SPECIAL REPORT 194

RADON POTENTIAL IN VENTURA COUNTY
2006 UPDATE

2006

DEPARTMENT OF CONSERVATION
California Geological Survey

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RADON POTENTIAL IN VENTURA COUNTY 2006 UPDATE

By

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2006

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EXECUTIVE SUMMARY

Radon gas is a naturally occurring radioactive gas that is colorless and odorless. It forms from the radioactive decay of small amounts of uranium naturally present in rocks and soils. Breathing air with a concentrated level of radon gas can result in an increased risk of developing lung cancer. In 1995, through an interagency agreement with the California Department of Health Services (DHS), the California Geological Survey (CGS) developed a 1:100,000-scale radon potential map for Ventura County. The 1995 map was developed based on airborne-radiometric survey data (NURE project data—National Uranium Resource Evaluation project, a U.S. Department of Energy program in the 1970s and early 1980s), indoor-radon measurement data available at that time from DHS and university research projects, and geologic maps from the Dibblee Foundation and California Geological Survey (CGS, a.k.a. California Division of Mines and Geology). The 1995 radon potential map for Ventura County was not formally published by CGS but was made available to Ventura County and later placed on the CGS website for viewing and downloading. A 2005-2006 project to update this map has been recently completed.

This report provides supporting information for the updated (2006) Radon Potential Map for Ventura County. The updated map utilizes the same information as the 1995 radon potential map, plus additional indoor radon data compiled by the DHS radon program since 1995, and information about geologic rock units and indoor-radon and radon mapping procedures developed during the preparation of the radon potential map for southern Los Angeles County, completed in 2005 (Churchill, 2005).

The 2006 update of the radon potential map for Ventura County is based on the relative radon potentials of the different geologic units. Geologic unit radon potentials are evaluated using short-term indoor-radon measurement data provided by the Department of Health Services-Radon Program, and airborne radiometric data from the NURE project. Information on geologic units and indoor-radon measurements in Los Angeles and Santa Barbara counties were also considered in assigning radon potentials to geologic units in Ventura County. The DHS indoor-radon data for Ventura County range from less than 0.2 picocuries per liter (pCi/l) to 28.6 pCi/l (the detection limit is 0.2 pCi/l). The radon level at which the U.S. EPA recommends considering remedial actions for radon reduction in residences is 4.0 pCi/l

Three radon potential zones were developed for the updated map as in the 1995 map: High, Moderate, and Low. Statistical comparisons of indoor-radon measurement data for each zone shows that: the High Zone data population is statistically different from the Low Zone data population and the Moderate Zone population is statistically different from the Low Zone population. The High Zone and Moderate Zone data populations cannot be shown to differ statistically. This situation likely results from the small number of data (n=10) currently available for the High Zone and is expected to change with additional High Zone measurements. Based on currently available data, the estimated percentages of buildings in each zone with indoor radon levels of 4.0 pCi/l or higher are: 30 percent in the High Zone; 20.3 percent in the Moderate Zone, and 3.7 percent in the Low Zone. The main differences in the radon zones between the updated 2006 map and the 1995 map are:

1) Expansion of the moderate zone in the Thousand Oaks area
2) Expansion of the high zone in the southeast corner of the county
3) Change from moderate to high zone status for a small area near Oak Park
4) Reduction in some of the high and moderate zone areas near Ojai and southwest of Ojai
5) Change of some high zone areas to moderate potential zones.

The revised high and moderate zones comprise about 12.9 percent of Ventura County by area but contain 47.2 percent of the 4.0 pCi/l or higher sites in the DHS radon database. Within these two zones an estimated 9,666 individuals live in buildings likely to have radon levels of 4.0 pCi/l or higher based on short-term tests. If the high, moderate and low zones are considered together, an estimated 35,845 individuals, about 4.8 percent of the total county population, live in buildings that are likely to have radon levels of 4.0 pCi/l or higher based on short-term tests. These exposure estimates, and the presence of some radon measurements above 4.0 pCi/l in all radon potential zones, underscore the importance of indoor radon testing regardless of location. Although the exposure to elevated indoor radon levels is possible in all zones, the Ventura County radon potential map is useful because it identifies those areas with the greatest chance for such radon exposures to occur.

Indoor radon measurements and surveys have been made in Ventura County since the late 1980s. However, some areas and geologic units with possible radon significance in the county still have little or no indoor radon data for associated buildings. Future Ventura County indoor-radon surveys should target these areas and units.

The California Department of Health Services, Radon Program provided funding for this project through Interagency Agreement No. 04-36016

INTRODUCTION

Purpose

This report documents the procedures used by the California Department of Conservation, California Geological Survey (CGS), to produce the 2006 update of the radon potential map of Ventura County for the California Department of Health Services (DHS). This report also describes radon potentials for geologic formations in Ventura County. Only minimal background information on radon and radon health issues is included, and radon testing and remediation practices are not discussed. The following websites contain information about radon and health issues, testing and remediation: http://www.dhs.ca.gov/radon and http://www.epa.gov/iaq/radon/pubs.

Background Information on Radon and Health

Radon gas is a naturally occurring, radioactive gas that is odorless and colorless. It forms from the radioactive decay of small amounts of uranium and thorium naturally present in rocks and soils. Typical concentrations of uranium and thorium for many rocks and soils are on the order of a few parts-per-million (ppm). The average uranium content for the earth's continental crust is about 2.5-2.8 ppm. Certain rock types, such as organic-rich shales, some granitic rocks, and rhyolites can have uranium and thorium present at levels of tens to hundreds of ppm. While all buildings have some potential for elevated indoor-radon levels, buildings located on rocks and associated soils containing higher concentrations of uranium will have an increased likelihood of elevated indoor-radon levels.

Radon gas moves readily through rock and soil along micro-fractures and through pore-spaces between mineral grains. Radon movement away from its site of origin is typically limited to a few meters to tens of meters because of the relatively short half-lives of radon isotopes (3.8 days to less than 1 minute), but may be hundreds of meters in some cases. Many conditions affect how far radon can move in the subsurface. Because radon-222 (a daughter element of uranium-238) has the longest half-life of the several radon isotopes, it is usually the predominant radon isotope in indoor air. Radon gas moves from the soil into buildings in various ways. It can move through cracks in slabs or basement walls, pores and cracks in concrete blocks, through-going floor-wall joints, and openings around pipes. Radon enters buildings from the soil when air pressure inside the buildings is lower than the air pressure outside. When exhaust fans are used, or the inside air is heated, or wind is blowing across the building, the building's internal air pressure is lowered. Because radon enters buildings from the adjacent soil, radon levels are typically highest in basements and ground floor rooms. It can also enter those buildings that use private wells. The ground water drawn from wells contains dissolved radon gas, which can be released, for example, through the use of the bathroom shower. However, radon gas from this source typically accounts for only about 5 percent of the total radon in indoor air (WRRTC, 1997).

Breathing air with an elevated level of radon gas results in an increased risk of developing lung cancer. Not everyone exposed to radon will develop lung cancer. However, the estimated annual number of lung cancer deaths in the United States attributable to radon is 15,000 to 22,000 according to the U.S. Environmental Protection Agency (U.S. EPA) (U.S. EPA, 2002). The average radon concentration for indoor air in American homes is about 1.3 pCi/l, based on a 1991 national survey (U.S. EPA, 1992). The average radon concentration in outdoor air is about 0.4 pCi/l. The U.S. EPA recommends that individuals avoid long-term exposures to radon concentrations ≥ 4.0 pCi/l. Based on long-term radon test statistics, the U.S. EPA estimates that more than 6 million houses (about 1 out of 15) in the United States have radon levels ≥ 4.0 pCi/l and more than 60,000 homes have radon levels above 20 pCi/l (U.S. EPA, 1992).

Although radon levels are used as a guide for acceptable levels of exposure and for action levels, it is primarily the inhalation of two radon daughter elements polonium-218 and polonium-214 that leads to lung cancer. These elements have very short half-lives and when they enter the lungs they attach to lung tissue or trapped dust particles and quickly undergo radioactive decay. This is in contrast to the longer-lived radon-222 that is mostly exhaled before it undergoes radioactive decay. The alpha particles emitted during decay of polonium-218 and polonium-214 are thought to cause cancer by damaging the DNA (deoxyribonucleic acid) in lung tissue cells, resulting in abnormal or tumorous cell growth (Brookins, 1990).

The most common radon testing methods utilize either charcoal or alpha-track type detectors. These detectors are exposed to the air in a building for a period of time, according to the manufacturer's instructions, and then sent to a laboratory for analysis. Charcoal detectors are usually exposed for a few days under closed building conditions (a short-term test), while alpha track detectors are typically exposed for periods of weeks or months under normal building conditions (a long-term test). These tests are simple and inexpensive and homeowners can do this testing themselves. Test results are reported in units of picocuries per liter (pCi/l). Longer-duration measurements (alpha-track detector measurements) have an advantage because they "average out" short-term fluctuations in radon levels that relate to factors such as weather changes. Consequently, long-term measurements should be more representative of long-term average radon levels. However, short-term measurements are more common because of the shorter time required.

Use and Limitations of Radon Potential Maps

Radon potential maps are maps that identify areas where geologic conditions are more likely to contribute to excessive indoor radon levels. They are intended to assist federal, state and local government agencies and private organizations in targeting their radon program activities and resources. These maps are not intended for determining which buildings have excessive indoor radon levels. In addition to geology, indoor radon levels can be influenced by local variability in soil permeability and climatic conditions, and by factors such as building design, construction, condition, and usage. Consequently, radon levels for a specific building can only be determined by indoor radon testing of that building, regardless of what radon zone it is located within.

DEVELOPMENT OF THE VENTURA COUNTY RADON POTENTIAL MAP—2006 UPDATE

Project Overview

The 2006-update of the 1995 Radon Potential Map for Ventura County utilizes short-term indoor radon test data, NURE airborne gamma-ray data and geologic information available in 1995 and additional short-term radon data compiled by the DHS Radon Program since 1995, and available geologic maps from the Dibblee Foundation. Information on radon and geologic units developed during the southern Los Angeles County radon-mapping project (Churchill, 2005) were also utilized. This radon potential map update primarily focused on the portion of Ventura County south of Latitude 34.5 degrees north (i.e., from a couple of miles north of Ojai), where the majority of the Ventura County population is located and where the indoor-radon data measured after 1995 are located.

The approach taken to develop the radon potential zones assumes that geologic units with higher percentages of test data ≥ 4.0 pCi/l and units with NURE equivalent uranium (eU) data at 7.5 ppm or greater will have more buildings with radon levels exceeding 4.0 pCi/l (e.g., higher radon potential). Equivalent uranium is a uranium estimate calculated using gamma-ray data from bismuth-214, one of the uranium-238 daughter elements. The steps in developing the radon potential zones were:

1. Use a GIS (Geographical Information System) to relate the indoor-radon test data and NURE data to specific geologic units.

2. Rank geologic units for relative radon potential on the basis of the percentage of measurements ≥ 4.0 pCi/l (see Appendix A).

3. Subdivide the geologic units into three groups—high, moderate and low, using the percentages determined in step 2. Units ≥ 21 percent are considered high potential, units < 21 percent and ≥ 6 percent are considered moderate potential, and units < 6 percent are considered low potential.

4. Review NURE data (see Appendix D) to adjust the high, moderate and low potential categories as needed. Note: several geologic units were added to the moderate" category based on NURE data.

5. Compare geologic unit categories for Ventura County with those in Los Angeles County and apply the Los Angeles County classification for those units without indoor radon data in southeastern Ventura County.

6. Compare geologic unit categories for Ventura County with those in Santa Barbara County (1995 Radon Potential Map and supporting report) and apply the Santa Barbara classification for those units without indoor radon data in west-central Ventura County.

Table 1 and Appendix B list the final groups of geologic units selected during this screening process and their assigned radon potential.

The location of high and moderate radon potential zone areas in Ventura County is tied to the locations of geologic units classified as having high or moderate radon potential in Table 1 and Appendix B. The final high radon potential and moderate radon potential zone boundaries were established 0.2 miles out from the high and moderate potential geologic unit boundaries. This 0.2 mile wide buffer zone was used to account for uncertainties in geologic unit boundaries and for situations where high or moderate radon potential units may be close to the surface but covered by a low radon potential unit (i.e., below surface but close enough to the surface to still able to impact buildings). The 0.2-mile buffer was not used in areas where sufficient indoor-radon data were available to suggest the ≥ 4.0 pCi/l incidence rate was below moderate zone criteria. Three radon potential zones were ultimately developed for Ventura County: “High,” “Moderate,” and Low. Low potential areas are all areas outside of High or Moderate potential areas. In some cases, high or moderate potential geologic units are close enough so that their buffer zones overlap each other. In such cases, the High Zone buffer areas received priority over the Moderate Zone buffer areas.

Table 2a and Table 2b contain information about the radon data characteristics for each radon zone. Table 3a and Table 3b provide information about the occurrence of different ranges of indoor-radon measurements for the three radon zones.

The statistical significance of the final three radon potential zones was checked using the non-parametric Mann-Whitney rank sum test. The test compared the indoor-radon data populations for each radon potential zone and found that the Low Zone population is statistically different from the Moderate and High Zone populations, but the Moderate and High Zone populations are not necessarily statistically distinct. The latter probably results because of the small number of High Zone data.

Map Unit-Information (From Dibblee Foundation Maps. Modified by Churchill)	**Incidence Rate of DHS Indoor-Radon Measurements ≥ 4 pCi/l, in percent**	**Radon Zone Designation**
Tud-Unnamed Shale (upper Modelo Formation by others, equivalent to Sisquoc Formation of Dibblee in Ventura Basin)	**Rate uncertain (*no data*), n=0*** (*Likely above 21% from Los Angeles County radon mapping*)	**High**
Tush-Unnamed Shale (upper Modelo Formation or Santa Margarita Formation by others; equivalent to Sisquoc Formation of Dibblee in Ventura basin)	**Rate uncertain (*no data*), n=0** (*Likely above 21% from Los Angeles County radon mapping*)	**High**
Tr-Rincon Shale	**Rate uncertain (*no data*), n=0** *(Likely to be above 21% from previous Santa Barbara County radon studies***)**	**High**
Tm-Tml-Qa High—A selected area near Oak Park containing Monterey Formation-upper shale unit, Monterey Formation-lower shale unit, and Recent Alluvium	**Rate uncertain (*too few data*), n=9** Data ≥4.0 = 3 Maximum = 6.5 pCi/l	**High** (In Oak Park area)
Tm-Monterey Formation or Shale (Modelo) upper shale unit *Exclusive of Tm in Oak Park area, which is included in the Tm-Tml-Qa High zone area—see the table entry immediately above*	**Rate 19.4%, n=31** Data ≥4.0 = 6 Maximum = 7.9 pCi/l	**Moderate** (Exclusive of Oak Park)
Tml-Monterey Formation-lower shale unit	**Rate uncertain (*too few data*), n=8** *Previous radon mapping in Los Angeles and Santa Barbara counties suggest a moderate radon potential for this unit*	**Moderate**
Tsq-Sisquoc Shale	**Rate uncertain (*no data*), n=0** *May be equivalent to high radon potential units in Los Angeles County in part)*	**Moderate**
Qoa-Older Dissected Surficial Sediments-youngest gravel terraces--only the Qoa in the Fillmore area	**Rate uncertain (*too few data*), n=5** *1991-92 DHS Elementary School Study suggests moderate radon potential for this unit in the Fillmore area*	**Moderate** (In Fillmore area only)

*n=the number of DHS indoor-radon data available from houses located on the geologic unit indicated in the first column of the table.

Table 1. Summary of Priority Units and for Radon Zone Designation (see Appendix B for additional information on these geologic units and their zone designations)

Significant changes to the 1995 Ventura County radon potential map resulting from this update include:

1) Revision of some radon potential zone areas (e.g., increasing the size of the moderate potential area at Thousand Oaks, and decreasing the size of radon potential areas near Ojai and to the southwest), and

2) Reclassification of some portions of the 1995 zones in light of new information, and to make them more consistent with 2005 Los Angeles County radon potential map (e.g., areas along the Ventura County and Los Angeles County border, and the east-west oriented high zone south of Fillmore and Santa Paula).

Use of Geologic Maps

This project utilized the 1:250,000-scale geologic map for the Los Angeles 1X2 degree quadrangle prepared in 1969 by the California Division of Mines and Geology (the previous name for the California Geological Survey), and more recent 7.5-minute quadrangle geologic maps (1:24,000-scale) published by the Dibblee Foundation.

The Ventura County area lies within the Los Angeles 1X2 degree quadrangle. This map was available at the time of the NURE project in the 1970s and airborne gamma-ray data were referenced to the geologic units depicted on this map. The portion of Ventura County updated in this review, south of latitude 34.5 degrees, is contained within all or parts of 22 7.5-minute quadrangles. The Dibblee Foundation has published geologic maps for all of these 22 quadrangles (the quadrangles listed in Appendix C).

Dibblee Foundation maps are utilized for this project in order to maintain map unit consistency across the Ventura County area. Their use also allows the geologic unit-based radon zones for Ventura county to be compared and related to the radon potential zones previously developed for Los Angeles and Santa Barbara counties, which are also based on geologic-map units defined on Dibblee Foundation maps. Finally, the 7.5-minute Dibblee Foundation maps depict map units in sufficient detail for development of the radon potential map at 1:100,000 scale. Enlarging the 1:250,000-scale geologic maps to 1:100,000-scale is not a viable approach as it magnifies the limitations of detail that can be shown at 1:250,000 scale, creating inaccuracies in features such as geologic boundaries.

Zone	n	Median pCi/l	pCi/l at 25%	pCi/l at 75%	Min pCi/l	Max pCi/l
High	10	2.7	1.7	5.6	0.5	6.5
Moderate	69	1.5	0.8	3.525	0.3	28.6
Low	510	0.9	0.5	1.4	0.2	23.6
All	589	0.9	0.5	1.5	0.2	28.6

Table 2a. Radon Zone Data Characteristics

Zone	n	n ≥ 4.0 pCi/l data	% data ≥ 4.0 pCi/l	N ≥ 10.0 pCi/l data	% data ≥ 10.0 pCi/l	N ≥ 20.0 pCi/l data	% data ≥ 20.0 pCi/l	Area (sq-mi)
High	10	3	30	0	0	0	0	25.0
Moderate	69	14	20.3	1	1.45	1	1.45	216.1
Low	510	19	3.7	3	0.59	1	0.20	1624.9
All	589	36	6.1	4	0.68	2	0.34	1866

Table 2b. ≥ 4.0 pCi/l Incidence per Radon Potential Zone

Zone	% of all ≥ 4.0 pCi/l measurements	% of all ≥ 10.0 pCi/l measurements	% of all ≥ 20.0 pCi/l measurements	% Area	Cumulative % of n ≥ 4.0 pCi/l measurements	Cumulative % of Ventura County Area
High	8.33	0	0	1.34	8.33	1.34
Moderate	38.89	25	50	11.58	47.22	12.92
Low	52.78	75	50	87.08	100.00	100.00
All	100.00	100.00	100.00	100.00		

Table 3a. ≥ 4.0 pCi/l Incidence Rates for Ventura County by Radon Potential Zone

Zone	Average Rate: n ≥ 4.0 pCi/l measurements per square mile	Average Rate: All measurements per square mile
High	0.12	0.4
Moderate	0.065	0.32
Low	0.037	0.31
All	0.019	0.32

Table 3b. Radon Data Distribution by Radon Potential Zone

Use of Indoor-Radon Test Data

The DHS Radon Program provided CGS with indoor-radon data from 589 locations within Ventura County (Figure 1). These data are short-term radon measurements of homes made using charcoal canister detectors between January 1990 and November 2003. The data range from below 0.2 pCi/l (the detection limit) to 28.4 pCi/l. Thirty-six sites had results that equaled or exceeded 4.0 pCi/l (Figure 2). The charcoal canisters were analyzed either at a National Environmental Health Association certified lab or, for the older data, a lab certified under the U.S. EPA Radon Proficiency Program.

Multiple radon analyses were available for some sites. Usually these analyses were made at different times, varying from weeks to months but sometimes years apart. Typically, the earliest analysis detected the highest radon level at a site. For the Ventura County study, only the highest radon level for each site was utilized because of the possibility that later lower radon measurements were made after some remediation activity had occurred. No information is available regarding remediation activities at particular sites.

Comparison of Indoor Radon Test Data with Geologic Units

Using GIS, the DHS short-term indoor radon data were compared with the geologic map units indicated on 7.5-minute geologic maps for Ventura County. The results of this comparison are tabulated in Appendix 2. Twenty-one geologic units had at least one associated indoor radon measurement. However, only 4 geologic units had 23 or more radon measurements (enough for at least minimal confidence in their statistics). Table 4 lists these 4 units in decreasing order by percentage of ≥4.0 pCi/l measurements. The unit with the highest percentage of ≥4.0 pCi/l measurements (21.2 percent) is the Monterey Formation (Upper Shale Unit—Tm), a Miocene marine siliceous shale. The NURE data screening process, discussed in the following section, also recognized this marine shale as potentially significant for radon. The remaining three units, Older Dissected Surficial Sediments (Qoa), Surficial Sediments-alluvium (Qa) and Older Dissected Surficial Sediments (Qog), have significantly lower percentages of ≥4.0 pCi/l measurements, 5.6 percent, 5.5 percent and 4.4 percent respectively.

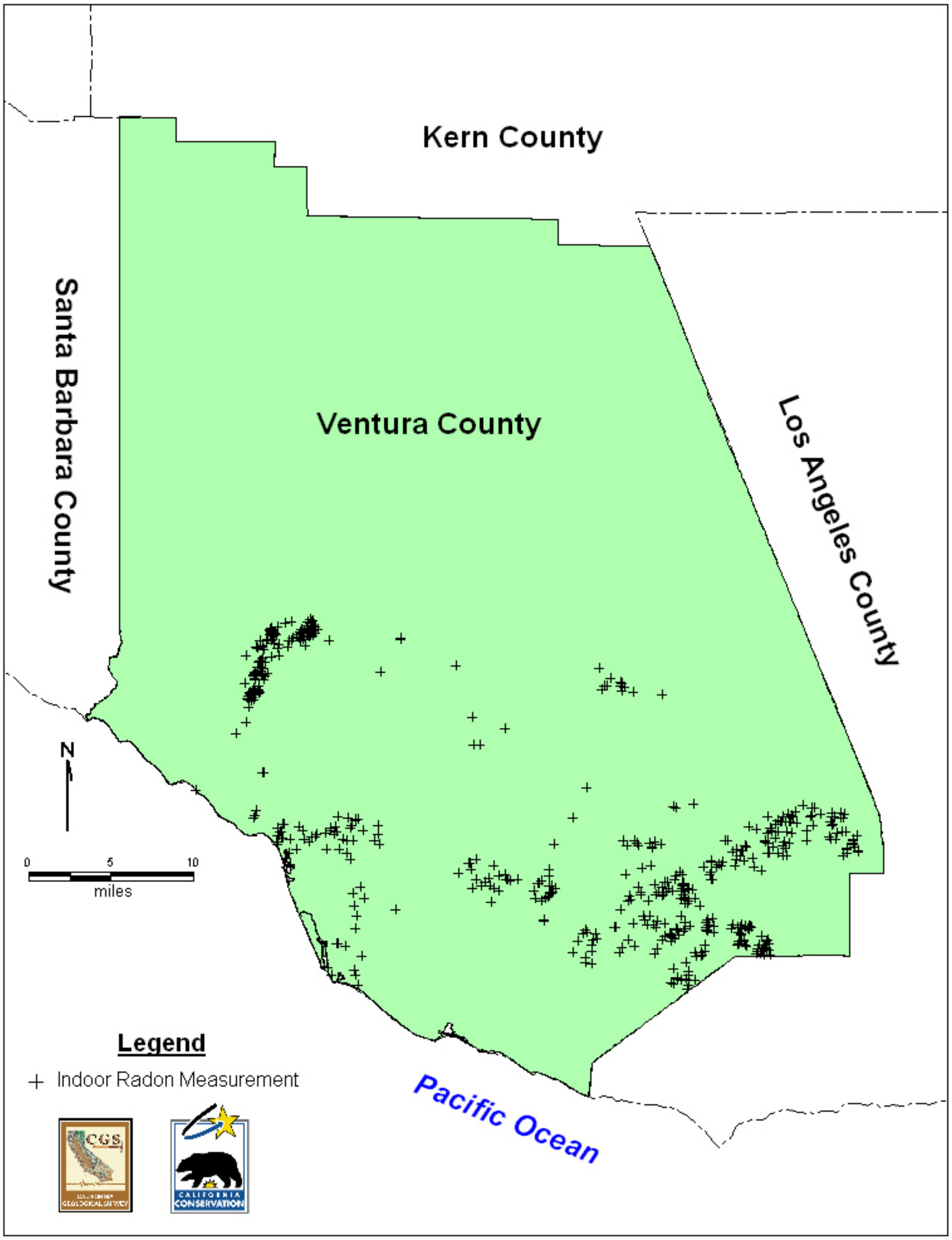

Figure 1. DHS Short-Term Radon Tests for Ventura County

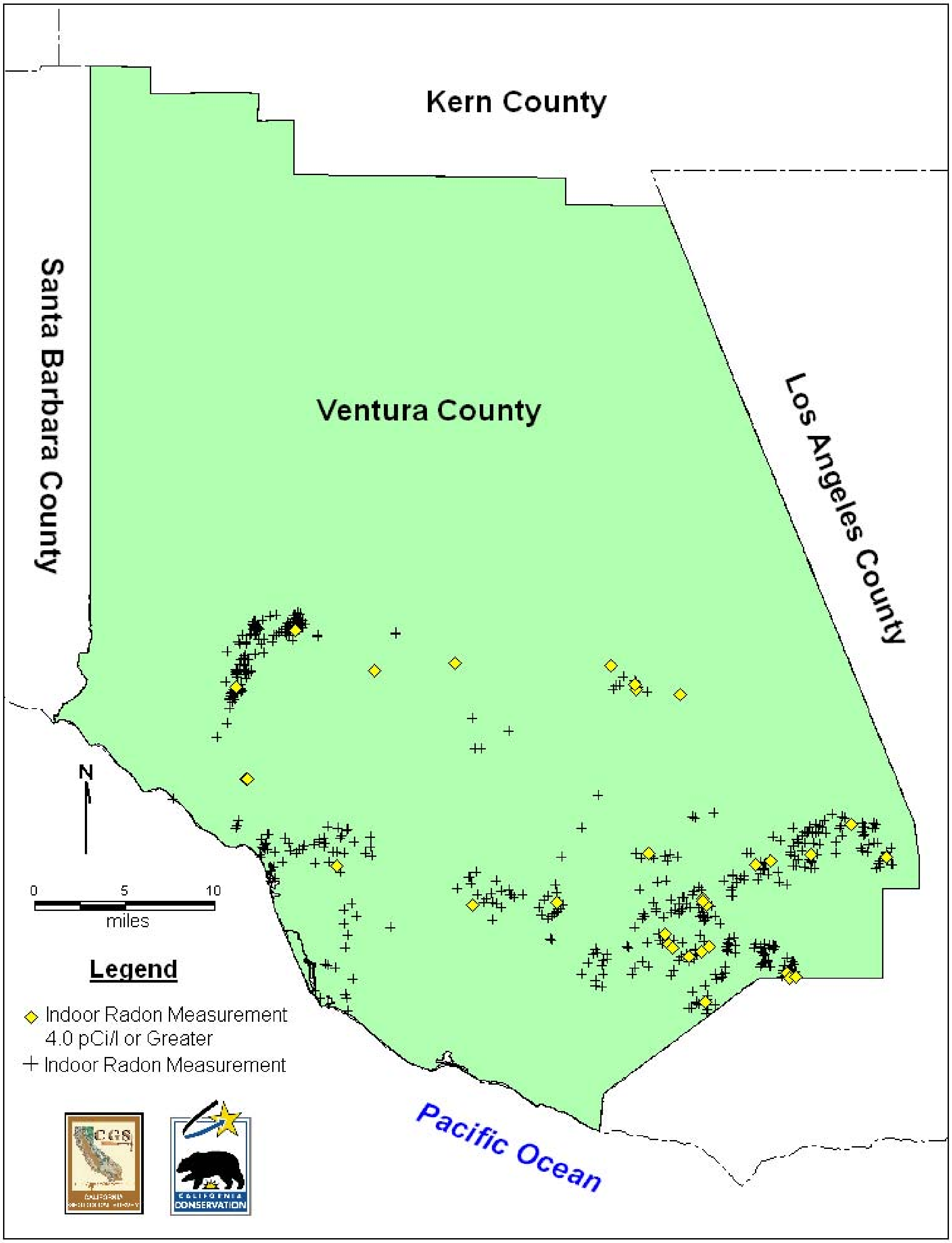

Figure 2. DHS Short-Term Test Results--4.0 pCi/l or Greater

Unit Symbol	Lithologic Summary	n	n ≥ 4.0 pCi/l	Percent ≥ 4.0 pCi/l	High (pCi/l)	Low (pCi/l)
Tm	Monterey Formation: Miocene marine siliceous shale	33	7	21.2	7.9	0.3
Qoa	Older Dissected Surficial Sediments: alluvial gravel, sand and clay (terraces)	143	8	5.6	7.0	0.2
Qa	Surficial Sediments-alluvium: silt, sand, gravel	291	16	5.5	28.6	0.3
Qog	Older Dissected Surficial Sediments: cobble-boulder gravel fan or fanglomerate or intermediate (in age) terrace	23	1	4.4	5.8	0.3

Table 4. Map Units with 23 or More Radon Measurements

Use of NURE Airborne Radiometric Data

During the 1970s, airborne gamma-ray spectral data were collected throughout the United States along a grid of east-west and north-south flight lines as part of the National Uranium Resource Evaluation project (NURE). East-west lines are typically 3-6 miles apart and north-south lines are typically 12 miles apart. The NURE project used helicopters with special analytical equipment to detect and record the intensity of gamma-ray energy from the decay of bismuth-214 from the uppermost 20 to 30 cm of the surface of soil and rocks at a number of locations along each flight line. The helicopters flew several hundred feet above the surface and measurements were collected, on average, a little more than 100 feet apart along the flight lines. Estimates of the soil and rock uranium content at each location, in parts per million, were calculated using the gamma-ray data that were collected. These estimates are designated by the abbreviation eU (equivalent uranium) to distinguish them from a conventional chemical analysis of uranium. The estimates are possible because bismuth-214 is one of the radioactive decay products for uranium-238 and, with some exceptions, the amount of bismuth-214 present will be proportional to the amount of uranium-238 present in the rock or soil.

The goal of the NURE airborne gamma-ray study was to identify new uranium ore deposits. Areas identified as having higher eU were uranium exploration targets for follow-up examination on the ground by geologists. Because radon-222 is also a decay product of uranium-238 and is followed closely in the decay path by bismuth-214, NURE data are also useful in identifying areas more likely to have elevated radon levels in soil and rock. In preparing the radon potential map for Ventura County, the NURE data were used to identify specific areas along flight lines likely to have elevated radon in soil and rocks based on the presence of elevated eU. These areas were then compared with geologic maps to identify those map units more likely to have elevated radon levels.

NURE Airborne Gamma-ray Spectral Data for Ventura County

In the 1995 radon-mapping project for Ventura County, the NURE data were reviewed from microfiche records and the locations of continuous multiple readings exceeding 5 ppm eU were identified and the underlying geologic unit noted and recorded manually. The NURE flight-line data used in the 2006 update project were obtained from a U.S. Geological Survey compilation in digital format (Duval, 2000). For this update only the NURE data south of latitude 34.5 degrees north were reviewed. Ventura County south of this latitude, where the vast majority of county residents live, contains approximately 438.0 miles of flight lines with data for 19,110 locations along the flight lines (see Figure 3 and Appendix C). Flight-line spacing in this portion of the county is generally about 3.1 miles between east-west oriented lines and 11.8 miles between north-south lines.

NURE Data Analysis

The digital format (not available in 1995) facilitated NURE data review and identification of all data locations in excess of a given eU ppm level. In this update, NURE data equal to or exceeding 7.5 ppm eU (about 3 times the average uranium content of the earth's crust) were used because they appear to be more indicative of geologic units likely to underlie elevated radon buildings than the 5 ppm eU screening level utilized for the 1995 Ventura County Radon Map and the 2005 Southern Los Angeles Radon Map. A screening level of 7.5 ppm eU for Ventura County is further supported by results from Azzouz (1990, Table 8) who found that NURE data for Ventura County that ranged up to 5.8 ppm eU was associated with indoor radon levels no higher than 2.9 pCi/l. For the portion of Ventura County south of 34.5 degrees north latitude, 2.37 percent of the data points (i.e., 452 of 19,110 locations along the flight-lines) equal or exceed 7.5 ppm eU (Figure 4).

The results of this screening activity are summarized in Appendix D, which shows that 24 geologic map units contain at least one NURE data point at or exceeding 7.5 ppm eU. Three rock units, Monterey Formation-upper shale unit, Monterey Formation-lower shale unit, and Rincon Shale, stand out in that they account for 44.0 percent of the 7.5 ppm eU or greater data points in southern Ventura County, and up to 55.3 percent if data points within landslide areas of these units are included.

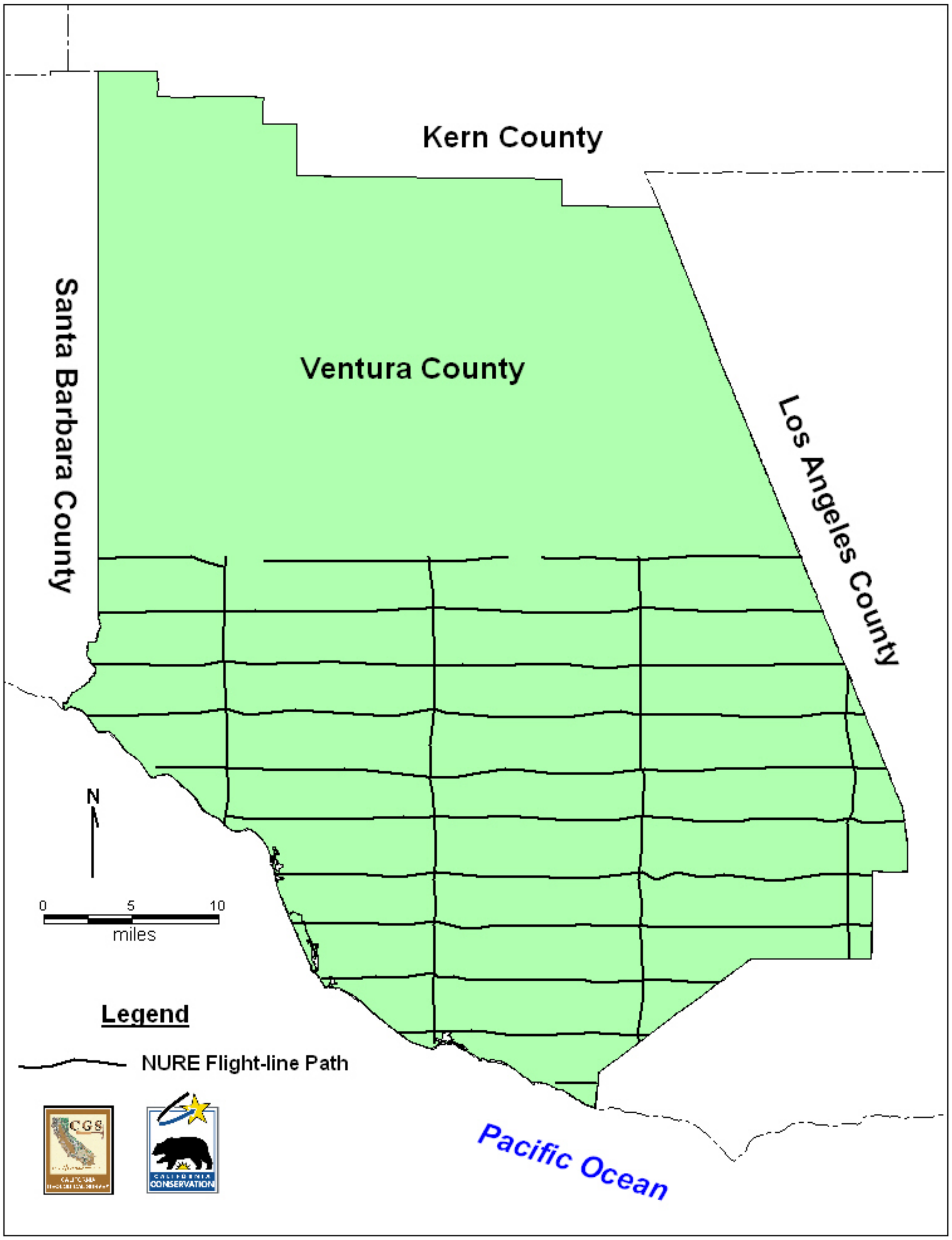

Figure 3. Map of NURE Flight-line Coverage for Ventura County

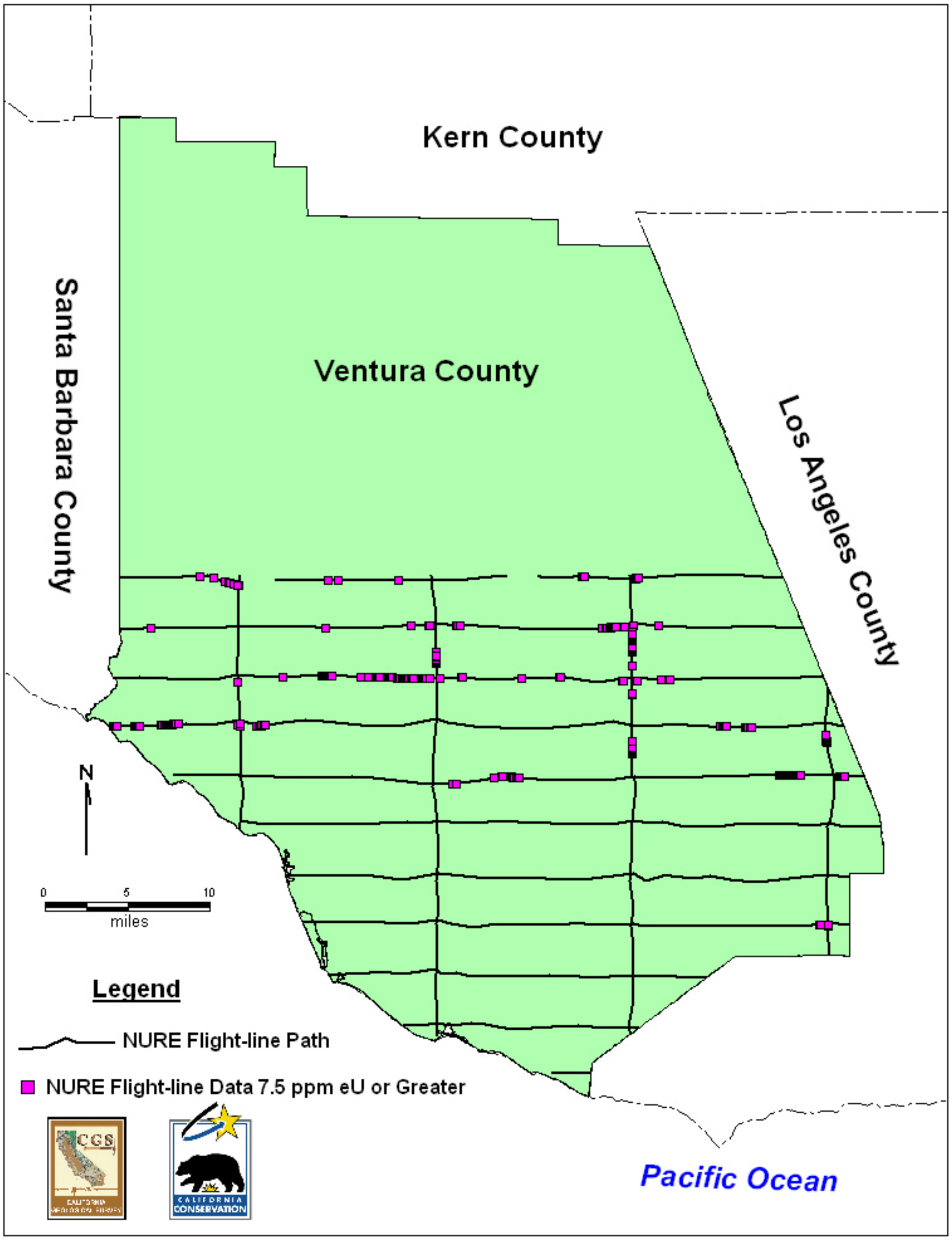

Figure 4. NURE Data Locations Where eU Levels Are ≥ 7.5 ppm.

The upper and lower Monterey Formation units and the Rincon shale are defined on Dibblee Foundation geologic maps as follows:

> The marine Monterey Formation-upper shale unit (Tm) is composed of thin bedded, hard, platy to brittle, siliceous biogenic shale of Miocene age. Other geologists have mapped this unit as Modelo Formation.
>
> The marine Monterey Formation-lower shale unit (Tml) is composed of soft, fissile to punky clay shale with interbeds of hard siliceous biogenic shale and thin limestone or dolomitic strata of Miocene age. Other geologists have mapped this unit as Modelo Formation.
>
> The Rincon Shale (Tr) is a poorly bedded Miocene marine clay shale and siltstone unit that contains occasional dolomitic concretions.

Summary of NURE Airborne Gamma-ray Spectral Data Screening Results

The NURE data screening process identified those geologic units that contained measurements ≥ 7.5 ppm eU. Of the 24 geologic units identified, three units (including mapped landslide areas associated with these units) account for approximately 55.3 percent of the ≥ 7.5-ppm eU data. These units are Miocene marine biogenic siliceous and clastic shales. These rock types have been previously identified as often containing background uranium levels above the average crustal background level of 2.5 ppm (Durham, 1987; Leventhal, 1989; Churchill, 1997, 1991; Otton, 1993; Carlisle and Azzouz, 1993) and have been associated with elevated indoor radon levels in homes and schools in Santa Barbara, Ventura, and Los Angeles Counties (Churchill, 2005, 1997, 1991; Churchill and Youngs, 1993; Carlisle and Azzouz, 1993) and at some schools on the Palos Verdes Peninsula in Los Angeles County (Duval and others, 2004).

RADON POTENTIAL ZONE CRITERIA

Radon Zone Area Designations

In keeping with the approach previously used for Ventura County and more recently used for Los Angeles County radon maps, high, medium and low radon potential zones have been designated for the revised Ventura County Radon Potential Map. The radon potential zones are based on the radon potential assignments of geologic units made and discussed in the previous sections of this report and are defined as follows:

High Potential—geologic map units that have 21 percent or more of associated residences with radon levels equal to or exceeding 4.0 pCi/l in short-term tests.

Moderate Potential---geologic map units that have 6 to 21 percent of associated residences with radon levels that equal or exceed 4.0 pCi/l. in short-term tests.

Low Potential—geologic map units that likely have fewer than 6 percent of associated residences with radon levels that equal or exceed 4.0 pCi/l.

Those geologic units with High or Moderate Potential designations are listed in Table 1.

Radon Zone Boundaries

Figure 5 is a generalized version of the revised radon potential zones shown on the 1:100,000-scale map (Plate 1). The relationships between these zones, ≥ 4.0 pCi/l radon data and ≥ 7.5-ppm eU data are shown in Figure 6. The radon potential zone boundaries for the High and Moderate potential zones are based on the boundaries for geologic map units, or portions of geologic map units, with those radon potential designations. The final boundaries for these zones were derived by adding a 0.2-mile wide buffer zone to those units designated as having high or moderate potential (several exceptions are discussed in the following paragraph). This 0.2-mile buffer zone is utilized to compensate for uncertainties in the locations of map unit boundaries (e.g., in areas with poor rock exposure). The 0.2-mile wide buffer also should include some, if not most, of the situations where high potential or moderate potential geologic units are covered by a thin layer of alluvium, but are still close enough to the surface to potentially influence indoor-radon levels in buildings. The most likely place for this situation to occur is just outside of the mapped boundaries for high and moderate potential units. Where resulting high potential (buffered) areas and moderate potential (buffered areas overlap, areas with high potential were given preference for the final map.

In a few cases a buffer zone was not added and the geologic unit boundary is the radon potential zone boundary. These cases are as follows:

- Buffer zones around very small areas of Monterey Formation and Rincon Shale surrounded by alluvial units near Casitas Springs, Oak View and southwest of Ojai on the 1995 Ventura County radon potential map have been removed in this revision because indoor-radon measurements in these areas made since 1995 do not support their use.

- Buffer zones were not added to several small Monterey Formation occurrences in the Thousand Oaks 7.5-minute quadrangle because of buffer zones for small Monterey Formation occurrences were not supported by subsequent indoor radon measurements the Casitas Springs-Oak View-southwest Ojai areas.

The Low Potential zone areas were simply defined as all areas that are not designated as High Potential or Moderate Potential areas.

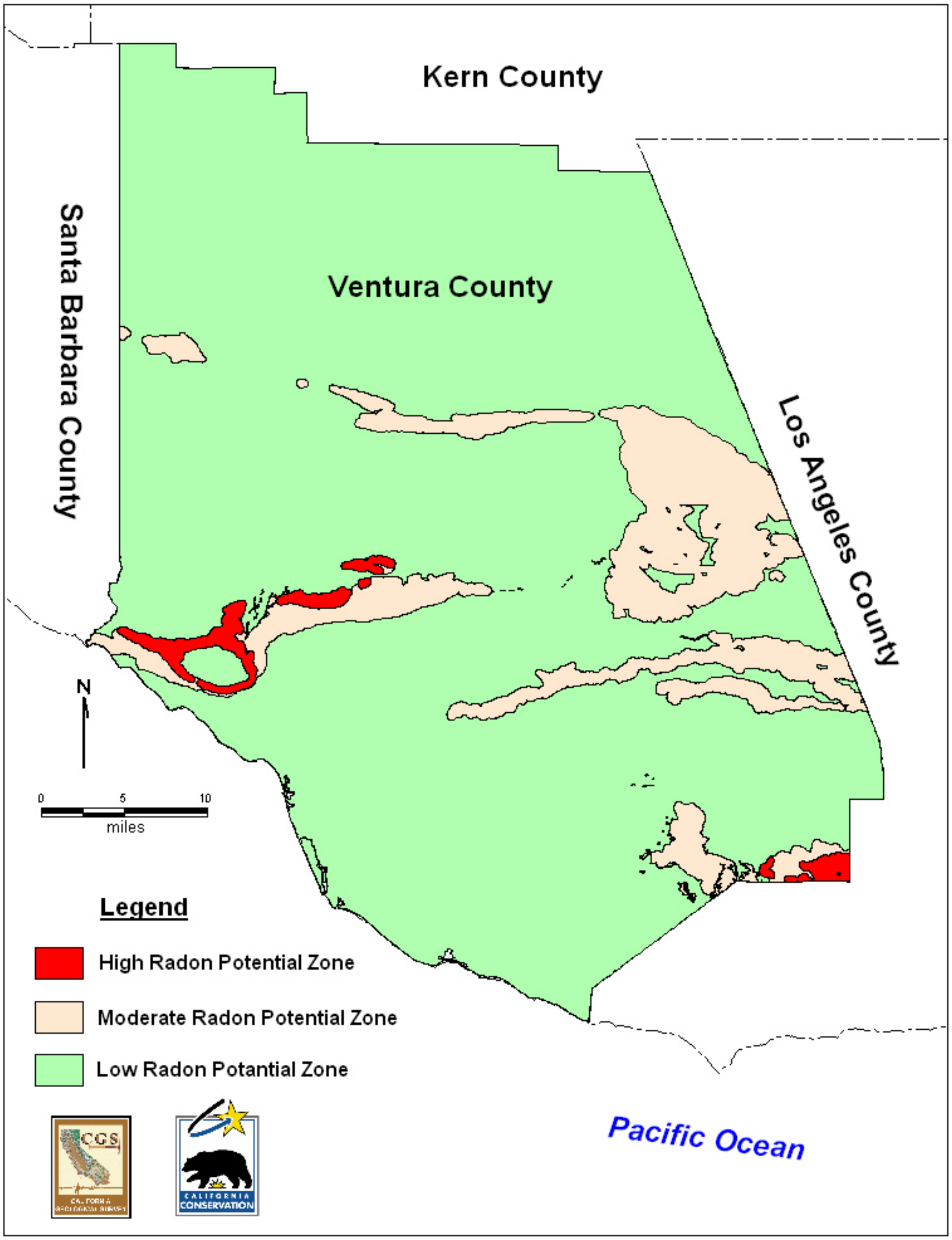

Figure 5. Radon Zones for Ventura County

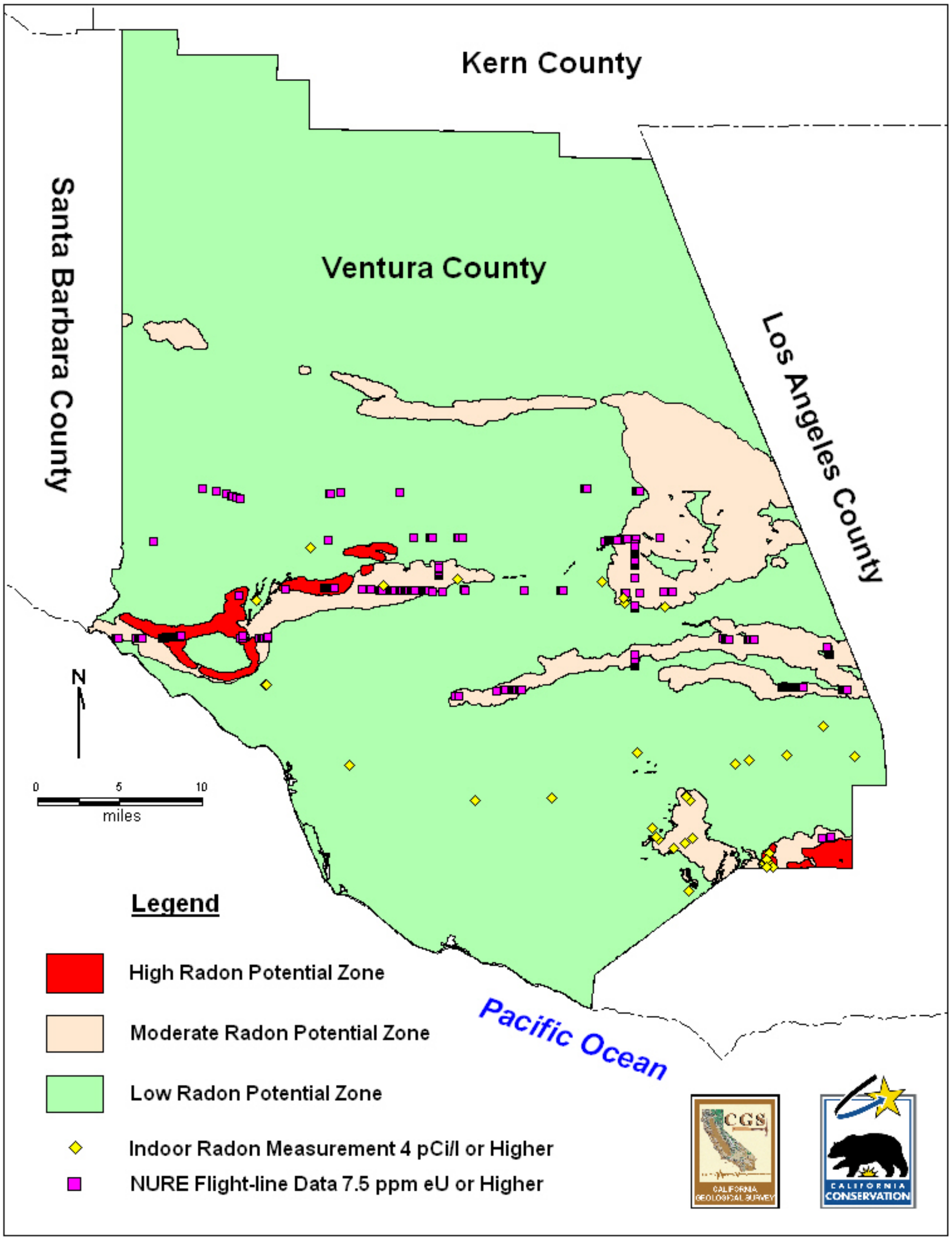

Figure 6. Comparison of 4.0 pCi/l or greater Indoor Test Data Locations and 7.5 ppm or greater eU NURE Data Locations with Radon Potential Zones for Ventura County

RADON POTENTIAL ZONE STATISTICS

Indoor-radon Measurement Data Characteristics

The statistical characteristics of the untransformed and log(10) transformed DHS indoor radon data for Ventura County radon potential zones are provided in Appendix E and Appendix F).

Indoor-Radon Measurement Frequency Distributions

Frequency distributions of trace elements in rocks and soils, such as uranium and radon, are often approximated using the lognormal distribution. However, because of the variety of geologic units and complex history of processes affecting them, geochemical data such as radon data cannot always be fitted to a specific frequency distribution (Rose and others, 1979, p. 33). The indoor-radon data for Ventura County are an example of this. Taken as a whole, the indoor-radon test data from DHS fail the Kolmogorov-Smirnov normality test in both untransformed and log-transformed modes (Table 5). Consequently, all the data, considered together, are neither normally nor lognormally distributed. The non-normal frequency distribution may be because the data are a combination of samples from many different populations—each rock unit radon population having its own unique distribution. On an individual basis, the rock unit radon populations may be lognormal, but the aggregate population is not lognormal. This possibility is demonstrated by the log(10) transformed Moderate Zone data passing the Kolmogorov-Smirnov Normality Test (Table 5). This zone consist of just a few closely related rock types.

Data non-normality has important implications for certain statistical operations. For example, T-test comparisons should not be used for comparing non-normal (non-parametric) populations. For this reason, the Mann-Whitney rank sum test is used for comparisons of sub-populations of the indoor-radon test data by radon zone in this study and the results are discussed in a following section. Non-normality may also have negative consequences for predictions of percentages of homes with indoor-radon levels exceeding 4.0 pCi/l if the predictions assumed a lognormal population distribution for the radon data.

The results of the statistical comparisons of radon potential zones for Ventura County are listed in Table 6. The results show that the indoor-radon data populations for the moderate and low radon potential zones and the high and low radon potential zones are significantly different. However the moderate and high radon potential zones may not be statistically different. This situation may relate to the low number of measurements currently available for Ventura County High Radon Potential Zones and additional data may result in a statistical difference being documented for these two zones.

Data	N	K-S Distribution	P	Result
All Data—Untransformed	589	0.288	<0.001	Failed
All Data—Log (10) Transformed	589	0.095	<0.001	Failed
High Zone—Untransformed	10	0.209	>0.200	Passed
High Zone—Log(10) Transformed	10	0.139	>0.200	Passed
Moderate Zone—Untransformed	69	0.267	<0.001	Failed
Moderate Zone—Log(10) Transformed	69	0.085	>0.200	Passed
Low Zone—Untransformed	510	0.283	<0.001	Failed
Low Zone—Log(10) Transformed	510	0.110	<0.001	Failed

Table 5. Results of the Kolmogorov-Smirnov Normality Test for Untransformed and Log(10) Transformed Indoor-Radon Data, by Radon Potential Zone

A test that fails indicates that the data varies significantly from the pattern expected if the data were drawn from a population with a normal distribution

A test that passes indicates that the data matches the pattern expected if the data were drawn from a population with a normal distribution

Mann-Whitney Rank Sum Test					
Group	N	Missing	Median	25%	75%
High Zone	10	0	2.7	1.7	5.600
Moderate Zone	69	0	1.500	0.800	3.525
Result	T = 512.000 n(small)=10 n(big)=69 (P=0.100) The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P=0.100)				
High Zone	10	0	2.7	1.700	5.600
Low Zone	510	0	0.900	0.500	1.400
Result	T = 4344.000 n(small)=10 n(big)=510 (P=<0.001) The difference in the median values between the two groups is greater than would be expected by chance; there is a statistically significant difference (P=<0.001)				
Moderate Zone	69	0	1.500	0.800	3.525
Low Zone	510	0	0.900	0.500	1.400
Result	T = 26510.000 n(small)=69 n(big)=510 (P=<0.001) The difference in the median values between the two groups is greater than would be expected by chance; there is a statistically significant difference (P=<0.001)				

Table 6. Mann-Whitney Rank Sum Test Comparisons of Indoor-Radon Data by Radon Potential Zone

Estimated Population Exposed to 4.0 pCi/l Radon or Greater Indoor-air Ventura County

Population estimates for each radon potential zone were obtained by overlaying the Ventura County radon potential zones with 2000 census tract data. For census tracts not completely within a radon potential zone, a portion of census tract population proportional to the percent area of the census tract falling within the radon potential zone was used as the population contribution of that census tract to the total population of the radon potential zone. The estimated populations for the different radon potential zones are listed in Table 7.

Radon Potential Zone	Estimated Total Population within Zone—2000 Census Statistics	Estimated Total Households within Zone (avg. 3.04 persons per household)
High	4,091	1,346
Moderate	41,570	13,674
Low	707,536	232,742
All Ventura County	753,197	247,762

Table 7. Population Estimates for Ventura County Radon Zones Areas (based on 2000 U.S. Census Data).

Table 8 shows the estimated populations of residents for each radon potential zone and the estimated number of residences exposed to different radon levels. These estimates are based on the estimated population for each zone multiplied by the ≥4.0 pCi/l percentages for each zone from Table 2.

Potential Radon Impacts on the Population of Ventura County

The High and Moderate radon potential zones contain 12.92 percent of the Ventura County area and 6.06 percent of the county population. These zones also contain:

- 26.96 % of the Ventura County population estimated to live in residences with indoor-radon levels of ≥ 4.0 pCi/l
- 12.62% of the Ventura County population estimated to live in residences with indoor-radon levels of ≥ 10.0 pCi/l
- 29.88% of the Ventura County population estimated to live in residences with indoor-radon levels of ≥ 20.0 pCi/l

These results indicate that geology based radon potential zones can target areas within Ventura County where excessive indoor radon levels are more likely to be found (i.e., where the highest percentages of buildings with excessive indoor-radon levels are expected to occur). Such information is helpful for government agencies and non-profit organizations involved in public health by indicating where the greatest benefit may be obtained from radon testing programs and public awareness efforts. However, the results also show that buildings with excessive indoor radon levels occur in all zones in Ventura County. Factors other than geology, such as soil permeability, building condition, design and usage also have important impacts on indoor radon levels. Therefore, anyone concerned about possible exposure to radon in his or her residence should test, regardless of location. The U.S. EPA recommends testing of all residences regardless of location.

Rn Zone	Estimated Total Population* for Zone	Estimated Population* at ≥ 4.0 pCi/l Conditions	Estimated Population* at ≥ 10.0 pCi/l Conditions	Estimated Population* at ≥ 20.0 pCi/l Conditions	Percent Area/Square Miles
High	4,091 *0.54%*	1227 *3.42%* 30% rate	0 *0%* 0% rate	0 *0%* 0% rate	1.34% 25.0 mi^2
Moderate	41,570 *5.52%*	8,439 *23.54%* 20.3% rate	603 *12.62%* 1.45% rate	603 *29.88%* 1.45% rate	11.58% 216.1 mi^2
Low	707,536 *93.94%*	26,179 *73.03%* 3.7% rate	4174 *87.38%* 0.59% rate	1,415 *70.12%* 0.20% rate	87.08% 1624.90 mi^2
Population Estimates Weighted by Radon Zone					
Totals (weighted by zone)	753,197 *100.00%*	35,845 *99.99%* 4.76% rate	4,777 *100.00%* 0.63% rate	2,018 *100.00%* 0.27% rate	100.00% 1866 mi^2
Population Estimates by Radon Level Without Regard to Data Location or Zone					
All Ventura County (not weighted by zone)**	753,197	45,945 6.1	5,122 0.68	2,561 0.34	100.00% 1866 mi^2

Table 8. Estimates of Ventura County Population Exposed to 4.0 pCi/l or Greater Indoor Radon Levels in Residences (based on 2000 U.S. Census Data)

*Information in the population column cells: 1) Population; 2) Percent of the population

**Based only on radon test results, not weighted for location

Comparison of Short-term and Long-term Indoor Radon Test Data for the Revised 2006 Ventura County Radon Potential Zones

In a 1989-1990 DHS study, Lui and others (1991) surveyed 862 residences in Ventura County and northwestern Los Angeles County for indoor-radon levels using long-term alpha-track detectors. The detectors were exposed for one year in these residences. Lui and others (1991) found approximately three percent of the tested residences had average annual radon levels ≥ 4.0 pCi/l. This rate exceeded the 0.8 percent 4.0 pCi/l residences estimated for the state from previous DHS work. The Lui and others approach utilized random sampling by zip code zone and they estimated percentages of residences exceeding 4.0 pCi/l at 14 percent, 8 percent and 1 percent for their “high,” “medium” and “low” regions respectively. Their report recommended that more detailed radon studies based on geology, soil permeability, and building type, rather than random zip code based sampling, be conducted to more accurately define high-risk areas in the region.

The Lui and others study had 502 indoor measurements within Ventura County, which ranged from 0.1 to 12.7 pCi/l. The locations of these measurements were compared to the radon potential zones developed using more recent short-term measurements for Ventura County compiled by the DHS Radon Program. The results of this comparison are shown in Table 9.

Radon Zone (This Study)	Number of measurements	Median pCi/l	Low pCi/l	High pCi/l	Percent ≥ 4.0 pCi/l
High	3	1.0	1.4	2.3	0
Moderate	33	2.0	0.3	5.3	6.1
Low	466	1.6	0.1	12.7	0.64

Table 9. Comparison of DHS Long-term Alpha-track Measurements to the 2006 Ventura County Radon Potential Zones

Comparison of the 2006 radon potential zones with the long-term data of Lui and others (1991), using the same statistical method used for the short-term data (Mann-Whitney rank sum test), found that the moderate zone and low zone long-term radon data populations are statistically different. The low zone and high zone long-term radon data populations are also statistically different. The moderate and high zones are not statistically different but this may be the result of the small number of measurement in the high zone (the same issue as previously discussed with the short-term measurement data).

Estimates of the number of individuals living in residences with radon levels ≥ 4.0 pCi/l based on the DHS 1989-1990 long-term data and the 2006 radon potential zones and are provided in Table 10.

Radon Zone	Estimated Population in Residences with Radon Levels ≥ 4.0 pCi/l
High	?*
Moderate	2,536
Low	4,529
Total	7,065

Table 10. Radon Exposure Estimates Based on Long-Term Radon Measurements

*Two few high zone measurements are available to establish an incidence rate of ≥ 4.0 pCi/l residences, so a population estimate cannot be made for this zone category.

SUMMARY OF PROCEDURES AND RESULTS

Short-term indoor radon test data from DHS, and NURE project airborne radiometric data, were used to identify geologic units with relatively higher or lower radon potential in Ventura County. Geologic units were classified as having high, moderate or low radon potential based on the percentage of 4.0 pCi/l or higher indoor-radon data and the percentage of 7.5 ppm or higher eU airborne radiometric data. This information, and information developed for the 2005 Radon Potential Map for southern Los Angeles County were used to revise boundaries of radon potential zones on the 1995 Ventura Radon Potential Map.

High radon potential zones on the Ventura County radon potential map correspond to the locations of high radon potential geologic units. Moderate radon potential zones correspond to the locations of moderate radon potential units. Low radon potential zones are composed of the remaining geologic units, which may have either low radon potential or an unknown, but likely low, radon potential.

Buffer zones, 0.2 miles wide were added to the boundaries of high potential and moderate potential geologic units to form the final High Radon Potential and Moderate Radon Potential Zone Boundaries in most areas. Exceptions, e.g., where buffer zones were not added, are where the high or moderate potential unit occurrence is very small and where existing indoor-radon measurement data indicate that a buffer zone is not warranted. High Radon Potential Zone buffer areas receive preference where they overlap Moderate Radon Potential Zone areas on the Ventura radon potential map.

The final radon potential zones have the following characteristics:

High Radon Potential Zone: this zone comprises 1.34 percent (25.0 square miles) of Ventura County and contains 8.33 percent of ≥ 4.0 pCi/l short-term radon data in the DHS database.

Moderate Radon Potential Zone: this zone comprises 11.58 percent (216.1 square miles of Ventura County and contains 38.89 percent of ≥ 4.0 pCi/l short-term radon data in the DHS database.

Low Radon Potential Zone: this zone comprises 87.08 percent (1624.9 square miles of Ventura County and contains 52.78 percent of ≥ 4.0 pCi/l short-term radon data in the DHS database.

All three radon potential zones contain short-term indoor-radon measurements above 4.0 pCi/l. The maximum measurement for each zone is: High, 6.5 pCi/; Moderate, 28.6 pCi/l; and Low, 23.6 pCi/l.

Statistical comparison of the indoor-radon data for the three radon potential zones, using the Mann-Whitney rank sum test, shows that the moderate and low zones, and the high and low zones are statistically different from each other but the high and moderate zones may not be statistically different. This latter situation likely results from the limited number of indoor-test data available for the high zone (10 measurements). The fact that the low potential zone is statistically different from the moderate and high potential zones supports the validity of the approach used in this study to identify areas of higher and lower radon potential in Ventura County.

An estimated 9,666 individuals live in residences likely to measure ≥ 4.0 pCi/l in short-term radon tests within the combined High and Moderate Radon Potential Zone areas (i.e., concentrated within 12.9 percent of the Ventura County area). An additional 26,179 individuals are estimated to live in residences likely to measure ≥ 4.0 pCi/l in short-term tests within the Low Radon Potential Zone area (i.e., scattered throughout 87.1 percent of the Ventura County area.

Just over 2,000 individuals are estimated to be exposed to indoor-radon levels measuring 20 pCi/l or higher based on short-term test results in Ventura County. Of these individuals, about 600 are estimated to live within the Moderate Zone and about 1,400 are estimated to live within the Low Zone. The available indoor-data are insufficient to predict the number of individuals exposed 20 pCi/l or higher levels within the High Zone (*If the rate is similar to that for Los Angeles County, 6.1 percent, then about 250 individuals would be predicted for this exposure category in Ventura County.*). These exposure estimates, and the identification of elevated radon levels in residences in all radon potential zones, underscore the importance of radon testing to determine the radon levels in buildings regardless of the location.

Long-term alpha track measurements (502 measurements) from a 1989-1990 DHS study of a portion of Ventura County generally support the radon potential zones developed from the short-term test data. Population estimates for exposures to ≥ 4.0 pCi/l radon levels in residences based on the long-term measurements are lower for the High, Moderate, and Low zones than estimates based on short-term measurements. The overall estimates for the population exposed to ≥ 4.0 pCi/l radon levels in residences in Ventura County are 7,066 based on long-term measurements and 35,845 based on short-term measurements.

Finally, although indoor-radon testing in Ventura County began in the late 1980s, data are still lacking for residences on geologic units that have moderate to high radon potentials in Los Angeles and Santa Barbara counties. These geologic units are:

- Rincon Shale (Tr)
- Monterey Formation (both the Tm and Tml units)
- Tud (an unnamed shale unit, after Dibblee; may be equivalent to Modelo Formation or Sisquoc Formation)
- Tush (an unnamed shale unit, after Dibblee; mapped as Modelo or Santa Margarita Formation by some geologists)

Future indoor radon surveys targeting houses on these geologic units should be considered in Ventura County.

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REFERENCES

Brookins, D.G., 1990, The Indoor Radon Problem; Columbia University Press, New York, 229 p.

Carlisle, D. and Azzouz, H., 1993, Discovery of radon potential in the Rincon Shale, California—a case history of deliberate exploration; Indoor Air, v.3, p. 131-142.

Churchill, R.K., 2005, Radon Potential in Southern Los Angeles County, Special Report 182, California Geological Survey, 52 p., and map.

Report link:
http://www.consrv.ca.gov/cgs/minerals/hazardous%5Fminerals/radon/SR182Text.pdf

Map link:
http://www.consrv.ca.gov/cgs/minerals/hazardous%5Fminerals/radon/SR182Map.pdf

Churchill, R.K., 1997, Radon Mapping-Santa Barbara and Ventura Counties; California Geology, v. 50, no. 6, pp. 167-177.
http://www.consrv.ca.gov/cgs/minerals/hazardous_minerals/radon/Radon_Mapping.pdf

Churchill, R.K., 1995, Report to Accompany the Radon Zone Maps for Santa Barbara and Ventura Counties, California, unpublished project report for the Department of Health Services, Interagency Agreement No. #1094-036, 92 p.

Churchill, R.K., and Youngs, L.G., 1993, The Department of Health Services Elementary School Radon Survey: Relationships Between Geology, Soils and Indoor Radon; unpublished report for the California Department of Health Services, 109 p.

Churchill, R.K., 1991, Geologic Controls on the Distribution of Radon in California, unpublished report prepared for the California Department of Health Services by the California Division of Mines and Geology (now known as the California Geological Survey), 41 p. Available at:
http://www.consrv.ca.gov/cgs/minerals/hazardous_minerals/radon/Geo_Controls_Dist_Radon.pdf

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

Duval, J. S., Fukumoto, L.E., Fukumoto, J.M., and Snyder, S.L., 2004, Geology and Indoor Radon in Schools of the Palos Verdes Peninsula Unified School District, Palos Verdes Peninsula, California, http://pubs.usgs.gov/of/2004/1050/index.htm

Duval, J.S., 2000, Aerial Gamma-Ray Surveys of the conterminous United States and Alaska: Aerial Gamma-Ray Surveys of California and Oregon, U.S. Geological Survey Open-File Report 99-562-K, CD-Rom.

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.

Liu, Kai-Shen, Chang, Yu-Lin, Hayward, S.B., and Huang, Fan-Yen, 1991, Survey of Residential Radon Levels in Ventura County and northwestern Los Angeles County—Unpublished Final Report, Indoor Air Quality Program, Air & Industrial Hygiene Laboratory, California Department of Health Services, 2151 Berkeley Way, Berkeley, CA 94704, 41p.

Otton, J.K, 1993, Preliminary Geologic Radon Potential Assessment of California, in U.S. EPA Region 9 Geologic Radon Potential Summary; U.S. Geological Survey Open-File Report 93-292-I, 24 p.

U.S. EPA, 2002, "A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family From Radon (4th ed,)," EPA Document 402-K02-006, 12 p. Available at http://www.epa.gov/iaq/radon/pubs/citguide.html

U.S. EPA, 1992, A citizen's guide to radon, second edition, U.S. EPA, Office of Air and Radiation, EPA Document #402-K92-001.

WRRTC, 1997, Radon control techniques for new building construction in California: booklet by the Western Regional Radon Training Center, University of Colorado, Colorado Springs, Colorado, for March 6, 1997 workshop in Ventura, CA sponsored by the California Department of Health Services and the County of Ventura Environmental Health Division, 87 p.

APPENDIX ~~A~~

Dibblee Geologic Map Units and Indoor Radon Data for southern Ventura County

Unit Symbol	Unit Name and Lithology Summary	n	n ≥ 4 pCi/l	% ≥ 4 pCi/l	Low (pCi/l)	High (pCi/l)
Kcs	Chatsworth Formation-sandstone	12	0	0	0.2	2.7
Tcva	Conejo Volcanics-andesite flows and mud flow breccia	2	0	0	0.7	0.8
Tcvad	Conejo Volcanics-andesite-dacite breccia	1	0	0		1.3
Tcvb	Conejo Volcanics—basaltic flows or basaltic flow breccia	9	0	0	0.3	1.2
Tcvbp	Conejo Volcanics-basaltic flows (pillows), minor breccias	5	0	0	0.3	1.3
Tlsc	Detrital Sediments of Lindero Canyon-conglomerate (gr)	1	0	0		0.9
Tlvc	Detrital Sediments of Lindero Canyon-basal epiclastic (reworked) conglomerate of detritus derived from Conejo Volcanics	10	0	0	0.3	2.9
Tll	Llajas Formation-micaceous claystone and siltstone	3	0	0	0.6	1.8
Tm	Monterey Formation or Shale (Modelo) upper shale unit-siliceous shale, upper siliceous shale to lower diatomaceous, locally cherty	33	7	21.2%	0.3	7.9
Tml	Monterey Formation or Shale-lower shale unit, siliceous to semi-siliceous silty clay shale, some thin dolomite	8	2	25.0%*	0.3	8.6
Qoa	Older Dissected Surficial Sediments—alluvial gravel, sand and clay (terraces)	143	8	5.6%	0.2	7.0
Qog	Older Dissected Surficial Sediments-cobble-boulder gravel fan or fanglomerate; or intermediate (in age) terrace	23	1	4.4	0.3	5.8

Qs	Surficial Sediments-beach sand deposits	8	0	0	0.2	1.0
Tp	Pico Formation-claystone, siltstone, mudstone, sandstone, micaceous claystone, minor sandstone, locally pebbly	1	1	--		7.4
Tsu	Santa Susana Formation-micaceous clay shale or micaceous claystone siltstone	6	0	0	0.3	1.5
QTs	Saugus Formation-alluvial pebble cobble or boulder-cobble pebble conglomerate with sand and clay	13	0	0	0.3	1.7
Tsp	Sespe Formation-fluvial bedded sandstone, arkosic, locally pebbly; silty shale or claystone with interbeds of sandstone	7	0	0	0.3	1.5
Qa	Surficial Sediments-alluvium—silt, sand, gravel	291	16	5.5%	0.3	28.6
Qf	Surficial Sediments-alluvial fan	8	0	0	0.3	1.3
Ttlc	Lower Topanga Formation-micaceous clay shale, or sandstone with interbeds of mica siltstone	4	1	25*	0.3	18.1
Ttus	Upper Topanga Formation-sandstone or upper sandstone	1	0	0		1.2
totals		589				

Note: Only 4 geologic map units out of 120 have 23 indoor measurements or more, only 7 have 10 or more data, and only 21 have any data (1 or more).

APPENDIX B

Radon Priority Units and Justification for Radon Zone Designation

Map Unit-Information (From Dibblee Foundation Maps. Modified by R. Churchill)	**7.5 minute Quadrangle Maps Where the Map Unit is Present**	**Radon** Data	**Radon Zone Designation**	**Justification for Radon Zone Designation and Targeting for Additional Testing**
Tud-Unnamed Shale (upper Modelo Formation by others, equivalent to Sisquoc Formation of Dibblee in Ventura Basin)	Calabasas	**Rate uncertain** (No data, likely above 21%) n=0 *Rate in southern Los Angeles Co.= 31.6%, n=19*	**High**	Although no Indoor-test data are available for this geologic unit in Ventura County, data in Los Angeles County suggest more than 20 percent of the associated buildings will have indoor radon levels exceeding 4 pCi/l (Churchill, 2005) *Radon testing of buildings located on this geologic unit should be a priority*
Tush-Unnamed Shale (upper Modelo Formation or Santa Margarita Formation by others; equivalent to Sisquoc Formation of Dibblee in Ventura basin)	Calabasas	**Rate uncertain** (No data, likely above 21%) n=0 *Rate in southern Los Angeles Co.= 29.8%, n=57*	**High**	Although no Indoor-test data are available for this geologic unit in Ventura County, such data in Los Angeles County suggest more than 20 percent of the associated buildings will have indoor radon levels exceeding 4 pCi/l (Churchill, 2005); *Radon testing of buildings located on this geologic unit should be a priority*
Tr-Rincon Shale	Fillmore, Matiliji, Ojai, Piru, Pitas Point, Ventura, White Ledge Peak	**Rate uncertain** (No data, likely to be above 21%) n=0 *Preliminary estimate of rate in Santa Barbara City area = 40 to 50 percent*	**High**	Although no Indoor-test data are available for this geologic unit in Ventura County, a preliminary review of DHS short-term measurement data for buildings on this geologic unit in Santa Barbara County suggests a ≥ 4.0 pCi/l incidence rate of 40 to 50 percent Priority supported by NURE airborne radiometric

				data. *Radon testing of buildings located on this geologic unit should be a priority.*
Tm-Tml-Qa High—A selected area near Oak Park containing Monterey Formation-upper shale unit, Monterey Formation-lower shale unit, and Recent Alluvium	Thousand Oaks, Calabasas	**Rate uncertain** (few data, rate may be above 21 percent) n=9 ≥4.0 = 3 Max=6.5 pCi/l	**High** (in Oak Park area)	Selected area of about 0.78 sq.mi., consisting of portions of Tm, Tml, and Qa geologic units, where limited test data suggest more than 21 percent of the associated buildings may have indoor radon levels exceeding 4 pCi/l *Additional testing of buildings in this area should be a priority*
Tm-Monterey Formation or Shale (Modelo) upper shale unit *Exclusive of Tm in Oak Park area which is included in a High zone area—see the table entry immediately above*	Calabasas, Fillmore, Matilija, Moorpark, Newbury Park, Ojai, Piru, Pitas Point, Santa Paula, Santa Paula Peak, Santa Susana, Simi, Thousand Oaks, Val Verde, Ventura, White Ledge Peak	**Rate 19.4%** (exclusive of Oak Park Tm sites) n=31 Max=7.9 pCi/l *Note: Overall rate for Tm, including Oak Park Tm sites, is 20.6%* *n= 34* *≥ 4.0 = 7* *Max = 7.9 pCi/l*	**Moderate**	The available DHS short-term indoor radon data indicate a ≥ 4.0 pCi/l incidence rate between 6 and 21 percent is likely Priority supported by NURE airborne radiometric data. *Additional testing of buildings on this unit is recommended.*
Tml-Monterey Formation- lower shale unit	Fillmore, Matilija, Moorpark, Ojai, Piru, Pitas Point, Santa Paula Peak, Santa Susana, Simi, Thousand Oaks, Ventura, White Ledge Peak	**Rate uncertain** (few data, rate may be above 6 percent) n=8 ≥ 4.0 = 2 Max = 8.6 pCi/l	**Moderate**	Rate of ≥ 4.0 pCi/l buildings uncertain—Limited indoor test data and NURE Airborne radiometric data suggest that more than 6 percent of the associated buildings may contain indoor radon levels exceeding 4.0 pCi/l; south Los Angeles County data suggest less than 20 percent of associated buildings will exceed 4.0 pCi/l (Churchill, 2005);

				Additional testing of buildings on this unit is recommended.
Tsq-Sisquoc Shale	Matilija, Moorpark, Ojai, Piru, Pitas Point, Santa Paula Peak, Santa Susana, Simi, Val Verde, Ventura, White Ledge Peak	**Rate uncertain** (No data, may be in part related to high potential units in Los Angeles County) n=0	**Moderate**	May be equivalent to Tud or Tush Dibblee map units, which have more than 20 percent of associated buildings with indoor air exceeding 4.0 pCi/l in Los Angeles County (Churchill, 2005); Priority supported by NURE airborne radiometric data; *Additional testing of buildings on this unit is recommended.*
Qoa-Older Dissected Surficial Sediments-youngest gravel terraces--only the Qoa in the Fillmore area	Fillmore (only Qoa in the Fillmore area)	**Rate uncertain** (few data, former study suggests a rate above 6 percent) n=5 ≥ 4.0 = 2 Max = 5.4 pCi/l *(Max=12.8 pCi/l in 1991-92 DHS Elementary School Study)* *Note: Qoa rate outside of the Fillmore area= Rate = 4.4%* n= 13	**Moderate** (in Fillmore area only) *Available data suggest that Qoa has low radon potential elsewhere in Ventura Co.*	Rate of ≥ 4.0 pCi/l buildings uncertain but may exceed 6 percent in Fillmore based on a DHS elementary school study in early 1990s (Churchill and Youngs, 1993) in which 6 of 54 school rooms in Fillmore were ≥ 4.0 pCi/l *Additional testing of buildings on this unit in the Fillmore area is recommended.*

APPENDIX C

NURE Flight-line Miles and Data Points by 7.5-minute Quadrangle for southern Ventura County

7.5 minute Quadrangle Name	Miles of NURE Project Flight Line	Number of Data Locations Along Flight Line
Calabasas	15.1	631
Camarillo	30.0	1116
Fillmore	29.3	1435
Matilija	27.4	1359
Moorpark	30.1	1243
Newbury Park	30.1	1242
Ojai	21.3	1126
Oxnard	20.3	749
Piru	19.9	738
Pitas Point	5.0	140
Point Dume	0	0
Point Mugu	9.7	396
Santa Paula	30.1	1241
Santa Paula Peak	27.7	1547
Santa Susana	25.3	1176
Saticoy	21.4	845
Simi	21.4	919
Thousand Oaks	17.5	741
Trifuno Pass	10.4	417
Val Verde	7.8	315
Ventura	26.6	1167
White Ledge Peak	11.6	567
Totals	438.0	19110

APPENDIX D

NURE Airborne Radiometric Equivalent Uranium Data Equal or Greater Than 7.5 ppm by Dibblee Map Geologic Unit

Dibblee Map Unit		Number of Flight-line data points at 7.5 ppm eU or greater	Percent of all Flight-line data points at 7.5 ppm eU or greater	7.5-minute quadrangles containing 7.5 ppm eU or greater locations
Kucg	Unnamed Marine Strata (Jalama Fm?)-conglomerate	1	0.2	Matilija
Qa	Surficial Sediments-alluvium	17	3.8	Fillmore, Matilija, Moorpark, Ojai, Santa Paula Peak, Santa Susana
Qf	Surficial Sediments-alluvial fan	3	0.7	Matilija, Santa Paula Peak
Qg	Surficial Sediments-stream channel deposits	14	3.1	Fillmore, Matilija, Santa Paula Peak, Santa Susana
Qls	Landslide and Talus Debris-includes slopewash of sandstone detritus	51	11.3	Matilija, Ojai, Santa Paula, Santa Paula Peak, Santa Susana, Ventura-Pitas Point
Qoa	Older Dissected Surficial Sediments-youngest, lowest gravel terraces	4	0.9	Fillmore, Ventura-Pitas Point
Qog	Older Dissected Surficial Sediments-intermediate, higher gravel terraces	10	2.2	Fillmore, Ojai, Ventura-Pitas Point
Tcw	Coldwater Sandstone-marine regressive hard sandstone	14	3.1	Fillmore, Santa Paula Peak, White Ledge Peak
Tjsh	Juncal Formation-marine micaceous shale	2	0.4	Ojai

Tjss	Juncal Formation-marine arkosic sandstone	2	0.4	Ojai
Tm	Monterey Formation-upper shale unit (Modelo Formation)-marine biogenic siliceous shale	97	21.5	Calabasas, Fillmore, Moorpark, Ojai, Piru, Santa Paula, Santa Paula Peak, Santa Susana, Simi, Ventura-Pitas Point
Tma	Matilija Sandstone-marine hard arkosic sandstone	4	0.9	Santa Paula Peak
Tmd	Monterey Formation-diatomaceous shale	1	0.2	Ojai
Tml	Monterey Formation-lower shale unit (Modelo Formation)-marine biogenic siliceous shale and dolomite	49	10.8	Ojai, Simi, Ventura-Pitas Point
Tmss	Monterey Formation-lower sandstone member (Modelo Formation)-marine biogenic; similar to Tmsu	2	0.4	Fillmore, Piru
Tp	Pico Formation-marine claystone and siltstone	27	6.0	Moorpark, Santa Paula, Santa Paula Peak
Tpr	Pico Formation-Repetto Member-marine claystone	3	0.7	Ventura-Pitas Point
Tps	Pico Formation-marine bedded sandstone	20	4.4	Santa Susana
Tr	Rincon Shale-marine clay shale and siltstone	53	11.7	Fillmore, Ojai, Ventura-Pitas Point

Tsc	Saugus Formation-nonmarine pebbly sand similar to QTs	4	0.9	Moorpark
Tsp	Sespe Formation-nonmarine sandstone and lesser amounts of claystone	24	5.3	Fillmore
Tsq	Sisquoc Formation-marine clay shale	34	7.4	Ojai, Santa Paula Peak, Santa Susana, Ventura-Pitas Point
Ttos	Towsley Formation-marine sandstone	9	2.0	Santa Susana
Tvq	Vaqueros Sandstone-shallow marine transgressive massive sandstone	7	1.6	Fillmore
totals		452	99.9	

APPENDIX E

Descriptive Statistics and Statistical Comparison of Indoor Measurement Data (non-transformed) for Ventura County Radon Zones

	All Indoor Rn Data	High Zone Rn Data	Moderate Zone Radon Data	Low Zone Radon Data
Size	589	10	69	510
Mean	1.448	3.250	2.620	1.254
Std Dev	2.114	2.144	3.726	1.714
Std Error	0.0871	0.678	0.449	0.0759
C.I. of Mean	0.171	1.534	0.895	0.149
Range	28.400	6.000	28.300	23.400
Max	28.600	6.500	28.600	23.600
Min	0.200	0.500	0.300	0.200
Median	0.900	2.700	1.500	0.900
25%	0.500	1.700	0.800	0.500
75%	1.500	5.600	3.525	1.400
Skewness	7.120	0.588	5.244	7.288
Kurtosis	73.231	-1.169	35.100	77.055
K-S Dist.	0.288	0.209	0.267	0.283
K-S Prob.	<0.001	0.239	<0.001	<0.001
Sum	852.800	32.500	180.800	639.500
Sum of Squares	3861.680	147.010	1417.960	2296.710

APPENDIX F

Descriptive Statistics and Statistical Comparison of Indoor Measurement Data (Log10-transformed) for Ventura County Radon Zones

	All Indoor Rn Data	High Zone Rn Data	Moderate Zone Radon Data	Low Zone Radon Data
Size	589	10	69	510
Mean	-0.023	0.408	0.203	-0.0620
Std Dev	0.367	0.344	0.421	0.343
Std Error	0.0151	0.109	0.0507	0.0152
C.I. of Mean	0.0297	0.246	0.101	0.0299
Range	2.155	1.114	1.979	2.072
Max	1.456	0.813	1.456	1.373
Min	-0.699	-0.301	-0.523	-0.699
Median	-0.0458	0.429	0.176	-0.0458
25%	-0.301	-0.230	-0.0969	-0.301
75%	0.176	0.748	0.547	0.146
Skewness	0.564	-0.729	0.245	0.549
Kurtosis	0.384	0.662	-0.135	0.536
K-S Dist.	0.0951	0.139	0.0852	0.110
K-S Prob.	<0.001	0.724	0.241	<0.001
Sum	-13.542	4.077	14.017	-31.636
Sum of Squares	79.527	2.730	14.897	61.901