

Radon Distribution in Domestic Water of Texas

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ABSTRACT

Concern is mounting over possible adverse health effects associated with exposure to elevated domestic alpha radiation levels (Bean *et al.*, 1982); Petersen *et al.*, 1966; Lyman *et al.*, 1985; Cothorn, 1987). Radon released during domestic use of ground water is one of the potential routes of such exposure. However, relatively little is known worldwide about the distribution of alpha-emitting radioisotopes in ground-water supplies. In Texas, deposits of uranium occur, rich enough to be mined commercially, and the possibility existed that significant concentrations of uranium disintegration products may have been present in ground-water supplies. Cech *et al.* (1987a) identified two regions with anomalously high concentrations of radium-226: in the Gulf Coast, down dip from uranium deposits, and in west-central Texas, on the periphery of an igneous uplift. Radium-226 is a parent of radon-222 which is a focus of the present paper. Concentrations of radon up to 3300 pCi/l were observed in several domestic-water supplies. This study suggests that it may be external sources (interaction of Tertiary aquifers with salt domes, leaky faults, and uranium-bearing volcanic ashes) and not the bulk mineralogy of the aquifers, which cause anomalous concentrations of alpha-emitting radioisotopes in well water. The distinction is important, as it offers the possibility of avoiding high risk areas when selecting well drilling locations.

INTRODUCTION

Radon-222, a member of the uranium-238 decay series, is an alpha-emitting noble gas that is found in various concentrations in ground water. Exposure to radon has been associated with lung

cancer in miners (Sevc *et al.*, 1970; Archer *et al.*, 1973; National Research Council, 1980), and recently radon has received national attention because of high concentrations observed in houses in some parts of the United States [US Environmental Protection Agency (EPA), 1986a and b]. Although radon may enter a dwelling from several different sources, in some regions releases from ground water used domestically contribute a significant share of indoor radon.

The EPA estimates that "over a period of 70 years (the average lifetime in the United States), between 2000 and 40,000 lung cancer fatalities are caused by inhalation of natural radon released from US public water supplies" (Cothorn, 1987). It was further said that "the average concentration of radon in these water supplies generates a lifetime risk of about 1 in 10,000, the highest level of risk allowed for any contaminants currently regulated under the Safe Drinking Water Act." Yet, as it stands now, present regulations for radionuclides in the US public-water supplies do not involve radon.

Because the limits for radon in domestic-water supplies have not been set under the Safe Drinking Water Act, no regulatory authority monitors radon on a regular basis. As a result, there is no reliable overall knowledge of the geographic distribution of radon as is needed to guide water-supply planning and development. During the period 1984 to 1986, we conducted three separate studies of radon in domestic water in selected regions of Texas. A total of 150 samples were collected and mapped (Figures 1-3). Because of the timely significance, we wish to share our information regarding radon distribution in domestic-water supplies.

METHOD

The selection of regions to sample was based on geological reasoning and included both areas where rock compositions suggested elevated terrestrial radioactivity and also where no such sources were known or suspected to be present. The latter were included in order to determine background concentrations for water sources in Texas. Samples were collected from both rural-domestic and

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public-water supplies. The sampling scheme was as follows:

1. Twenty samples were obtained in seven counties in the northern part of the Texas Panhandle, from the area constituting the North Plains Ground Water District (Figure 1). The source of water in this region is the Ogallala aquifer (Figure 4).

2. Fifteen samples were obtained from three counties of the Llano Uplift in west-central Texas (Figure 2). Sources of water in this region are two minor aquifers, the Hickory Sandstone and the Ellenburger-San Saba Limestone (Figure 4).

3. A rather detailed sampling, reflecting the complexity of the water-supply system, was carried out in a heavily populated part of the upper Gulf Coast. A total of 116 samples were collected from wells and also from distribution systems in and around Houston. Samples were taken in Fort Bend and Montgomery Counties, but the main focus was Harris County (Figure 3). With 2,684,000 people, Harris County is the most populated county in Texas and has 18 percent of the state's population. The southeast part of Harris County is supplied by surface water, but the rest of the study area derives water from the Gulf Coast aquifer.

The physical size of Texas makes gathering data from remote parts of the state difficult. Samples from individual rural wells involved visiting private residences where permission was secured from heads of households to collect water samples. Samples of municipal drinking water were obtained from commercial and household taps and, where necessary, directly from wells. Locations were selected to obtain a representative coverage of drinking-water sources typically used in the study areas. Samples were taken in duplicate to assure the reproducibility of the laboratory results.

Radon concentrations were determined by drawing a 15-ml sample directly from a source into a clean syringe. Care was taken to prevent aeration of the samples in the process. The samples were then injected beneath a 5-ml layer of mineral-oil-based scintillation solution in 20-ml vials. The vials were vigorously shaken to promote phase contact, held for at least three hours to permit radon daughter ingrowth, and assayed with a liquid scintillation counter. The results were corrected for the amount of radon decay between sampling and assay. All analyses were carried out in the University of Texas School of Public Health laboratory. The data gathered as a result of this investigation were synthesized by means of computer mapping, SYMAP (Doughnik, 1975), and other graphic techniques.

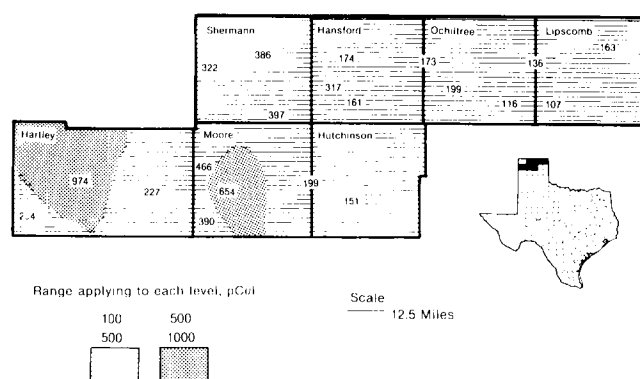


Fig. 1. Radon-222 concentrations in domestic-water supplies derived from Ogallala aquifer, North Plains Ground Water District.

RESULTS

Figures 1-3 show the distribution of radon in the water received at the consumers' taps in various parts of Texas. It is evident that concentrations of radon in the domestic water vary greatly. Radon concentrations observed in wells tapping the Ogallala aquifer, the major source of water in northwest Texas, varied from about 100 pCi/l to about 1000 pCi/l, but predominant concentrations were low (Figure 1). This observation applied equally to rural-domestic and public wells. The median radon concentration was about 300 pCi/l. Only two samples (one from a rural-domestic and another from a public-water source) had concentrations greater than 500 pCi/l.

In water supplies derived from Hickory Sandstone and Ellenburger-San Saba Limestone aquifers (Figure 2), radon concentrations varied from less

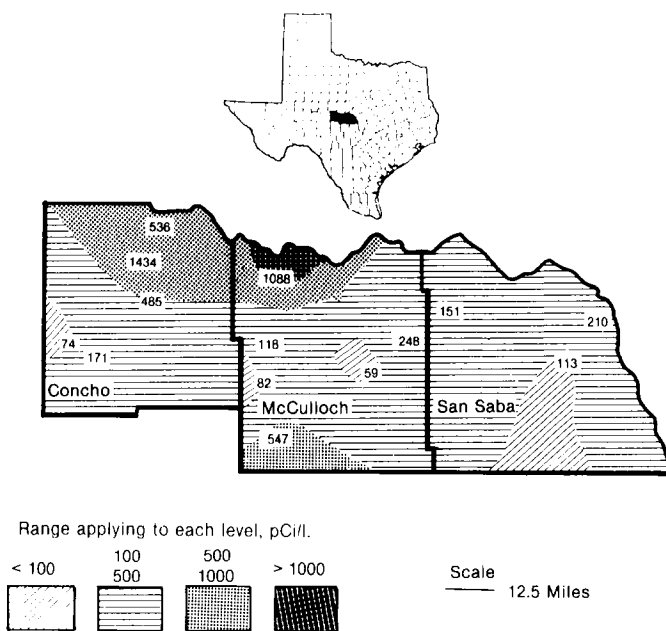


Fig. 2. Radon-222 concentrations in domestic-water supplies derived from Hickory Sandstone and Ellenburger-San Saba limestone aquifers, Llano Uplift region.

than 100 and up to 1400 pCi/l. The median concentration was again about 200 pCi/l; however, the mean concentration was somewhat greater, about 400 pCi/l, reflecting several comparatively high measurements. In four samples, concentrations were in excess of 500 pCi/l and in two of these four, in excess of 1000 pCi/l. The highest radon concentration, 1400 pCi/l, was observed in a rural well near the top of the Brady Mountain of the Llano Uplift.

Figure 3 shows concentrations of radon observed in the tap water on the Texas Gulf Coast, in and around Greater Houston in Harris County. The range of variation was from undetectable to as much as 3300 pCi/l. No appreciable radon concentrations were observed in the southeast part of Houston, where water of surface origin or a mixture of surface and ground water is distributed. However, in northwest and southwest Harris County, ground water exhibited greater than trace levels of radon.

The first anomaly was located in northwest Harris County. Up to about 3300 pCi/l of radon

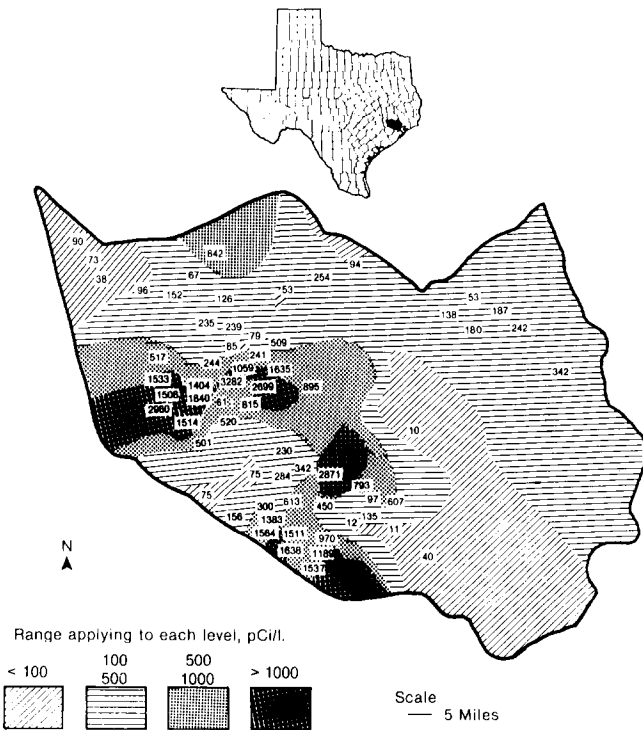


Fig. 3. Concentrations of radon-222 in domestic-water supplies on the Upper Gulf Coast in Harris County. Note: tap water in southeastern Harris County is from the surface source, Lake Houston; because concentrations were uniformly low and water is from the same surface reservoir, only a limited number of samples were collected in this part of the study area. All observations of elevated radon were associated with ground water and in this category with medium-to-deep wells (from 100 to 600 meters).

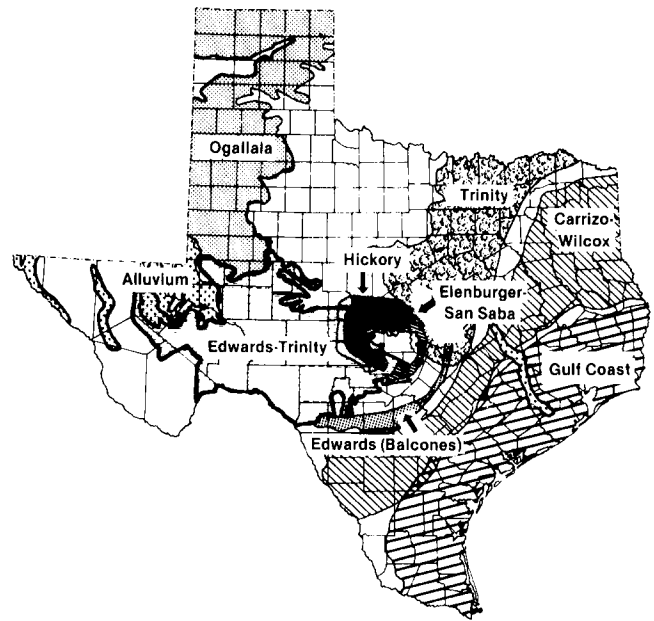


Fig. 4. Location of the major ground-water aquifers in Texas. Minor aquifers important in this study, Hickory and Elenburger-San Saba, are shown also.

were found in an area about 13 to 16 km south-southeast of the salt domes near Hockley and Tomball (Figure 5) and geographically adjacent to two local streams (Logenbaum and White Oak, left tributaries of upper Buffalo Bayou). The second anomaly, with radon concentrations up to about

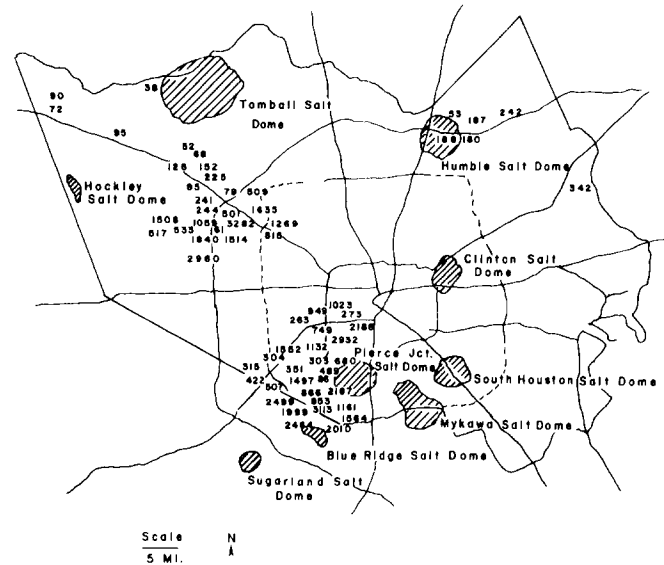


Fig. 5. Point-source measurements of radon-222, in the Upper Gulf Coast in Harris County, Texas. Samples were obtained either directly at well heads or from single-source municipal utility districts. Shown also are locations of salt domes. Note: the data shown on Figure 5 represent anomalously high concentrations for the region; this is evident by comparing Figure 5 with Figure 3 where all the data are presented.

3110 pCi/l, was found in wells developed near (less than 3 km) a piercement-type salt dome, Blue Ridge, in the upper Sims Bayou watershed. In the southwest-central part of Harris County, radon concentrations up to 2900 pCi/l were observed near a salt dome at Pierce Junction.

The relationship of radon concentrations to depth and location of the water source was further investigated in the Upper Gulf Coast area, using data collected directly at the well heads. For this purpose, a subset of 64 points representing a diverse distribution of water sources was formed and subjected to statistical analysis. The point-source locations are shown on Figure 5 (except for additional points to the north, in adjacent Montgomery County). While details and documentation of statistical tests are provided in a separate report (Cech *et al.*, 1987b), some of the most salient observations might be summarized as follows:

1. Radon concentrations tended to increase with depth. Figure 6 shows increase in radon concentrations with depth measured, respectively, to

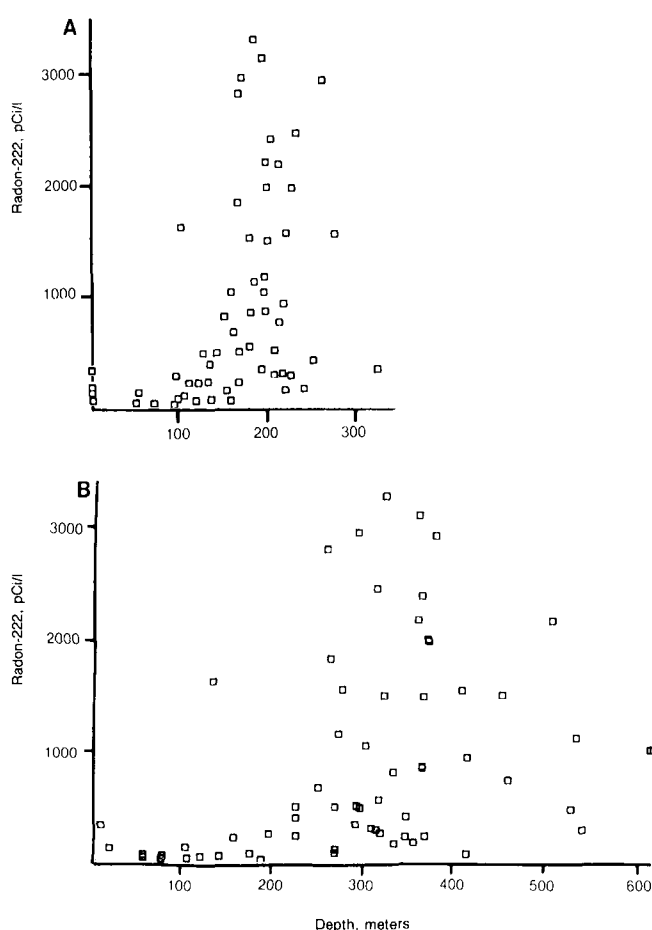


Fig. 6. Distribution of radon-222 in well water from the Gulf Coast aquifer with depth. A—upper limit of pumping range; B—lower limit of pumping range, Gulf Coast aquifer.

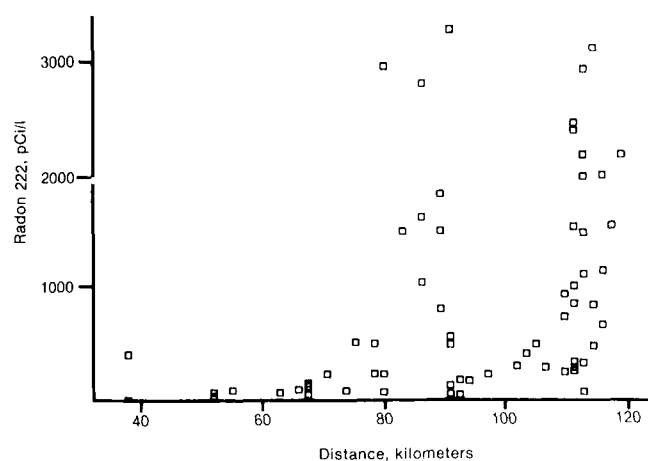


Fig. 7. Distribution of radon-222 with the distance down-dip from recharge area of the Gulf Coast aquifer.

the uppermost (6A) and the lowermost (6B) screening intervals in wells. The linear model was appropriate to describe the vertical concentration profile for radon ($p < 0.01$) in both situations.

2. Concentrations also tended to increase in direction toward the Gulf Coast. Figure 7 shows radon concentrations along the northwest-to-southeast axis down-dip from the recharge zone of the Gulf Coast aquifer. The first increase in concentrations occurred 90 km down-dip from the recharge area (coincident with the geological fault stretched between Hockley and Tomball salt domes, and about 13 and 16 km southeast of the domes). The second anomaly existed 25 km down-dip from the first (coinciding with the area of the fault system associated with Blue Ridge salt dome). The linear model fitted to this distribution had a positive slope with increasing distance from the recharge zone (inversely, with decreasing distance from the Gulf) and was statistically significant ($p < 0.01$). Since water-bearing strata in the study area dip toward the coast, the tendency of radon concentrations to increase toward the coast possibly resulted from increase in well depths in the same direction.

3. The proximity of salt domes was an important predictor for the presence of radon in well water, particularly medium-to-deep wells. The inverse relationship ($p < 0.01$), increase in concentrations with decreasing distance from the dome, was particularly evident for wells developed near Blue Ridge and Pierce Junction salt domes (Figure 8). Because of rural location, no deep municipal wells were present in the vicinity of the Hockley, Tomball, and Humble salt domes, and this fact might have obscured the statistical association. The correlation of radon with other salt

domes in Harris County could not be made because they were situated in a part of the county which was supplied by surface water.

DISCUSSION

The origin of radon observed in the water supplies in Texas is natural given that uranium and radium are present in rocks (Kier *et al.*, 1977; Cook, 1980) and in the water (Cech *et al.*, 1987a). Figure 9 shows known deposits of mineral uranium on which our observations regarding radium and radon are superimposed. Not claiming comprehensiveness, this map allows pinpointing areas where elevated concentrations of radon and its paternal radium in the domestic water were documented with reasonable certainty. Since radon is a progeny of radium, the geographic distribution of two isotopes obviously coincides. Quantitatively, however, the correlation of radium and radon observed under field conditions was not always perfect. The variations in distribution may be due to differential retention, accumulation, and diffusion properties of dissolved radium and gas radon. This tells us that radium measurements are not necessarily a reliable surrogate variable to be substituted to represent unavailable magnitudes of radon and vice versa.

In some parts of the State, Precambrian igneous and metamorphic rocks are uplifted and exposed. One such uplift exists in the Llano area in west-central Texas. Studies identified a radium-226 anomaly at the base of Brady Mountain of the Llano Uplift, where Cambrian-age Hickory sandstones and dolomite and limestones of Cambrian and Ordovician ages are the main sources of ground

water (Cech *et al.*, 1987a). The anomalous radium concentrations (up to 65 pCi/l) were associated with deep wells, from 370 to 670 meters. The present study shows that radon concentrations up to 1400 pCi/l were found in spots in the Llano Uplift area. Two samples with concentrations over 1000 pCi/l were both from relatively shallow individually owned rural wells. Radon concentrations observed in tap water derived from deep wells were up to 500 pCi/l.

Cambrian sandstones were deposited in this area upon unevenly eroded Precambrian rocks. Although no uranium deposits are explicitly shown on the geological map in the Llano area, igneous rocks typically contain greater amounts of uranium than other crustal rocks (Kathren, 1984). Radon found in the ground water in the Llano area most likely relates to the products of erosion of Precambrian rocks.

Radium observed in ground water in the Gulf Coast evidently relates to uranium present in Eocene and younger deposits. Known host rocks are the Catahoula tuffs of the Miocene age. Uranium was present in volcanic ashes brought by northeasterly winds into the Texas region during eruptions of the Mexican Rockies in the Miocene era (Texas Department of Health, 1982). According to Cook (1980), uranium subsequently circulated with the ground water until stratigraphic traps (i.e., faults that may have served as barriers to circulation) or reducing conditions (hydrogen sulfide, lignite deposits, methane gas, or carbonaceous matter) were encountered which caused uranium to precipitate and form ores. Fluvial transport and a series of redissolution and reprecipitation caused uranium and its decay products to travel considerable distances away from their source deposits and toward the modern-day coast; this process continues today.

The Catahoula formation which is mined for uranium in south Texas extends along the entire Gulf Coast from the border with Mexico to the Louisiana border (Figure 9); it crops out parallel to the coast at some distance inland and dips toward the Gulf so that near the coastline it is more than 1.5 km below the land surface (Popkin, 1971). Many water wells have been developed in the Gulf Coast, with depths varying from as shallow as 6 meters to as deep as 600 meters. The density of medium-to-deep wells has been particularly great in a heavily populated part of the Upper Gulf Coast at Houston. As evident from the data gathered in our study, some of the public wells developed in the Houston area encountered elevated radon concentrations.

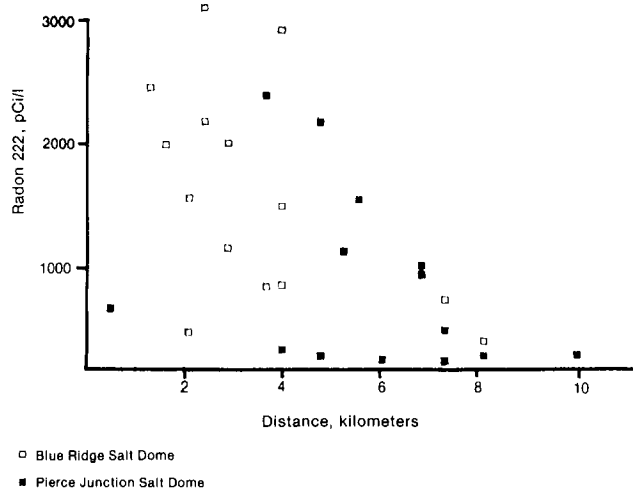


Fig. 8. Distribution of radon-222 in well water from the Gulf Coast aquifer with the distance to Blue Ridge and Pierce Junction salt domes.

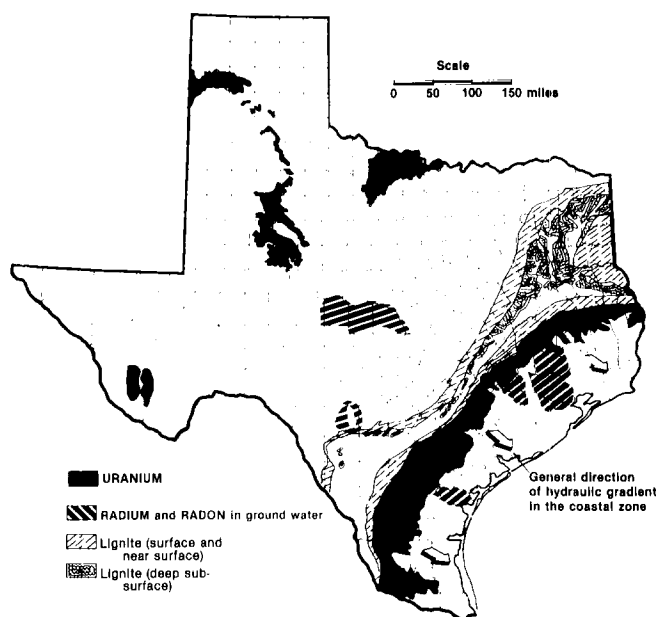


Fig. 9. Radioactive deposits in Texas. Compiled by superimposing radium and radon data gathered by Cech *et al.* (1987) on a map of uranium deposits adapted from Kier *et al.* (1977).

The characteristics of the Gulf Coast aquifer have been described elsewhere (Wood *et al.*, 1963; Gabrysch, 1967; Popkin, 1971; Wesselman, 1972; Kreitler *et al.*, 1977). Basically, the aquifer consists of numerous alternating beds of clays and sands. Formations crop out in bands roughly parallel to the coast and dip toward the Gulf at an angle which is greater than the slope of the land surface and increases with depth. In the study area, the Miocene age formations dip toward the Gulf at a rate of about 17 m/km (Popkin, 1971); younger formations have progressively decreasing dip, from 15 to 18 m/km in the intermediate beds to about 2 m/km in the youngest beds.

Deeper units in the Gulf Coast aquifer typically have greater potentiometric heads compared to more shallow units (Wesselman and Aronow, 1971). The greater heads result from greater elevations of the recharge zones for the older formations and from the absence of reasonable downdip regional discharge zones. The combination of factors causes pressure to build up. Water moves under the influence of gravity from areas of recharge to areas of discharge in a general direction from northwest to southeast, toward the Gulf. In much of the area, confining beds of clay create artesian conditions; however, these confining clays are not continuous, and there is hydraulic communication around clay beds. Interconnections along the sides of piercement-type salt

domes may also provide opportunities for discharge of ground water.

The Catahoula sandstone is the deepest fresh-water-bearing unit in the Gulf Coast aquifer complex. Although geologically the formations which constitute the Gulf Coast aquifer range in age from sandstones of Oligocene and Miocene eras to alluvium of the Quaternary period, the actual production of well water involves strata of the Pliocene-Pleistocene (Evangelina and Chicot aquifers), rather than the Catahoula of the Miocene age. The presence of radon in well water derived from the Evangelina and Chicot aquifers may be evidence of cross-formational seepage; that is when deeper water, with its greater potentiometric head, seeps upward between confining clay beds. The upward seepage may have been most prominent on the flanks of piercement-type salt domes, along faults, and through permeable sediments deposited by streams.

The vertical concentration profile observed for radon supports this interpretation, but it is also possible that radon in well water relates to uranium and radium present directly in the Evangelina aquifer. Those may be the products of Catahoula erosion redistributed by fluvial transport. Uranium deposits have been found in the rocks that flank or overlay Gulf Coast salt domes, such as Palangana dome (Weeks and Eargle, 1960) and Hockley dome (Kyle and Price, 1986), and may be the source for radium and radon. The uranium presumably is precipitated in the reducing environment surrounding the dome. As ground water flows past the dome, it entrains the soluble radium and radon.

In our study, the proximity of salt domes was found to be a predictor of radon presence in well water, especially medium to deep wells. Ordinarily, radon concentrations in clastic aquifers were quite low. In 20 samples of well water collected from the Ogallala aquifer of the Texas High Plains, the median concentration of radon was about 200 pCi/l and none was greater than 1000 pCi/l. The median concentration in the Llano region, likewise, was about 200 pCi/l. These observations are in contrast with up to 1400 pCi/l observed in spots in the same Llano uplift region or up to 3300 pCi/l found on the Gulf Coast. This large variation suggests that it may be external sources, e.g., salt domes, uranium, or leaky faults, and not the bulk mineralogy of the aquifer which caused elevated concentrations. This should be an important consideration when decisions are made about sites for drilling water wells. We advise against developing domestic wells near salt domes and associated faults.

Returning to Figure 9, one should note a belt of lignite deposits which stretches parallel to the uranium belt all the way from the western to the northeastern borders, being particularly prominent in East Texas. Lignite has been shown to contain variable amounts of uranium-238 and its radioactive derivatives Ra-226 and radon-222 (Preusse, 1982). Our sampling thus far has not involved East Texas, but it seems appropriate to extend attention to this particular region in future sampling.

Tertiary clastic aquifers extend in the United States from south Texas all the way to the mid-Atlantic states. The presence of high radon documented in the Upper Gulf Coast may be suggestive of unsuspected radon anomalies in other coastal water supplies. Conversely, the presence of high radon may result from the interaction of Tertiary coastal aquifers with salt domes, faults, and uranium-bearing volcanic ashes. In this case, the extent of high radon ground water in Texas might have been underestimated previously and may not be confined to the South Texas uranium belt. Halbouty (1979) reported that there are at least 467 salt domes documented by drilling in the United States Gulf region and in the Isthmian embayment of southwestern Veracruz and western Tabasco, Mexico, and probably scores of other domes where salt has not yet been penetrated by the drill. Other authors (e.g., Eby, 1956; O'Brien, 1957; Trusheim, 1960; Kennedy, 1965; Ayme, 1965; Kent, 1965) documented and mapped a worldwide distribution of salt domes outside the Gulf region.

The significance to health of radon anomalies observed in several parts of Texas is not yet known since such an assessment has not been made. As we pointed out earlier, the levels at which radon becomes significant to human health have not been firmly established and the maximum allowable levels for radon in the domestic water have not been set. Parts of the Gulf Coast area have been identified in the literature as being in the highest decile in the nation for respiratory cancer mortality (Mason *et al.*, 1975; Riggan *et al.*, 1983). The geographic distribution of cancer mortality in Texas by counties, cities, and by water sources was described for the period from 1964 to 1976 by Cech and coinvestigators (1982). The analogies of the pattern depicted on Figure 10 with those on Figures 9 and 4 are worth noting. Counties with high respiratory cancer mortality rates lined up down the hydraulic gradient from uranium deposits. The average age-adjusted rate for white males in ground water using counties of the

Panhandle (Ogallala aquifer) was 43 per 100,000, but it was 54 per 100,000 in Llano region (Ellenburger-San Saba and Hickory aquifers), 62 per 100,000 in the Gulf Coast aquifer, and 74 per 100,000 in the downdip counties of the same Gulf Coast aquifer (Tables 1a and 1b). This gradient in average annual county mortality rates was not eliminated statistically when several other county-based characteristics (socioeconomic differences, proportion of employed in cancer risk industries, ethnic diversity, mobility, and degree of urbanization) were taken into account as covariables. The variations observed for white females were in the same direction but not statistically significant.

The cohesiveness of patterns alone is not sufficient evidence that water may be a causal factor in respiratory cancer. The lifestyle and other environmental cancer risk factors are too complex and too intertwined to allow for disentanglement simply by comparing mortality and environmental patterns. A much more rigorous analytical treatment of the subject is necessary. The concentration of petrochemical, shipping, and other industries on the Gulf Coast makes industrial air pollution high on the list of suspect causal factors in respiratory cancer. There may be regional differences in smoking patterns within the State of Texas. However, even though the risk from other cancer-provoking agents might also differ markedly geographically, it would be unwise to ignore the possible contribution of water-conveyed factors.

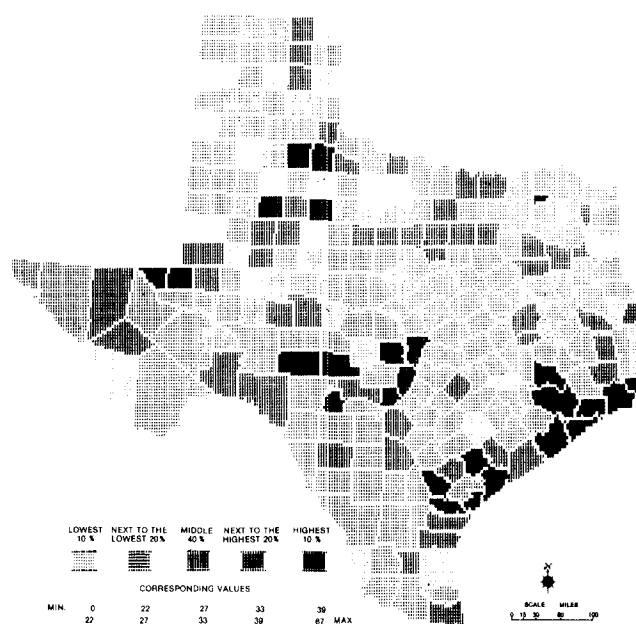


Fig. 10. Mortality by Texas counties from malignant neoplasms of respiratory organs, 1969-1976 (age-adjusted annual average rates per 100,000). Source: Cech *et al.*, 1982.

Table 1. a. Means of Age-Adjusted Annual Average Respiratory Cancer Mortality Rates by Aquifer and Significance of Differences by ANOVA*—Ground-Water Using Counties†, Texas, 1964-1976

Aquifers	Number of counties	Aggregate population	Rates per 100,000	
			Male	Female
Ogallala	25	25	43	10
Ellenburger-San Saba and Hickory	5	30	54	8
Gulf Coast	36	32	62	13
Significance		≤0.05	≤0.01	—

Table 1. b. Means of Age-Adjusted Annual Average Respiratory Cancer Mortality Rates by Location on the Outcrop or Downdip of the Gulf Coast Aquifer and Significance of Differences by ANOVA*—Ground-Water Using Counties†, Texas, 1964-1976

Outcrop	26	30	57	12
Downdip	10	38	74	15
Significance		P ≤ .01	P ≤ .01	—

† Inclusion criteria: population of at least 1,000 (1970 census); more than 50% of the population was on ground water, and no changes in source of drinking water (ground/surface) occurred over the study period.

* Source: Cech *et al.*, 1982.

With an emphasis on air-tightness needed for energy-efficient buildings typical for the hot and humid climate of Texas, it is conceivable that domestic ground water may contribute an appreciable amount of radon to indoor environment. The observed pattern was sufficiently suggestive to warrant further attention to environmental radon and to call for future investigators to include data on radon in their epidemiologic studies.

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REFERENCES

- Archer, V. E., J. K. Wagoner, and R. E. Lundin. 1973. Lung cancer among uranium miners in the U.S. *Health Phys.* v. 25, pp. 351-371.
- Ayme, J. M. 1965. The Senegal Salt Basin. In: *Salt Basins Around Africa*. The Institute of Petroleum, London. pp. 83-90.
- Bean, J., R. Isacson, R.M.A. Mahne, and J. Kohler. 1982. Drinking water and cancer incidence in Iowa. II. Radioactivity in drinking water. *Amer. J. Epidemiol.* v. 16, no. 6, pp. 924-932.
- Cech, I., A. H. Holguin, A. S. Littell, G. F. Bogdan, J. K. O'Connell, and J. P. Henry. 1982. Relation of cancer rates and sources of drinking water. Part I—Texas. Report to the University of Texas Health Science Center, School of Public Health, Houston, Texas.
- Cech, I., H. M. Prichard, A. Mayerson, and M. Lemma. 1987a. Pattern of distribution of radium-226 in drinking water of Texas. *Water Resources Research.* v. 23, no. 10, pp. 1987-1995.
- Cech, I., M. Lemma, H. M. Prichard, and Ch. W. Kreidler. 1987b. Radium-226 and radon-222 in domestic water of Houston-Harris County, Texas. In: *Radon, Radium, and Other Radioactivity in Ground Water: Hydrologic Impact and Application to Indoor Airborne Contamination*. Proceedings of National Water Well Association Conference. Lewis Publishers. pp. 377-402.
- Cook, L. M. 1980. The uranium district of the Texas Gulf Coastal Plain. In: *Natural Radiation Environment III*. Edited by T. F. Gesell and W. M. Lowder. U.S. Department of Energy, Washington, D.C. pp. 1602-1922.
- Cothorn, C. R. 1987. Estimating the health risks of radon in drinking water. *JAWWA.* v. 79, no. 4, pp. 153-158.
- Dougenik, J. A. 1975. SYMAP User's Manual. Laboratory of Computer Graphics and Spatial Analysis. Harvard University, Cambridge.
- Eby, J. B. 1956. Salt dome interest centers on Gulf Coast. In: *World Oil. Proc. International Geol. Cong.* v. 143, no. 5, pp. 143-150.
- Gabrysch, R. K. 1967. Development of ground water in the Houston District, Texas, 1961-65. *Texas Water Development Board Report* 63.
- Halbouty, M. T. 1979. Salt Domes, Gulf Region, United States and Mexico. Gulf Publishing Company, Houston.

- Kathren, R. L. 1984. Radioactivity in the Environment: Sources, Distribution, and Surveillance, Harwood Academic Publishers, New York.
- Kennedy, W. Q. 1965. The influence of basement structure on the evolution of the coastal (Mesozoic and Tertiary) basins. In: Salt Basins Around Africa, The Institute of Petroleum, London. pp. 7-16.
- Kent, P. E. 1965. An evaporite basin in southern Tanzania. In: Salt Basins Around Africa. The Institute of Petroleum, London. pp. 41-54.
- Kier, R. S., L. E. Garner, and L. F. Brown. 1977. Land Resources of Texas. Bureau of Economic Geology, The University of Texas at Austin.
- Kreitler, C. W., E. Guevera, G. Granada, and D. McKalips. 1977. Hydrogeology of Gulf Coast aquifers, Houston-Galveston area, Texas. Transaction of Gulf Coast Association of Geological Societies. v. xxvii, pp. 72-89.
- Kyle, T. P. and P. E. Price. 1986. Metallic sulfide mineralization in salt cap rocks, Gulf Coast, U.S.A. Trans. Inst. Metall. v. 9J, pp. 1310-1316.
- Lyman, G. H., C. G. Lyman, and W. Johnson. 1985. Association of leukemia with radium ground water contamination. JAMA. v. 254, pp. 621-626.
- Mason, T. J., F. W. McKay, R. Hoover, W. J. Blot, and J. F. Fraumeny. 1975. Atlas of Cancer Mortality for U.S. Counties, 1950-1969. DHEW Publication (NIH) 75-80.
- National Research Council. 1980. The Effects of Population Exposure to Low Levels of Ionizing Radiation. National Academy of Sciences, Washington, D.C.
- O'Brien, C.A.E. 1957. Salt Diapirism in South Persia. Geologie en Mijnbouw Nieuwe Serie, 19e Jaargang. pp. 357-376.
- Petersen, N. J., L. D. Samuels, H. F. Lucas, and J. P. Abraham. 1966. An epidemiologic approach to low-level radium-226 exposure. Public Health Rep. v. 81, pp. 805-814.
- Polednak, A. P., A. F. Stehney, and R. E. Rowland. 1978. Mortality among women first employed before 1930 in the United States radium dial-painting industry: a group ascertained from employment lists. Am. J. Epidemiol. v. 107, pp. 179-195.
- Popkin, B. P. 1971. Ground-Water Resources of Montgomery County, Texas. Texas Water Development Board Report 136.
- Preusse, M. J. 1982. Radioactivity at coal and lignite-fired power plants in Texas. Paper presented to the South Texas Chapter of the Health Physics Society. Austin, Texas.
- Riggan, W. B., J. Van Bruggen, J. R. Aquavella, and J. Beaubier. 1983. U.S. Cancer Mortality Rates and Trends, 1950-1979. NCI/EPA, Washington, D.C.
- Sevc, J. E., E. Kunz, and V. Placek. 1970. Lung cancer in uranium mines and long-term exposure to radon daughter products. Health Phys. v. 30, pp. 433-437.
- Texas Department of Health, Bureau of Radiation Control. 1982. Environmental Assessment, Safety Evaluation Report, and Proposed License Conditions Related to Anaconda Minerals Company-Rhode Ranch Project, McMullen County, Texas. Austin, Texas.
- Trusheim, F. 1960. On the mechanism of salt migration in northern Germany. Bull. AAPG. v. 44, no. 9, pp. 1519-1540.
- United States Environmental Protection Agency. 1986a. A Citizen's Guide to Radon: What It Is and What to Do About It. U.S. Department of Health and Human Services Report OPA-86-004. Washington, D.C.
- United States Environmental Protection Agency. 1986b. Radon Reduction Methods: A Homeowner's Guide. U.S. Department of Health and Human Services Report OPA-86-005. Washington, D.C.
- Weeks, A. D. and D. H. Eargle. 1960. Uranium at Palangana Salt Dome, Duval County, Texas. U.S. Geological Survey Prof. Paper 400-B. Austin, Texas.
- Wesselman, J. B. 1972. Ground-water resources of Fort Bend County, Texas. Texas Water Development Board Report 155. Austin, Texas.
- Wesselman, J. B. and S. Aronow. 1971. Ground-water resources of Chambers and Jefferson Counties, Texas. Texas Water Development Board Report 133. Austin, Texas.
- Wood, L. A., R. K. Gabrysch, and R. Marvin. 1963. Reconnaissance investigation of the ground-water resources of the Gulf Coast region, Texas. Texas Water Commission, Bull. 6305. Austin, Texas.
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