Surficial Geology and Hydrogeology of the Northern Half of the Proctor 7.5-Minute Quadrangle, Vermont

A view from Sugar Hollow Road looking south towards Cox Mountain, with a kame terrace and wetland area in view.

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1.0 – Executive Summary

During the summer and fall of 2018, I mapped the surficial geology and utilized 169 spatially rectified private water wells. I identified and mapped ten distinct surficial units using traditional field and digital mapping techniques and information gathered from the rectified wells. I also collected GPS coordinates for 332 bedrock outcrops and 288 surficial field sites. Bedrock outcrop locations were collected and combined with well logs to help refine bedrock topography and facilitate the production of an overburden isopach map and one cross-section.

Bedrock topography generally mimics surface topography in the highlands and both the well logs and isopach map suggest the northern reach of the Otter Creek Valley contains the thickest surficial deposits. The lack of gravel wells in the study area suggests there is limited surficial aquifer potential, however the thickest surficial deposits are comprised of coarse lake and deltaic sand resting on clay-rich lake deposits and glacial till. Well yields are highest in the southeastern quadrangle where these surficial deposits are underlain by the Winooski and Dunham Dolostones. A few wells in the Castleton River Valley have moderate yields where clay to sandy alluvium is underlain by the Ira Formation and Winooski Dolostone. Static water levels from well log data were used to interpolate a potentiometric surface, which indicates groundwater generally flows into the lowlands, mimicking surface topography and drainage valleys. All of this suggests the area with the highest aquifer potential is in the southeastern corner of the quadrangle, consistent with Figures 17 and 18 in Stewart (1972).

Field mapping identified deposits of a thin Wisconsin age dense, clay-rich till occurring as a surface veneer mimicking the underlying topography and a less extensive thicker till mantling valley walls and creating gently sloping topography. The second most extensive surficial material is coarse sandy lake deposits. This material is variable in thickness from approximately 10 to greater than 200 feet. Alluvium is present in numerous small brooks but the most extensive deposits are found filling the Castleton and Otter Creek Valleys. There are isolated kame terrace deposits in Sugar Brook Hollow and similarly limited deltaic deposits along Furnace Creek.

The quadrangle is dominated by bedrock that doesn't preserve striations well. However, numerous crag and tail landforms are easily identified on the 0.7-m LIDAR and most common in the eastern highlands surrounding Cox Mountain.

2.0 – Background

This report summarizes the results of surficial mapping and digital mapping efforts within the northern half of the Proctor 7.5-minute quadrangle. Field mapping occurred over approximately 5 months during the summer and fall of 2018. I collected GPS coordinates for approximately 332 bedrock locations and 288 field sites (Figure 1) and interpretation took place during the subsequent 4 months. Private water wells within the quadrangle were rectified by Griffin Shelor, an undergraduate at Green Mountain College, during spring of 2018 and additional wells were located by the author during summer of 2018.

The purpose of this project was to develop a 1:24,000 scale map of the surficial geology and integrate this information with subsurface data derived from private well logs. This mapping project also produced nine derivative maps that provide additional information regarding bedrock and unconsolidated aquifers. These maps can be used to inform land-use and water resource concerns for towns within the Proctor quadrangle (Table 1).

Table 1: Summary of Map Layers Produced for This Report.

1. Surficial Geology of Proctor Quad	5. Recharge Potential to Shallow Aquifers
2. Depth to Bedrock	6. Recharge Potential to Deep Aquifers
3. Potentiometric Surface + Flow Lines	7. Potential Aquifer Resources
4. Bedrock Geology + Well Yields	8. Simplified Hydrogeologic Units
	9. Location of Wells, Field Sites, and Bedrock

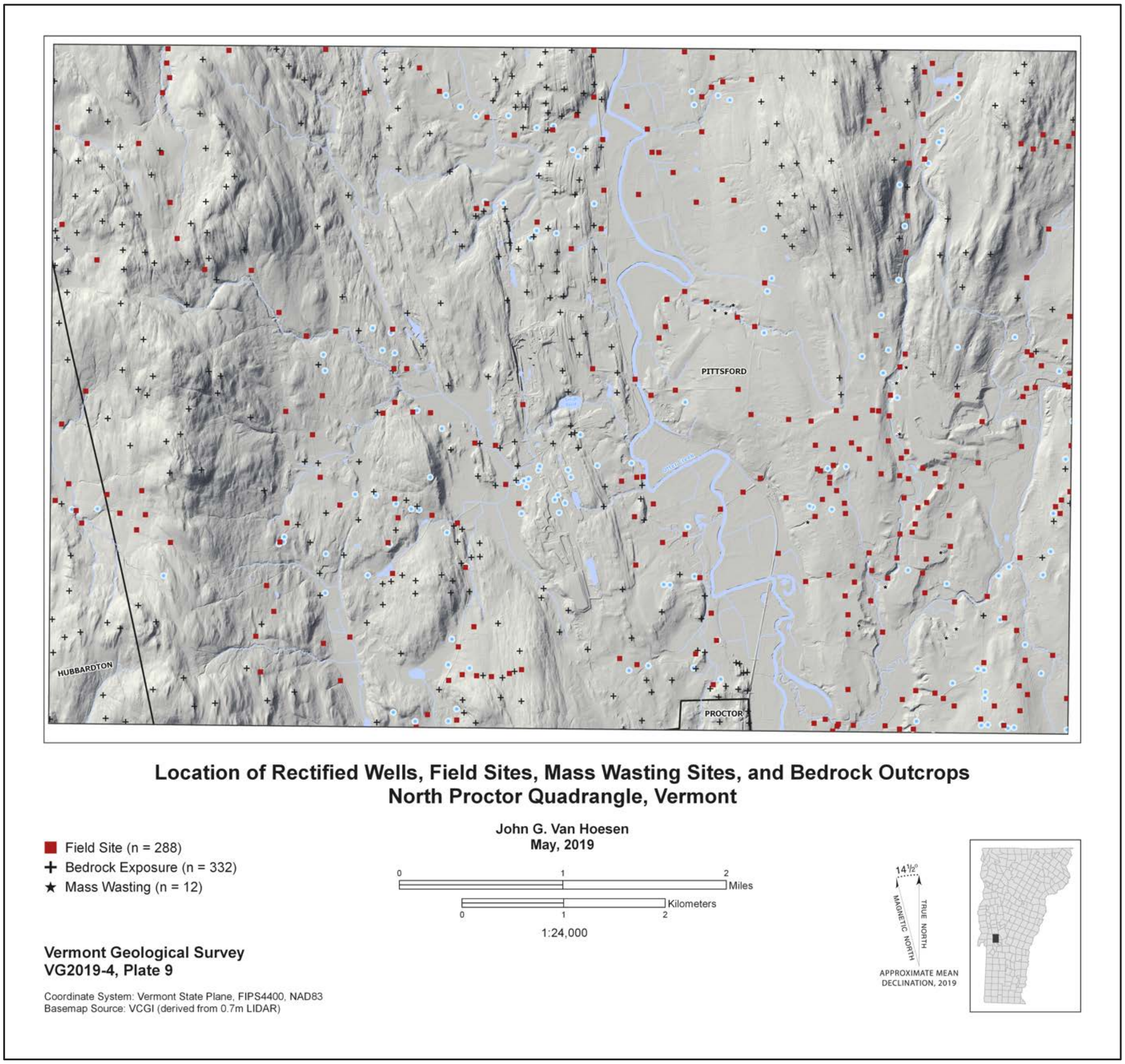

Figure 1: Spatial distribution of rectified water wells, mass wasting sites, exposed bedrock outcrops, and field sites where surficial material was either naturally exposed or revealed using a shovel or soil auger.

3.0— Location and Geologic Setting

3.1 – Physiographic Characteristics

The mapping area covers approximately 70 km^2 and includes the towns of Hubbardton, Brandon, Proctor and Chittenden but mostly contained within the town of Pittsford. Elevations range from approximately ~95 to 625 meters (~310 to 2,050 feet) with the greatest topographic relief occurring along the western edge of the quadrangle. There are two valleys running north-south through the quadrangle filled with fluvial and lacustrine sediment. The western valley is traversed by the Castleton River and the central valley is dominated by the Otter Creek. This large valley is also fed by Sugar Hollow Brook, Little Brook, and Furnace Brook that drain the eastern slopes of the quadrangle. The eastern half of the quadrangle is also characterized by sporadic bedrock cliffs, bedrock-cored hills, and thick deposits of valley filling sediments (Figure 2).

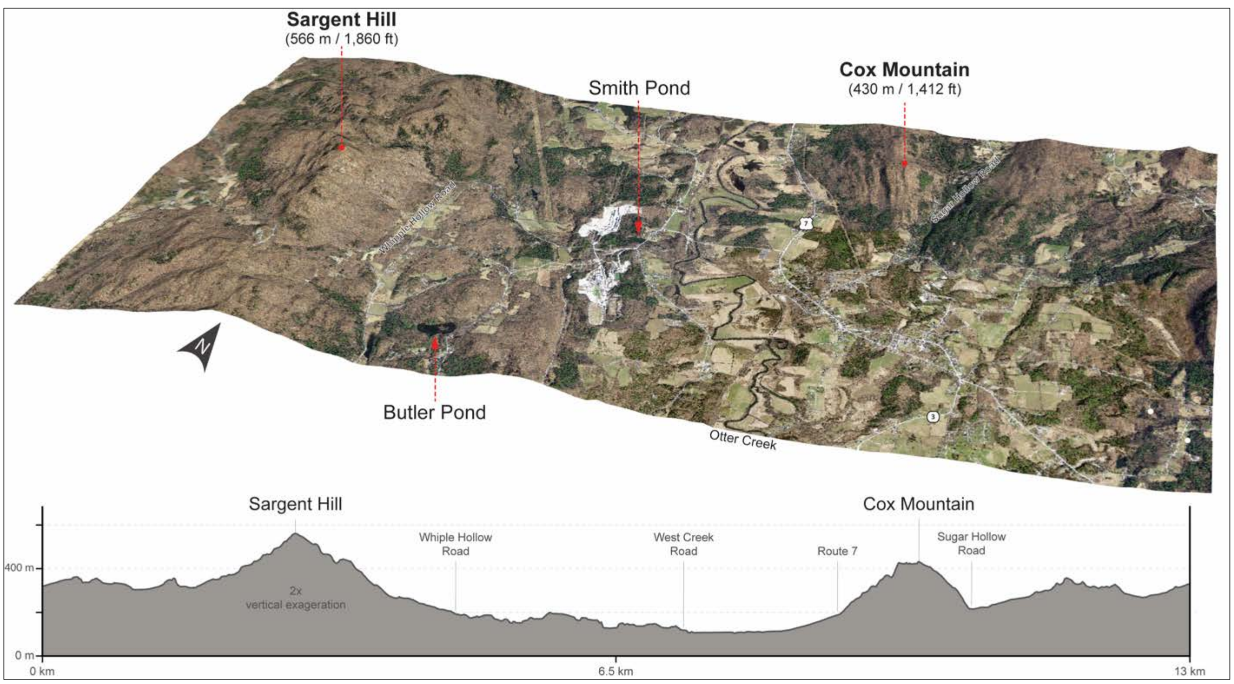

Figure 2: A National Agriculture Imagery Program (NAIP) imagery draped over LIDAR and an elevation profile illustrating topographic variation throughout the study area.

The region is primarily underlain by Paleozoic carbonates, conglomerates, phyllites, slates, and quartzites with additional exposures of Precambrian rocks (Figure 3). The western third of the quadrangle is dominated by rocks associated with the Taconic Allochthon; phyllites and quartzites of the Bull Formation (Czbm & CZzh), the Biddie

Knob quartzite (CZbk) and predominantly slates of the West Castleton Formation (Cwc). The central valley is mostly rocks of the Vermont Valley Sequence and Middlebury Synclinorium; primarily limestones, shales and phyllite of the Ira Formation (Oi, Oii), rare outcrops of limestones of the Bascom Formation (Ob) and limited outcrops of Shelburne Marble (Os) and dolostone of the Clarendon Springs Formation (Cspl). The eastern half of the quadrangle is comprised of rocks associated with the Green Mountain massif. This region is dominated by the Winooski Dolostone (Cw), Cheshire Quartzite (Cc), dolostone of the Danby Formation (Cd) with limited exposures of Precambrian schists and quartzites of the Forestdale Formation (Czfd), Pinnacle Formation (CZps), Moosalamoo Formation (CZmp), and Dalton Formation (CZdq and CZds).

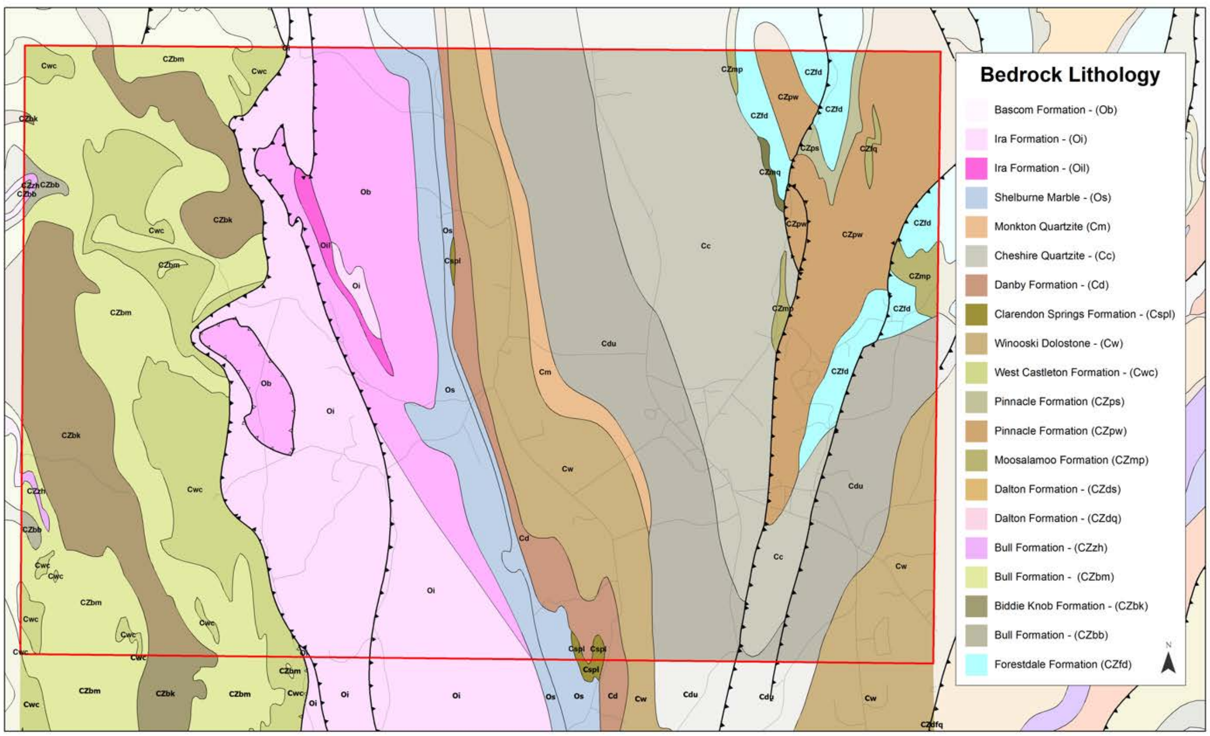

Figure 3: Bedrock geology of the northern half of the Proctor 7.5-minute quadrangle - from the Bedrock Geologic Map of Vermont (2011).

3.2 – Previous Work

Early reconnaissance surficial mapping in the area was undertaken by Stewart (1956–1966), which was incorporated into the Surficial Geologic Map of Vermont by Stewart and MacClintock (1970). Later work by Stewart (1972), De Simone (2006), Van Hoesen (2009), and Van Hoesen (2018) provided regional context for surficial mapping conducted in this quadrangle.

4.0 – Methodology

4.1 – Field Techniques

Traditional field techniques were employed to differentiate between deposits depicted on the final surficial geologic map. Road exposures, soil augers and hand-dug soil pits were used to sample below weathered soil horizons. I used an iPhone 10 running FulcrumApp coupled with a Bad Elf GNSS GPS unit for an accuracy of 0.5 to 1 meters depending on atmospheric conditions and canopy interference. Many streams were walked, all gravel pits and exposures were visited and mapping was conducted both in the highlands and valleys. I collected frequent GPS coordinates of exposed bedrock and inspected numerous outcrops for glacial striations.

4.2 – GIS-Derived Map Products

Using rectified well location logs and field site and bedrock outcrop locations, I used a geographic information system (GIS) to produce the surficial geologic map and all ancillary derivative maps. All interpolation and extrapolation techniques in this report used 0.7-meter LIDAR data obtained from the Vermont Open GeoData Portal.

4.2.1 – Approximate Depth to Bedrock

An isopach map was constructed using both the overburden attribute provided in well logs and the location of bedrock outcrops. To facilitate the process of isopach map production and provide a surface covering the entire map area and not just those areas with wells, I chose to extrapolate an overburden layer using a kriging function and contour the data using automated functions within a GIS. To help determine which extrapolation function was best suited for these data, I used ESRI's ArcPro and Geostatistical Analyst extension to evaluate whether the data exhibited a normal distribution or spatially dependent trends.

The data is not normally distributed but rather strongly weighted towards thin overburden and bedrock exposures (Figures 4 and 5) and there isn't a strong trend in one direction or another, so ordinary kriging was used following Gao et al. (2006), Locke et al. (2007) and Van Hoesen (2014). The tetraspherical variogram model was identified as the best choice using the ArcPro 'Parameter Optimization' function because it provided the best fit based on minimizing the mean square error (Johnston et al. 2001).

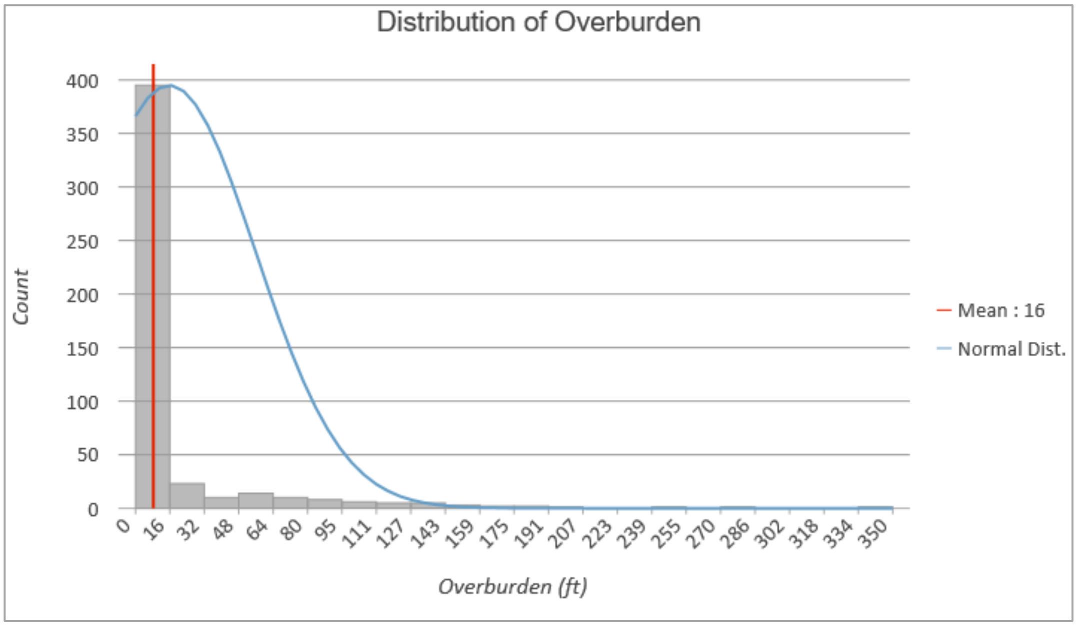

Figure 4: A histogram of well data and bedrock outcrop locations illustrating a non-normal distribution influenced by abundant thin till cover coupled with over-sampling of bedrock outcrops to increase control on overburden. However, the histogram is still strongly influenced by lower values when only using well data overburden (i.e., no outcrop points).

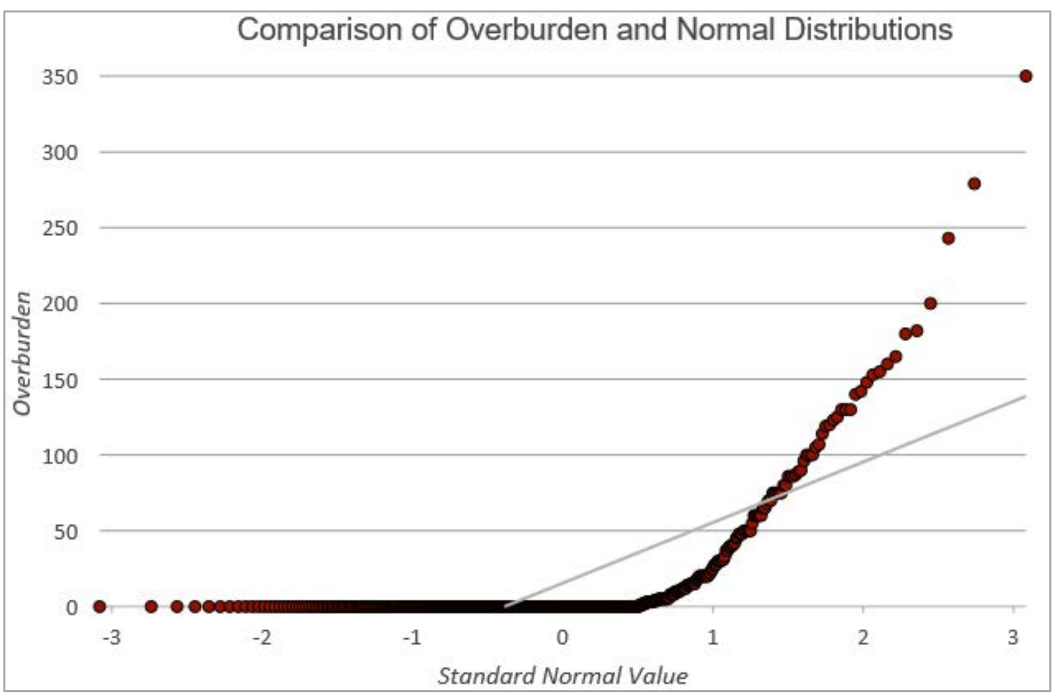

Figure 5: A general QQ plot is a graph on which the quantiles from two distributions are plotted versus each other. For two identical distributions, the QQ plot will be a straight line. This analysis also suggests the overburden values do not exhibit a normal distribution.

I symbolized the resulting layer using Filled Contours for ease of interpretation (Figure 6). I applied limited smoothing to the contours, which is helpful in creating a better cartographic representation of reality, following the argument of Xang and Hodler (2002) that certain techniques may be more “visually faithful to reality” even though their statistical behavior is not always the best.

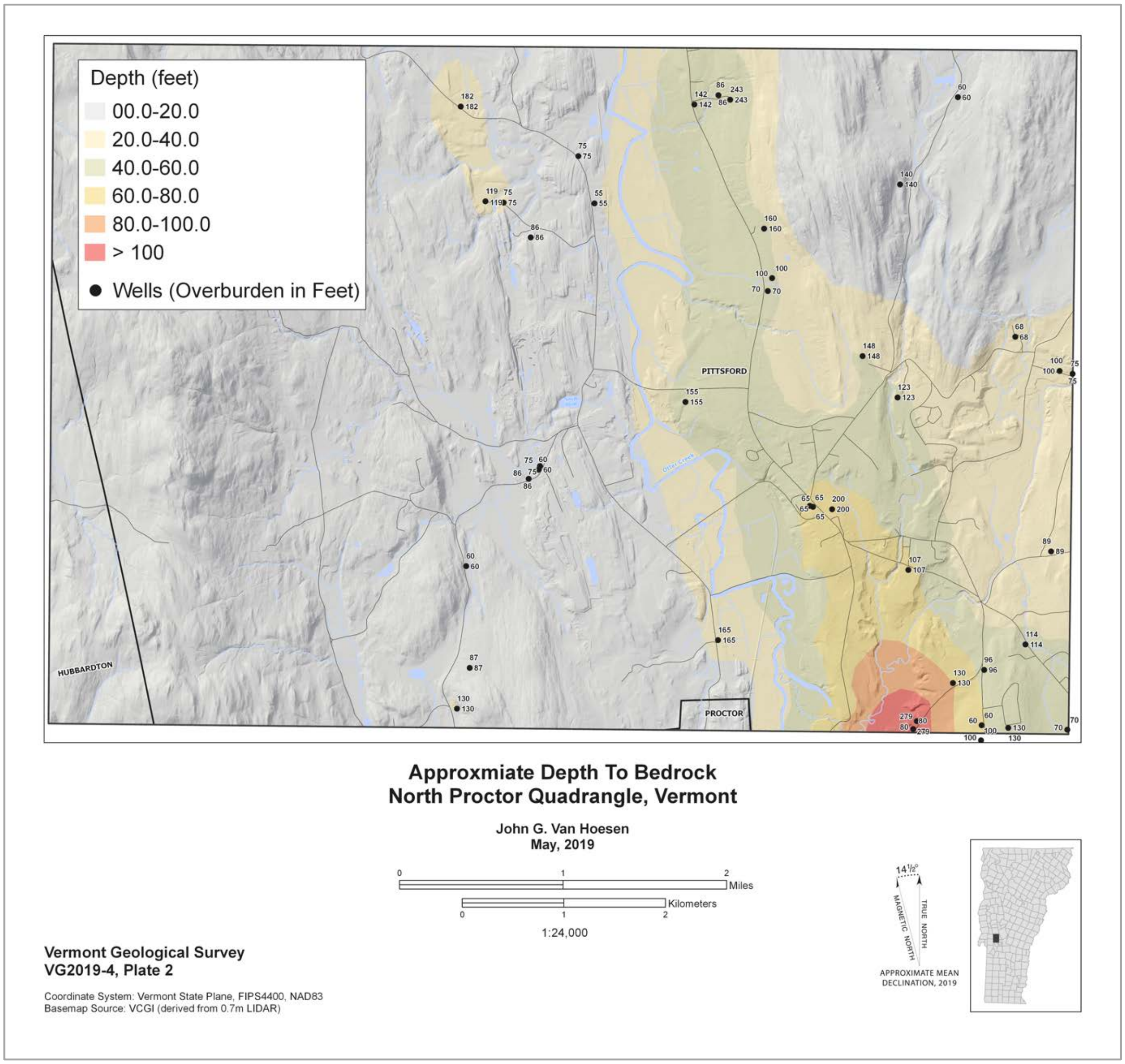

Figure 6: Approximate depth to bedrock in the northern Proctor Quadrangle extrapolated using ordinary kriging based on well log data and bedrock exposures.

4.2.2 – Potentiometric Surface Map

A potentiometric surface was interpolated using the static water level attribute provided in the well logs and a 0.7-meter DEM. The depth to the static water in each well was subtracted from the grid cell within the DEM directly beneath the well location and added to the attribute table to identify the elevation of water within each well. Like the isopach map, to facilitate the process of potentiometric surface production and provide a continuous surface covering the entire map area and not just those areas with wells, I interpolated this surface using an inverse distance weighting function (IDW) and contoured the data using automated functions within a GIS following Van Hoesen (2014), Hamad (2008), Spahr et al. (2007), and Bajjali (2005).

The Geostatistical Analyst suggest the data is close to normally distributed (Figures 7 and 8). The piezometric surface produced using IDW interpolation was contoured using 40-foot increments to illustrate the approximate hydraulic gradient (Figure 9).

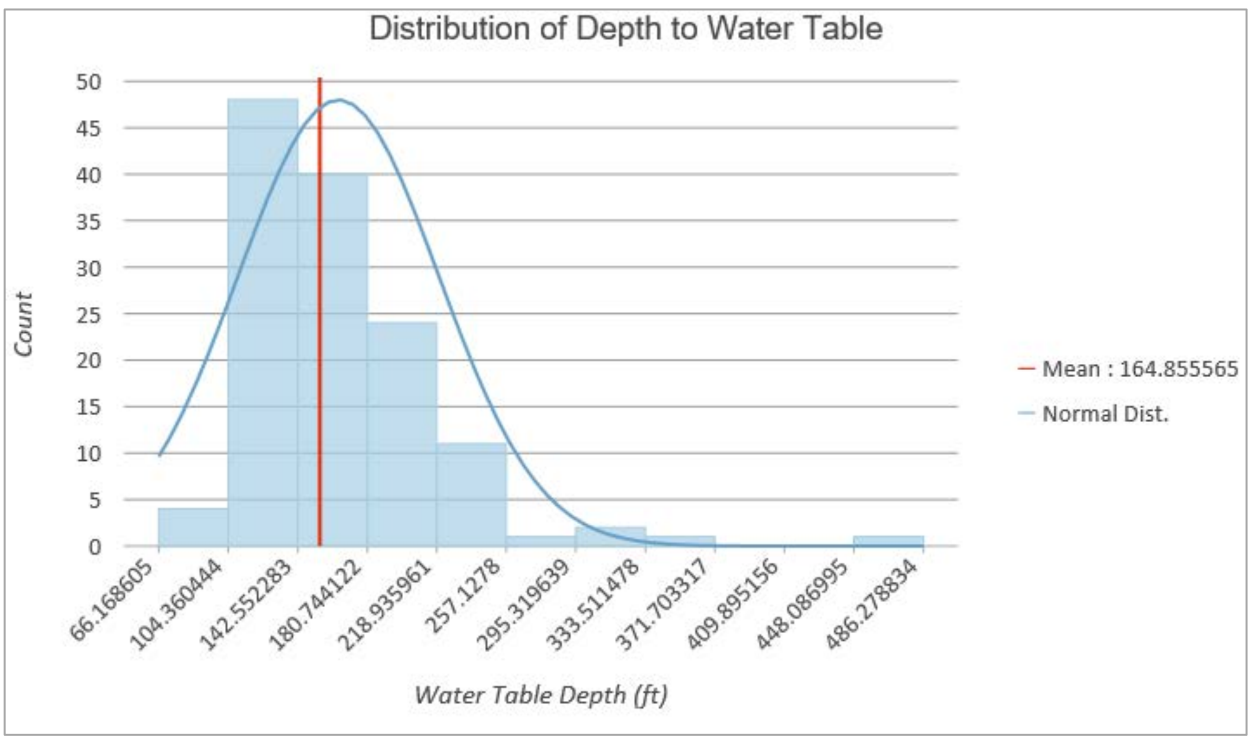

Figure 7: A histogram of static water depth that illustrates a more evenly distributed range of values.

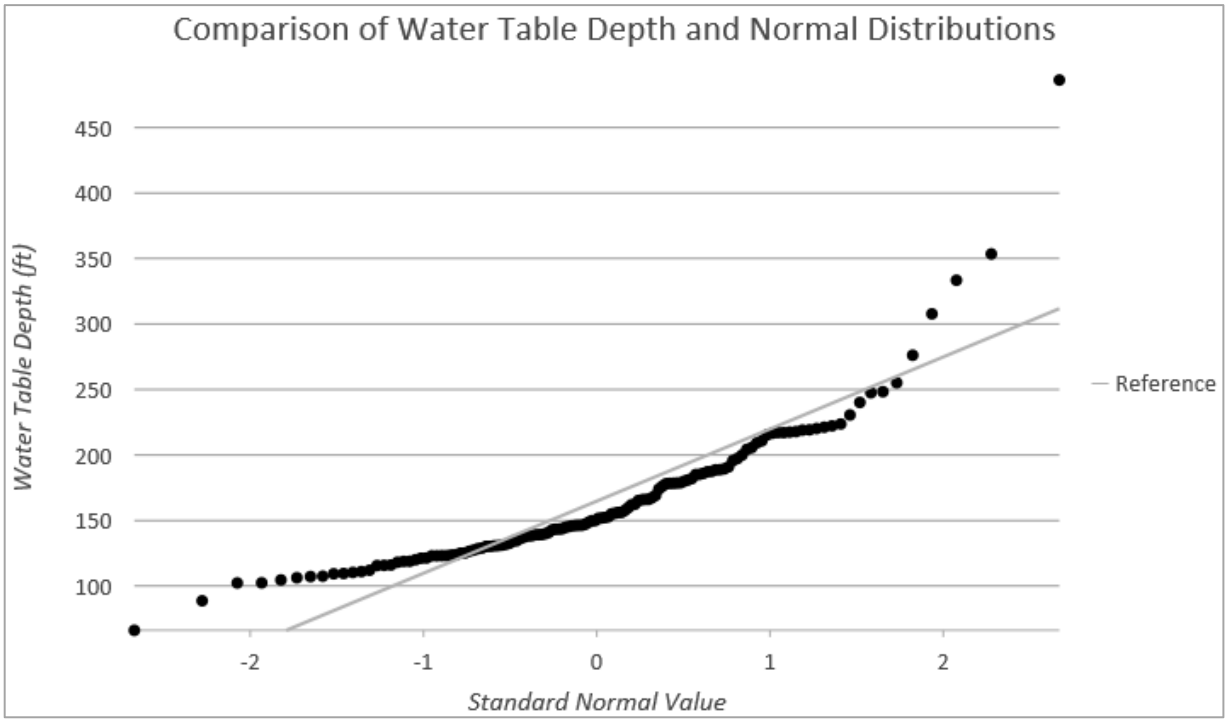

Figure 8: A general QQ plot is a graph on which the quantiles from two distributions are plotted versus each other. For two identical distributions, the QQ plot will be a straight line. This analysis suggests the static water depth values have a close to normal distribution.

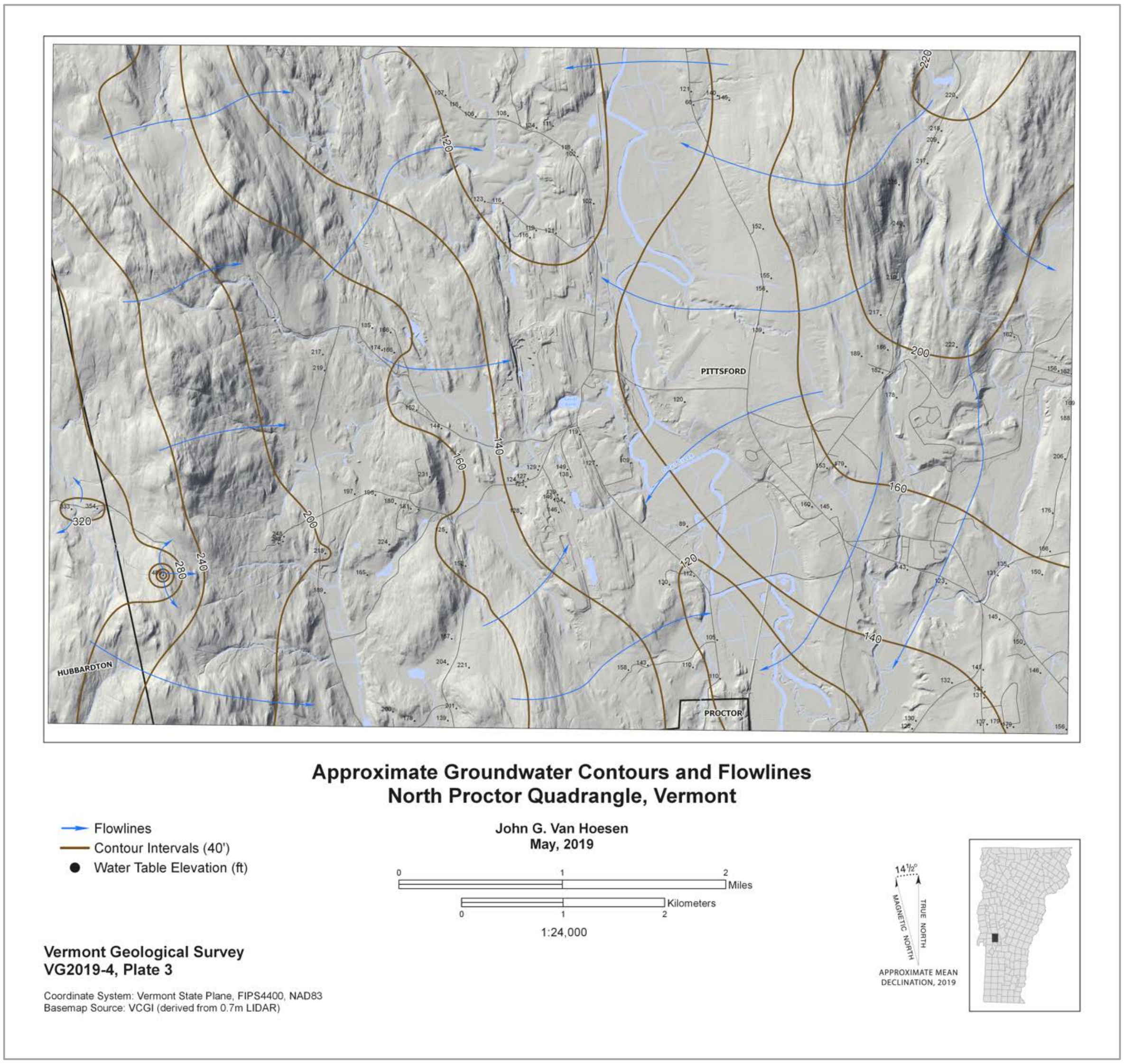

Figure 9: Approximate groundwater contours (potentiometric surface) and flowlines for the northern Proctor Quadrangle created using private well log data.

5.0 – Results & Interpretations

5.1 – Surficial Units

Alluvial Fan Deposits (Haf): poorly-developed and limited in extent, these deposits of boulders/cobbles/pebbles are found near the inflection point of small tributaries draining steeper topography onto the valley bottom.

Wetland Deposits (Hw): well-sorted, well-stratified silt/clay deposits associated with concave topography lacking drainage. There are extensive deposits covering the Castleton and Otter Creek valleys, which are underlain by alluvium and coarse lake sediments. However, many smaller deposits also occur in the uplands overlying till.

Alluvium (Ha): deposits of well-sorted, well-stratified, fluvial deposits adjacent to or in stream channels composed of sand, silt, pebbles, and cobbles. It has variable thickness depending on location in the field area, ranging from a thin veneer within mountain streams to more extensive and thicker deposits filling the Castleton and Otter Creek valleys (Figure 10).

Figure 10: Characteristic level topography associated with extensive alluvium and wetland deposits filling the Castleton and Otter Creek Valleys. Taken in Otter Creek Valley looking west.

Colluvium and/or Talus (Hc): unconsolidated, unsorted cobbles/boulders found in the upland regions at the base of steep strongly weathered cliffs and at the base of small hogback hills throughout the quadrangle.

Alluvial Terrace Deposits (Hat): well-sorted, well-stratified sand, silt, pebbles, cobbles that represent historical floodplain sediments above, and often dissected by, modern streams (Figure 11). They are common along Sugar Hollow Brook.

Figure 12: Historical alluvial terraces observed along Sugar Hollow Brook after it crosses Plains Road, just upstream from the Pittsford Recreation Area.

Kame Terrace Deposits (Pik): Composed of stratified sand and gravel with abundant rounded cobbles and small boulders. Located along upper reach of Sugar Hollow Brook.

Lacustrine Sediments, Coarse-grained (Plc): well-sorted silt-to-sand deposited in shallow water (Figure 12) that commonly forms distinctive lobate topography in the valley bottoms (Figure 13).

Figure 12: Exposure of laterally extensive lake sand along Florence Creek Road (left) and a borrow pit exposing lake sand off Kendall Road (right).

Figure 13: Characteristic lobate topography associated with lake sand deposits.

Lacustrine Deposits, Delta (Pld): well-sorted sand to pebbles and cobbles deposited in glacial lake (Figure 14). Located where Furnace Brook enters the quadrangle.

Figure 14: Course sand and cobbles associated with small delta along Furnace Brook.

Till (Pt): exposures of dense to unstratified clay-dominated till ranging in thickness from less than 3 meters to greater than 30 meters. Area of thin till are characterized by frequent bedrock exposures, abundant surface cobbles or boulders of varying lithology, with common rock walls and, a veneer that mimics topography (Figure 15). Areas of thicker till create rolling hills and streamlined topography.

Figure 16: Typical characteristic streamlined topography of regions mantled with thick glacial till located on the western slopes of Cox Mountain.

5.2 – Cross-Section Interpretations

I created one cross-section using well log data and surficial geologic mapping observations. The location of the cross-sections is noted on the Surficial Geologic Map of the Proctor 7.5-minute quadrangle (Figure 16) and was chosen to illustrate the subsurface relationships of surficial deposits within the study area.

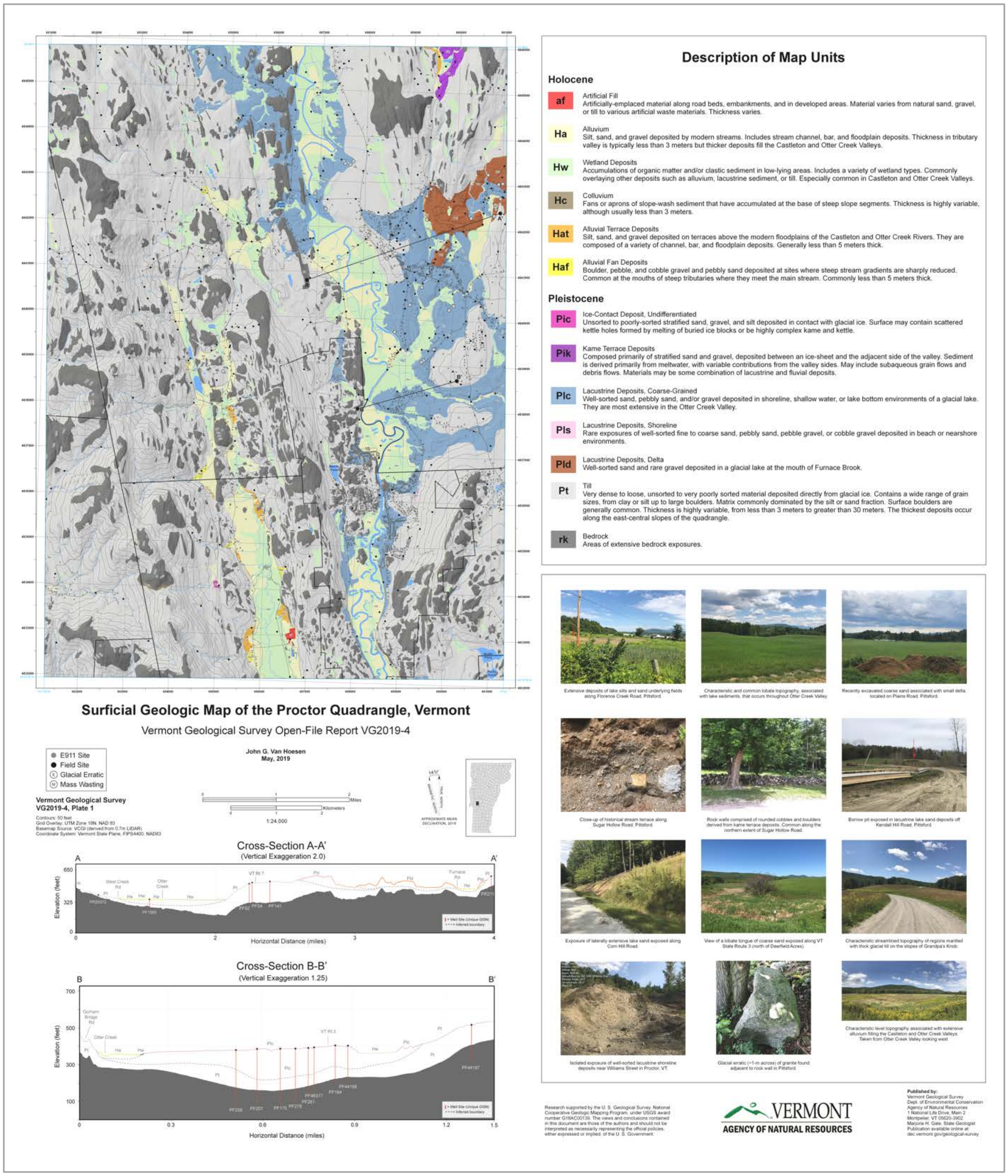

Figure 16: Surficial geologic map of the entire Proctor quadrangle, Vermont.

5.2.1 – Otter Creek Cross-Section (A-A')

This cross section extends approximately 4 miles west to east across the northern reach of the Otter Creek Valley. Surficial deposits in the western section are dominated by bedrock and slopes of thin till (Pt). These transition into valley-filling deposits of well-sorted and well-stratified alluvium (Ha) and larger areas dominated by wetland deposits (Hw). East of Vermont Route 7, the majority of the valley is filled with thick deposits of undifferentiated coarse-grained, lake sediment (Plc), which rests on a mixture of finer-grained lake clay and clay-rich glacial till. Thick deposits of coarse sand and gravels associated with a delta deposit (Pld) cover much of the eastern section. Thinner deposits of alluvium overlie course lake sands and transition into thin glacial till. All six wells along this cross-section pass through variable thickness overburden and terminate in bedrock (Figure 17).

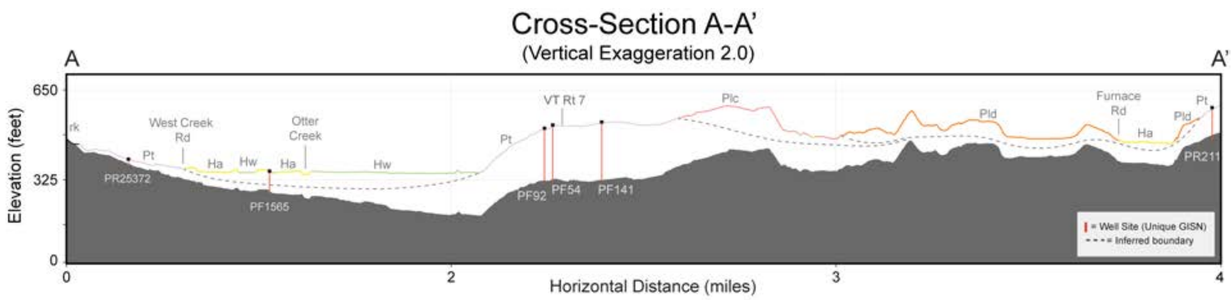

Figure 17: Cross-section constructed using well-log data and surficial geologic map.

5.3 – Depth to Bedrock Map

This map (Figure 6) is consistent with well data, surficial deposits, and the distribution of bedrock outcrops. Areas of thin or no overburden are common throughout the town but most obvious along the western and eastern highlands of the quadrangle. Sporadic areas of thicker till are found throughout the region. However, the thickest deposits occur as alluvium and coarse-grained lake sediments that fill the Castleton and Otter Creek Valleys. The southern extent of the Otter Creek valley contains unconsolidated alluvium and sandy lacustrine sediments ranging from approximately 20 to > 200 feet thick. Overburden thickness thins moving north in the valley. Like the southern half of the quadrangle, this area was explored by Stewart (1972) and after conducting seismic profiling, suggested this area "*has probably the highest water potential of any area in the Rutland-Brandon region*."

5.4 – Summary of Bedrock Well Yields

All of the 169 rectified wells in the northern quadrangle terminate in bedrock. Figure 18 illustrates the distribution of well yields versus bedrock lithology. In addition, four bedrock hydrogeologic units were delineated based on rock properties and mean well yields (Figure 19). The primary hydrogeologic unit in the study area is the Type I sequence (110 wells), sixteen wells occur in the Type II sequence, there are no wells in the Type III sequence, and only two well occurs in the Type IV sequence. A summary of wells within each hydrogeologic unit and their associated geologic formations, yield and depth are summarized in Table 2.

Well yields are highest (mean = 27 gpm) in the Type III unit, however there are very few wells in this unit. Given that slate and phyllite are the dominant lithology, without additional data I wouldn't assume this relationship holds true for future wells. There is one well in the Type I unit that has a yield of 1200 GPM, which is an outlier with respect to all the wells and potentially a data entry error.

Table 2: Summary of well yield and depth for wells within specific hydrogeologic units.

Hydrogeologic Unit	**Well Yield (gpm)** Mean	**Well Depth (ft)** Mean
Type I Sequence (n = 147) Exposures of carbonates, quartzite, and conglomerate of the Shelburne, Danby, Winooski, Dunham, Ira, Monkton, Cheshire, and Clarendon Springs Formations.	13	328′
Type II Sequence (n = 1) Exposures of slate, phyllite, and minor limestone of the West Castleton Formation.	5	225′
Type III Sequence (n = 3) Exposures of slate, phyllite, and minor limestone of the Bull Formation.	27	293′
Type IV Sequence (n = 18) Exposures of slate, phyllite, quartzite, and conglomerates of the Pinnacle, Moosalaomoo, Forestdale, and Biddie Knob Formations.	10	328′

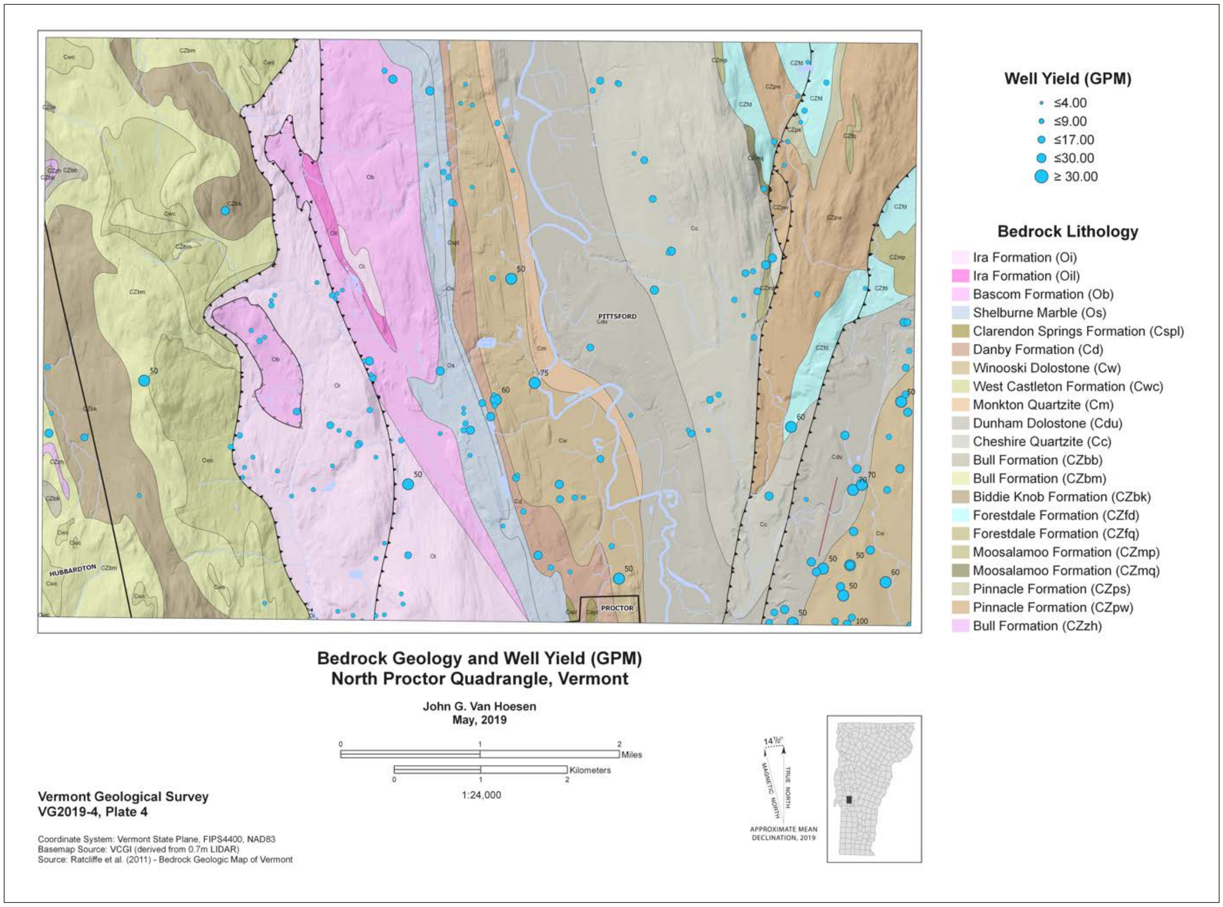

Figure 18: Classification of bedrock geology and well yield.

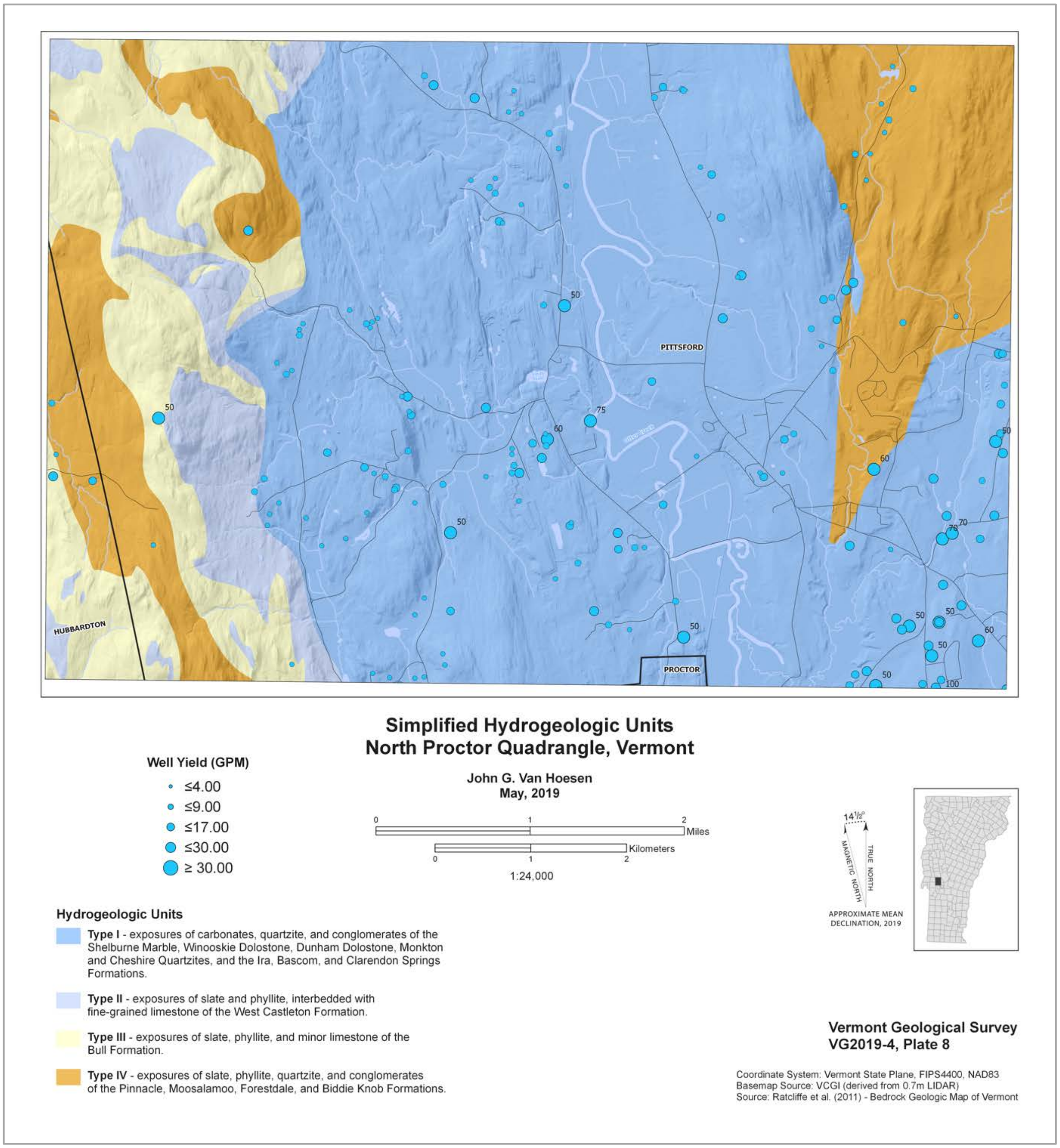

Figure 19: Simplified classification of hydrogeologic units and well yield.

5.5 – Potentiometric Surface + Flow Lines

The interpolated potentiometric surface is consistent with well data, surficial geology, and surface topography. A potentiometric surface does not typically characterize the physical top of the water table but is a proxy for the potential energy available to move groundwater within an aquifer. The map depicts 40-foot contours extracted from the underlying potentiometric surface (Figure 9).

Because private and municipal wells are not evenly distributed through the town uncertainty exists in the inferred flow direction in some areas of the map. However, the general trend of flowing down gradient towards the valleys is readily apparent in the resulting interpolated surface.

5.6 – Recharge Potential to Shallow and Deep Aquifers

Areas of highest recharge potential to shallow aquifers occur in the valleys where there are gentle slopes and extensive deposits of alluvium, wetlands, and coarse lake sediments (Figure 20). This combination of sediment with higher porosity, permeability, and increased surface ponding leads to higher rates of infiltration.

Areas of highest recharge potential to deep aquifers occur in the highlands, which are primarily covered by thin till and frequent rock outcrops (Figure 21). This facilitates infiltration into the underlying fractures and foliation of the bedrock. However, bedrock type and weathering of the exposed till and bedrock influences infiltration rates. Areas with low recharge potential are characterized by impermeable thick, compacted glacial till, and wetland areas. Areas of thick, dense till typically inhibit infiltration because of low permeability associated with compaction and clay content. Although alluvium and fluvial terraces typically have higher porosity and permeability than dense till, it is more likely that groundwater flows through these deposits and discharges into adjacent streams rather than recharging the bedrock aquifer. However, it is important to recognize that the hydraulic conductivity of these deposits was not field-tested in this study area.

The integration of information about high-yielding wells and the areas with the highest potential recharge allows for the approximation of those locations in the quadrangle with the highest overall aquifer potential (Figure 22).

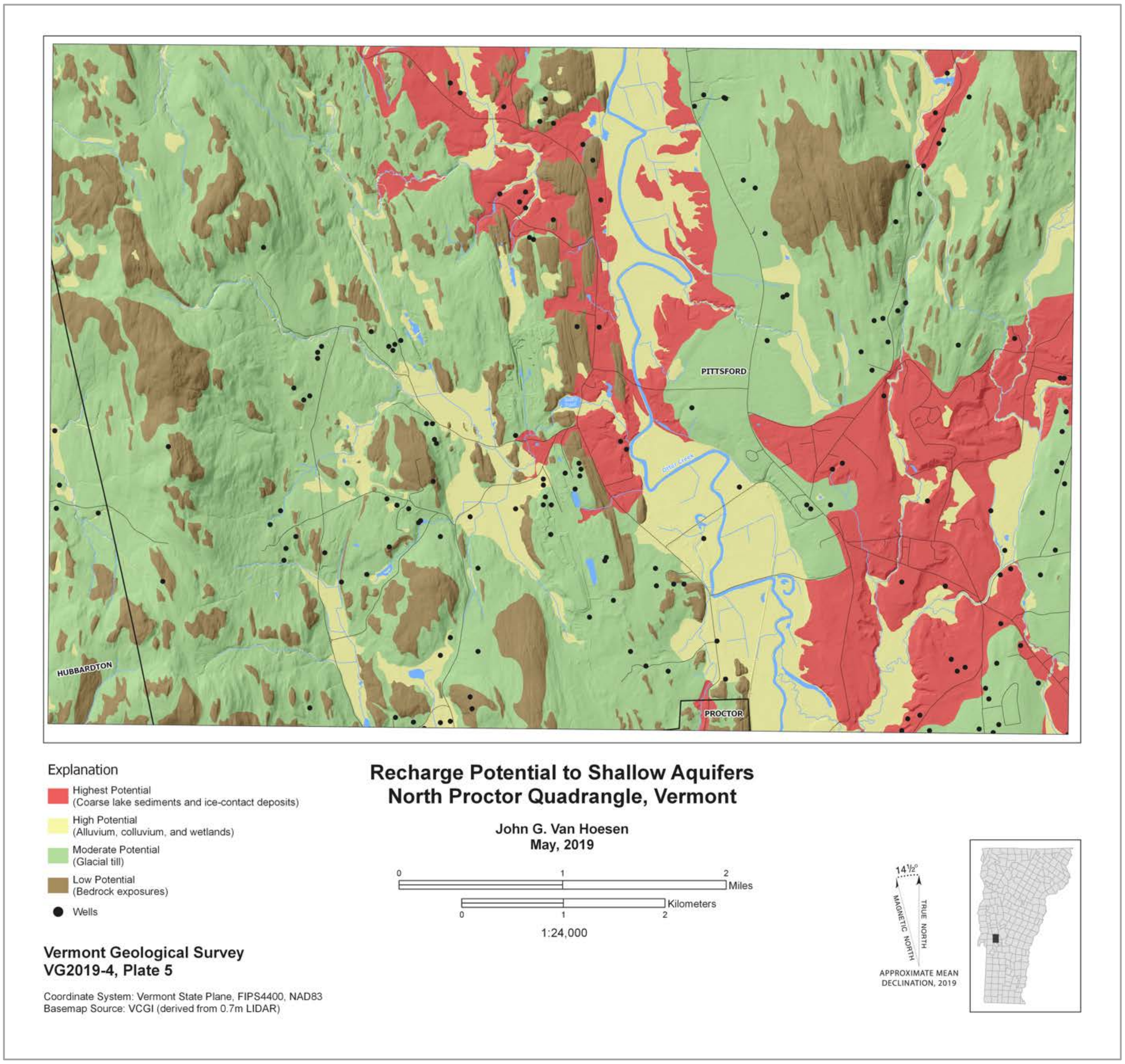

Figure 19: Map illustrating the potential favorability for recharge of groundwater to shallow aquifers.

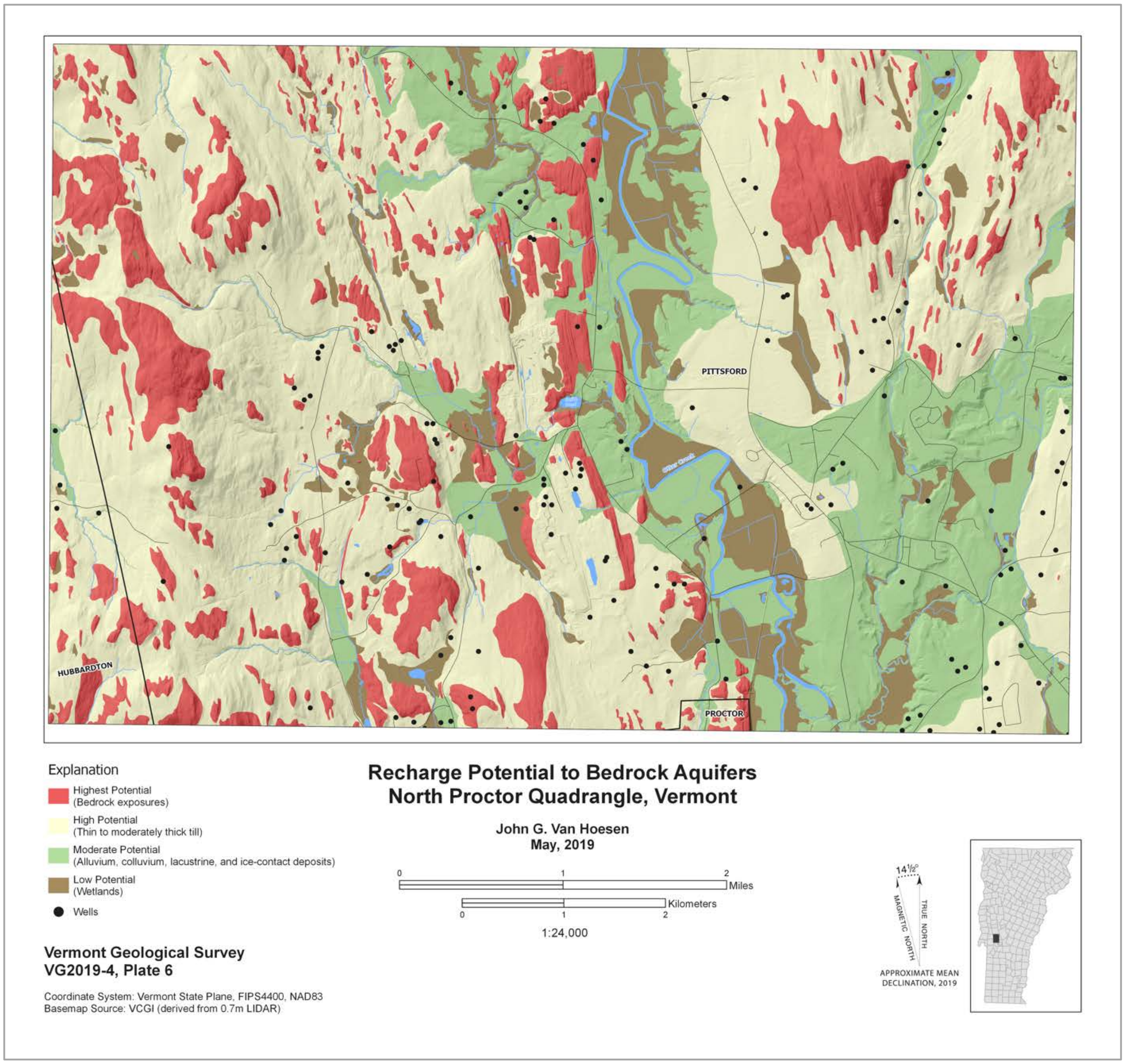

Figure 20: Map illustrating the potential favorability for recharge of groundwater to deep aquifers.

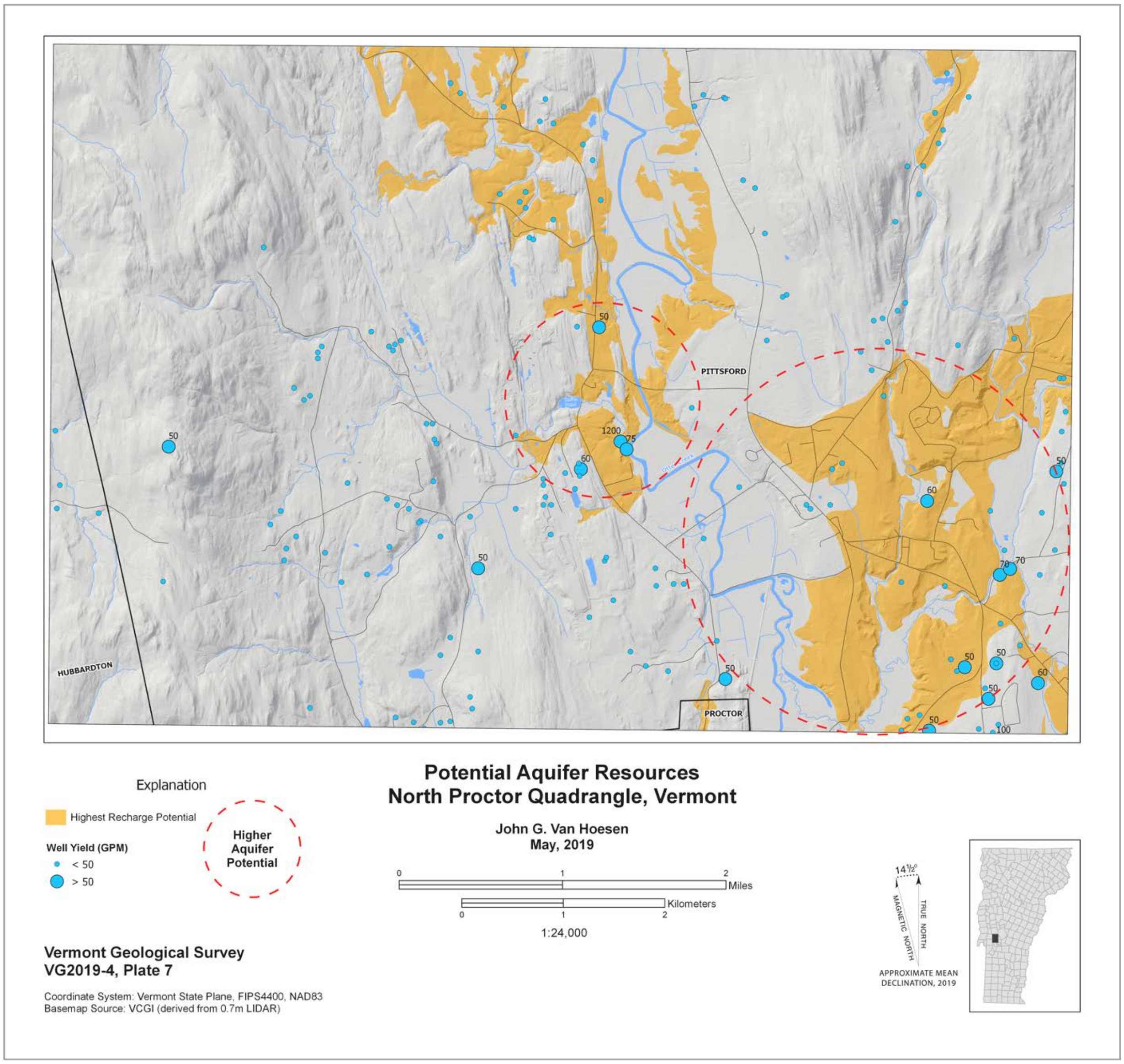

Figure 21: A generalized map showing the overlapping areas where there is high yield from wells and potential yield from - and recharge of - surficial aquifers. This is meant to be used as a general location map not as a definitive tool for high-yielding areas.

6.0 — References

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