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MAXIMIZING GROUNDWATER PRODUCTION THROUGH VLF MAPPING METHODS

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Abstract

Random drilling for commercially productive groundwater wells is commonly a haphazard approach 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 90 meters 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 15 and 25 meters below grade. Pump tests indicate that each of the three wells was a commercial success.

Introduction

Commercial 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.

Keywords: Very Low Frequency (VLF) Geophysical Surveys, Groundwater Investigation, Rock Fractures, Southwestern Pennsylvania.

Within southwestern Pennsylvania, the 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 and others, 1992). 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). 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). The transmitters 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.

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 a commercial transmitter that 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 supply contractors. Nevertheless, the tool can provide an inexpensive alternative to random drilling or other intrusive investigations.

Many of the commercially available instruments measure 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. Consequently, on one side of the target, the angle between the vectors of the primary and secondary components of the radio wave 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 (Ramesh Babu and others, 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 F_i is:

$$F_1 = (M_3 + M_4) + (M_1 + M_2) \tag{1}$$

The first value F_1 is plotted half way between positions M_2 and M_3; the second value is plotted halfway between M_3 and M_4.

Current Density Filtering

Many instruments can calculate a current density from the magnitude of the measured magnetic field (Reynolds 1997). 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 (as shown later in Figure 3). The depth profile can be calculated from:

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

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

Case Studies

Several VLF surveys were performed to determine drilling locations for the placement of water wells that would be able to produce commercial amounts of groundwater. The water is needed to replenish nearby streams that have lost significant amounts of water as result of long wall mining (Figure 1). The Clean Water Act (CWA) protects streams from pollution and loss of flow. During long-wall operations fractures are vertically-induced into the coal overburden as the panels are developed (Figure 1). Consequently, the subsidence induces vertical fractures that reach the stream bed and drain it into the long-wall mine. The loss of stream water violates the CWA and the incoming water is a financial burden as the water must be pumped out. Further, incoming water can be a health hazard as it may destabilize the deep-mine.

The 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 was 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 areas. 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.

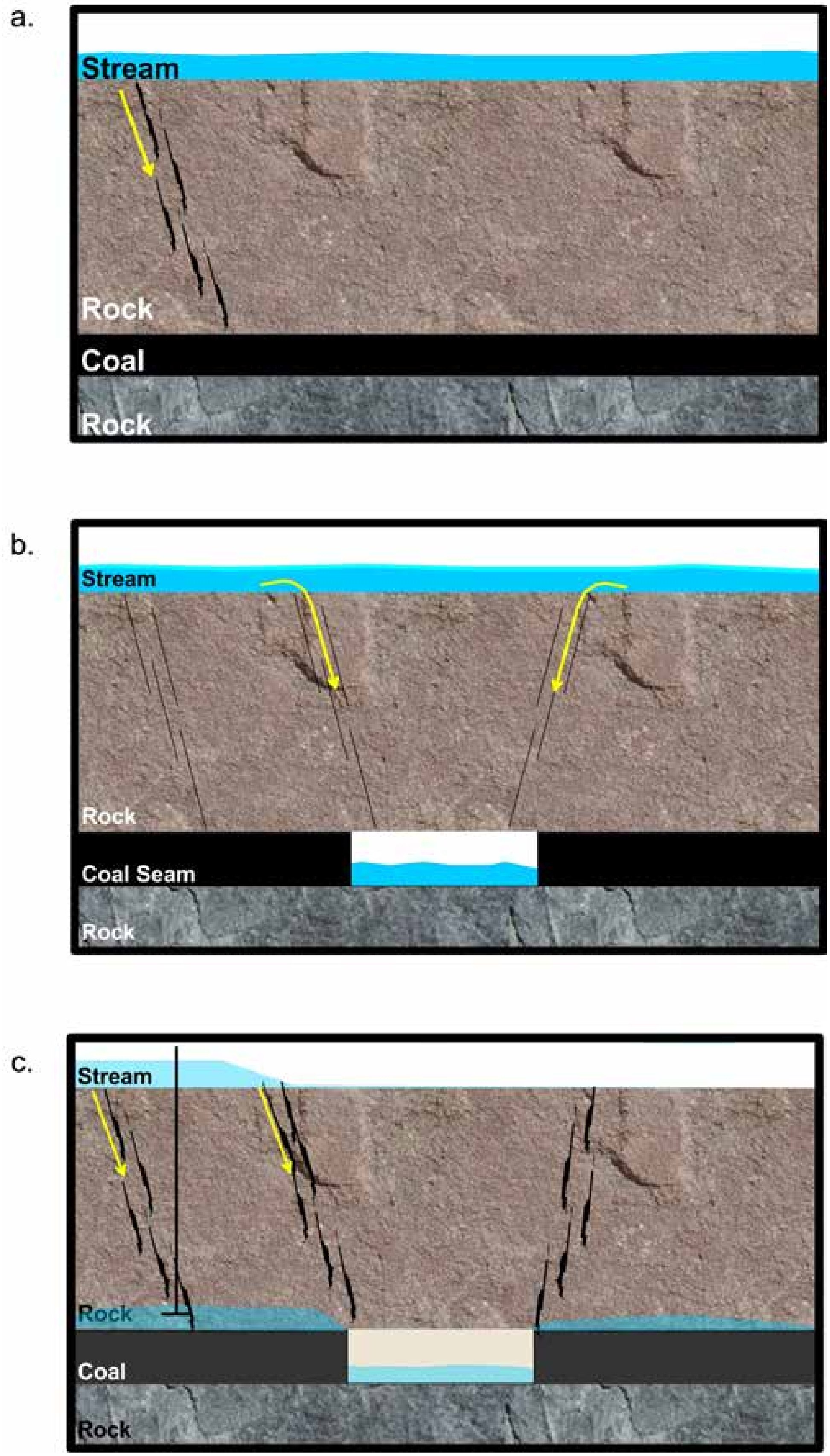

Figure 1: A stylized profile of a coal seam, prior to long-wall mining, showing existing fractures that may or may not transport water vertically downwards (**a**). Post long-wall mining shows that fractures developed during subsidence transmit water vertically downwards (**b**). The net effect is capturing the stream flow and flooding the deep-mine (**c**).

Case Study 1

A commercial venture required a continuous source of water of at least 1,000 l/min in the southwestern portion of Pennsylvania (Figure 2). 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 well-developed 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 1150 l/min. After 19 hours, drawdown was only 2.9 m indicating that commercial quantities of groundwater were available.

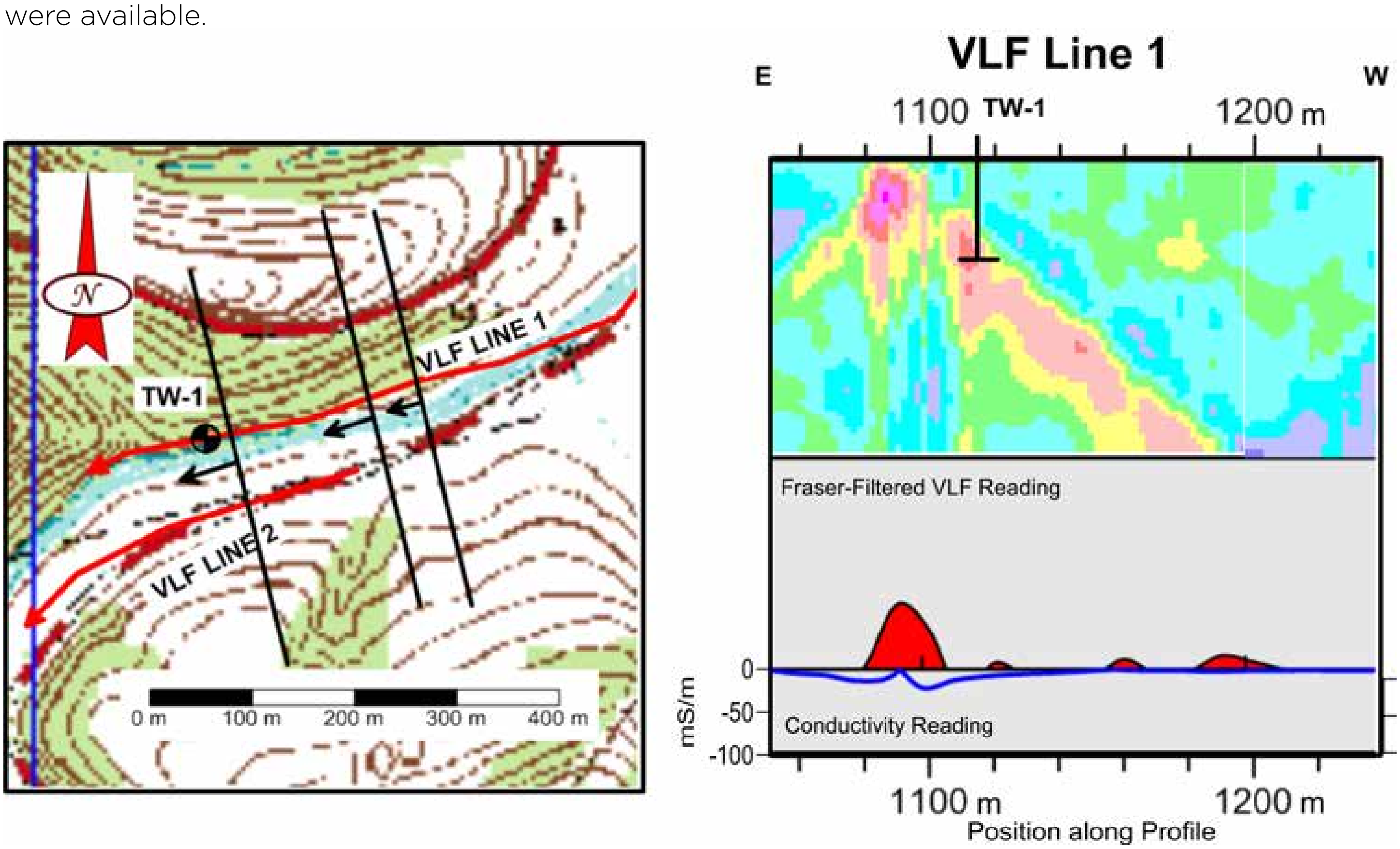

Figure 2: The left image is a plan map of the Case 1 study area. The right image shows the processed data in the form of 3 graphs: the upper graph is a representation for the fracture profile derived from the inphase component of the signal (RAMAG program; Walden, 2004) where reds represent a fracture 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 Study 2

Another commercial venture required a continuous source of water of at least 500 l/min in the southwestern portion of Pennsylvania (Figure 3). 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-9 was advanced to 54.9 meters below grade and encountered well-developed 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 1325 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.

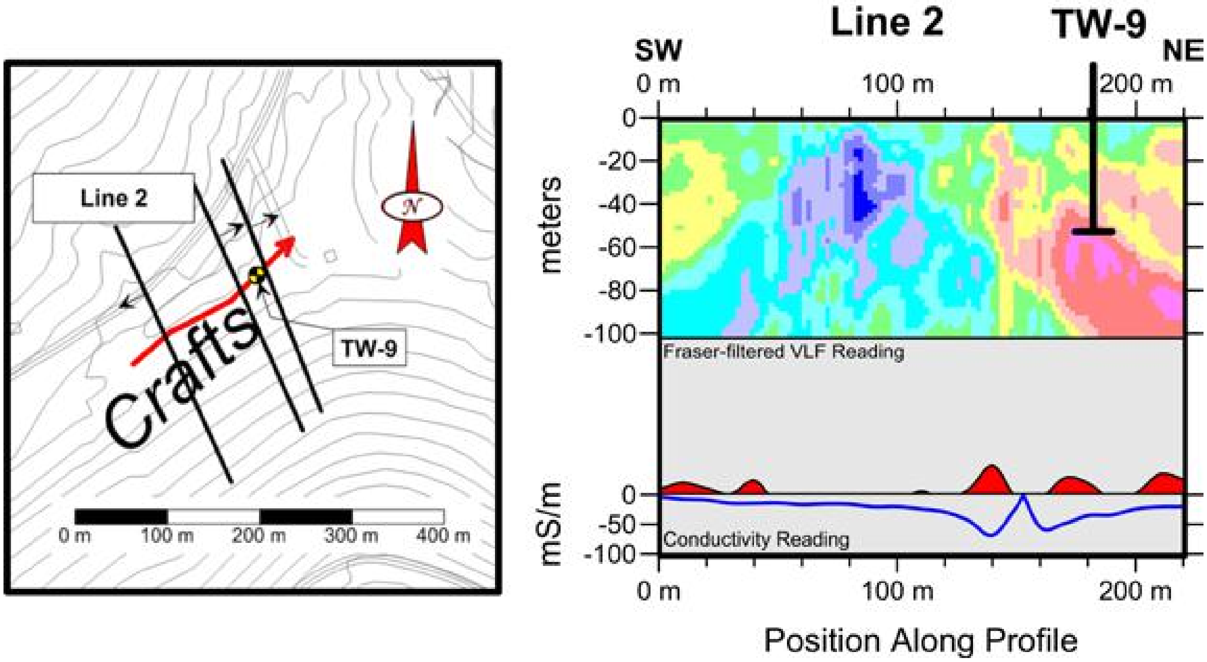

Figure 3: The left image is a plan map of the Case 2 study area. The right image shows the processed data in the form of 3 graphs (see Figure 2 caption for description of this image).

Case Study 3

The third commercial venture required a continuous source of water of at least 400 l/min in the southwestern portion of Pennsylvania (Figure 4). Several VLF profiles were collected adjacent to Templeton Creek, a creek assumed to be created by fracturing parallel to the creek bed. Boring TW-303 was advanced to 18.3 meters below grade and encountered well-developed 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.

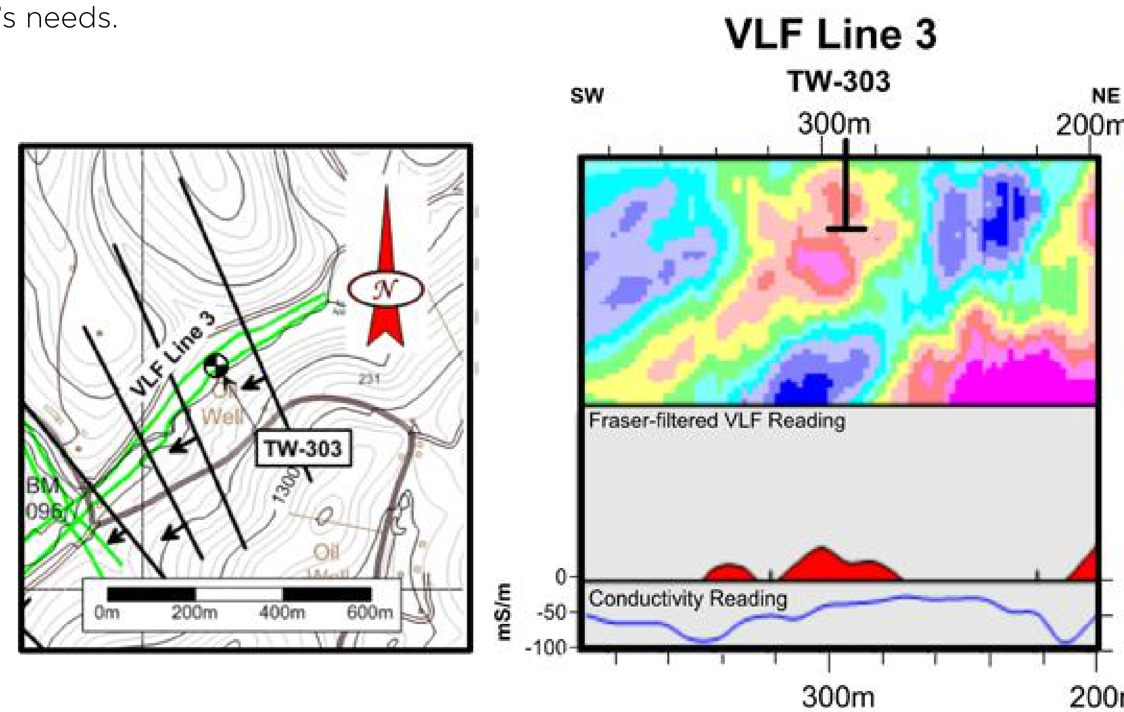

Figure 4: The left image is a plan map of the Case 3 study area. The right image shows the processed data in the form of 3 graphs (see Figure 2 caption for description of this figure).

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. The method works particularly well in a low permeability/porosity rock setting where random drilling is unreliable at locating large water-bearing fractures. Three prospective areas in Southwestern Pennsylvania 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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