GROUNDWATER PURVEYING USING VERY LOW FREQUENCY FRACTURE DELINEATION METHODS

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Abstract

Random drilling for commercially-productive groundwater wells is a haphazard method within the Pennsylvanian-aged rocks of the Appalachian Plateau Region of southwestern Pennsylvania. These rocks have low permeability and porosity and the average production well produces only enough yield for homeowner use. Often these wells are installed as an open hole to 300 feet to insure an adequate water supply for the homeowner since the well bore acts as a storage reservoir during recovery and drawdown.

Three sites mapped with Very Low Frequency (VLF) methods delineated fractures with the potential to maximize bedrock production through increased fracture-induced permeability. A boring was advanced from a location at each of the three sites selected through VLF mapping. The borings penetrated fractures at the anticipated depths of between 10 and 20 meters below grade. Pump tests indicate that these three borings can produce between over 1,000l/min with little drawdown. Each of the three wells is a commercial success.

Introduction

Commercially quantities of groundwater are rarely discovered in southwestern Pennsylvania. Most wells average 75 liters per minute (L/m) or less (Piper, 1933). Often, deep open-hole borings (>100 m) substitute as groundwater storage within these tight rocks. Random drilling, often for homeowners, invariably exacerbates the notion of low production potential within these Pennsylvanian-aged rocks. Curiously, fracture-induced permeability is available but rarely exploited.

Southwestern Pennsylvanian-aged rocks are classic examples of cyclothemic sediments. These deposits consist of shale, claystone, siltstone, sandstone, coal and minor amounts of limestone. Due to the high concentration of very fine-grained sediments, these rocks have very low permeabilities and low porosities. Consequently, secondary porosity and permeability are necessary to achieve groundwater yields of greater than 400 L/m. Areas of localized fracturing are ideal for the production of commercial quantities of groundwater.

Most streams within southwestern Pennsylvania were created by fracture-mediated weathering and erosion following Pleistocene glacial retreat and eustatic uplift. Unfortunately, fracture-controlled streams do not have high specific yields unless a fracture cuts the stream channel (Olson, Hutchinson, Woods, 2002). The intersection of 2 fractures maximizes the potential for elevated production (ABEM, 2001),

Very Low Frequency (VLF) surveying is an effective method for detecting long, straight, electrical conductors and has been used to locate fractures, to image subsurface voids, to map landfill margins and to delineate buried conductive utilities (Hutchinson and Barta, 2002). High-powered military transmitters operating in the 15 to 30 kHz range propagate far-field planar electromagnetic waves that can induce secondary eddy currents in electrically conductive linear and planar targets. VLF meters record responses to the induced current and through filtering can accurately locate linear and steeply-dipping planar subsurface anomalies.

Although VLF surveying is simple and quick to use, geophysicists have been reticent to employ this method. This apparent oversight is difficult to explain; however, it is probably borne from lack of source control (i.e., transmitter is operated by the military, and subject to their control), and partial knowledge of the tool's capabilities and limitations. The hand-held VLF meter records the transmitted signal derived from any one of 42 global ground military communication transmitters that operate in the very low frequency radio range (15 to 30 kHz) (ABEM, 2001). Paterson and Ronka (1971) reported that the first commercial ground VLF meter was available in 1964. Currently, there are several commercial instruments that can measure the VLF signal and through microprocessors collect both the in-phase (real or tilt angle) and out-of-phase (imaginary, ellipticity or quadrature) components of the signal's response to a subsurface conductor (Reynolds, 1997).

VLF surveying has many advantages, including ease of use, rapid deployment, simple processing, and low cost. Limitations of this method include lack of control of the transmitter operation, sensitivity to ferrous and non-ferrous cultural noise, single-point data collection, and relatively shallow depth of investigation. Transmitter operation is dependent on the military; therefore, the transmitter may be turned off during a data collection event. Dependence upon a military transmitter can be obviated by the use of commercial transmitter, which decreases the rapid deployment of the tool. Further, the tool's depth of the investigation (probably no more than 100 meters) is shallow but still within the depth window of groundwater purveyors. Nevertheless, the tool can provide an inexpensive alternative to random drilling or other intrusive investigations.

Theory

VLF surveying falls into the far-field system of electromagnetic data collection. The VLF transmitter is a military-based communications antenna that emits a very powerful electromagnetic wave, which when detected tens of kilometers from the source, behaves as a horizontally propagated plane wave (Nabighian and Macnae, 1991).

The propagating signal has horizontal and linearly polarized magnetic and electrical components of the radiowave field in the absence of a subsurface conductor. However, eddy currents are generated when the radiowave field passes through a buried conductor, creating a secondary electromagnetic field (Figure 1). The increase in the flow of induced currents causes the magnetic field to tilt in the vicinity of conducting structures (McNeil, 1988). Since this causes a phase shift with respect to the homogeneous primary field, the total field is elliptically polarized and tilts with respect to the horizontal axis. Consequently, tilt-angle variations follow a response across the anomaly and thus the cross-over point coincides with the center of the anomaly (Figure 2).

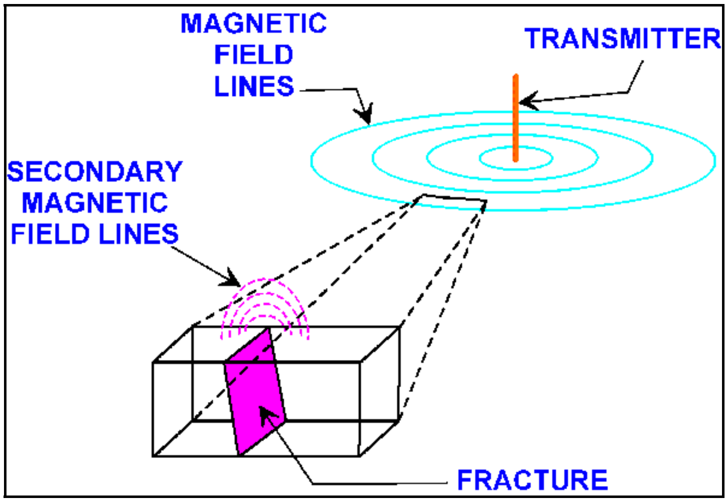

Figure 1: Schematic diagram of very low frequency radiowave with enlargement of secondary magnetic field. Note the horizontal orientation of the electrical and magnetic components of the radiowave field.

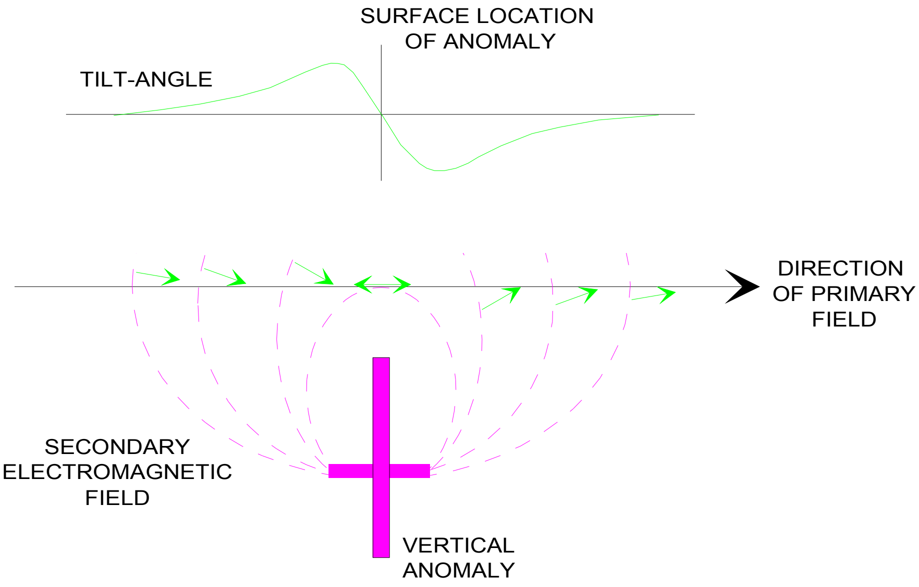

Figure 2: Schematic diagram of the tilt-angle profile over a vertical anomaly.

Many commercial instruments measure the changes in the different parameters of the total field. For example, some instruments measure the dip of the major axis and the ellipticity of the polarization ellipse; whereas other instruments measure the vertical and horizontal field components. These components of the anomalous field can be converted into ratios of the vertical anomalous field to the horizontal primary field for tilt angle analysis. Further, a current density can be calculated with respect to depth from the measured magnetic field.

For example, a buried sheet conductor in a resistive medium in a horizontal primary magnetic field will induce changes in the amplitude and direction of the primary field in proximity to the target (Figure 2). Consequently, on one side of the target, the angle between the vectors of the primary and secondary components of the radiowave field will reach a maximum near an object and change to a minimum upon passing a buried target. The point at which the tilt angle passes through zero, the "crossover" point lies immediately above the target (Babu, Ram and Sundararajan, 2007). If the target dips, then the tilt-angle measurements on one side of the anomaly are accentuated at the expense of the tilt-angle measurements on the other side of the target.

The tilt angle and current density derived from the anomalous magnetic field can be used in subsequent statistical analyses to locate and to image the subsurface target.

Linear filtering

Linear filtering of the tilt-angle measurements can aid in locating the position of a buried target. Fraser (1969) proposed a simple linear statistical filter of tilt-angle data that converts tilt-angle crossovers into peaks for ease of analysis. Fraser-filtering consists of averaging the tilt-angle measurement produced by a subsurface conductor. In a linear sequence of tilt-angle data M_1, M_2, M_3,..., M_n measured at a regular interval, the Fraser filter $\mathbf{F}_i$ is:

$$F_1 = (M_3 + M_4) - (M_1 - M_2) \qquad \textbf{(1)}$$

The first value $\mathbf{F_1}$ is plotted half way between positions $\mathbf{M_2}$ and $\mathbf{M_3}$; the second value is plotted halfway between $\mathbf{M_3}$ and $\mathbf{M_4}$.

Current Density Filtering

Many instruments can calculate a current density from the magnitude of the measured magnetic field (Reynolds 1987). Karous and Hjelt (1983) developed a statistical linear filter, based upon Fraser (1969) and linear field theory of Bendat and Piersol (1968). This filter provides an apparent depth profile from the current density (H_0) which is derived from the magnitude of the vertical component of the magnetic field at a specific location (Figure 3). The depth profile can be calculated from:

$$I_a(0) = \frac{2\pi(-0.102H_{-3} + 0.059H_{-2} - 0.561H_{-1} + 0.561H_1 - 0.059H_2 + 0.102H_3)}{z} \qquad (2)$$

Where, the equivalent current density $\mathbf{I_a}$ at a specified horizontal position and depth $\mathbf{z}$ is based upon a symmetrical filter of the measured current (from the measured magnetic component of the anomalous field).

VLF surveys are conducted to locate fractures that can be exploited for groundwater production. Several surveys were performed using the ABEM Wadi and a 23.9-kHz signal from the transmitter located in Cutler, Maine. A sub-meter-accurate Global Positioning System (GPS) was used for exact spatial positioning of collected data. The tilt-angle data were collected every 10 meters parallel to a portion of the stream bed. Fraser (1969) filtering of the tilt-angle data was performed to locate any targets.

Three types of anomalies were located and represent small-, medium- and large-sized fractures or fractured zones. Discrete, low tilt-angle readings are interpreted to represent shallow fractures or poorly developed fractures. Many small-sized fractures were identified throughout the survey area. Medium-sized anomalies are interpreted to be well-developed deep-seated (greater than 20 meters deep) fractures with a regional extent. These fractures are normally sealed and thus provide limited opportunity for commercial production of groundwater. Large-sized fractures represent regional deformation and integrate a large area and many fractures, thus have a much greater potential for production than smaller shallow fractures. The working hypothesis for these investigations consisted of mapping fractures that may cross creek beds and increase the potential for fracture production of groundwater. Most creeks within southwestern Pennsylvania are created through fracture-mediated erosion and weathering (Olson, Hutchinson, and Wood, 2002).

Case Studies

Case 1

A commercial venture required a continuous source of water of at least 1,000 L/min in the southwestern portion of Pennsylvania. Two VLF profiles were collected adjacent to an unnamed creek, presumed to be fracture induced.

The boring TW-1 was advanced to 32.8 meters below grade and encountered water-bearing fractures at 9.31 m and 17.0 m below grade. Water level stabilized at 8.29 m below grade.

The boring was cased to 6.1 m below grade and completed as an open hole. A pump test conducted for 19 hours indicated a production rate of 1,150 l/min. After 19 hours drawdown was only 2.9 m indicating that commercial quantities of groundwater were available.

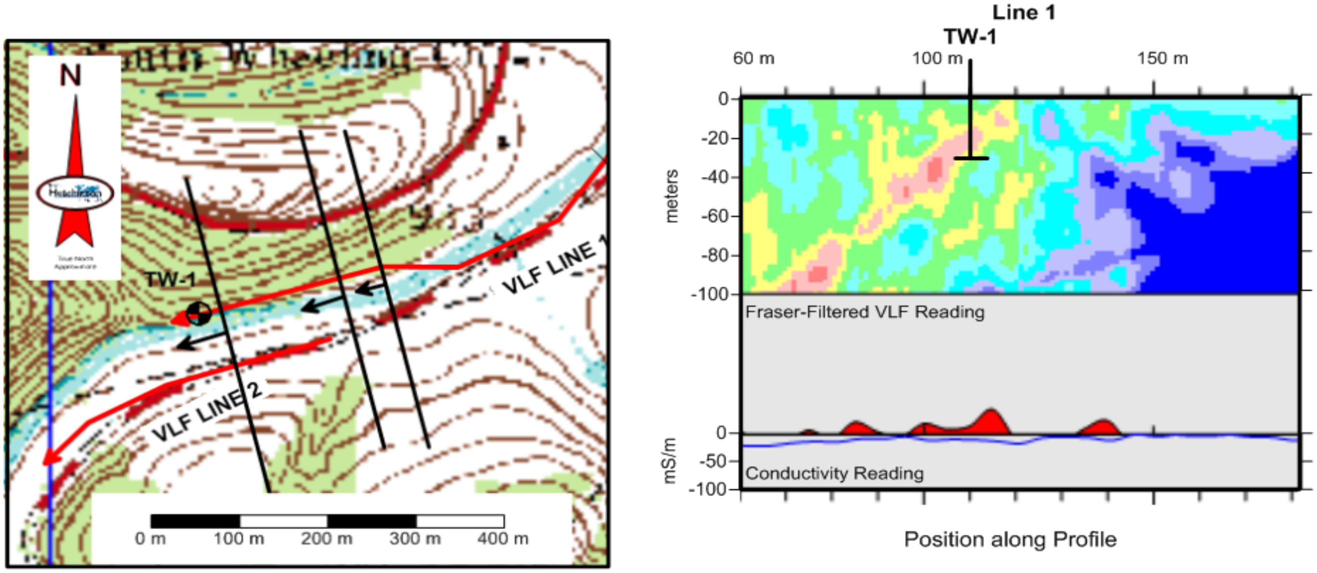

Figure 3: The left figure is a plan map of the Case 1 study area. The right figure shows the processed data in the form of 3 graphs; the upper graph is a representation for the fracture profile derived from the inphase component of the signal (RAMAG program; Walden, 2004) where reds represent a fracture and blues non-fractured rock; the middle graph is the presentation of the Fraser-filtered inphase signal (arbitrary scale); and the bottom graph is the quadrature phase converted linearly to terrain conductivity.

Case 2

Another commercial venture required a continuous source of water of at least 500 l/min in the southwestern portion of Pennsylvania. One VLF profile was collected adjacent to Crafts Creek. Again the creek is assumed to be created by fracturing parallel to the creek bed.

Boring TW-2 was advanced to 54.9 meters below grade and encountered water-bearing fractures at 8.5 m and 15.2 m below grade. The boring was cased to 5.8 m below grade and completed as an open hole. Water level stabilized at 0.9 m below grade after completion of the well.

A pump test was conducted for 13.6 hours at a production rate of 1,325 l/min. After 13.6 hours of production, drawdown was only 5.4 m below grade indicating that this well met the design basis for the commercial user.

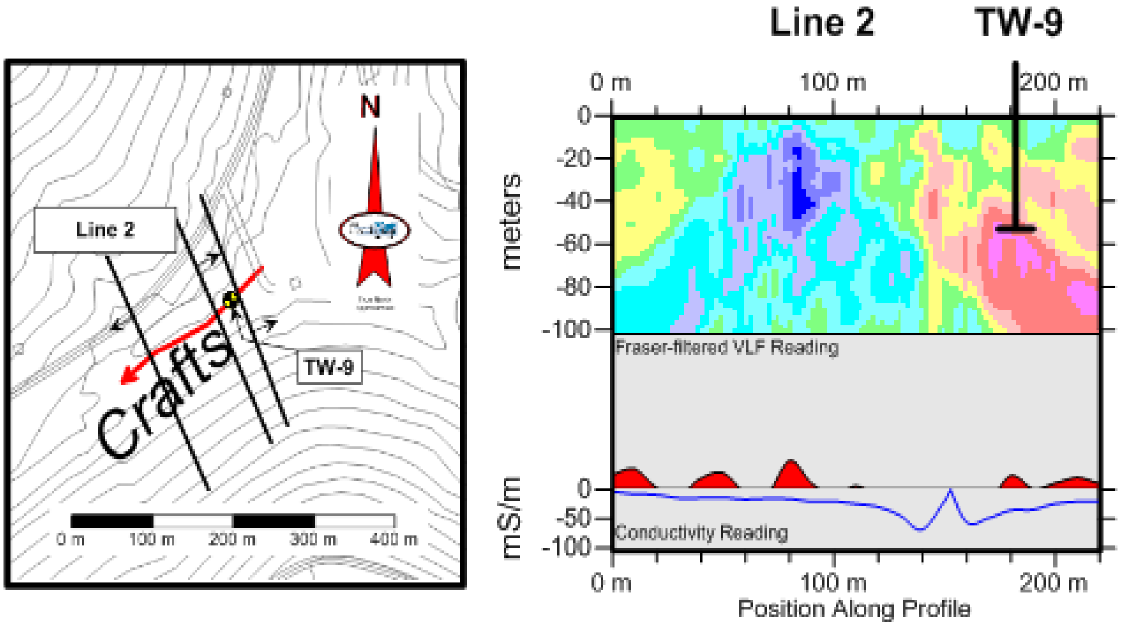

Figure 4: The left figure is a plan map of the Case 2 study area. The right figure shows the processed data in the form of 3 graphs; the upper graph is a representation for the fracture profile derived from the inphase component of the signal (RAMAG program; Walden, 2004) where reds represent a fracture and blues non-fractured rock; the middle graph is the presentation of the Fraser-filtered inphase signal; and the bottom graph is the quadrature phase converted linearly to terrain conductivity.

Case 3

The third commercial venture required a continuous source of water of at least 400 L/min in the southwestern portion of Pennsylvania. Several VLF profiles were collected adjacent to Templeton Creek, a creek assumed to be created by fracturing parallel to the creek bed (Figure 5).

Boring TW-3 was advanced to 18.3 meters below grade and encountered water-bearing fractures at 8.5 m below grade. Water level stabilized at 4.9 m below grade.

The boring was cased to 6.1 m below grade and completed as an open hole. A pump test was conducted for 24 hours at a production rate of 475 L/min. After 24 hours, drawdown was only 2.2 m indicating that this well met the client's needs.

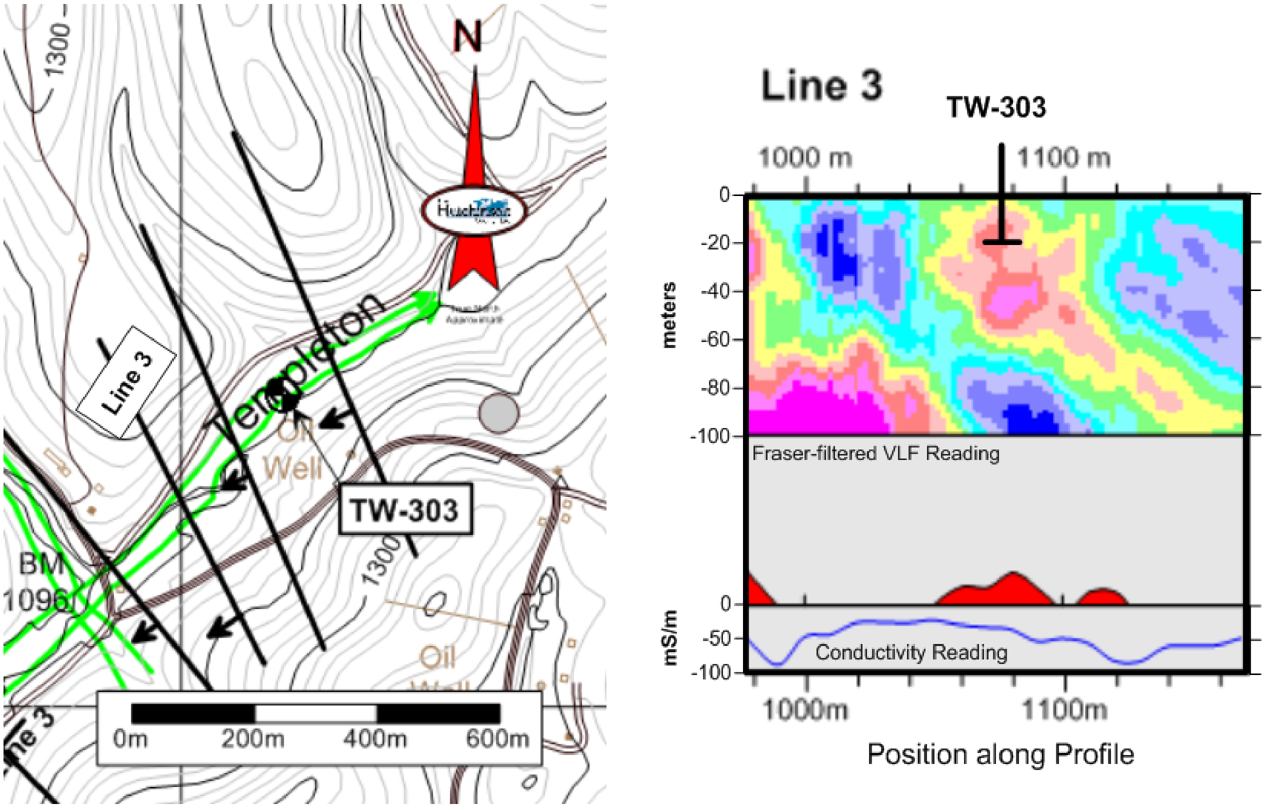

Figure 5: The left figure is a plan map of the Case 3 study area. The right figure shows the processed data in the form of 3 graphs; the upper graph is a representation for the fracture profile derived from the inphase component of the signal (RAMAG program; Walden, 2004) where reds represent a fracture and blues non-fractured rock; the middle graph is the presentation of the Fraser-filtered inphase signal; and the bottom graph is the quadrature phase converted linearly to terrain conductivity.

Conclusion

VLF mapping has been deployed for decades as a useful tool in detecting steeply dipping water-filled fractures and is a useful tool to delimit fractures for commercial water production.

Applying structural geology and VLF mapping to a groundwater production investigation increases the prospect for finding wells that have significant yields. Three prospective areas delineated by VLF mapping were drilled. All three wells intercepted productive fractures and their sustainable yields are well above the required design basis.

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