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RADON DISTRIBUTION ON THE ISLAND OF GUAM AND CORRELATIONS TO SURFICIAL GEOLOGY AND DEPOSITION MODELS

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ABSTRACT

Short-term radon measurements were performed in 47 schools and 208 residences on the Island of Guam, USA. All tests were conducted under closed building protocols. The survey revealed high radon potentials in many of the schools and homes tested. The radon potentials (as represented by the highest radon reading in each school) shows a correlation to the local surficial geology. This geological distribution of the radon invites conjecture as to the genesis of the radon. Some possible radon sources are discussed including the recent model for wind deposition of uranium dusts as proposed by Muhs.

INTRODUCTION

Guam is an unincorporated territory of the United States. It is the southernmost island in the Marianas Archipelago, and located at 13 degrees 28 minutes north latitude and 144 degrees 44 minutes east longitude (approximately 3,700 miles west-southwest of Hawaii) (Tracey, 1964).

The island of Guam is 30 miles long and between 5 and 8.5 miles wide. It was formed through uplift, pyroclastic events and undersea lava flow and subsequent coral building and is surrounded by coral reefs near the shore. The northern and southern half of the island represent two distinct surficial geological areas of approximately equal size. The northern part of the island is a high limestone plateau rising up to 850 feet above sea level. The southern region is mountainous, of volcanic origin, with elevations from 700 to 1300 feet.

Guam's tropical climate is warm year-round; temperatures range between 75 and 86 degrees Fahrenheit, with a mean annual temperature of 81 degrees. May and June are the hottest months. The average yearly rainfall is approximately 90 inches. Constant tradewinds blow from the northeast during the dry season, December through April. Drought-like conditions can occur during this period and the majority of the rain falls during the summer months.

The population of Guam is distributed among 19 districts which conform to 21 villages. These villages range in population from 897 people in Umatac on the southwest coast to as many as 31, 728 in the village of Dededo in the north central part of Guam. Excluding the areas controlled by U.S. military bases, the villages are distributed more or less evenly across the northern and central parts of the island, but in the southern half of the island, primarily confined to coastal areas. Since every village has at least one school which was tested, the survey results (and any conclusions drawn from them) are necessarily weighted. In particular, there were no schools, and hence, no test results from the very center of the southern part of the island which is called the Interior Basin in Fig. 1.

The resident population of Guam according to the 1990 Census was 133, 152 people. Almost half (46.5% of the population is 18 years or younger (1990 Guam Census, 1990). Due to the high percentage of school age children, and the discovery of elevated radon levels at two military installations on the island, the Guam Legislature approved Public Law 20-184 which mandated radon testing in public schools on Guam. The scope of the survey was later increased to include private schools (who wished to participate) and a representative number of private residential dwellings.

The Guam Environmental Protection Agency (GEPA), under the direction of one of the authors (Castro), was charged with overseeing the survey. Accordingly, in 1991, two of the authors (Burkhart and Kladder) directed the setting up of a charcoal canister laboratory on Guam and the subsequent testing of all 36 public schools and 11 private schools. In addition, 208 residences were tested. This report will focus on the 47 school results because: (1) the schools are believed to have been tested under more uniform conditions (i.e., closed school conditions) and (2) the school locations were more precisely known, enabling subsequent mapping of the schools on USGS maps.

TESTING METHODOLOGY

Two identical gamma ray scintillometers were employed for the counting of the radon progeny lead-214 (with photo peaks at 240 kev, 290 kev and 350 kev) and bismuth-214 (using the 610 kev photopeak). The radon was collected with 4" open faced charcoal canisters filled with approximately 75 grams of activated charcoal which were exposed for a nominal 48 hours.

All the usual quality assurance checks were in place, including system audits, performance audits, blanks and duplicates. Blank canisters were used at the rate of 1 per 20 regular tests where an acceptable blank result would be a reported radon less than 1 pCi/L. In actual practice, almost all blanks were reported at less than 0.1 pCi/L. Duplicate canisters were expected to have a relative percent difference (RPD) of 10% or less (if the average of the duplicates was 4.0 pCi/L or better) where:

$$RPD = \frac{(\text{test \#1 - test \#2})}{\text{average of 2 tests}} \times 100$$

Of the 111 duplicate pairs of canisters that were recovered and read, the RPD was 5.9 %.

The canisters were placed, opened and closed by school personnel who had received proper training at one of several sessions conducted by the authors. Since the laboratory technicians were not involved in the canister deployment, the identities of blank and duplicate canisters remained hidden from the lab technicians thus preserving the integrity of the QA checks.

Because the survey was conducted during the summer vacation period, there was little worry of the test devices being tampered with. To assure that the radon results would truly mirror the actual potential for radon to enter the structure, the schools were closed for 12 hours prior to the test and for the 48 hours of the testing period.

Within the school building, all offices, classrooms, lunchrooms, libraries and gymnasiums were tested. Storage areas and closets were not tested. A few schools had classrooms on a second floor. These were not tested. Also, no school on Guam has a basement of any kind.

DESCRIPTION OF BUILDINGS

All of the school buildings that were investigated were slab-on-grade, with spread footings at a minimum depth of 3 feet. Expansion joints were constructed at the floor wall area to compensate for building movement during earthquakes. The expansion joint could sometimes be seen as a 1/2 inch asphalt impregnated fiber board between the slab and the wall, however in many instances this was not obvious since a wood 2x4 inch board was laid against the foundation wall with the concrete poured up and over it, thus causing the concrete to form a 1/2 inch skin over the top of it. This floor to wall joint represented the radon entry point on a surface area basis.

All of the buildings were constructed with the classrooms in a single row with the doors of the classrooms being doors that open directly to the outside. There were no enclosed hallways. This design caused each classroom to have two exterior walls and two walls common to another classroom, except for the end classrooms which had three exterior walls. The exterior walls had approximately 1/3 of their area fitted with louvers that were originally designed to be opened to the outside for ventilation. However in some cases the louvers had been sealed over with plexiglass as part of an on-going project to retrofit the classrooms with air conditioning. In all cases except for one, no central air handling systems existed. That is, the air conditioning systems were unitized for each classroom. The unit air conditioning systems that were utilized were either of a typical window style residential unit or a split style air conditioning system with the evaporators located in the rooms. In either air conditioning approach, either no provisions for fresh air make-up was in evidence, or, if there, provided minimal fresh air.

SUMMARY OF RESULTS

In Table 1, the 1,247 short-term results are summarized by dividing them into four categories; radon results greater than 100 pCi/L, between 20 to 100 pCi/L, between 4 and 20 pCi/L and below 4 pCi/L. When reading these results keep in mind that the average radon concentration found in private residences during this same testing period was 6.27 pCi/L, based on 208 homes geographically distributed across the island.

TABLE 1

Short-Term Result (pCi/L)	Number of rooms	Percentage of rooms
over 100 pCi/L	1	< 1 %
20 to 100 pCi/L	44	3.5 %
4 to 20 pCi/L	124	9.9 %
less than 4 pCi/L	1073	86 %

As mentioned earlier, the authors are using the single highest radon reading reported for each school as the indicator of a potential radon source beneath the building. It is assumed that this highest radon reading will characterize the school when making comparisons to the local surficial geology. Furthermore, our experience on Guam leads us to believe that as more and more of the classrooms are air conditioned, the radon concentrations in a typical classroom (which may be quite low at present) will approach the higher levels as represented by the highest radon concentrations found in the school (unless design changes which allow for sufficient fresh air make-up are implemented). Table 2 tabulates these highest readings for each school, using all 1,247 short-term results.

TABLE 2

Number of Public Schools tested	36
Number of Private Schools tested	11
Number of Schools with at least one room above 4.0 pCi/L	27
Percentage of Schools with at least one room above 4.0 pCi/L	57 %

The locations of the 47 schools tested are shown on a simplified surficial geology map of Guam in Fig. 1.# The locations are shown as circles, triangles or diamonds. The open circles represent the locations of schools in which the highest radon reported for the school was less than 4.0 pCi/L. The other symbols represent the single highest readings in a school which is between 4 and 20 pCi/L, 20 and 100 pCi/L and greater than 100 pCi/L as explained in the legend of Fig. 1.

Ten of the schools were located above the surficial geology unit called Barrigada limestone in the center of the northern part of Guam. This limestone is at least 500 feet in depth and characterized by the presence of fossils of Foraminifera, from which the white limestone was formed in late Tertiary times. These Forams were deposited on the sea floor when the surface was approximately 300 to 600 feet below sea level. The schools located here tended to be high in radon and all but one of the schools in this area had at least one room with radon above 4.0 pCi/L. Using the single reading from each school which represented the highest radon concentration, we found the average of these highest readings was 19.7 pCi/L with a standard deviation of 19.0 pCi/L.

The surficial geology of the remainder of the northern part of Guam is the Mariana limestone, which was formed from corals and mollusks during more recent Quaternary times when sea water covered the surface in a lagoonal environment. This limestone also forms the geology for the Orote Peninsula (on the west coast) and the bulk of the southeast coast line. In the central "waist" of Guam, the Mariana limestone is approximately 200 feet in depth, but it thins to less than 100 feet in depth in the northern part of Guam where it caps the older, Barrigada formation. Of the 23 schools above the Mariana limestone, all but six had rooms exceeding 4.0 pCi/L. Also, the school with the highest reported radon concentration, 117 pCi/L, was found here. Averaging the single highest reading from each school gave 21.4 pCi/L with a standard deviation of 30.4 pCi/L.

Of the 14 remaining schools, none of which are on Mariana or Barrigada limestone, only one school had any room with a radon concentration greater than 1 pCi/L. The one school which had a radon reading in excess of 1 pCi/L (8.79 pCi/L) was found to be about 100 feet from the base of cliffs formed by the Mariana limestone in downtown Agana (on the west coast of the central "waist" of Guam) and may well have actually been sitting on limestone which had been capped with a thin layer of beach deposits. Excluding this one high reading, the balance of the schools average radon concentration (again, only using the single highest radon reported for each school) was 0.48 pCi/L with a standard deviation of 0.19 pCi/L.

The 14 schools, not built above limestone, were located above a variety of surficial geologies. Two of the schools (including the one school with an elevated reading) had been constructed on beach deposits. These beach deposits, formed in middle quaternary times (subsequent to the Mariana limestone deposition period), seldom exceed 30 feet in thickness and are composed of calcium carbonates eroded from the nearby reefs. Three of the schools were above alluvial clay deposits, 30 to 100 feet thick, deposited in early quaternary. None of these

Adapted for the author's purposes from USGS surficial geology map of Guam (Tracey, 1964)

schools (one in Agana, one in Agat on the west coast of southern Guam and one in Umatac on the extreme southwest coast) had a single room in excess of 0.5 pCi/L.

Of the nine remaining schools, six were found above the Umatac formation and three above the Alutom formation. Both of these formations are volcanic in origin and form the basement rock for all of Guam and the surficial geology for the bulk of the southern half of Guam. The Alutom formation contains the oldest surface rocks on Guam and dates back to Eocene and Oligocene times when a volcano to the northwest of present-day Guam (it is believed) laid down a series of pyroclastic and flow material. Other than thin beds of fossiliferous limestone, the Alutom formation is composed of non-limestone rocks: tuffaceous shale, blocks of basalt and sandstone. The maximum thickness is believed to be 2000 feet. The three schools above this formation had no rooms above 0.77 pCi/L.

The six schools above the Umatac formation were equally low in radon with no room exceeding 0.76 pCi/L. The Umatac formation, also formed by underwater lava flow (from a volcano believed to be southwest of present day Guam), is younger than the Alutom formation but is basically made up of the same kinds of rocks: basalt, tuffaceous shale, tuff breccia and minor amounts of interbedded limestone and calcareous shale.

Strikingly evident is the fact that no school which is located over the Umatac formation in the lower half of southern Guam nor any school located over the Alutom formation in the upper half of southern Guam has a single room above 4.0 pCi/L. By contrast, most of the schools in northern, central, and the southeast coast of Guam do have rooms in excess of 4.0 pCi/L. These schools are all above Mariana and Barrigada limestone.

As one would suspect, the surficial geology of Guam is complex and can change on a small scale. To reduce uncertainties in the location of the schools (and the surficial geology beneath the schools), each of the school sites was revisited and mapped on the USGS Geologic map with as much precision as a 1:50,000 scale map allows. Then, to verify that there was indeed a correlation between the highest radon found in a school and the surficial geology beneath the school, a standard computer statistical package (ABSAT) was used to analyze the data above. We used one-way analysis of variance (ANOVA) as the statistical technique with surficial geology expressed on a nominal scale with individual formation's names as the units. The dependent variable was the radon concentration in the highest room of each school and was expressed on a ratio scale.

Table 3 shows the results of ANOVA. The F statistic of 7.37 indicates that the surficial geology is a strong independent contributor to radon levels at the 99% confidence level.

TABLE 3

DF	Sum of Squares	Mean of Squares	F	Significance
1	3868.58	3868.58	7.36773	.0094
45	23628.2	525.071		
46	27496.8			

Previous experience with a similar mapping project in Colorado hinted that there may be a correlation between the radon concentrations in buildings and the proximity of a building to a major, known fault (Burkhart, 1993). Therefore, the authors mapped the positions of the schools on Guam and measured the distance between each school and a known fault, A linear regression test was done using the highest radon concentration in each school as the dependent variable and the distance to the nearest known major fault as the independent variable. However, the linear regression, with an r square of 0.25, indicates that the distance to a fault is not strongly correlated to radon levels.

DISCUSSION

The results of Anova, while interesting, only point to further questions, some of which have been answered, some have not. The strong correlation to surficial geology would seem to indicate that the limestone is the source of the radon. It is believed that the radon is indeed emanating from the top few feet of the limestone but we do not believe that the limestone was the original source of the uranium-238 and radium-226 which are the precursors of radon-222. This conclusion seems to be supported by the results found from a series of rock samples that were taken from a quarry near Barrigada in which Mariana limestone was being extracted from the 200 foot deep quarry. Samples were taken at the surface and, again, at additional sites at every 25 feet increase in depth. Great care was taken so that exposed and weathered rock would not be included in the sample. The radium-226 content of the near surface limestone was 7.08 pCi/gram and the radium-226 content of all lower samples was around 1.0 pCi/g. This would seem to indicate that the limestone has a relatively low concentration of radium-226, except near the surface.

An independent measurement of natural gamma radiation in a series of bores by Appalachian Geophysical Surveys also showed high gamma counts at the surface for 2 of the boreholes. Their report, issued in 1992, commented that "The readings at these wells were several times normal readings for even the 'hottest' natural clays" (Appalachian Geophysical Surveys, 1992).

Another test to see if the limestone is the original source of the radon-222 is to compare the radon in the schools above the Mariana limestone with the radon in the schools above the Barrigada limestone. Presumably, biological uptake of the uranium-238 and radium-226 by the coral, mollusks and Forams would be the mechanism for getting radon into the limestone. Of special interest is, of course, the uranium-238 with its longer half-life. Since the uranium-238 uptake by Forams is limited to 1.2 ppm or less, there should be a measurable difference between schools above the Barrigada limestone (primarily composed of Foraminiferal limestone) and the schools above the Mariana limestone (primarily composed of coral which contains between 2 and 4 ppm of Uranium- 238) (Delaney, 1980, Ku, 1965, Mo, 1973). However, a Student t-test comparing the radon in the schools above each of the two geologies as separate sample sets gave a t statistic of .165 which says that the two sample sets are not distinct and come from the same population (with a probability of 87 %).

Finally, recall that the linear regression test found no correlation between the highest radon in each school and the distance between the school and a major, known fault. Since some of these school were very close to known faults, it would appear that the radon is not being transported from great depths, through the faults, to the surface. If it were, schools near the faults would show elevated levels of radon. It follows that the limestone itself (at least that part of the limestone lying at hundreds of feet in depth) is probably not the main source of the radon.

One conclusion that could be drawn from these tests is that the true source of the uranium-238 and radium-226 is the soil. Since no radioisotope analysis of the soil has been done, to our knowledge, such reasoning is pure conjecture at this point. However, it is the case that all of Guam is covered by soil, albeit a quite shallow soil in some places. The southern half of Guam is dominated by Akina-Agfayan soil, a red, acidic silty clay and clay which is found on slopes and ridgetops. The northern half of Guam is covered by very shallow Guam soil, which is a red cobbly clay loam (Young, 1988). If these soils are the true uranium-238 and radium-226 source, then one of two possibilities exist. Either the uranium and radium were put into the soil locally (possibly, during the same volcanic episodes that created the geology from which the soil was later formed) or else the uranium-238 and radium-226 were imported.

Several researchers have postulated that the uranium-238 is indeed imported by the deposition of wind-blown soils (Muhs, 1990, Prospero, 1970). This hypothesis would be consistent with our measurements to date, although we have not done sufficient soil sampling or radioisotope comparisons of imported dust deposited on Guam to be able to make any comment more definitive. We suspect that, if the uranium-238 is being carried on dust and deposited on the soil on Guam, that it is being leached out of the dust and carried down through the soil. In the southern part of the island, the uranium is either washed out to sea during the many torrential rainfalls that occur on Guam or trapped in deep sinkholes which are found in the volcanics. In either case, the relatively soluble uranium is not adsorbed by the relatively non-porous underlying volcanic surficial geology. Above the limestone, however, the uranium is possibly leached out of the soil and adsorbed in the upper few feet (possibly even the upper few inches) of the porous limestone.

CONCLUSIONS

There is a definite correlation between the type of surficial geology and the highest radon concentration found in a school as verified by ANOVA. In almost all cases, elevated radon concentrations are found in schools above Barrigada and Mariana limestones but are not found in schools above alluvial clay deposits, beach deposits, and volcanics (Umatac and Alutom formation.)

There appears to be no correlation between the highest radon found in a school and the proximity of the school to a known fault.

If the ultimate radon source is the limestone, the biological uptake of the parent isotopes of radon-222 (uranium 238 and radium-226) by the Forams, mollusks and corals that later made up the limestone does not appear to be the mechanism by which the radon gets into the limestone.

The radium-226 content of the limestone is greater, by several times, near the surface than it is 25 feet below the surface or deeper, at least in one set of samples taken in a quarry in the Mariana limestone.

These results are consistent with an hypothesis by Muhs (1990) and others that the uranium-238 is being transported as component of the dust carried by winds and deposited on limestones. Another part of this hypothesis is that the uranium-238 is leached out of the soil and is taken up by the porous limestone beneath the soil. This agrees with the findings in this article in that the radon is found in schools above limestone geologies but very little radon is found in schools above the relatively non-porous volcanics of south Guam.

Further work needs to be done in order to more fully understand the problems presented here. For example, at present the authors are mapping the positions of the schools on the soils map of Guam with the intention of looking for correlation between soil type and radon concentrations. Also, the equilibrium of uranium-238 and its decay products should be studied (Muhs, U.S.G.S. Circular 1033). Such measurements will help in the understanding of the uranium-238 mobility in Guam's soils and upper surficial geology. We would also like to measure and map uranium-238 and radium-226 concentrations in the various soils on Guam to see if there is a correlation to the geology from which the soil is derived. Further radioisotope measurements at various depths in boreholes needs to be done in order to verify our conjecture that the limestone is not the ultimate source of the radon. Other radon surveys have been done on Guam by the authors. It is intended that this additional data be incorporated into these mapping projects in order to increase the density of the data points and the precision of the resulting predictions. It goes without saying that if the main radon-222 sources are indeed in the upper few feet (or few inches) of the limestone, building code modifications (in particular, pertaining to structural fills) would be beneficial.

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Fig 1: Radon Potential in Schools Tested vs. General Geology on Guam