GEOLOGIC CONTROLS ON BEDROCK SPRINGS IN THE ST. CROIX RIVER VALLEY, NORTHERN WASHINGTON COUNTY, MN

by
ANDREW LEAF

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By
ANDREW LEAF
under the supervision of Professor James L. Welsh

ABSTRACT

Preferential groundwater flow causes springs along Minnesota and Wisconsin's St. Croix River Valley to emerge at the basal contacts of permeable rock layers with underlying non-permeable layers. Spring locations can indicate contacts where bedrock is covered. Over 320 spring locations spanning 13 miles of river between Stillwater, MN and Otisville, MN were located and mapped using low-angle air photos, GIS, and GPS. Spring elevations were determined using digital orthoquads and digitized USGS topographic quadrangles, and examined in relation to pre-existing measured sections of local stratigraphy, well-hole data, and field observations. This data was compiled into a geologic cross-section relating spring locations to bedrock geology. Spring locations exhibited excellent correlation with well-hole data, allowing individual members of the Franconia Formation to be mapped. Subtle variations in local dip and thickness of the strata were revealed. With further research, accompanied by a high density of quality well-hole data, this detailed two-dimensional picture of local bedrock structure could be extended westward, to create a three dimensional image. This would enhance prediction of groundwater flow in several heavily used aquifers underlying the rapidly expanding Twin Cities metropolitan area.

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INTRODUCTION

Along the bluffs of the St. Croix River valley, eastern Minnesota, abundant springs discharge groundwater from the Paleozoic sedimentary bedrock strata into the river basin. Preferential flow of groundwater causes springs to emerge along the basal contacts of permeable rock layers with underlying, non-permeable layers. Spring locations in this area are therefore useful indicators of geologic contacts, especially where bedrock is covered. The purpose of this project is to correlate the springs and stratigraphy, using previous stratigraphic studies combined with newer techniques, including remote sensing, an electronic County Well Index (CWI) of eastern Minnesota, and well-hole geophysical data. These data were organized using a Geographic Information System (GIS), and used to create a detailed cross-section of the study area, illustrating the relationship between the springs and bedrock geology. The mapped locations of the springs with their relation to stratigraphy can provide a starting point for more detailed investigations into local structure and groundwater flow.

GEOLOGICAL SETTING/SRATIGRAPHY

The area studied lies in the northeast corner of Washington County, Minnesota, covering 13 miles along the St. Croix River from Stillwater northward to Otisville (Figure 1). The bedrock geology in this area is characterized by Cambrian and Ordovician sedimentary strata deposited in a transgressive/regressive marine sequence of the early Paleozoic epicontinental Hollandale Embayment (Runkel, 2000) (Figures 2 & 3).

The Franconia Formation is the lowest exposed stratum within the study area. Although heterogeneous with regard to rock type, it is thought to have formed under conditions of nearly continuous deposition (Berg, 1954). The Tomah is the Franconia Formation's lowest exposed

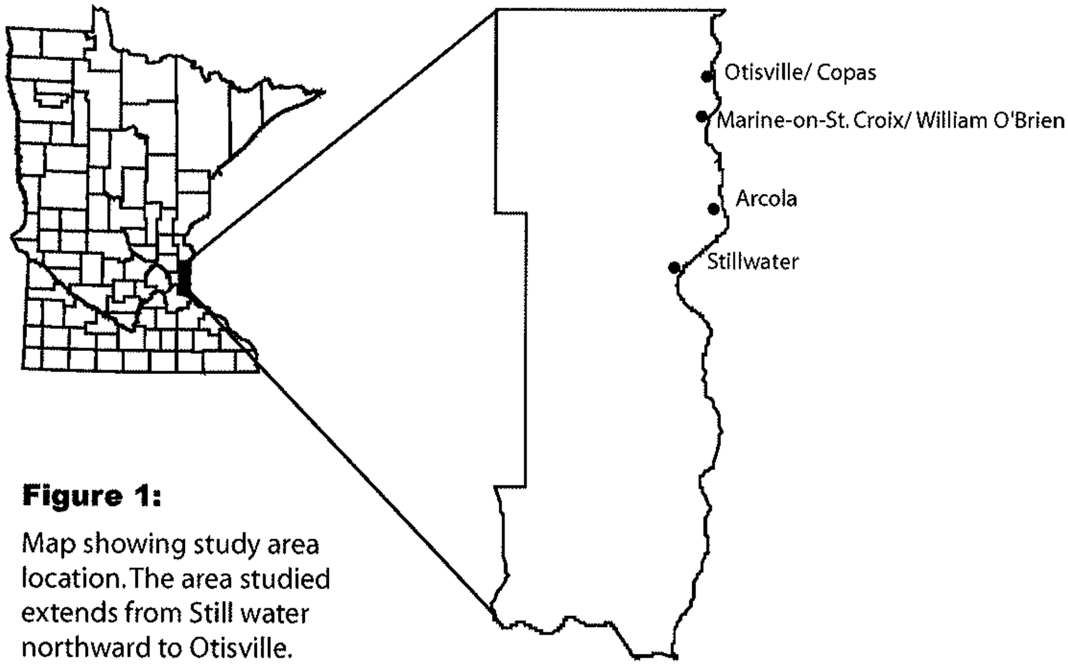


Figure 1:

Map showing study area location. The area studied extends from Still water northward to Otisville.

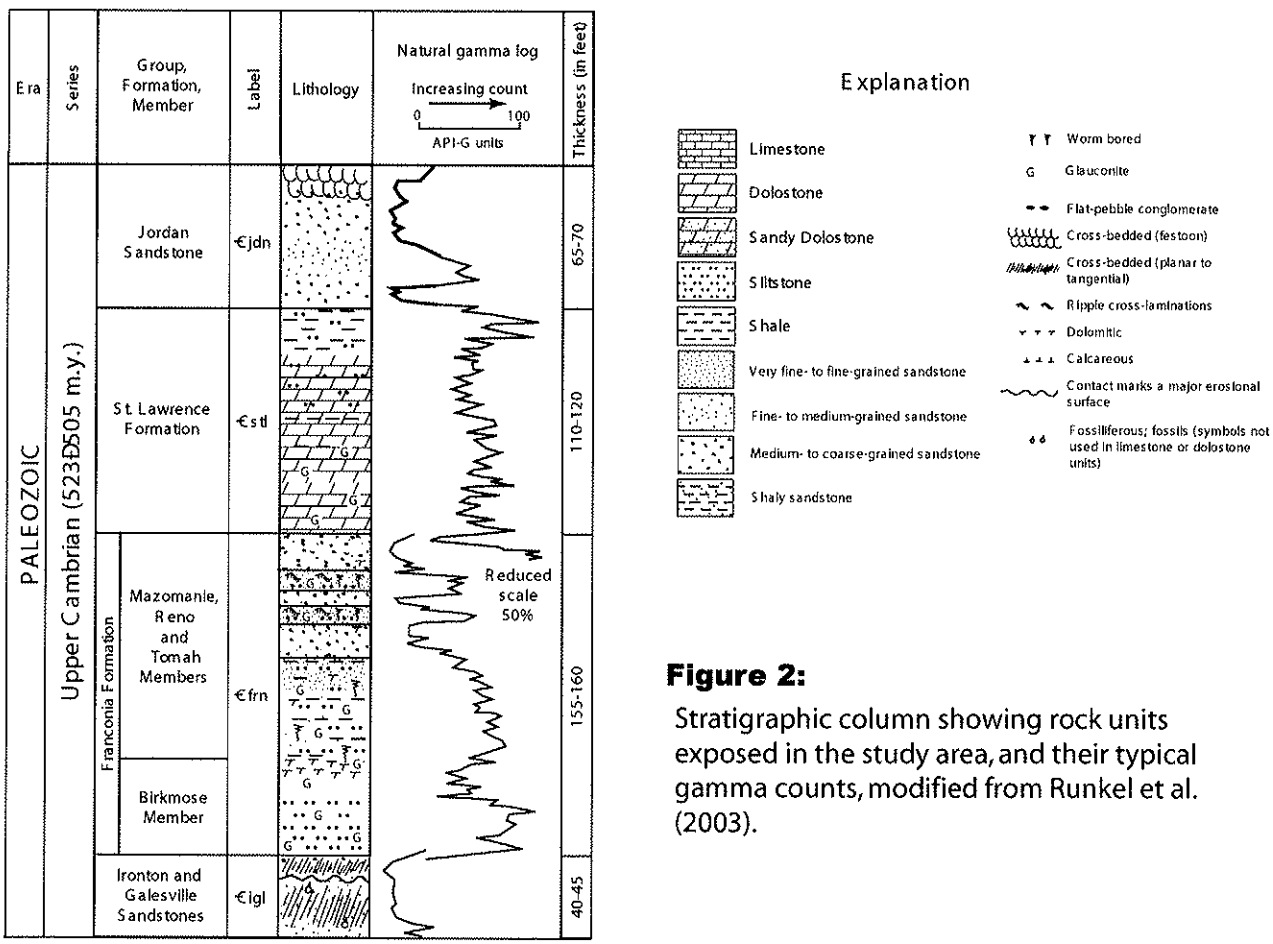


Figure 2:

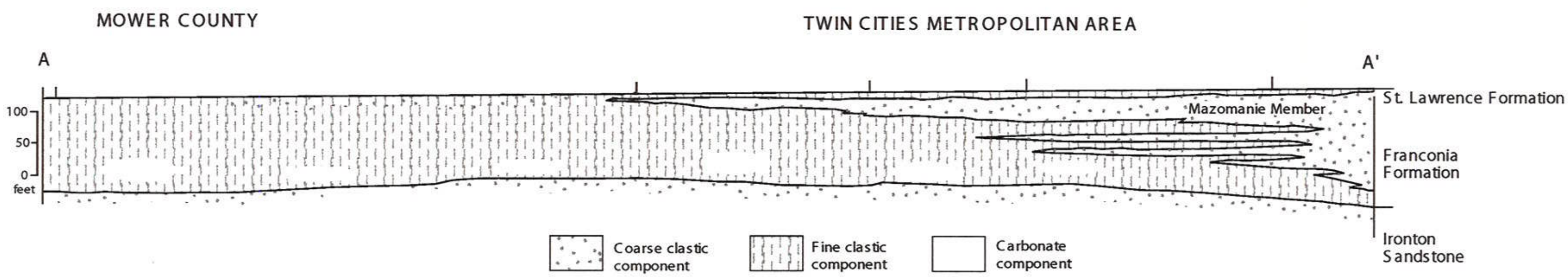
Stratigraphic column showing rock units exposed in the study area, and their typical gamma counts, modified from Runkel et al. (2003).

Figure 3 Geologic map of Northern Washington County (Minnesota Geological Survey 1996). Line shows path depicted in cross section. Red Box shows area depicted in Figure 8.

member, and crops out from Marine-on-St. Croix northward to Otisville (Figure 1). Berg (1954) described the Tomah as thinly-bedded, feldspathic sandstone, with 1-6 inch beds of light grey to yellow, fine-grained sandstone interbedded with 1-2 inch layers of mica-rich grey/green shale. The highly glauconitic (up to 30%) Reno Member overlies the Tomah. Fine-to very fine-grained glauconitic sandstone is the primary rock-type of the Reno Member. Also present is a fine-to very fine-grained cross-bedded sandstone that varies in color from gray to green depending on glauconite content. Interbedded with these two components are thin, mica-rich shale layers similar (but higher in glauconite) to those in the Tomah. Interfingering with the Reno Member is the Mazomanie Member; a coarser, quartzose, non-glauconitic sandstone. Two main varieties of sandstone exist in the Mazomanie: a thin-bedded type, and a thicker, dolomitic, cross-bedded type (Berg, 1954).

The relationship between the Mazomanie and Reno Members is particularly illustrative of a transgressive/regressive depositional sequence. According to Berg (1954), the Reno was deposited offshore, with the thin-bedded Mazomanie deposited in shallower water, and the cross-bedded, dolomitic Mazomanie representing a depositional environment closest to the strand line. Within the study area, two tongues of the Reno Member separate three tongues of the Mazomanie layer. Northwards the Reno layers pinch out, and only the Mazomanie is present, while southwards, the Mazomanie thins until it is absent (Figure 4).

This lithic heterogeneity in the Franconia Formation influences its hydrogeologic properties. The finer-grained layers of the Reno Member, which have relatively low hydraulic conductivity, act as confining units. The coarser-grained Mazomanie layers serve as individual aquifers. The Mazomanie layers are almost identical to the Jordan, St. Peter, and Ironton-



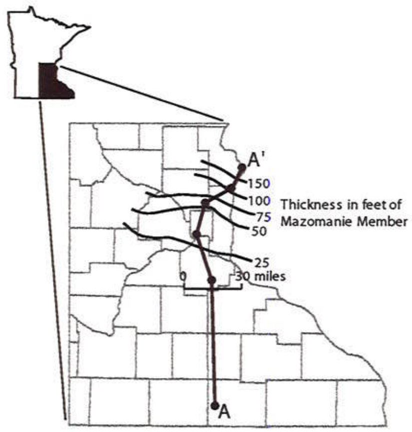
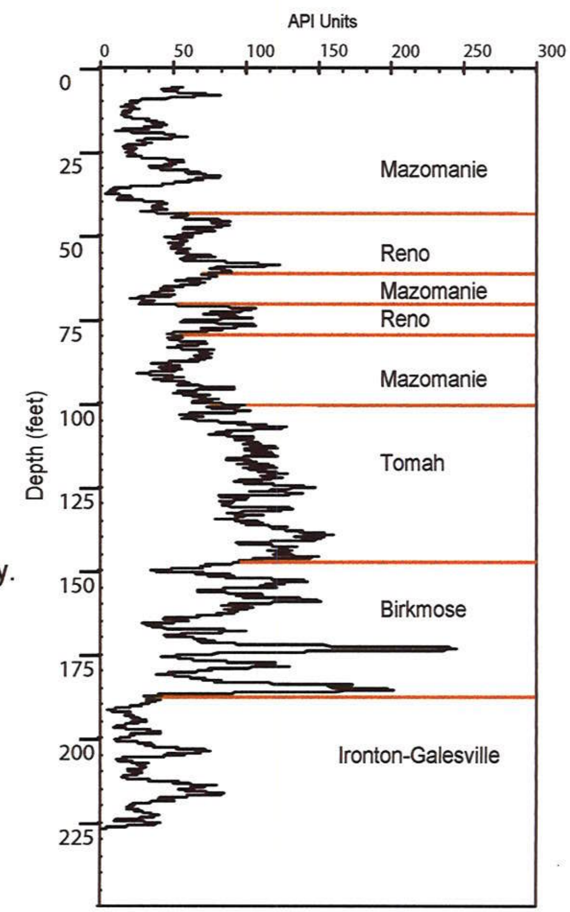


Figure 4:

Above: Cross section illustrating interfingering relationship between the Mazomanie and Reno members of the Franconia Formation.
Left: Vertical trace of cross section and isopachs depicting thickness of the Mazomanie member. From Runkel et al. (2003).

Figure 5:

Gamma-ray log of well number 587840, located just north of Marine-on-St. Croix (see Figures 8 & 9). Interpretations are based on measured sections from Berg (1954), and other nearby gamma-ray logs. Courtesy of the Minnesota Geological Survey.



Galesville sandstones in their hydraulic properties, and supply water to 95% of all wells drawing from the Franconia Formation in Minnesota (Runkel et al., 2003).

Overlying the Franconia Formation is the St. Lawrence Formation, composed of dolomitic siltstones and fine-grained dolomitic sandstones. Because of its low permeability, the St. Lawrence in northeastern Washington County is a confining unit. Above it lies the Jordan Sandstone, which ranges from fine- to coarse-grained, with a general fining-upward trend (Runkel et al., 2003). In the area studied, the Jordan acts mostly as an aquifer. Numerous springs emerging at its basal contact with the Franconia Formation confirm this.

Outcrops in the St. Croix River valley offer a limited picture of the local geology. Vegetation and glacial sediments cover most of the bedrock, with exposure decreasing with height above river level. Discrete springs, wet ground, changes in vegetation, or any combination of these serve as indicators of the basal contacts between aquifers and confining units, especially in areas where the bedrock is covered (Figure 7).

PREVIOUS WORK

Much stratigraphic work has been published for northern Washington County, including several measured sections of strata in this area. The first investigations were done by James Hall (1843) and David Owen (1852). The first geologic map was drawn in 1888 by Newton Winchell. Study of the sub-surface began in 1889, when a 3,500-foot well was drilled at Stillwater in search of gas and oil (Stauffer and Thiel, 1941).

In the first detailed stratigraphic study of the area, Stauffer and Thiel (1941) produced measured sections at Arcola, Marine-on-St. Croix, Meridian Lake (near present day William O'Brien State Park), and Copas (see Figures 1 or 3). These data are of limited usefulness to this study, however, due both to the distance between the sections, and their poor correlation with observed contacts and modern well-hole geophysical data. Berg (1954) studied the Franconia Formation in detail, noting the interfingering relationship between its Mazomanie and Reno Members.

As part of a series of quadrangle studies in the St. Croix valley, Quaschnick (1959) studied the area within the Marine Quadrangle, combining fieldwork with previous studies to produce a geologic map and cross section. He studied in detail a previously discovered fault just north of the study area near Falls Creek, suggesting some (albeit limited) structural deformation. Interestingly, Quaschnick (1959) noted a lack of springs in the study area, hypothesizing that this was due to a preferential flow of water in the opposite direction towards the Twin Cities Artesian basin. This was probably due to the relatively dry conditions the area was enduring at the time of his fieldwork, which contrast with our present period of increased precipitation. Since 1970, annual precipitation in Minnesota has averaged almost 3 inches above the long-term amount, as computed from records dating back to 1830 (Alexander, 2003). This change in climate is also evident in Quaschnick's outcrop locations. Several outcrops he lists no longer exist due to soil and vegetation cover.

Alexander (2002) suggested geological control for St. Croix River valley springs, noting their occurrence along Mazomanie/Reno and Jordan/St. Lawrence contacts. This study aims to build off of previous work, by correlating spring locations to the study area's stratigraphy. Previous stratigraphic studies can be combined with newer methods (air photos, GIS, gamma-ray well logs, GPS) to provide the most detailed, comprehensive picture of the study area stratigraphy to date.

METHODS

Remote Sensing

Aerial photos, as well as thermal and hyperspectral (Chlorophyll "A", Near Infra Red, Water Penetrating) video images of the study area were taken by A.W. Research Laboratories on April 3, 2003 with a clear sky, and an air temperature of –8.3 degrees C. The thermal and hyperspectral videos were taken with aircraft-mounted cameras. The aerial photos were taken with slide film on a 35mm camera.

The images were then scanned and examined on a desktop computer, using magnification of up to 350%. Springs were identified on the images, and with the use of geographic features (e.g. homes, roads, vegetation, etc.) as reference points, mapped as point features in a GIS (Figure 6). Digitized USGS topographic quadrangles (DRGs), as well as one-meter resolution digital orthoquads (DOQs, composite aerial photos corrected for camera tilt and terrain relief) made by the USGS, were utilized as base maps. Spring elevations were estimated using elevation contours on the DRGs. In the instances where landmarks on the DOQs did not match those on DRGs, the DRGs were used.

Gamma-Ray Well Logs

Well-hole geophysical data (gamma-ray logs) and driller's records from nearby wells, along with existing measured sections, were then examined and compared to the estimated spring locations and elevations in order to obtain a better picture of the local geology. Areas in the stratigraphy exhibiting lower gamma-ray counts were interpreted to be coarser sandstones, while areas with higher counts were interpreted as finer-grained sandstones and shales. These interpretations are based on the assumption that the finer strata contain higher amounts of potassium, which emits relatively high amounts of gamma-rays (Runkel et al., 2003). Gamma-ray logs are especially effective for interpreting stratigraphy of the Franconia Formation, as they contrast the high potassium content of the Reno and Tomah layers with the more quartzose Mazomanie (Figure 5).

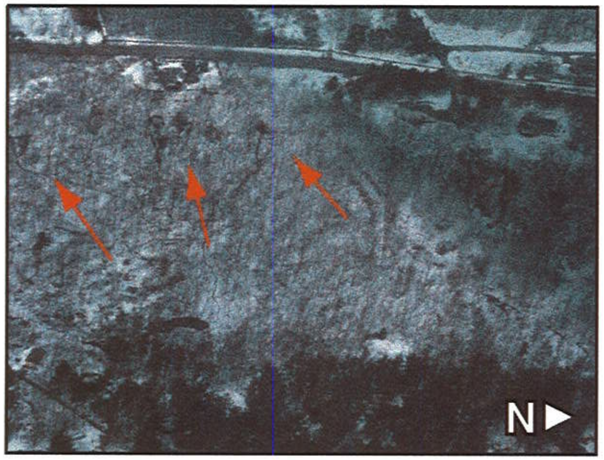
Fieldwork

Finally, several areas were examined more closely in the field to obtain the exact data necessary for creating a geologic map and cross section (Figure 7). A GPS unit using the 1983 Universal Transverse Mercator (UTM83) coordinates was used, when possible, to obtain accurate positions. GPS readings, especially in situations where an accurate reading wasn't possible, were supplemented through the use of landmarks, which appear on the DOQs.

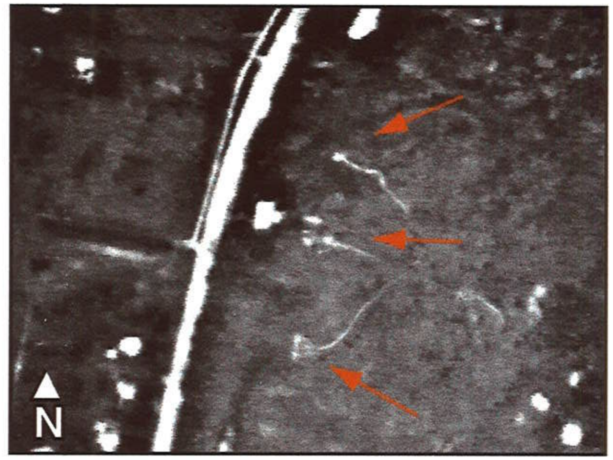
Problems with Spring Mapping

This method of mapping spring locations has some weaknesses, which should be noted. Some stretches of the river had inferior air-photo coverage. Images were either blurry, at too great of an angle, or missing. In the case of heat-sensitive image formats, heat absorbing structures like homes and driveways were sometimes mistaken (by A.W. Research, who compiled the images from the video footage) for groundwater. Future air-photo investigations of other areas could correct these coverage problems by utilizing a trained geologist and a high-resolution digital camera.

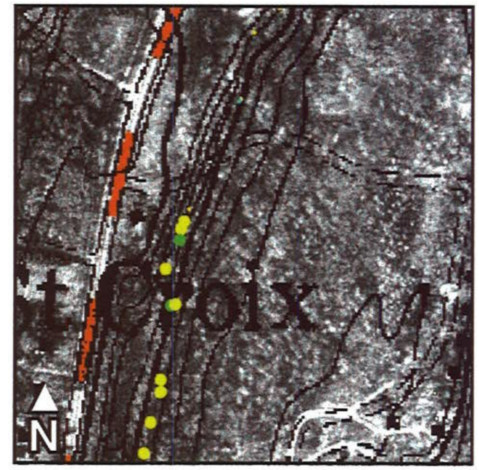
There are also some difficulties associated with ground-truthing. Fieldwork can be complicated by private property restrictions and dense vegetation. In the summer months, a tree canopy can inhibit GPS operation. Publicly owned lands, such as William O'Brien State Park, present their own difficulties. In the absence of GPS, a lack of man-made landmarks (such as roads and homes) increases the difficulty in determining location. Accurate mapping at William O'Brien was also complicated by in an inaccurate topographic map.



A. Visual

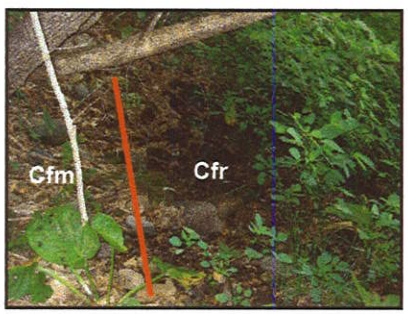


B. Thermal



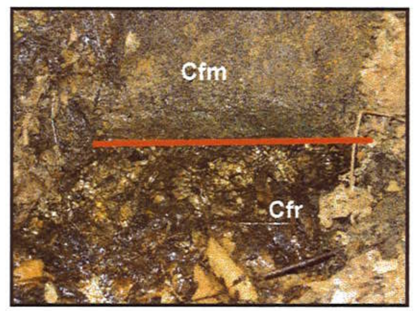
C. Screenshot

Figure 6: Aerial photographs of a spring line north of Marine-on-St. Croix. Springs are indicated by the arrows in the first two photographs. The third image (C) shows the springs mapped as point features in the GIS. The yellow dots indicate springs mapped from air photos, while the green dots indicate those ground-truthed with GPS.

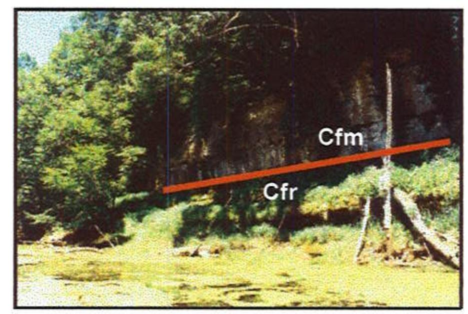


A.

B.



C.



D.

Figure 7: Photos A, B, and C all show springs in William O'Brien State Park, north of Marine-on-St. Croix. Figure D shows Weeping Bluff (see Figures 3 and 9). Water emerging from the base of the Mazomanie member (A and C) of the Franconia Formation clearly produces a change in vegetation (B), where a laterally continuous sheet of water flows beneath the coneflowers. In photos C and D, the Mazomanie/ Reno contact is clearly visible. Note both the shallower weathering profile of the shale, as well as the vegetation resulting from water seeping out of the contact.

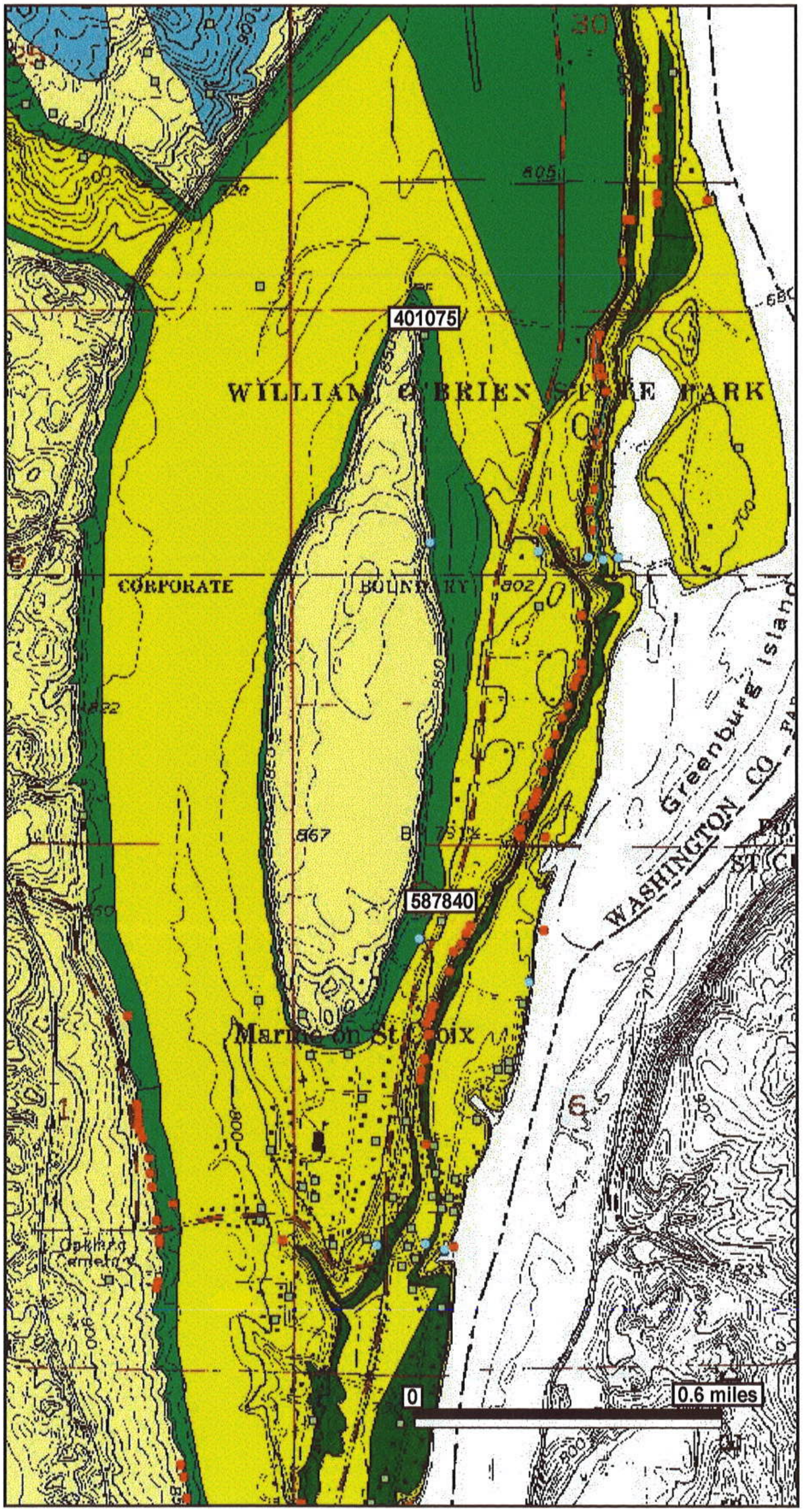
RESULTS

Over 320 discrete springs were identified and mapped along the 13 miles of river studied. The number of springs mapped is somewhat conservative, as individual springs were often close enough to each other to only warrant a single point on the map. In several cases, continuous seeps of water emanating from basal Mazomanie contacts were observed, ranging in lateral extent from a few hundred feet to half a mile.

As Alexander (2002) suspected, a strong correlation was found between spring elevations and the observed or inferred basal contacts of the Mazomanie and Jordan layers. Mapped spring locations were combined with measured sections from Quaschnick (1959), gamma-ray well logs, and CWI driller's logs to generate a geologic cross section of the study area (Figure 9). In addition, a geologic map was created, illustrating the horizontal relationship of spring locations to Jordan/St. Lawrence and Mazomanie/Reno contacts for the area near Marine-on-St. Croix and William O'Brien State Park (Figure 8).

The strong observed correlation between spring locations and basal contacts in the study area allows for a circular method of mapping. At some spring locations, the bedrock contact was visible (Figures 7C & D). In many other instances, as with the numerous springs emanating from the Jordan sandstone in Marine-on-St. Croix (Figure 8), correlation with the rock layer was based on gamma-ray well logs and spring elevations.

Visual and thermal air photos proved an effective means for spring mapping. An example is a line of springs north of Marine-on-St. Croix (Figure 6). Good visual and thermal image data allowed the springs to be remotely mapped in almost the exact same locations as determined by



Legend

- Spring locations
- Observed contacts & measured sections from Quaschnick (1959).
- CWI well locations
- 587840 — Wells with gamma-ray logs
- Opdc — Prairie Du Chein Group
- Cjdn — Jordan Sandstone
- Cstl — St. Lawrence Formation.
- Cfm — Franconia Mazomanie
- Cfr — Franconia Reno

Figure 8:

Geologic Map of Marine-On St. Croix Area, showing horizontal relationships of rock units, springs, observed contacts, and gamma-ray well logs. Revised from Quaschnick (1959).

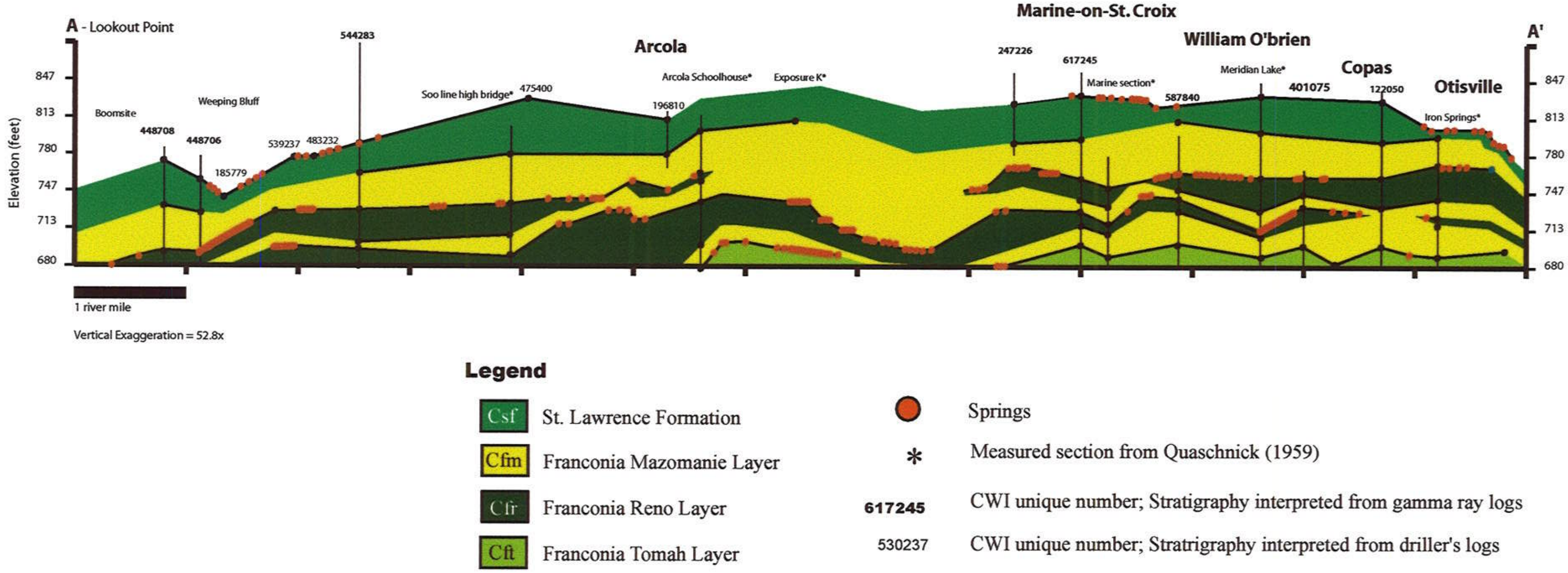


Figure 9:

Bedrock cross-section following the river, from Lookout Point (roughly 1 mile upstream from Stillwater to Otisville. Stratigraphy is based on spring locations, well-hole data, measured sections and observed contacts from Quaschnick (1959). Where inked contacts are absent, the contact was assumed. Because the data utilized is not completely contained within a vertical plane, the structure is probably slightly skewed.

GPS in the field (Figure 7C). These data agreed nicely with a gamma-ray log from well 587840 in the Marine Stugas housing development that lies just across the highway (Figures 5, 8, & 9).

DISCUSSION

Although basal contacts seem to be the most significant factor controlling spring locations in the area studied, the discrete locations of the springs, and their distribution in clusters suggests that other geologic factors could be channeling groundwater flow to affect their locations.

Fracture Flow

In southeastern Minnesota, preferential flow of groundwater along connected secondary pore spaces (fractures) is significant in the Franconia Formation's finer-grained layers. Runkel et al. (2003), emphasize its ability to increase hydraulic conductivity by over two orders of magnitude. This phenomenon can be observed in the "cascading" of water from horizontal bedding-plane fractures into test boreholes. Fracture flow was also hypothesized to dominate the coarse-grained Mazomanie layers. The "Boomsite" springs (north of Stillwater (Figures 3 & 9)), which stem from bedding plane fractures, are cited as evidence (Runkel et al. 2003).

This study's observed correlation between spring locations and basal aquifer contacts suggests, however, that fracture flow is of secondary significance for the area studied. The Boomsite springs mentioned by Runkel et al. (2003) were observed emerging from the Mazomanie/Reno contact (Figure 9). Local enlargement of bedding plane fractures at basal contacts could be a cause of the springs' discrete distribution.

Bedrock Structure

Bedrock structure (as observed through interpretations of well-data) has been shown to affect groundwater flow in the carbonate Galena group of southeastern Minnesota. Lopez Burgos et al. (2003) noted concentrations of sinkholes in areas of higher local dip. This is likely due to increased rates of rock dissolution caused by the preferential flow of groundwater through these areas. This phenomenon was visually noted in the occurrence of a road-cut spring inside the trough of a shallow synform (Lopez Burgos et al., 2003).

The study area cross-section (Figure 9) shows subtle variations in dip and bedrock thickness. Despite the larger influence of intergranular flow for the Mazomanie and Jordan aquifers in the area studied, bedrock structure remains a possible factor.

Although the cross section does not show a definitive correlation between local dip and spring locations, there is some evidence in the cases of Weeping Bluff (Figures 6D & 9) and the springs at William O'Brien state park (Figures 6D & 9). Both of these locations contain laterally continuous seeps of groundwater along Mazomanie/Reno contacts. In both cases, there are excellent stratigraphic data pointing to increased local dip. At Weeping Bluff, a southward dip in the strata can be visually observed as one travels northward along the river (Figure 6D).

There appears to be over an order of magnitude difference between the apparent regional dip, which is roughly 1.6:1,000, and the apparent local dips present at Weeping Bluff and William O'Brien, which are both in the 1:100 range. Springs mapped on the cross-section in apparently flat lying areas could be affected by three-dimensional structure dipping towards the river, which would not appear in a two dimensional representation.

CONCLUSIONS

Remote sensing techniques for mapping spring locations are most useful when there are excellent air photo data, abundant geographic landmarks to reference spring locations in a GIS, and an abundance of quality well-hole data. The occurrence of these phenomena and a heterogeneous hydrostratigraphy make the area studied ideal. Results produced by this project show a strong correlation between variations in the matrix porosity of the local stratigraphy and spring locations. They also suggest additional controls, such as fracture networks and variations in local dip. Additional research is needed to determine the exact contributions of these factors.

The data produced from this project will contribute to the ongoing study of bedrock controls on groundwater flow in Washington County. Extension of this mapping project westward away from the river could expand our picture of local bedrock structure into three dimensions, which would greatly enhance prediction of groundwater flow in several heavily used aquifers. Knowledge of the springs' locations and distribution is also valuable for future biological studies, as the constant annual temperature of groundwater supports unique aquatic ecosystems. Together, these two areas of research serve to better inform land-use decisions in a rapidly sprawling metropolitan area.

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