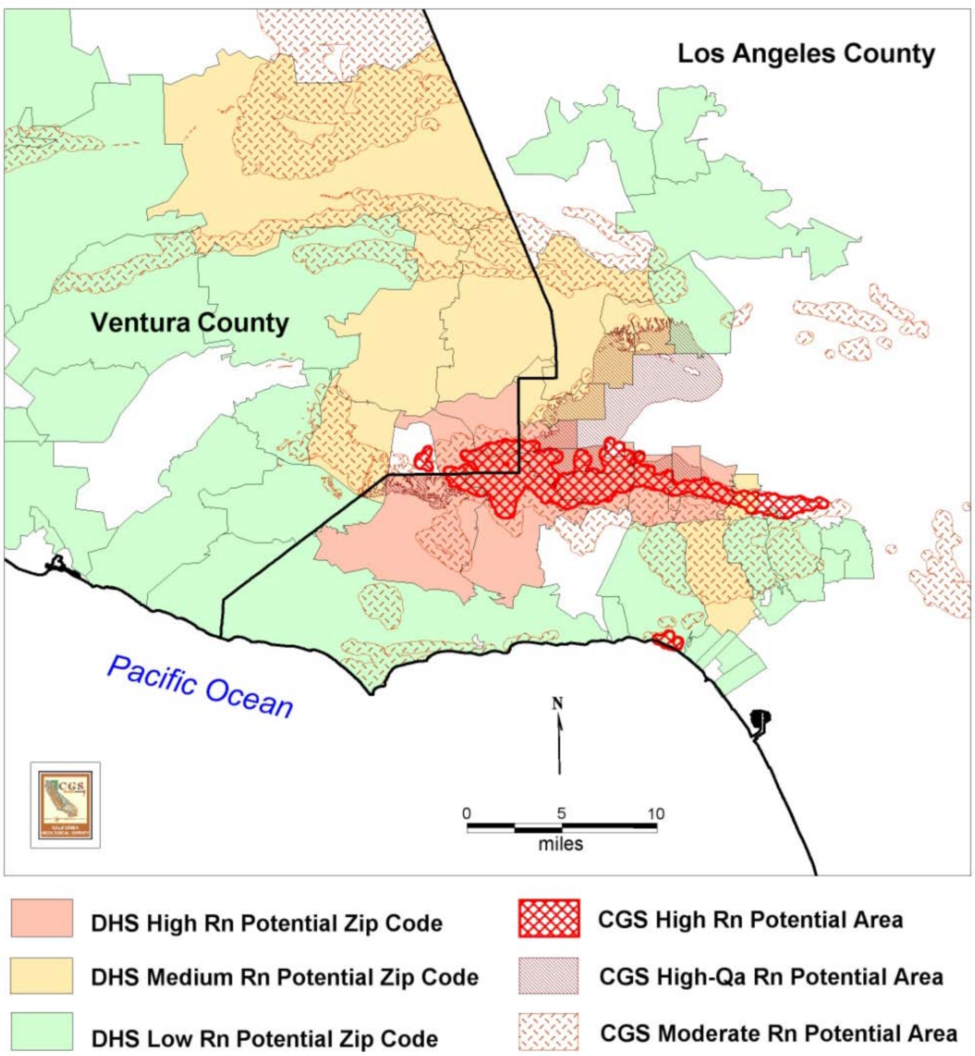


Figure 6. Comparison of CGS High and Moderate Radon Potential Areas with High, Medium and Low Radon Potential Zip Codes from Lui and others, 1991.

figure shows high and moderate CGS radon potential areas in close association with high and medium DHS zip code areas. The match is not perfect because CGS radon potential zone boundaries are based on geologic unit boundaries and Zip Code boundaries are administrative boundaries typically unrelated to geology. However, high and medium radon potential Zip Code areas generally contain significant portions of high and moderate CGS radon potential areas and high and medium Zip Code areas are not isolated from CGS high and moderate radon potential areas in the figure.

A small CGS high radon potential outlier is located along the Los Angeles County coast in a low potential DHS Zip Code 90272 (Pacific Palisades). Geologic mapping indicates high and moderate potential rock units present in the large east-west high potential area are also present at this location along the coast, exposed along canyons and likely underlying a younger alluvial unit. Limited indoor-radon data available during mapping was insufficient to confirm or reject a high radon potential classification for this area. The most recent 2010 update of the CDPH radon Zip Code database entry for this Zip Code shows about 4 percent of short-term home radon tests are ≥ 4 pCi/L (11 of 276). These results suggest a lower radon potential should be considered for this area if the south Los Angeles radon potential map is revised in the future.

For the second comparison, estimates for the average percent of residences exceeding 4 pCi/L were made for DHS High and Medium Radon Potential Zip Codes using CGS radon potential

County/Area	CGS Radon Potential Category	Percentage of ≥ 4 pCi/L Homes
southern Los Angeles	High	28.3
southern Los Angeles	High-Qa (alluvium)	20.6
southern Los Angeles	Moderate	9.7
southern Los Angeles	Low	2.4
Ventura	High	30.0
Ventura	Moderate	20.3
Ventura	Low	3.7

Table 2. CGS radon potential categories and percentages of ≥ 4 pCi/L homes for southern Los Angeles and Ventura counties provided in reports accompanying these maps.

	DHS average percent of residences exceeding 4 pCi/L reported by Lui and others (1991)	CGS estimate of average percent of residences exceeding 4 pCi/L
DHS High Radon Potential Zip Codes	**14***	**11.9**
DHS Medium Radon Potential Zip Codes	**8****	**7.7**

Table 3. Comparison of DHS and CGS estimates of High and Medium radon potential Zip Code areas in western Los Angeles and Ventura counties.

*The average of 7 Zip Code areas developed from 71 alpha track year-long measurements

**The average for 10 Zip Code areas developed from 169 alpha track year-long measurements maps and indoor-radon information from the map reports. To make these estimates, the relative percentage area for each CGS radon potential category present within each DHS Zip Code was obtained from the radon potential maps using GIS. This information and estimates for percentages of ≥ 4 pCi/L homes for each radon potential category, available from the Los Angeles and Ventura radon map reports, were used to make weighted average estimates of ≥ 4 pCi/L home percentages for each DHS Zip Code. These estimated percentages for each DHS Zip Code were then used to generate overall average percentages of ≥ 4 pCi/L estimates for DHS high and moderate radon potential Zip Codes. The individual Zip Codes vary in size (area). In developing the final averages, individual Zip Code ≥ 4 pCi/L home percentages were weighted to account for differences in Zip Code sizes. The right-hand column of Table 3 lists the resulting High and Medium Zip Code estimates derived from CGS radon maps and data. The High and Medium radon potential Zip Code averages from the 1991 DHS report, listed in the middle column of Table 3, compare well with the estimates derived from the CGS maps and reports.

In summary, similarities in geographic location and percentages of ≥ 4 pCi/L residences between high and medium DHS Zip Code radon potential areas and CGS high and moderate radon potential areas shown in Figure 6 and Table 3 are strong evidence supporting the validity of the CGS radon potential mapping approach.

Comparison of US EPA Radon Map and LBNL High-Radon Project Map with CGS Radon Potential Maps

The US EPA Map of Radon Zones, finalized in 1993, was developed from the US Geological Survey (USGS) Geologic Radon Province Map. To develop the radon province map, the USGS identified approximately 360 separate geologic provinces in the United States, evaluating provinces for radon potential using available indoor-radon data, geology, aerial radioactivity data, soil parameters and home foundation types (US EPA, 1993). California contains all or part of 12 geologic provinces. During winter 1989-1990 a random population based indoor-radon survey generated 2-7 day measurements for 1,885 homes to support this radon mapping effort (i.e., the state residential radon survey, SRRS, for California). Survey sampling rates for many California counties were relatively low, particularly considering county geologic complexity previously discussed. Of 58 counties, one was not measured, six had 1-5 measurements, and only 24 had 25 or more measurements generated from this survey (US EPA, 1993). At the SRRS sampling rates, many California Counties have more geologic units than indoor-radon measurements. This raises the question of just how well SRRS data represent actual radon conditions of California counties.

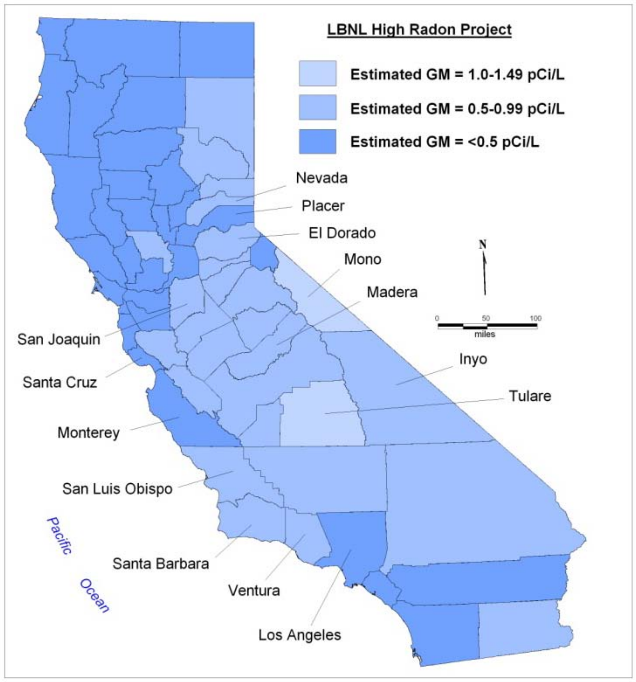
USGS radon geologic province boundaries do not coincide with county or state political boundaries but define areas of general radon potential. US EPA subsequently developed the Map of Radon Zones by extrapolating information from the province to county level and assigning one of three radon zones to every county in the United States. The EPA map Zones 1, 2, and 3 have predicted average radon screening levels of > 4 pCi/L, ≤ 4 and ≥ 2 pCi/L, and < 2 pCi/L, respectively. If a county contains more than one geologic province, the county is assigned the screening level of the province containing the largest portion of county land area (US EPA, 1993).

In showing only one radon zone per county, the US EPA recognized at the time that significant high and low radon potential areas within a county may be obscured (US EPA 1993, p. I-5). This situation had to be addressed during the development of the California portion of the U.S EPA Map of Radon Zones. The radon hot-spot associated with the Rincon Shale in Santa Barbara and Ventura counties ultimately resulted in a change for these counties from an initial EPA Zone 2 classification to a Zone 1 classification, even though the Rincon shale only accounts for about 1.3 percent of the combined two county surface area. There was no other way to indicate the presence of California's first confirmed radon hot-spot on the EPA map (Figure 2 shows the EPA Radon Zones for California).

Similar in style to the EPA Map of Radon Zones, the Lawrence Berkeley National Laboratory (LBNL) High Radon Project maps, produced in the mid-1990s, also used single county rankings for radon potential. The High Radon project produced two radon potential maps, one ranking counties by geometric mean and the other ranking counties by estimated percent of homes with long-term living-area concentrations ≥ 4 pCi/L. The High Radon Project developed its California county rankings using the same short-term radon survey data as used for the EPA Map of Radon Zones. However, it used a statistical approach to examine the correlation between monitoring data and physical factors such as soil, geology, house, and meteorological characteristics to predict local indoor concentrations and make long-term exposure estimates. Maps showing LBNL High Radon Project predicted geometric means and percentages of ≥ 4 pCi/L homes for California counties are shown in Figures 7 and 8 respectively. The maps in Figures 7 and 8 were developed using LBNL-High Radon Project data available online at: http://energy.lbl.gov/IEP/high-radon/ctypred.htm

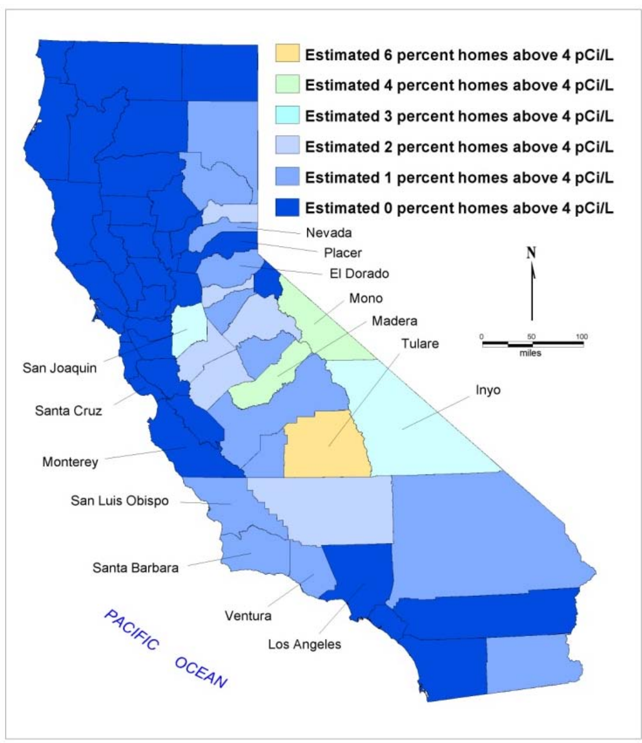
The visual impression presented by the EPA and LBNL radon maps are that most California counties do not have significant radon problems, especially when compared against counties in Midwestern and Northeastern states. Exceptions are Santa Barbara and Ventura counties on the EPA map with Zone 1 rankings. Tulare and possibly Madera, Mono, Inyo and San Joaquin counties are exceptions on the LBNL map with three to six percent estimated≥ 4 pCi/L homes (Figure 8). Interestingly, the LBNL map of estimated county geometric mean radon concentrations (Figure 7) gives a different impression than the≥ 4 pCi/L home percentages map. The county geometric mean map shows very low geometric mean estimates for Tulare, Madera, Mono, Inyo and San Joaquin counties. With single county radon ratings by design, the EPA and LBNL maps do not convey the presence of any sub-county variability in radon potentials. As a result, many people trying to become informed about radon do not realize that high, moderate, or low radon potential areas of significant size may be present in any county regardless of its zone ranking, geometric mean or estimated percentage of homes > 4 pCi/L.

In contrast to the US EPA and the LBNL High Radon Project maps, CGS mapping shows that within-county variability in radon potential is significant. Given the geologic complexity and relatively large land areas of California counties such variability is expected. Figure 9 shows CGS high and moderate radon potential areas overlain on the US EPA Map of Radon Zones for California. Table 4 provides information on total land areas and populations associated with CGS high and moderate radon potential categories by county.



Data source: http://energy.lbl.gov/IEP/high-radon/ctypred.htm

Figure 7. LBNL High Radon Project: Estimated Geometric Mean Radon Concentrations for California Counties



Data Source: http://energy.lbl.gov/IEP/high-radon/ctypred.htm

Figure 8. LBNL High Radon Project: Estimated Fraction of Homes with Long-term Living-area Radon Concentrations above 4 pCi/L for California Counties

Figure 9 and Table 4 show that high radon potential areas comprise relatively small percentages of county land area and population for counties mapped by CGS thus far. Moderate potential areas are usually larger in area and population than high radon potential areas. The remaining areas, consisting of low and unknown radon potentials, commonly account for the majority of county land area and population. These land area and population trends will likely continue for EPA Zone 2 California counties mapped in the future.

Individual high and moderate radon potential areas may contain large populations or be sparsely populated. In Figure 9, examples of sparsely populated high and moderate radon potential areas

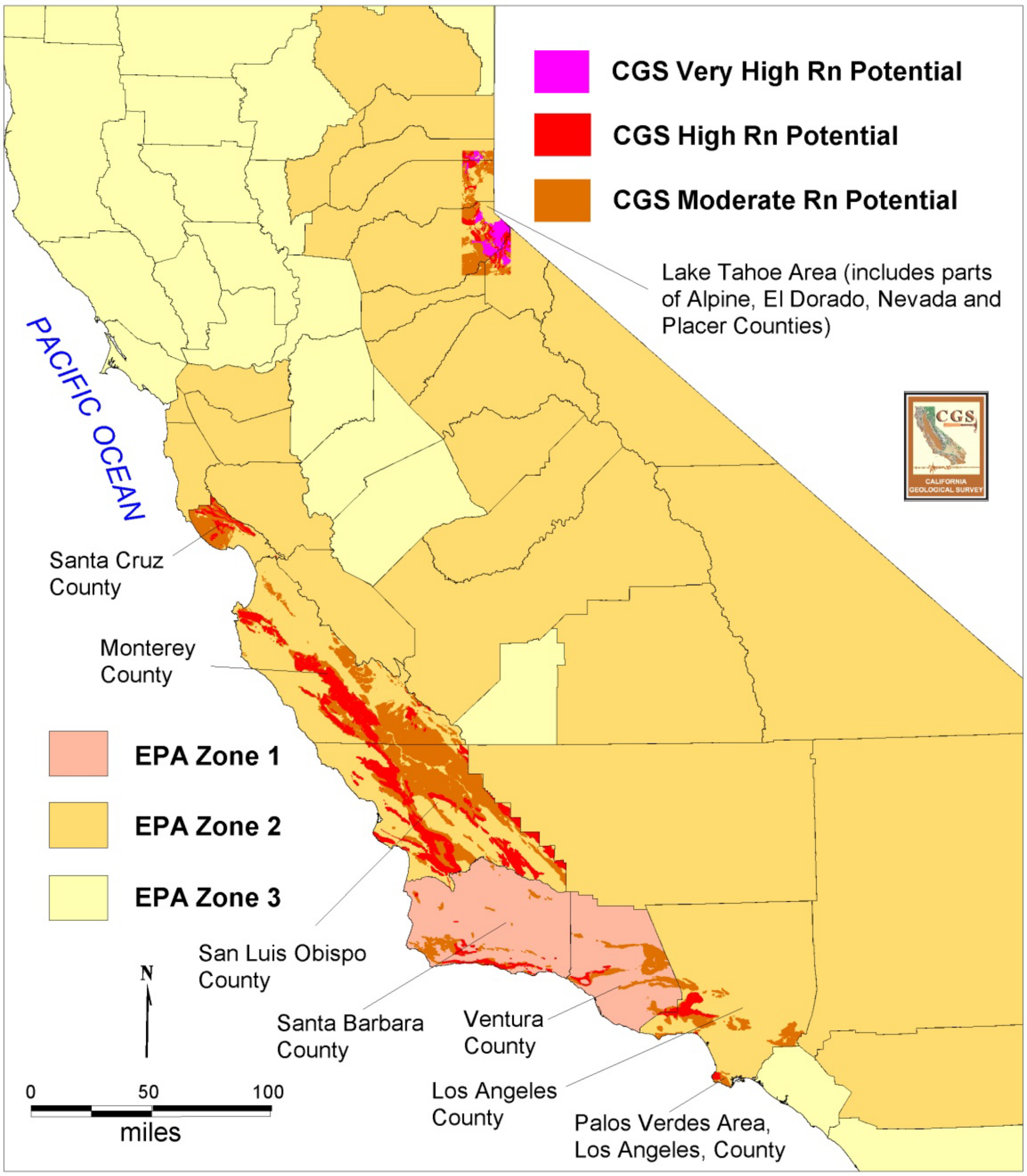


Figure 9. CGS very high, high and moderate radon potential areas overlain on part of the EPA Map of Radon Zones for California

County or Area Map	Radon Potential Category	Land Area (square miles)	Percent of County Land Area	Estimated Population (to nearest 1,000)	Percent of County Population
Santa Cruz	High	43.7	10.6	10,000	3.9
	Moderate	187.7	42.1	56,000	22.0
Monterey	High	361	10.9	11,000	2.7
	Moderate	671	20.2	66,000	16.4
San Luis Obispo	High	590	17.8	40,000	16.2
	Moderate	1025	30.9	48,000	19.4
Santa Barbara (1995 map)	High	72.2	2.6	Population estimates were not made for the 1995 Santa Barbara map	
	Moderate	140.7	5.1		
Ventura	High	25.0	1.3	4,000	0.5
	Moderate	216	11.6	42,000	5.6
Southern Los Angeles County including the Palos Verdes Area	High	36.9	0.9	132,000	1.4
	High-Qa	40.9	1.0	281,000	3.0
	Moderate	233.8	5.8	778,000	8.2
	County population =9,519,000; County and Area =4,061 square miles				
Lake Tahoe Area--Divided by County (population estimates not rounded to nearest 1000)					
El Dorado County	Very High	76.4	4.5	25,640	16.4
	High	51.5	3.0	4,708	3.0
	Moderate	142.5	8.3	1,873	1.2
	County population = 156,299; County land area = 1,711 square miles				
Nevada County	Very High	7.9	0.83	2,686	2.9
	High	8.1	0.85	3,120	3.4
	Moderate	21.1	2.2	3,970	4.3
	County population = 92,033; County land area = 957 square miles				
Placer County	Very High	2.6	0.2	15	0.0
	High	12.8	0.9	1,338	0.5
	Moderate	66.9	4.8	8,513	3.4
	County population = 248,399; County land area = 1,404 square miles				

Table 4. Land Area and Population Information for County High and Moderate Radon Potential Categories. The Lake Tahoe county estimates are for those portions of the counties within the Lake Tahoe radon potential map area. The south Los Angeles county estimates are for all of Los Angeles County. Total land area and populations for these counties are listed in the fourth row for each county.

are those located in central and southern Monterey County and in eastern and southern San Luis Obispo County. Examples of high and moderate radon potential areas with high population densities are those located in Los Angeles County and along the south coast of Santa Barbara County.

CGS radon potential areas and average annual radon exposure estimates

CGS very high, high and moderate radon potential areas are compared with LBNL estimated California county percentages of homes with long-term living-area concentrations $\geq$ 4 pCi/L in Figure 10. The CGS high and moderate radon potential areas are based on percentages of homes

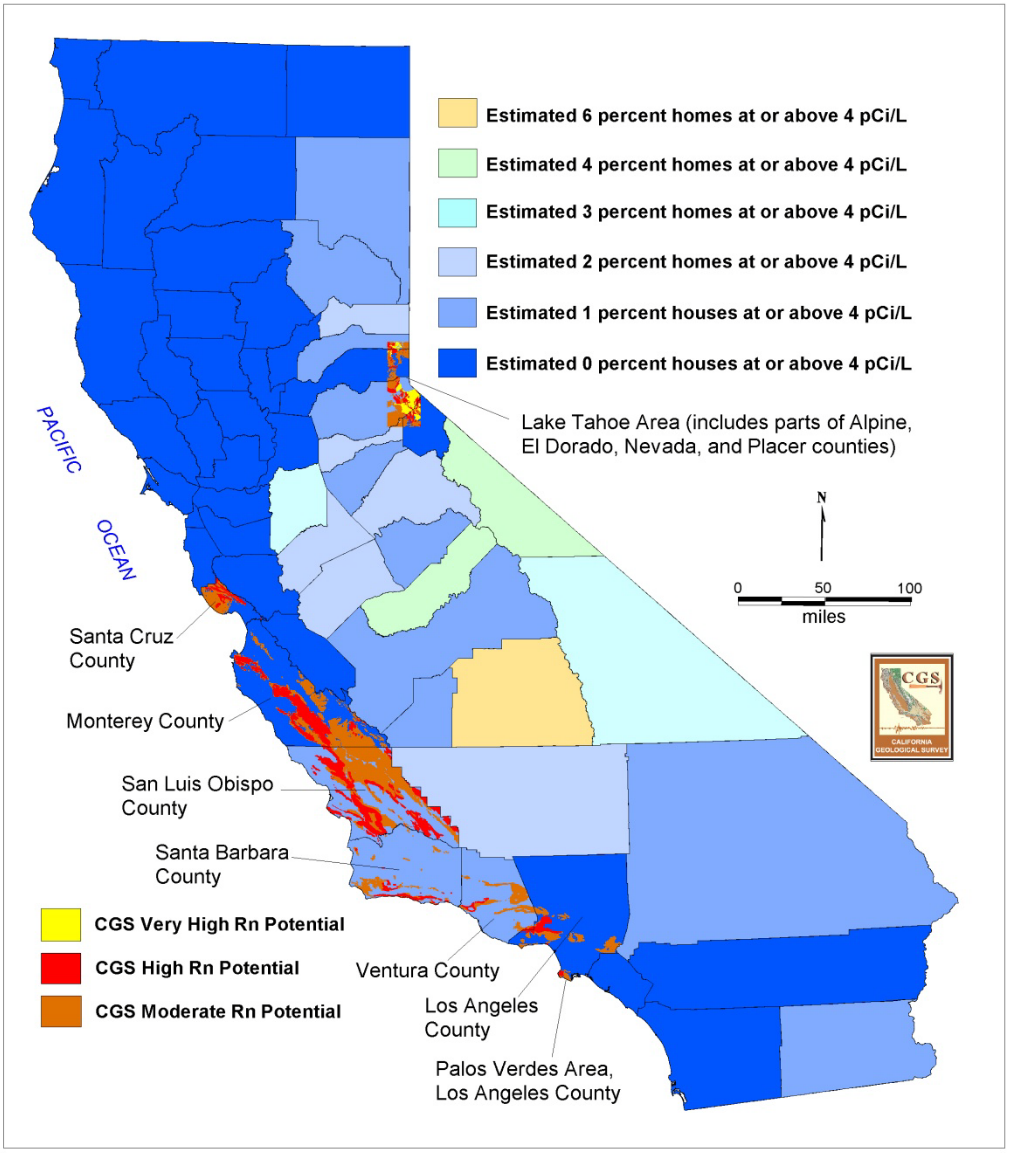


Figure 10. Comparison of LBNL High Radon Project estimated percent of ≥ 4 pCi/L county homes and CGS very high (Lake Tahoe only), high and moderate radon potential areas.

≥4 pCi/L in short-term tests. Short-term tests are closed-house "worst case" tests with seasonal bias compared to year-long open-house tests. Short-term tests from winter months generally exceed annual living area average radon conditions (Appleton, 2005; Lin and others, 1999; and Brookins, 1990). CGS percentage estimates of ≥ 4 pCi/L homes are shown in Table 5 for high and moderate radon potential categories and are very likely higher than what would be obtained from year-long radon test surveys of homes in these counties. In order to better compare CGS radon potential results with LBNL county estimates, a correction was applied to CGS short-term radon data to create simulated long-term indoor-radon databases for county high and moderate radon potential areas. Summary information for these simulated databases and associated population estimates are listed in Table 6.

Long-term radon concentration estimates based on short-term measurements are controversial and approximate. The estimated long-term radon measurement database used to build Table 6 was made using a correction factor from Lin and others (1999). These authors recognize the highly approximate nature of these corrections and state *"Due to the large temporal variability and other sources of variation, a short-term measurement can predict the long-term living area concentration only to within a factor of 1.8 or so, even after correcting for systematic biases."*

Radon Potential Group	CGS Percentage Estimates of ≥ 4 pCi/L Homes from Short-term data	Estimated Population exposed to ≥ 4 pCi/L radon concentrations
Santa Cruz County		
High	36.3	3,600
Moderate	11.6	6,500
Monterey County		
High	25.0	2,800
Moderate	6.0	4,000
San Luis Obispo		
High	24.6	9,800
Moderate	8.5	4,100
Santa Barbara County		
Population estimates were not made for 1995 Santa Barbara radon potential areas.		
Ventura County		
High	30.0	1,200
Moderate	20.3	8,500
Southern Los Angeles County		
High	28.3	37,400
High-Qa	20.6	57,900
Moderate	9.7	75,500
Lake Tahoe Area		
Very High	62.2	17,600
High	36.7	3,400
Moderate	16.5	2,400

Table 5. CGS percentage estimates of ≥ 4 pCi/L homes based on short-term indoor-radon data for county high and moderate radon potential areas

Several of the authors of this paper were principal contributors to the High Radon Project. The county estimates from the LBNL High Radon Project shown in Figures 8 and 10 are derived from short-term test data, as previously mentioned, by these individuals.

To estimate the percentages of homes with long-term living-area concentrations ≥ 4 pCi/L, CGS short-term test data were divided by a correction factor of 1.3. This correction factor implies that a 5.2 pCi/L short-term test is approximately equivalent to a 4.0 pCi/L year-long test (i.e., 5.2 pCi/L/1.3=4/0 pCi/L). This correction factor is recommended by Lin and others (1999) for use with southwestern United States short-term radon data from homes without basements measured during winter. Percentages of ≥ 4 pCi/L homes were then determined from the revised County radon data for very high, high and moderate radon potential categories and listed in Table 6.

In reviewing the short-term indoor-radon data from CGS mapping projects, 48 initial tests of 5.2 pCi/L or higher concentrations had follow-up short-term tests. These follow-up tests were made anywhere from 15 days to 301 days after the initial test. The follow-up tests were 4 pCi/L or higher 77 percent of the time (in 37 tests). For nine tests with initial values of 4.0-5.1 pCi/L,

Radon Potential Group	**Estimate of Percent Homes with average annual exposure of ≥ 4 pCi/L**	**Estimated Population exposed to ≥ 4 pCi/L average annual radon concentrations**
	Santa Cruz County	
High	30.0	3,000
Moderate	8.9	5,000
	Monterey County	
High	20.2	2,200
Moderate	4.2	2,800
	San Luis Obispo County	
High	18.4	7,400
Moderate	4.5	1,800
	Santa Barbara County	
Population estimates were not made for 1995 Santa Barbara radon potential areas.		
	Ventura County	
High	30.0	1,200
Moderate	11.6	4,900
	Southern Los Angeles County	
High	20.2	26,700
High-Qa	12.2	34,300
Moderate	7.5	58,400
	Lake Tahoe Area	
Very High	52.1	14,800
High	27.5	2,500
Moderate	11.0	1,600

Table 6. Percentage Estimates of Average Annual ≥ 4 pCi/L Homes for CGS High and Moderate Radon Potential Categories by County Based on Simulated Annual Radon Data Derived from Short-term Indoor-radon Measurements

only three follow-up tests were ≥ 4 pCi/L. These limited results suggest a 5.2 pCi/L threshold for short-term tests corresponding to ≥ 4 pCi/L long term -tests may have some merit.

Correction factors included in Lin and others (1999) range from 1.2, for a home in the Northwestern U.S without a basement, to 4.0 for a home in the Northwestern United States with a non-living area basement. However, most of their correction factors are below 2.4. Although there is uncertainty with these conversions, even if a 2.4 correction factor is used to convert CGS short-term radon data, the estimated annual average living area ≥ 4 pCi/L percentages for most CGS high radon potential areas will still significantly exceed the LBNL estimated county percentages shown in Figure 10.

The LBNL High Radon Project estimated zero percent ≥ 4 pCi/L homes for Santa Cruz, Monterey and Los Angeles counties. CGS mapping identified statistically significant high and moderate radon potential areas in these counties (DHS also did in Los Angeles and Ventura Counties in their study in 1991 Zip Code discussed above). These results point to the necessity of higher density radon surveys and a geologic approach to radon mapping for identifying the high and moderate radon potential areas typical for California.

Summary

In summary, CGS radon potential mapping using short-term home radon data, geologic mapping and other data has identified small but statistically significant high and moderate radon potential areas in eight counties and areas mapped since 2005. CGS mapping results agree closely with results from a 1991 DHS study of Los Angeles and Ventura county Zip Codes. That study used year-long radon-test data for homes, validating the CGS use of short-term radon-test data for homes and geologic mapping approach for identifying high and moderate radon potential areas in California.

High radon potential areas within California counties are typically small, often comprising just a few percent of county land area and with associated populations of a few thousand to a few tens of thousands of people. Los Angeles County is an exception because of its high population density and may have as many as 400,000 persons residing in high radon potential areas. Moderate radon potential areas typically are larger in county land area and population percentage than high radon potential areas. The combined high and moderate radon potential areas in a county are typically smaller in land area and population than the low radon potential portion of a county.

US EPA and LBNL radon potential maps, by design, are not able to represent the small to moderate sizes and scattered distribution of the high and moderate radon potential areas typical in California. The EPA radon map gives the impression that serious radon problems exist everywhere in Santa Barbara and Ventura counties, rather than for only about 2 percent of the land area (the high radon potential portions) of the counties. On the other hand, the EPA radon map does not convey the presence of small but significant high radon potential areas such as present in Los Angeles County. The LBNL map of estimated percentages of homes ≥ 4 pCi/L shows California counties generally have very low percentages and for some counties the estimated percentage is zero. CGS radon potential maps prepared for three counties with LBNL zero percent estimated ≥ 4 pCi/L homes found small but statistically significant high and moderate radon potential areas in these counties. In other counties CGS high and moderate potential areas are present with estimated ≥ 4 pCi/L homes much higher than the LBNL overall county estimates. That county radon problems have been missed or underestimated in the LBNL county assessments underscores the need for a more detailed radon assessment approach in California than that employed by LBNL. Both the US EPA and LBNL radon potential maps utilize SRRS indoor-radon survey measurements. At the SRRS sampling rates, many California Counties have more geologic units than indoor-radon measurements. This raises the question of just how well SRRS data represent actual radon conditions of California counties. The CGS approach relies on greater numbers of home short-term radon tests, uses those tests and other data to assess radon potentials of individual geologic units, and defines radon potential areas by the presence of similar radon potential geologic units. This approach has proven effective at identifying California's scattered small to moderate sized high radon potential and moderate radon potential areas.

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