

The spatial distribution of radiological contaminants in the Hickory aquifer and other aquifers overlying the Llano Uplift, Central Texas

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Abstract

The Llano Uplift is a Precambrian granite intrusion located in central Texas. Overlying this granite intrusion is a sequence of aquifers ranging from Precambrian fractured granites to Pennsylvanian limestones supplying groundwater for thirteen counties. Within this sequence are three locally important aquifers: the Cambrian-aged Hickory aquifer (sandstones and shales), the Ordovician-aged Ellenburger-San Saba aquifer (limestones), and the Pennsylvanian-aged Marble Falls Aquifer (limestone). Minor local aquifers include the Precambrian fracture granites, and the Cambrian-aged Cap Mountain Member (limestone), Lion Mountain Member (limestone), and the Welge Member (sandstone). Pennsylvanian-aged faulting has locally compartmentalized these aquifers.

The Hickory aquifer is comprised of up to a 550-foot-thick sequence of interbedded artesian sandstones and shales that are naturally radioactive. The dominant radiological contaminants with concentrations exceeding U.S. Environmental Protection Agency drinking water standards in the groundwater are radium and radon, which are natural radioactive decay products of uranium and thorium. The source of the uranium and thorium was the geochemical decomposition of the granites (feldspars) and accessory minerals (less than one percent of total) from the granite intrusives in the Llano Uplift. The radioactivity has been redistributed to phosphatic materials, interbedded shale laminae, and to a lesser extent hematitic cement within the Hickory aquifer. Locally, the overlying Ellenburger-San Saba and Marble Falls aquifers (not known as sources of radiological groundwater) may have been contaminated along faults by the artesian waters from the underlying Hickory aquifer.

Daniel B. Stephens & Associates, Inc. was hired by the City of San Angelo to investigate the spatial distribution of the radiological contaminants within the Hickory and the overlying aquifers. Radiological analyses have been conducted for a total of 257 wells completed in the Hickory aquifer. The spatial geographic distribution of these radiological analyses was investigated using a geographic information system. Review of the geographic distribution of the radiological concentrations in groundwater indicates that both the higher and lower concentrations appear to be somewhat clustered, suggesting that either chemical, physical,

temporal, or a combination of these variables may be influencing the geographic distribution. Scatter plots were created to investigate geochemical relationships. No statistically significant chemical correlations were identified with the available Texas Water Development Board water well chemistry data. However, a few geochemical or environmental variables were identified that seem to influence the geographic distribution of higher radium concentrations. These variables include well depth, sulfate and bicarbonate concentrations, and pH.

In addition, a Schlumberger Natural Gamma Ray Spectroscopy was used as part of a geophysical log suite to investigate the vertical zoning of radioactive sources within three Hickory aquifer municipal water supply wells in McCulloch and Menard counties. This high efficiency gamma spectroscopy tool measures unique spectral signatures of uranium, thorium, and potassium and calculates the respective concentrations of these elements within the formation. Clayey zones had the highest concentrations of thorium and uranium; thorium concentrations were generally three times that of uranium with maximum thorium peaks up to 35 parts per million; and uranium peaks up to 12 parts per million in the clayey horizons. Thorium and uranium concentrations in these sands were generally half to one-third that of the clays. Effective porosities of the sands/sandstones of the Hickory aquifer range from 10.7 to 23.8 percent with a mean of 16.1 percent.

Introduction

The Hickory aquifer is the major groundwater supply for four counties (Llano, Mason, McCulloch, and San Saba) and a minor supply for nine other counties in central Texas. The subsurface extent of the Hickory aquifer illustrated in Figure 1 is based on an isochem of 3,000 milligrams per liter total dissolved solids (that is, regions where total dissolved solids exceed 3,000 milligrams per liter are not shown).

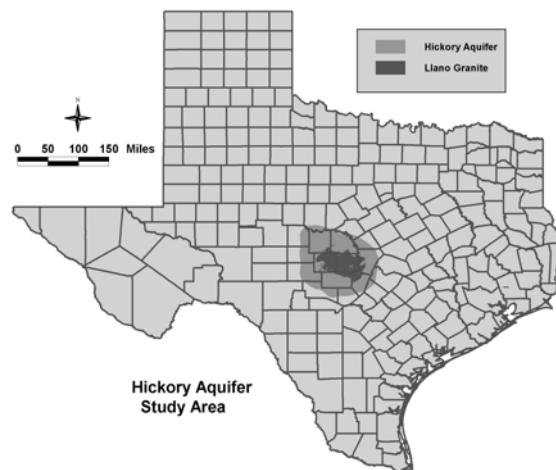


Figure 1. Hickory aquifer study area.

A number of local cities and towns, such as San Angelo, Brady, Mason, Eden, and Llano, use or plan to use the Hickory aquifer as their long-term water supply and have limited alternatives for other supply sources. However, federally imposed regulations concerning radiological

concentrations for public drinking water may severely limit the usage of this groundwater supply in the future. In an effort to evaluate the feasibility of using the Hickory aquifer as a public water supply, Danial B. Stephens & Associates was hired to investigate the spatial and geographic distribution of the radiological contaminants. This analysis of the spatial distribution of radiological contaminants within the Hickory aquifer is still in progress.

General geology, stratigraphy, and hydrology

Hickory Sandstone (or aquifer) is late Cambrian in age and is the lowest member of the Riley Formation (Moore Hollow Group) that lies unconformably on a complex of Precambrian metamorphic rocks into which postmetamorphic (Llano Granite) rocks were intruded approximately 1.1 billion years ago.

The Precambrian surface on which the Hickory Sandstone was deposited had a relief of 600 to 750 feet, and islands of Precambrian basement rock stood above the topmost beds of Hickory. Therefore, the thickness of the Hickory aquifer varies locally because of these irregular topographic Precambrian surfaces. Differential erosion of the Precambrian basement rocks left northwest-trending ridges that influenced the distribution of the different sedimentary facies of the Hickory aquifer (McBride and others, 2002).

Depositionally, the Hickory Sandstone has been interpreted as a marine transgressive sequence from fluvial to shallow marine. The Hickory Sandstone has been subdivided into three facies. The lower facies is a braided stream quartz sandstone sequence; is characterized by weakly cemented, medium to very coarse, poorly sorted sandstones; and has an average thickness of approximately 200 feet or more. The lower facies has excellent reservoir qualities with permeabilities up to several darcys (Zhurina, 2003; Figure 2).

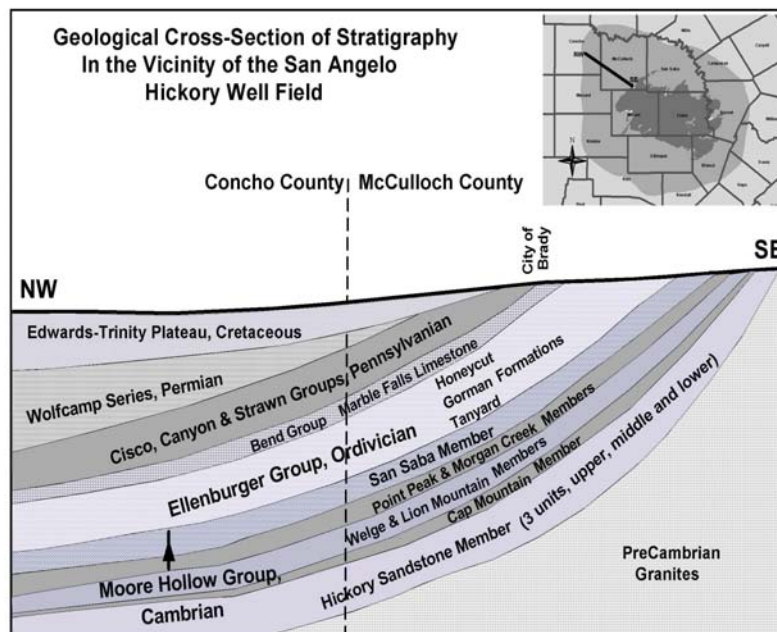


Figure 2. Geological cross section of San Angelo Hickory Well Field (not to scale).

The middle facies is a gradational fining upwards sequence consisting of interbedded fine- to coarse-grained quartzose sandstones with numerous laterally continuous mudstone laminae and interbeds. The middle facies is up to 200-feet thick and generally is a poorer aquifer interval locally acting as an aquitard between the lower and upper facies (Zhurina, 2003).

The upper facies, or ironstone facies, is up to 100-feet thick and consists of red to maroon, coarse-grained, moderately sorted, fossiliferous quartz sandstone interbedded with a few clay rich layers. The sandstone has been moderately to strongly cemented with iron oxide and calcite (Zhurina, 2003). Locally, the upper facies has been in the past considered as a potential iron ore deposit averaging 12 percent iron (McBride and others, 2002). Because of the pervasive iron oxide and calcite cement, this unit generally has poor aquifer characteristics.

The Hickory aquifer dips approximately 90 to 120 feet per mile (Carrell, 2000). Well depths range from less than 100 feet to almost 4,000 feet moving radially away from the Llano Uplift. Pumping tests and geological studies from the Texas Water Development Board water well database indicate that porosity ranges from 3 to 42 percent, the storage coefficient ranges from 0.0001 to 0.00004, and transmissivity ranges from 5,000 to 44,000 gallons per day per foot (Carrell, 2000; Bluntzer, 1992). Hickory aquifer wells can produce up to 1,000 gallons per minute, although the mean production capacity is 210 gallons per minute. The mean specific capacity is six gallons per minute per foot of drawdown. Aquifer thickness ranges from near 0 to 550 feet but averages 400 feet, and the groundwater is artesian in most confined areas (Bluntzer, 1992).

Faulting of the Hickory aquifer and overlying stratigraphic units through the middle Pennsylvanian occurred during the Ouachita Orogeny, resulting in numerous horsts and grabens (Johnson, 2004). These northeast-striking normal faults have up to 1,000 feet of throw, and trends range from N40E to N75W (Carrell, 2000). This faulting has resulted in the compartmentalization of the Hickory aquifer (Randolph, 1991; Johnson, 2004). Locally, the faults may serve as impermeable barriers or may have aligned the more productive lower facies of the Hickory aquifer with the less productive middle or upper Hickory facies (Zhurina, 2003; Carrell, 2000). Also locally, the overlying Ellenburger-San Saba and Marble Falls aquifers may have been contaminated along faults by the artesian waters from the underlying Hickory aquifer.

Overlying younger aquifers and aquitards

Cap Mountain Limestone Member, aquitard (Cambrian)

The Cap Mountain Limestone Member of the Riley Formation conformably overlies the Hickory Sandstone member, and the contact is transitional. The Cap Mountain Limestone consists chiefly of nearly pure granular limestone containing some beds of impure dark-brown limestone and calcareous sandstone, especially in the lower part of the unit. The observed thickness of the Cap Mountain Limestone ranges from 120 to 280 feet. The Cap Mountain Limestone is nearly impermeable except where it has been jointed or faulted and is not known to yield groundwater (Mason, 1961).

Lion Mountain Member, aquifer (Cambrian)

The Lion Mountain Sandstone Member, the uppermost member of the Riley Formation, conformably overlies the Cap Mountain Limestone. The Lion Mountain Sandstone consists largely of glauconitic sandstone containing fossiliferous limestone lenses in the lower portion of the member. The observed thickness of the Lion Mountain Sandstone ranges from 20 to 50 feet. The Lion Mountain Sandstone and the overlying Welge Sandstone Member form one single groundwater reservoir (Mason, 1961).

Welge Sandstone Member (Wilberns Formation), aquifer (Cambrian)

The Welge Sandstone Member consists of brown, poorly cemented, mostly nonglauconitic, quartzose sandstone. The contact with the Welge Sandstone with the underlying Lion Mountain Sandstone is fairly sharp. The Welge Member ranges in thickness from 20 to 50 feet. The Lion Mountain and the Welge Sandstone Member form one single groundwater reservoir (Mason, 1961). The wells completed in these formations can produce up to approximately 150 gallons per minute of potable water and have specific capacities ranging from 1 to 10 gallons per minute per foot of drawdown.

Morgan Creek Limestone and Point Peak Shale Members (Wilberns Formation, aquitard [Cambrian])

The Morgan Creek Limestone conformably overlies the Welge Sandstone and consists of medium- to coarse-grained glauconitic well-bedded limestone. The thickness of the Morgan Creek ranges from 70 to 140 feet. The Point Peak Shale Member consists of well-bedded soft-greenish shale containing beds of fine-grained dolomite, glauconitic limestone, and limestone pebble conglomerate. The Point Peak Shale averages about 160 feet thick. Neither formation yields significant amounts of water (Mason, 1961).

San Saba Limestone (Wilberns Formation), aquifer (Cambrian)

The San Saba Limestone Member of the Wilberns Formation conformably overlies the Point Peak Shale Member. The San Saba consists largely of beds of glauconitic limestone and dolomite replacing stromatolitic reef. The San Saba Limestone averages approximately 280 feet in thickness (Mason, 1961; Barnes and Bell, 1977). The wells completed in the San Saba Limestone can produce up to approximately 100 gallons per minute of potable water and have specific capacities ranging from 1 to 10 gallons per minute per foot of drawdown.

Ellenburger Group, aquifer (Ordovician)

The Ellenburger Group is a thick sequence of fine- to coarse-grained limestones and dolomites consisting of three formations: Honeycut, Gorman, and Tanyard. Much of the Ellenburger Group is fossiliferous, and chert is common in the upper part. The observed thickness ranges from 0 foot (eroded sections) to more than 600 feet but averages about 450 feet. Locally, areas of the Ellenburger have been karstified, resulting in higher well yields. Ellenburger wells can produce up to 1,000 gallons per minute (mean is 80 gallons per minute) and have specific capacities up to 70 gallons per minute per foot of drawdown (mean is 16 gallons per minute per foot of drawdown). Pumping tests and geological studies indicate that porosity ranges from 1 to 17 percent, the storage coefficient is about 0.0022, and transmissivity ranges from 56,000 to 96,000 gallons per day per foot (Bluntzer, 1992).

The Hickory aquifer and overlying stratigraphic units (Cambrian through Ordovician) through the middle Pennsylvanian (Marble Falls Formation) were faulted during the Ouachita Orogeny (Johnson, 2004). Late Pennsylvanian and younger formations were deposited on top of this faulted sequence.

Overlying younger Paleozoic and Mesozoic rocks (Silurian through Cretaceous)

Overlying the formations discussed above is a thick sequence of shales, limestones, and sandstones. Silurian, Devonian, and Mississippian formations are usually missing throughout the study area and have been eroded away.

The lower Pennsylvanian includes the Marble Falls Formation of the Bend Group. This limestone formation can be up to 600-feet thick and locally has undergone karstification. Marble Falls wells can produce up to 400 gallons per minute (mean yield is 90 gallons per minute) and have specific capacities up to 30 gallons per minute per foot of drawdown (TWDB well database). Locally, the Marble Falls and the underlying Ellenburger and San Saba aquifers may be hydrologically connected (Ashworth and Hopkins, 1995; TWDB well database).

On the surface, the Cretaceous Edwards-Trinity (Plateau) aquifer lies west and south of the study area. This major Texas aquifer does not have significant hydraulic connection with the Hickory aquifer and the other overlying Cambrian, Ordovician, and lower Pennsylvanian aquifers and will not be discussed further in this paper.

Chemical data for the study area

Borehole exploration in the Hickory aquifer for public drinking water with low concentrations of radiological contamination is problematic. Because radiological analyses of water generally require two or more weeks, this time delay could create costly logistical problems for field equipment and personnel while waiting on the laboratory results. The authors investigated available Texas Water Development Board borehole chemistry data with the hope of identifying other chemical variables indicative of low or high radium concentrations.

The Texas Water Development Board database includes 2,710 wells that are completed in the Precambrian (pre-Hickory) through the lower Pennsylvanian (Marble Falls Formation) aquifers in the thirteen-county area of interest. This sequence of formations was investigated because of the possibility of artesian Hickory aquifer waters leaking into overlying formations along faults. Geochemical analyses are available for a total of 930 of these wells, including some combination of cations (selective trace metals), anions, well depth, pH, oxidation reduction potential, and radiological data. Radium or its daughter decay product radon has been identified as the major source of radiological contamination in the Hickory aquifer. The U.S. Environmental Protection Agency (EPA) and Texas drinking water standard for radium ($\text{Ra}^{226} + \text{Ra}^{228}$) is five picocuries per liter (pCi/L).

Radiological analyses are available for a total of 257 of these wells, including alpha and/or beta and/or Ra^{226} or Ra^{228} (very few uranium detections) and some combination of other chemical analyses. Of these 257 wells with radiological analyses, a total of 105 (70 from the Hickory aquifer and 35 from overlying aquifers) detected one or more radiological concentrations that equaled or exceeded the EPA radiological drinking water standards (red stars in Figure 3). The

geographic distribution of 152 wells that had radiological concentrations less than EPA standards (non-Hickory, 101 wells [green circles] and Hickory, 51 wells [yellow circles]) in Figure3).

The geographic distribution of both the high and low radiological concentrations in Figure 3 are somewhat clustered, suggesting that either chemical, physical, or temporal influences, or a combination of these factors, may be influencing the geographic distribution.

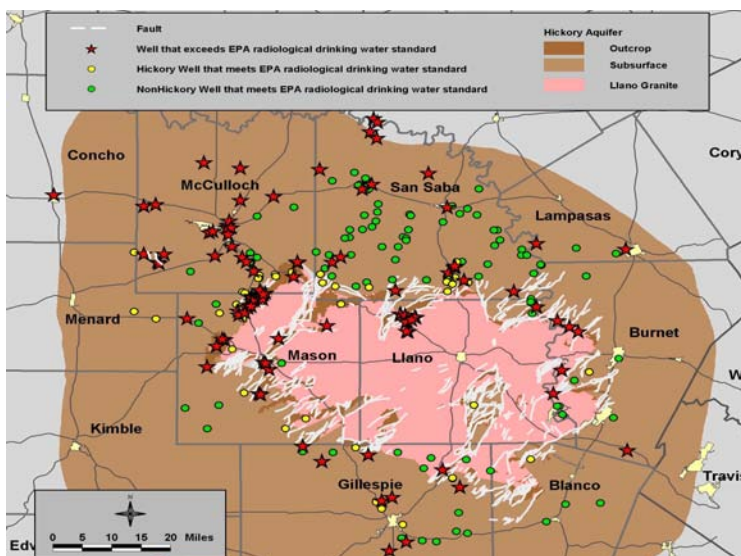


Figure 3. TWDB wells with radiological geochemistry.

A series of scatter plots of various combinations of chemical constituents were investigated using the geochemical data from 121 Hickory aquifer wells for which radiological analyses have been conducted. The following references were used to guide the selection of what chemical variables may cause the mobilization of radiological constituents:

- Upchurch and others (1991): pH, oxidation reduction potential, sulfate, strontium, barium, fracture traces, and water table fluctuations.
- CRCPDa (1994): oxidation reduction potential and temperature.
- Tuckfield and others (2004): pH.
- USGS (1998): pH and well depth.
- Landa (1999): pH, barium, and sulfate.

Well depths in the Hickory aquifer range from less than 100 feet at the outcrop to almost 3,500 feet deep down dip. A scatter plot of total dissolved solids concentrations versus well depth is shown in Figure 4. Data are shown for a total of 96 wells; however, this dataset may be somewhat biased because there are only four wells representing well geochemistry between 1,000 and 2,000 feet. The data distribution can probably be explained by demographics (population distribution and economics). A number of cities (that is, San Angelo, Brady, and Eden) in Texas have Hickory aquifer wells deeper than 2,000 feet, while irrigation wells near the outcrop area are generally less than 500 feet deep. A possible interpretation of Figure 4 may be

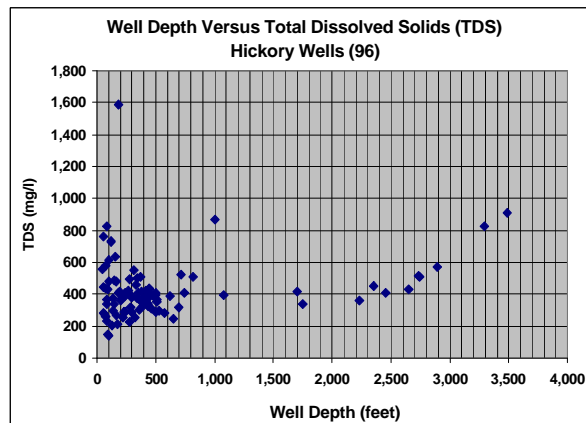


Figure 4. TDS concentration versus well depth.

that water quality (total dissolved solids) begins to rapidly deteriorate at approximately 2,700 feet but still may meet the Texas drinking water standards (1,000 mg/L) as deep as 3,500 feet.

The natural radioactive decay process of uranium and thorium produces radium. U^{238} decays by emitting alpha particles to produce Ra^{226} , and Th^{232} decays by emitting a beta particle (electron) to produce Ra^{228} . The radioactive isotopes Ra^{226} and Ra^{228} are equally soluble (USGS, 1998). Total alpha radiochemical analyses would include isotopes from all the alpha emitters: radium, radon, polonium, thorium, and bismuth. A total beta analysis would include isotopes from all the beta emitters: radium, lead, bismuth, and actinium (Argonne National Laboratory, 2001). Using the available geochemical information from the Texas Water Development Board database, the coefficient of determination (R^2) for total alpha versus $Ra^{226} + Ra^{228}$ is $R^2 = 0.720$; for total beta versus $Ra^{226} + Ra^{228}$, $R^2 = 0.824$. Total alpha analyses are the most common radiological analysis in the Texas Water Development Board database.

A scatter plot of total alpha versus well depth was initially investigated (Figure 5). Again, this dataset is limited due to the lack of available geochemical analyses between 1,000 and 2,200 feet. However, according to the available data, increasing well depth does not necessarily result in increasing total alpha concentrations.

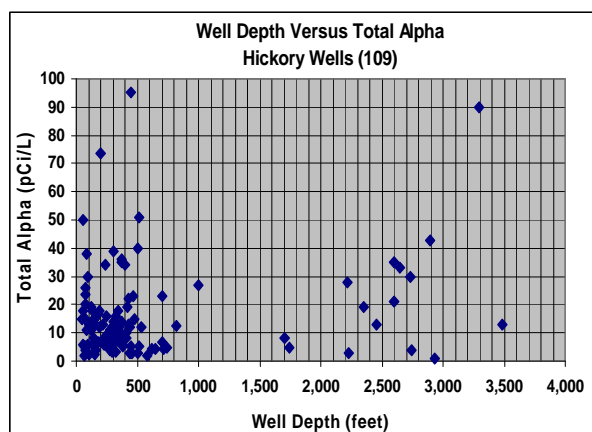


Figure 5. Total alpha versus well depth

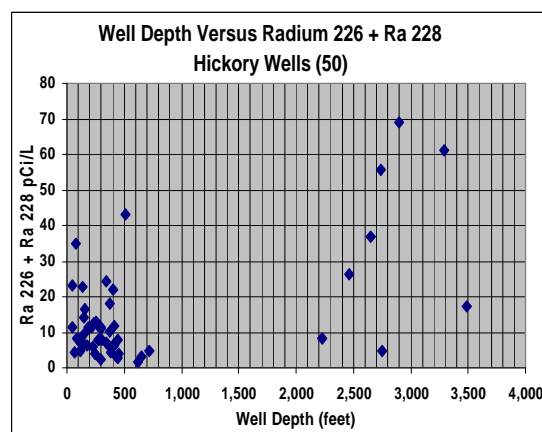


Figure 6. $Ra^{226} + Ra^{228}$ versus well depth

A scatter plot of $Ra^{226} + Ra^{228}$ versus well depth yields a more definitive result (Figure 6). Again, although there is no geochemical information available between 750 and 2,250 feet, the available information in this plot suggests that radium concentrations increase with increasing depth. The reason that these two plots were not more similar was not investigated. One probable explanation, however, is that the dominant radium isotope, Ra^{228} , is the result of beta decay from Th^{232} and therefore would not be detected in a total alpha analysis. Other possibilities for the observed variance may be the use of different laboratories, different detection limits, different laboratory analysis techniques, and other factors. Future analysis of new geochemical data and available water well data may help to resolve this problem.

A number of publications (for example, Llanda, 1999; Upchurch and others, 1991) state that radium can be mobilized as a sulfate complex. Once in the groundwater, radium is subject to adsorption in groundwater and adsorption onto aquifer mineral surfaces. Upchurch and others (1991) states that “Radium forms strong bonds with sulfate and carbonate.” The solubility of radium sulfate is quite low and limits radium mobility in most systems. Figure 7 is the scatter plot of sulfate concentration versus $Ra^{226} + Ra^{228}$. The coefficient of determination is very weak ($R^2 = 0.47$). Obviously, other variables are also influencing radium concentrations besides the availability of sulfate. However, sulfate had the highest R^2 along with radium. Scatter plots for 11 other chemical combinations with radium were created and analyzed (Ca, HCO_3 , Ba, Mg, Na, NO_3 , Sr, Ba, Cl, Fe, and B), none of which had statistically significant correlations.

Another possibility investigated was the potential for chemical concentration or chemical environmental ranges (pH, ORP, temperature, and others) to influence concentrations of Ra^{226} and Ra^{228} in the groundwater. Figure 8 is a scatter plot of bicarbonate concentration versus $Ra^{226} + Ra^{228}$. The highest radium concentrations (those greater than 20 pCi/L in Figure 8) generally seem to occur with bicarbonate concentrations between approximately 280 and 410 mg/L.

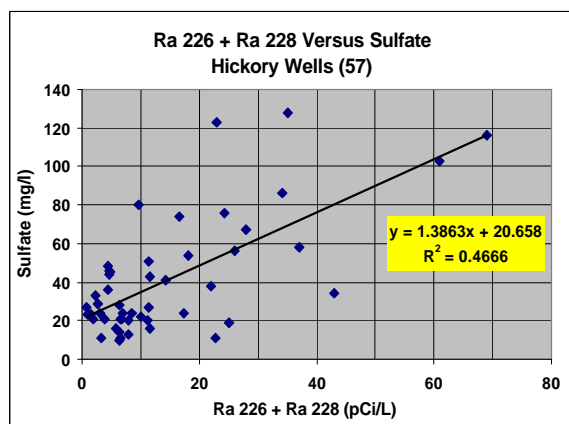


Figure 7. Sulfate concentration vs. $Ra^{226} + Ra^{228}$

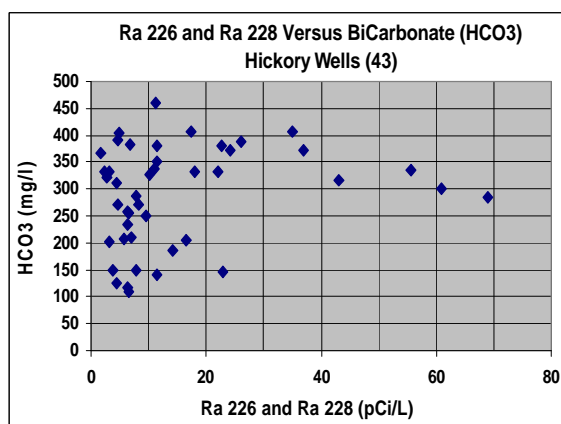


Figure 8. Bicarbonate Concentration vs. $Ra^{226} + Ra^{228}$

A similar pattern was also observed for pH versus $Ra^{226} + Ra^{228}$ (Figure 9). All 13 of the $Ra^{226} + Ra^{228}$ concentrations that were greater than 20 pCi/L fell between a pH range of 6.7 and 8.2. According to Upchurch and others (1991): “Adsorption/desorption is related to chemistry of the groundwater with adsorption being stronger with increasing pH. At the low (<5) pH range, an inverse correlation between radium level and pH, (i.e., increased radium mobility) is expected.

Radium is more mobile at acidic conditions because the solubility of minerals that contain radium (sulfates and carbonates) increases and adsorption of radium decreases. Thus, Ra^{226} and Ra^{228} concentrations should correlate with pH at pH values below 7.” In Figure 9, the observed pattern for $\text{Ra}^{226} + \text{Ra}^{228}$ concentrations versus pH suggests that other variables are more dominant in the geographic distribution of radium in the groundwater of the Hickory aquifer.

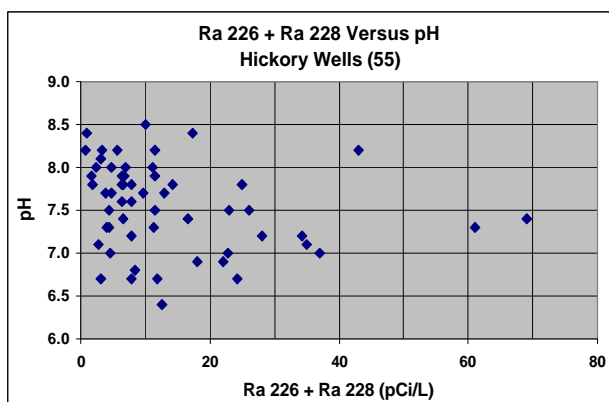


Figure 9. pH versus $\text{Ra}^{226} + \text{Ra}^{228}$

In summary, no statistically significant chemical correlations were identified with the available water well chemistry data. However, a few geochemical or environmental variables were identified that seem to somewhat influence the geographic distribution of higher radium concentrations. These variables include well depth, sulfate and bicarbonate concentrations, and pH. Hopefully, multivariable analyses of these and other geochemical variables in the future may identify a combination of chemical variables that can be used as exploration guides to estimate radium concentrations in Hickory aquifer groundwater.

Vertical radiological zoning within the Hickory aquifer

Lithology, stratigraphy, and structure may also influence the vertical distribution of radiological concentrations within the Hickory aquifer. Unfortunately, there are very few water, oil, or gas wells that penetrate the Hickory aquifer. Because the Ellenburger Formation was structurally faulted contemporaneously with the underlying Hickory during the Pennsylvanian, the Ellenburger and the Hickory have a similar structural history. Dr. Bob Loucks, considered a world authority on the Ellenburger Formation, was subcontracted and reviewed over 50 geophysical logs from Mason, McCulloch, Menard, and Concho counties. He constructed the regional stratigraphy from the Precambrian granites and Hickory aquifer through the Ellenburger and San Saba formations. The geophysical log suite used included nine San Angelo Hickory aquifer wells in southwestern McCulloch and northeastern Menard counties. Dr. Loucks compiled structural tops, bases, and isopach thicknesses for all known aquifers within the Cambrian to Ordovician stratigraphic sequence. All stratigraphic and structural picks used in this paper were based on Dr. Loucks work.

During the Fall of 2004, a Schlumberger Natural Gamma Ray Spectroscopy tool was used as part of a geophysical log suite for three San Angelo municipal water supply wells within the Hickory aquifer. This high-efficiency spectroscopy tool measured natural radioactivity and inferred the abundance of the naturally occurring radioactive concentrations of thorium, uranium, and potassium. These digital data were processed to evaluate the relationships between the lithology and/or stratigraphy and the vertical distribution of the radioactive horizons.

The Hickory aquifer section of the San Angelo Water Supply Well No. 3 is illustrated in Figure 10. The three characteristic facies of the Hickory aquifer are evident. The lower Hickory facies braided stream quartz sandstone sequence is relatively thin in this well (about 150 feet thick at depths from 2,240 to 2,390 feet below land surface). The middle facies, consisting of interbedded fine to coarse grained quartzose sandstones with numerous laterally continuous mudstone laminae and interbeds, is from 2,060 to 2,240 feet deep. The upper facies is strongly cemented with authigenic iron oxide and calcite and is a coarse-grained, fossiliferous, quartz sandstone from 1,920 to 2,060 feet deep (Figure 10). Pumping tests of this well indicate a well yield of approximately 510 gallons per minute and a transmissivity of 19,500 gallons per day per foot.

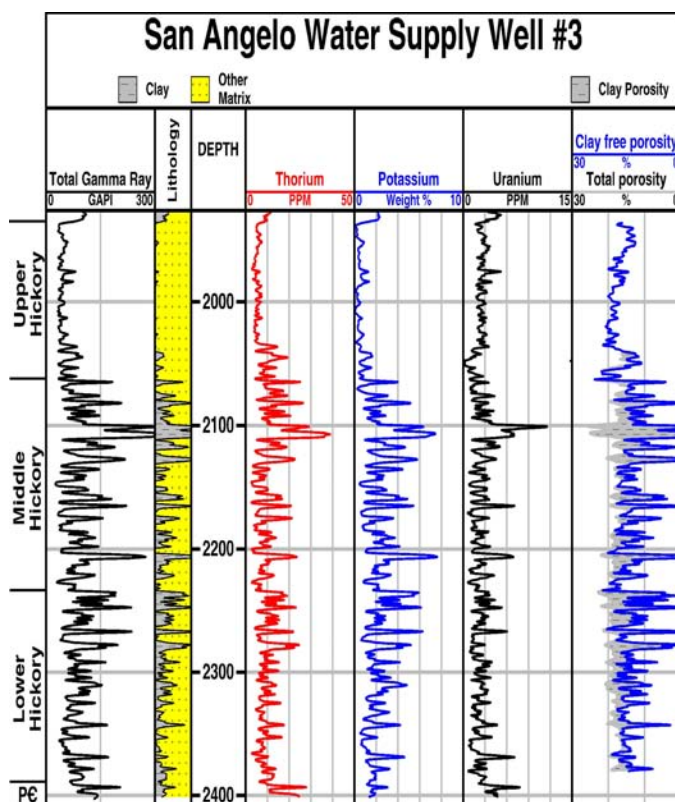


Figure 10. Natural gamma ray spectroscopy survey of San Angelo Well No. 3. Depth is in feet.

The mineralogical distribution of the natural uranium and thorium radioactivity was previously studied by Kim and others (1995). Precambrian and Hickory cores were used in this detailed petrographic study, which determined that the original local natural radioactivity was generated from the geochemical decomposition of the local granites (feldspars) and accessory minerals (less than one percent of total). The radioactive elements are redistributed to interbedded shale laminae, phosphatic materials and to a lesser extent hematitic cement within the Hickory aquifer. The aquifer rocks contain relatively high concentrations of thorium and uranium, with averages of 13.7 and 3.8 ppm, respectively (Kim and others, 1995).

A comparison of the spectral gamma peaks of thorium, potassium, and uranium with the corresponding “lithology” column in Figure 10 confirms that the clayey zones hold the highest concentrations of radiological contaminants. Thorium concentrations are generally three times that of uranium, with maximum thorium peaks up to 35 ppm and uranium peaks up to 12 ppm in the clayey horizons.

The iron-rich upper facies of the Hickory (1,920 to 1,920 feet deep) (Figure 10) seems to have relatively lower concentrations of thorium, potassium, and uranium. Kim and others (1995) observed a slight enrichment of uranium in the hematite cement of the upper facies. Hematite cement is up to 12 percent in this interval (McBride and others, 2002), and this iron concentration may possibly be masking the measured gamma spectra.

A plot of the geophysical digital effective (non-clay) porosity versus uranium concentrations for the sandy horizons within San Angelo Well No. 3 are illustrated in Figure 11. In addition, thorium concentrations are represented by the color scale along the x-axis. The thorium concentrations range from 2.6 to 19.3 ppm with a mean concentration of 6.9 ppm. The uranium concentrations range from 0.1 to 5 ppm with a mean concentration of 2.0 ppm. Thorium and uranium concentrations in the sands were generally half to one-third that of the clays.

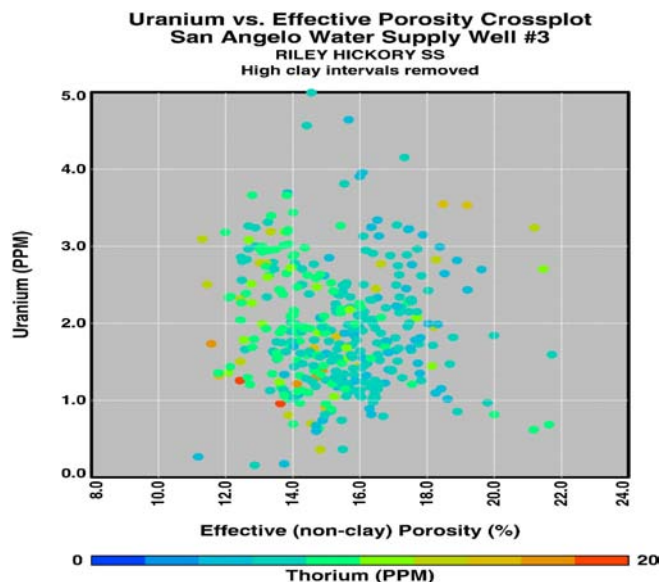


Figure 11. Uranium versus effective porosity cross plot with thorium, San Angelo Hickory Well No. 3.

Effective (non-clay) porosity ranges from 10.7 to 23.8 percent, with a mean of 16.1 percent (Figure 11). In general, the highest thorium concentrations seem to be associated with the lower effective porosities (11 to 14 percent). The uranium concentrations appear to be randomly distributed relative to the effective porosity of the sands.

A number of potential fault zones (including two in the San Angelo Hickory well field) were identified by Dr. Loucks during his stratigraphic evaluation of the geophysical logs. Because Upchurch and others (1991) had observed higher total alpha concentrations up to 0.3 kilometers (approximately 1,000 feet) laterally away from fracture traces, the authors investigated the potential for higher or lower radiological concentrations in the vicinity of faulting.

Unfortunately, the lack of strategically located water wells with radiological geochemistry combined with the relatively poor resolution for the fault locations resulted in inconclusive results. However, review of the existing data implies that faulting may influence radiological concentrations in the Hickory aquifer. Future refinement of fault locations and additional radiological well data may determine if there is a relationship between faulting and radiological concentrations.

It is presently unknown if the vertical variations in the distribution of thorium and uranium concentrations within the Hickory aquifer clays and sands actually result in vertical zoning of the radium. It is possible that sandy zones trapped between clays with the higher concentrations of uranium and thorium may act as sinks for radium. Review of the geophysical logs and data analyses of the three natural gamma ray spectroscopy geophysical surveys from the San Angelo Hickory well field (form a dip section dipping east to west, distance of dip section is approximately 5 miles) indicate that the clay/shale seams are relatively continuous downdip. In addition, the overall clay to sand ratio in the Hickory aquifer and the overall concentrations of thorium and uranium in the clay layers decrease downdip in this three well dip section.

Conclusions

Borehole exploration in the Hickory aquifer for public drinking water with low concentrations of radiological contamination is problematic. Because radiological analyses of water generally requires two or more weeks, this time delay could create costly logistical problems for field equipment and personnel while waiting on the radiological analyses results. The authors investigated available borehole chemistry data with the hope of identifying other chemical variables indicative of low or high radium concentrations.

The well geochemistry data was investigated to determine if there were any geochemical variables that influenced the geographic distribution of radium. In summary, no statistically significant chemical correlations were identified with the available water well chemistry data. However, a few geochemical or environmental variables were identified that seem to somewhat influence the geographic distribution of higher radium concentrations. These variables include well depth, sulfate and bicarbonate concentrations, and pH.

During the Fall of 2004, a Schlumberger natural gamma ray spectroscopy tool was used as part of a geophysical log suite for three San Angelo municipal water supply wells within the Hickory aquifer. This high-efficiency spectroscopy tool measured natural radioactivity and inferred the abundance of the naturally occurring radioactive concentrations of thorium, uranium, and potassium. Clayey zones had the highest concentrations of thorium and uranium. Thorium

concentrations were generally three times that of uranium with maximum thorium peaks up to 35 ppm and uranium peaks up to 12 ppm in the clayey horizons.

Thorium and uranium concentrations in the sands were generally half to one-third that of the clays, and the effective (non-clay) porosity ranged from 10.7 to 23.8 percent with a mean of 16.1 percent. It is presently unknown if the vertical distribution of thorium and uranium concentrations within the Hickory aquifer clays and sands actually results in the vertical zoning of the radium.

The questions that will hopefully be answered in future studies include the following:

1. Do the higher radium concentrations (daughter decay products of thorium and uranium) occur in close proximity to the higher clayey zones?
2. Are the sandy zones trapped between these clayey zones sinks for higher radium concentrations?
3. What combination of chemical, physical, and/or temporal conditions control the distribution of radium?
4. Do the concentrations of uranium and thorium decrease with depth in the clays and how does that affect radium concentrations?

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