North Carolina Geological Survey Information Circular 37:

Interactive Radon Potential Map of North Carolina Referenced to Underlying Geology

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ABSTRACT

Relative to human health, radon-222 is the only naturally occurring isotope of radon having a sufficiently long half-life that is released from earth material. The health effects are well documented. The North Carolina Department of Health and Human Services – Radon Program (NC Radon Program) has distributed home radon air quality test kits throughout the State, providing a robust dataset from which researchers at the North Carolina Geological Survey (NCGS) have been able to georeference radon-222 values to the underlying geologic mappable units. A map of radon potential from the underlying geology has been produced to provide a first-pass, geology-based graphic view of the radioactive radon-222 isotope's naturally occurring potential source for the state of North Carolina. This interactive map relates a more detailed representation of the naturally occurring radon potential than the qualitative geologic unit descriptions on available state geologic maps. The map has been made available to the public via an interactive web map service hosted by the NCGS through the Environmental Systems Research Institute, Inc. (Esri) ArcGIS Online (AGOL) platform.

INTRODUCTION

Uranium is the first element in a long series of solid decay products that eventually produces radium. Radon-222, in turn, is a gas produced by the radioactive decay of radium.[1,2,3] The rate of decay for each radioactive daughter element occurs at a specific rate. Whereas the half-life (the time for one half of a given amount of the element to decay) of uranium is 4.4×10^9 years, the half-life of radon-222 is a mere 3.8 days.[4] Most soils in the United States contain pore space air with radon values between 200 and 2,000 picocuries per liter (pCi/L), however radon values in groundwater range from approximately 100 to 3,000,000 pCi/L.[5,6] The causes for radon levels to vary so widely between soil air and groundwater lay primarily with the host materials' geologic controls.

Unlike uranium, which is fixed in the solid matter of rocks and soil, radon-222 is a gas and therefore has much greater mobility potential due to pore space within the rocks and soils (porosity) and the ability of a material to transport fluids (permeability). Radon-222 easily escapes rocks and soils by seeping through fractures in rocks and pore spaces between grains of soil.[7] Radon-222's mobility is further driven by the pressure differential between the pore space within the solid matter (relative high pressure) and atmospheric-air space (relative low pressure). If radon-222 has the ability to easily move through a particular pore space, then the gas will mobilize a greater distance before it decays. Due to the greater density of water, radon-222 in water mobilizes at a reduced velocity compared to an air medium. The distance that radon travels before the majority of it decays is less than 1 inch (approximately 2.54 cm) in water-saturated rocks and soils but as much as 6 feet (approximately 2 meters) through dry rocks and soils.[8] High topographic relief provides additional opportunities for radon mobility. Topography with high relief provides ample water drainage potential, producing a drier medium allowing for radon-222 to mobilize further before it decays.

BACKGROUND

To date, naturally occurring radon research has been overwhelmingly focused on radon identified from groundwater sources.[9] This abundance of groundwater-based radon research has served to demonstrate the influence of geologic controls from naturally occurring radon. Regionally, the highest average radon concentrations occur in areas underlain by granites and intrusive rocks generally, but particularly of granitic orgin[10], while the lowest concentrations have been recorded in the Atlantic Coastal Plain physiographic province.[11] Intermediate concentrations between these endmembers are characteristic of the large areas of North Carolina underlain by gneisses, schists, and metavolcanic rocks [Figure 1].[11,12] Despite the differences in radon-222's mobility potential in a liquid medium (groundwater) verses a gas medium (atmospheric air and soil air) and radon's concentration potential in groundwater verses air, the similar spatial distribution trends from the available groundwater analyses[11] and the air quality distributions observed, discussed herein, are compelling.

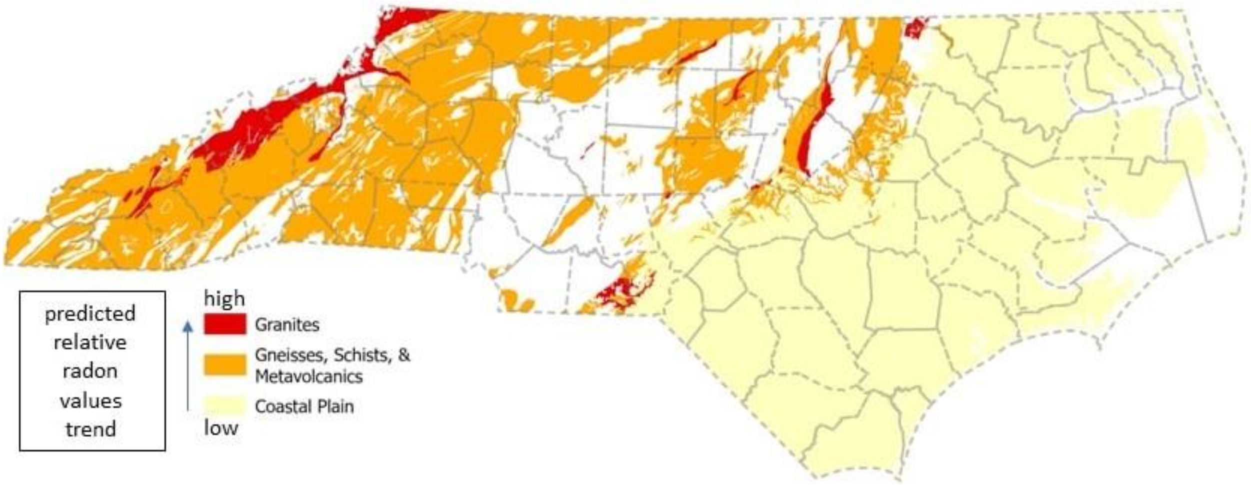

Figure 1: Predicted, general trends, for relative radon values. Previous studies have shown extents underlain by granites to have relatively high radon values compared to areas dominated by gneisses, schists, and metavolcanics (intermediate radon values) and the Coastal Plain physiographic province (low radon values).

Radon air quality home test sample kits used in this analysis were distributed and collected by the North Carolina Department of Health and Human Services – Radon Program (NC Radon Program) between 2018 and 2022 to and from property owners in all 100 counties across the State. In 2023, the sample data were utilized by researchers at the North Carolina Geological Survey (NCGS) to reference the sample values to the underlying geologic units in a public-facing interactive statewide radon potential map.[13] For mapping spatial resolution consistency, the last comprehensive statewide geologic map compiled in 1985 was utilized as the basemap for the statewide radon potential map and analysis.[14]

Because a public-facing interactive radon map of North Carolina with an emphasis on the underlying geologic units has not been available to this point, the interactive map discussed herein is an effort to aid in satisfying this informational gap. For consistency at the same spatial resolution of geologic mapping, the last statewide geologic map of North Carolina is used as the geologic basemap for the interactive radon map. The statewide 1985 North Carolina Geologic Map was produced at a small-scale and as a result lacks the geologic detail that is sometimes preferred locally. Also, since 1985, geologic unit delineation conventions and mapping practices regarding North Carolina's geology have changed. Mapping North Carolina's geology in more detail, together with these evolving geologic mapping concepts, is a continuous and on-going agency effort. While considering these constraints, it was determined that the consistent geologic map scale coherency was preferred over greater scale resolution locally.

METHODS

Data Collection

The NC Radon Program provides test kits to its citizens to encourage radon testing. Program staff are not responsible for placement or analysis of these test kits. Homeowners are responsible for sample collection. These test kits were chosen because they are simple, meet the United States Environmental Protection Agency (US EPA) criteria for radon testing, and have agreed to share data on a voluntary basis. The test kits require no calibration. Included in the test kits are instructions and links to videos to demonstrate how to use the devices. They use pre-paid mailing envelopes for ease of return delivery for analysis.

The NC Radon Program follows a Quality Assurance Project Plan (QAPP) that is reviewed annually and submitted to the US EPA for review. Radon test kit data is obtained quarterly from the following laboratories: Air Chek, Alpha Energy, Pro-Labs, and RSSI. These laboratories manufacture their kits, distribute the kits through retail settings in retail settings, then consumers test their environment and return the kit. The laboratory analyzes the test kit and a request for the test kit data is submitted by the NC Radon Program to the laboratory manager. Data is then sent to the NC Radon Program Coordinator by email in the following file types; .csv or .xls.

Data provided by the test analyzing laboratory includes a test kit number, date of analysis, test result of air (pCi/L), location in the home where the test was conducted, zip code of building tested, county of test location, latitude and longitude or physical street address. The data is stored on two different staff computers and is stored indefinitely.

Preparing The Radon Home Test Kit Data

The radon home kit sample data collections were initially organized in Microsoft Excel spreadsheets. After database smoothing, there were 154,065 original sample points, reported to the fourth decimal of accuracy for both latitude and longitude (approximately 11.1 meters). During the database smoothing process, data points were eliminated from analysis inclusion for the following reasons: test result values were recorded as “ERROR”; blank cells were recorded for test result values, latitude values, or longitude values; and latitude or longitude values with obvious erroneous information (i.e., placing the location point outside the State). Additionally, samples with the same location values (both latitude and longitude values were the same for multiple samples) were compared for radon values. These duplicate locations with different radon values were determined to likely be from different elevations in the same building structure. Presuming the lesser value to be from a higher elevation in the building structure, and therefore where the radon concentration more diffuse, the lesser value sample point was eliminated from analysis while the greater value was retained; the presumption being that the higher value is closer to ground level elevation. The sample “point cloud” highlighting a disproportionate distribution of sample kits can be seen from a statewide plan view (Figure 2). Further, additional database smoothing required searching for test results recorded as being less than the instrument limit of detection (LOD) (designated in the database by a leading lesser-than chevron, “<”). Next, following previous similar studies, these sample designations were assigned a value equal to $LOD/2^{1/2}$ for computation of geometric means.[15,16] The LOD is the minimum level at which the measurement has a 95% probability of being greater than zero.[16]

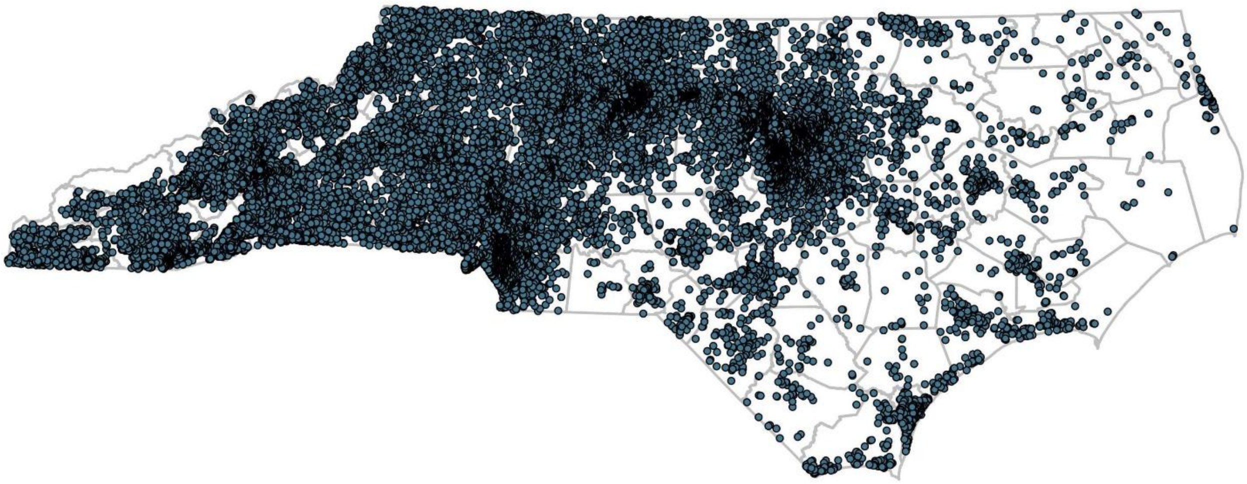

Figure 2: Point cloud from 154,065 unique radon home test kit sample points. Density of kits skews toward the high-population urban centers in the Piedmont physiographic province.

Populating The Geologic Map

The 1985 Geologic Map of North Carolina is composed of 203 unique map units, or geologic units. “Geologic units” is the preferred term for the distinct geology units on this map because not all of the units are formally recognized geologic formations. The map was first digitized in 2007 as a Geographic Information System (GIS) shapefile in the North Carolina state plane FIPS 3200 projected coordinate reference system and first hosted as an online service in 2011 via Esri ArcGIS Online (AGOL).

Using Esri ArcGIS Pro version 3.1, a duplicate copy of the 1985 geologic map feature class was created – file geodatabases with feature classes have steadily been replacing shapefiles as the standard storage format for digital vector data since adding topology to geodatabases was introduced in 2002.[17] Creating radon values for each geologic unit was a two-step process. First, using a select-by-attributes function, each geologic unit was identified individually, isolating the geologic unit polygon and rendering the target geologic unit as the only selectable geologic unit in the geology map feature class. Next, after isolating the individual geologic unit polygon, a select-by-location function was utilized to target where the radon sample points intersected the isolated geologic unit polygon. This process was repeated for all 203 geologic map units [Figure 3]. Note that a radon sample point could potentially be factored for multiple geologic units should it be located on a polyline separating geologic units. In such cases, instead of randomly assigning the sample point to one map unit over another, or disregarding the sample point, it was determined that incidences of this kind were infrequent enough, and the total weight influence minor enough, that the weighted-influence of the radon sample value would be assigned to both of the geologic units.

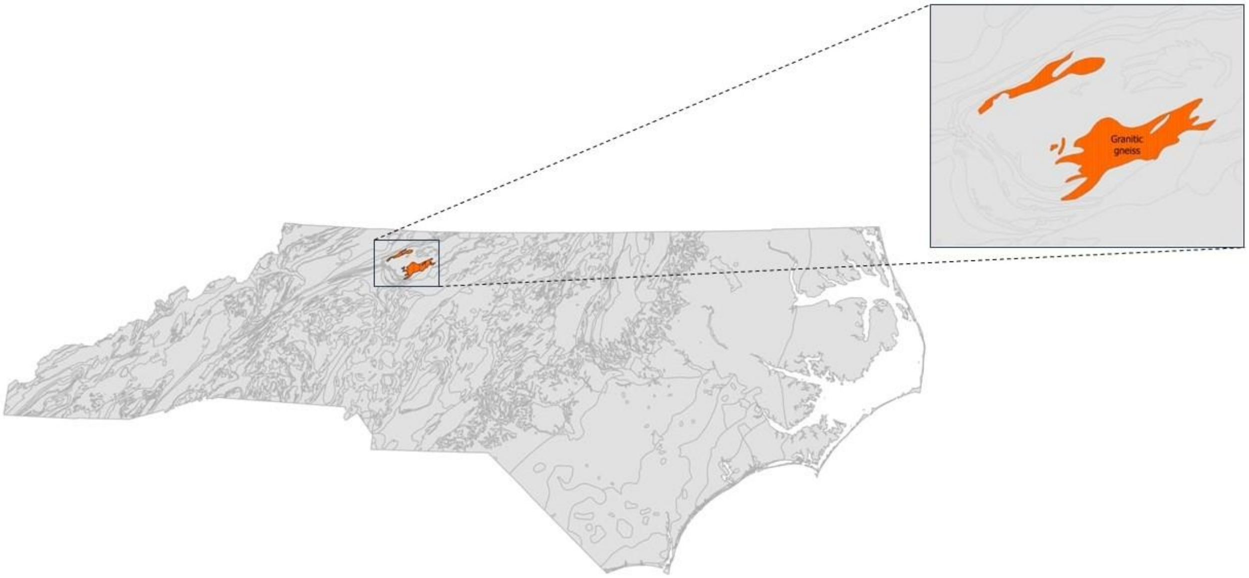

Figure 3: Example of isolating a single geologic map unit in order to capture sample locations within the unit bounds.

Sample point radon values within the bounds of a geologic unit were calculated to find the third quartile (75th percentile) to represent the radon value for that geologic unit. Following the guidance of similar previous research,[18] the third quartile was used as the representative value for risk consideration in analyses of relationships between radon and human health. Choosing the third quartile also serves to provide a robust representation of a population sample while also dampening the effect of outlying sample values. In the newly created feature class layer's attribute table, seven new columns were added to record the following: the representative radon value for a geologic unit (the third quartile); the minimum radon value; the maximum radon value; the mean radon value; the median radon value; the radon sample count within the bounds of a geologic unit polygon feature; and the sample density within a geologic unit (number of samples per geographic extent of the geologic unit surface area).

The representative radon value for each geologic unit was then used to symbolize the interactive map. A color-blind sensitive red-green-blue-alpha (RGBA) color space (hexadecimal benchmark values: #00807dff; #00bab5ff; #d2f7edff; #ad8b62ff; and #664015ff) was chosen to display the radon potential map as a continuous color ramp. The symbology color transition is more finely parsed through the geologic units with representative radon values that are within the standard deviation of the mean (mean: 3.9 pCi/L; ±SD: 2.52 pCi/L) [Figure 4]. Geologic units without any sample points intersecting them were symbolized as full opacity black and as a separate layer. These units are small and mostly clustered along the State's western border and upon close inspection, can be viewed in the statewide radon potential map [Figure 5].

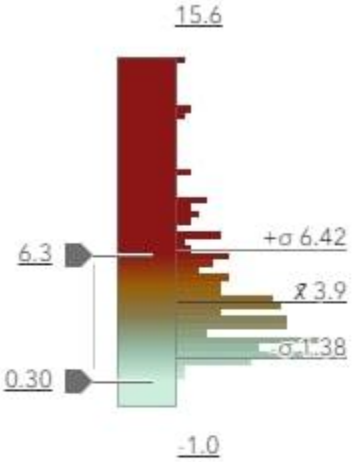

Figure 4: The map's symbology color ramp showing that the color transition is more finely parsed through the geologic units which have representative radon values that are within the standard deviation of the mean.

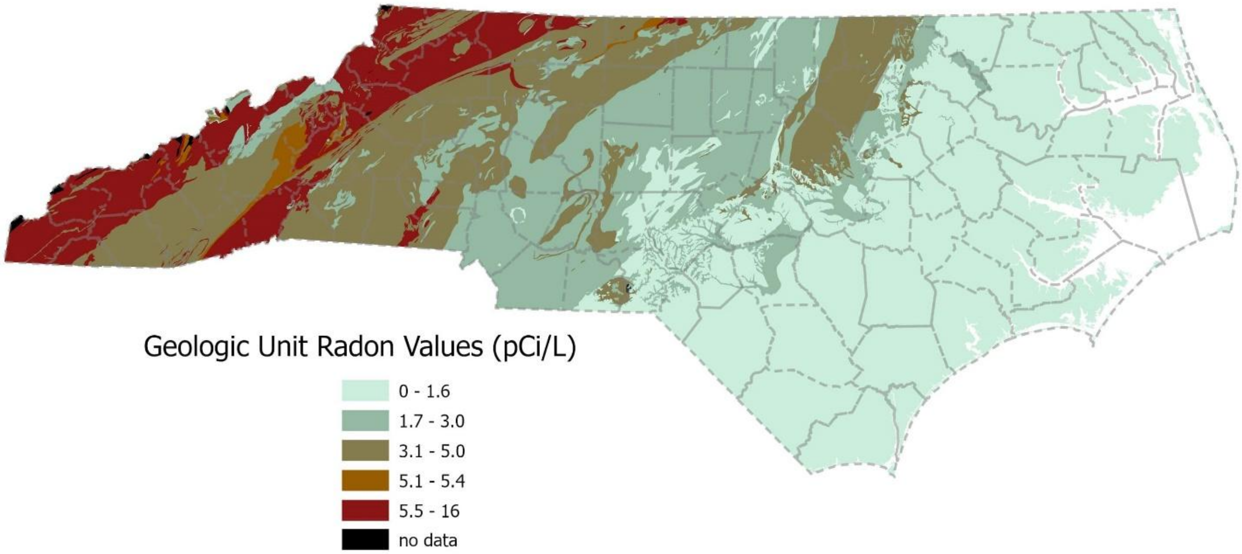

Figure 5: Radon potential map of North Carolina from air quality radon values assigned to the State's mapped geology.

Developing The Online Interactive Map

The Esri AGOL web map was built with one essential hosted feature layer consisting of 203 polygons - the augmented 1985 geologic map of North Carolina with the seven additional calculated columns discussed previously. Additionally, a polygon feature layer maintained by North Carolina One Map (NC OneMap)[19] was utilized to provide county spatial context and to aid the delineation of county radon-related spatial statistics.

In order to develop more functionality for the end-user, the radon potential web map was packaged inside an Esri Web Experience. In addition to user instructions, information about the map viewer, and organizational information, the Web Experience Builder also enables the end-user to retrieve a selection of the geologic map unit radon summary statistics (geologic unit representative radon value, maximum value, minimum value, mean value, sample point density, median point value, and the total number of sample kits contained within the bounds of the geologic map unit polygon). Also, county data is available, linking the end-user to county fact sheets prepared and hosted by the NC Radon Program on their agency website. Finally, the project is served in an Esri Story Map, allowing for more textual context regarding the radon outreach efforts in the State's public service domain.

DISCUSSION

The time of year that a sample is taken has been widely considered an influential variable in past models. Previous modeling suggested that radon-222 levels tended to reach higher levels during the winter due to large pressure differentials formed by warmer air inside a building structure contrasting with the much cooler air outside, thereby creating a vacuum effect from the warm air escaping through window and door seams. This dynamic, it was thought, pulls the cooler air from lower levels, which is more likely to contain radon gas. However, recent research suggests that seasonal effects are either minimal or even non-existent.[20]

The relatively low radon-222 value readings throughout the Coastal Plain physiographic province are consistent with current models concerning radon-222 in Coastal Plain margins.[21] Radon-222 flux from the ocean is several orders of magnitude smaller than the flux from the soil and thus radon-222 concentrations above oceans are much smaller than above bare earth inland. As a result, radon concentrations measured over land are the lowest in the Coastal Plain where mixing between low radon-222 marine air and continental air masses occurs.[21]

The 75th percentile was the benchmark determinant chosen by the authors, following a convention discussed in the Methods section. There were many other viable choices at this juncture that would have produced differing geologic unit representative values, however the overall general trends would have remained. Additionally, the sample distribution within the State is not ideally proportional, as can be seen in Figure 2. Since the sample kits distribution concentration is coupled with population density, the population centers in the Piedmont physiographic province are better sampled.

Naturally occurring radon-222 gas is a silent threat to human health and its presence is dictated by the underlying geology. There have been many local radon-222 groundwater studies, which have provided valuable insight into the geologic dictates of the gas' natural controls. From the groundwater studies, we know that, generally, relative high radon-222 values are located adjacent to rock types of granitic origin, skewed to the western Piedmont and Blue Ridge physiographic provinces. Relative low radon-222 values are dominate in the Coastal Plain physiographic province, and relative moderate values are underlain by gneisses, schists, and metavolcanic rock types. The statewide radon potential map produced from air quality test kit samples has generally supported these previous findings (see Figure 4b). Beyond the favorable rock types for radon-222 dominating the western portion of North Carolina, the extreme elevation variation in this region allows for dryer ground surface media potential from which the gas has the ability to travel further distances before its decay.

The goal of this interactive map of naturally occurring radon potential is to offer a first-pass statewide estimation of radon hazard coupled with county-level recommendations provided by the NC Radon Program[22]. Future investigations to establish a comprehensive statewide and locally precise naturally occurring radon potential map will require the integration of air quality data with groundwater data. Also, a methodology for quantifying qualitative rock descriptions is necessary to establish precision radon-222 value boundary benchmarks. Not only will more radon sampling be required from both air quality and groundwater studies, but an aggressive statewide rock geochemical analyses effort is needed.

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