VLF surveying to delineate longwall mine-induced fractures

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Very low frequency (VLF) surveying is an effective method for detecting long, straight, electrically charged conductors, and it has been used to locate fractures, image subsurface voids, map landfill margins, and to delineate buried conductive utilities. High-powered military transmitters operating in the 15-30-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.

VLF surveying is easy to use, deploy, and process. It is also inexpensive. But geophysicists have been reticent to employ it because of the lack of source control (i.e., transmitter is operated by the military and it may be turned off during data collection) and limited knowledge of the tool's capabilities and limitations. Although dependence on a military transmitter can be obviated by the use of a commercial transmitter, this decreases the rapid deployment of the tool.

Other limitations of VLF surveying are sensitivity to ferrous and nonferrous cultural noise, single-point data collection, and relatively shallow depth of investigation (probably no more than 75 m, but still within the depth window of environmental investigations). Nevertheless, the tool can provide an inexpensive alternative to drilling or other intrusive investigations.

The handheld 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 (15-30 kHz). The first commercial ground VLF meter became available in 1964. Today there are several commercial instruments that can capture 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.

VLF surveying can delimit fractures induced by longwall mining of coal. These fractures can propagate to the surface, intersect a stream bed, and capture surface water flow. The loss of water in streams is a major environmental concern in the Appalachian coal basin. VLF surveys can identify fracture locations that can be subsequently grouted. Grouted fractures show attenuation of response-magnitude in postgrouting VLF surveys. Attenuation in electrical conductivity of a fracture suggests that conductive fluids no longer exploit the mine-induced fracture.

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). Because 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 crossover point coincides with the center of the anomaly (Figure 2).

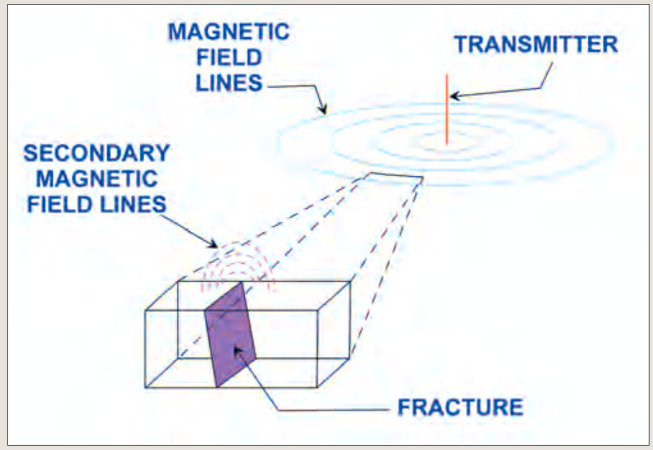

Figure 1. VLF radiowave with enlargement of secondary magnetic field. Note the horizontal orientation of the electrical and magnetic components of the radiowave field.

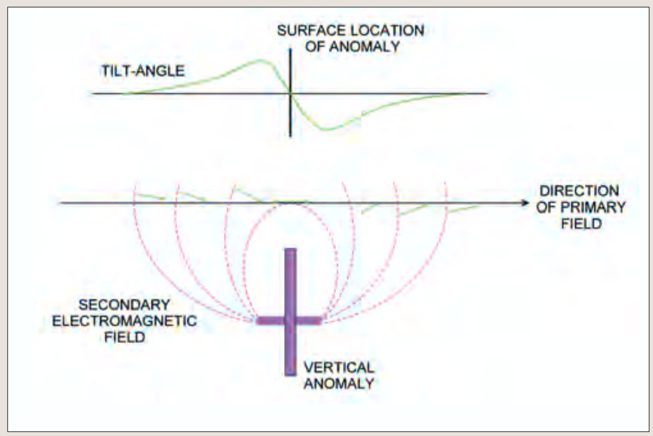

Figure 2. Tilt-angle profile over a vertical anomaly.

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 (Reynolds, 1988). 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 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

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

The first value F_1 is plotted halfway 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. Karous and Hjelt developed a statistical linear filter, based on Fraser and linear field theory of Bendat and Piersol. 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 I_a at a specified horizontal position and depth z is based on a symmetrical filter of the measured current (from the measured magnetic component of the anomalous field).

Case studies. The longwall mining process involves the removal of a panel of coal up to 3 m thick, 300 m wide, and 200-3000 m long. The removal of the coal induces the vertical upward propagation of fractures along the edges of the panel and across the panel as overburden settles into the void. Fractures associated with subsidence can reach the near surface, intercept stream beds, and dewater the streams. Further, groundwater baseflow to streams can be captured prior to discharge to the streams further exacerbating the loss of stream flow. These effects can be an anathema to the local stream biotic community and are deemed as a negative impact on the environment by the regulatory and environmental community.

Case 1—Edge-of-panel fracturing. Longwall mining at a depth of 500 ft in a southern West Virginia area caused stream dewatering. A VLF survey was conducted to locate deep mine-induced fractures that were responsible for the stream-flow loss. The survey was performed using the

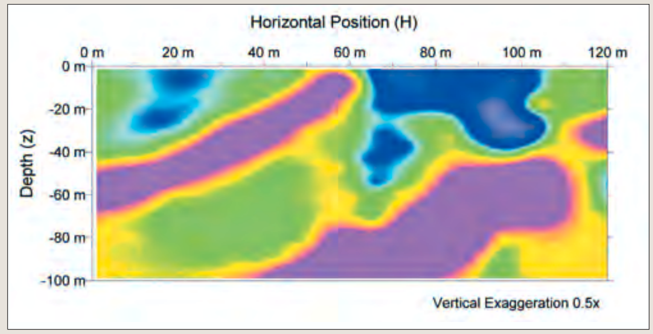

Figure 3. Processed depth profile of VLF current density measurements showing statistical projections of fractures at depth. Fracture package located at the edge of a deep longwall panel mine in southwestern Pennsylvania.

ABEM Wadi and a 23.9-kHz signal from the transmitter located in Cutler, Maine. A handheld Global Positioning System (GPS) was used for exact spatial positioning of collected data. The tilt-angle data were collected every 10 m 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 along the stream bed and represent small-, medium- and large-sized fractures or fracture zones (Figure 4). 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 m deep) fractures with a regional extent. Only one medium-sized anomaly was identified in the study area at the northwestern portion of the site (Figure 4). These fractures are normally sealed and thus provide limited opportunity for vertical downward migration of surface water.

Two areas of large tilt-angle measurements located at the edge of the panel are interpreted to be large, deep-seated fractured zones associated with the subsidence of rock within the panel (Figure 4). Fractures within these two zones are narrow and probably vertical, suggesting that they are mine-induced fractures. These two tension fracture zones opened across the panel edges and are interpreted to have caused the stream-flow loss.

This example also shows that deep mine-induced fracturing did not occur within the panel but along its edge. Other surveys have shown that panel subsidence can create large deep-seated fractures within panels.

Case 2—Sealing the fractures. Longwall mine activities along a portion of a creek bed in southwestern Pennsylvania were the apparent cause of stream-flow loss. Mining occurred in the Pittsburgh Coal at a depth of about 400 ft below grade. A VLF fracture survey was performed after longwall mining activities were completed to determine the location of any fractures that may have developed due to the subsidence of the overburden. The survey was performed using the ABEM Wadi with the 23.9-kHz signal, and VLF tilt-angle data were collected every 10 m parallel to the stream bed. A handheld GPS was used for spatial positioning of each record. Fraser filtering of the tilt-angle data was performed to locate the exact position of each fracture.

Two fracture zones were identified at the edge of a longwall mine panel. A large narrow anomaly was located at the edge of the panel (30 m; Figure 5). The elevated tilt-angle measurement and the narrow shape of the anomaly is interpreted as one discrete deep-seated fracture. Another zone located within the panel area consists of several deep-seated

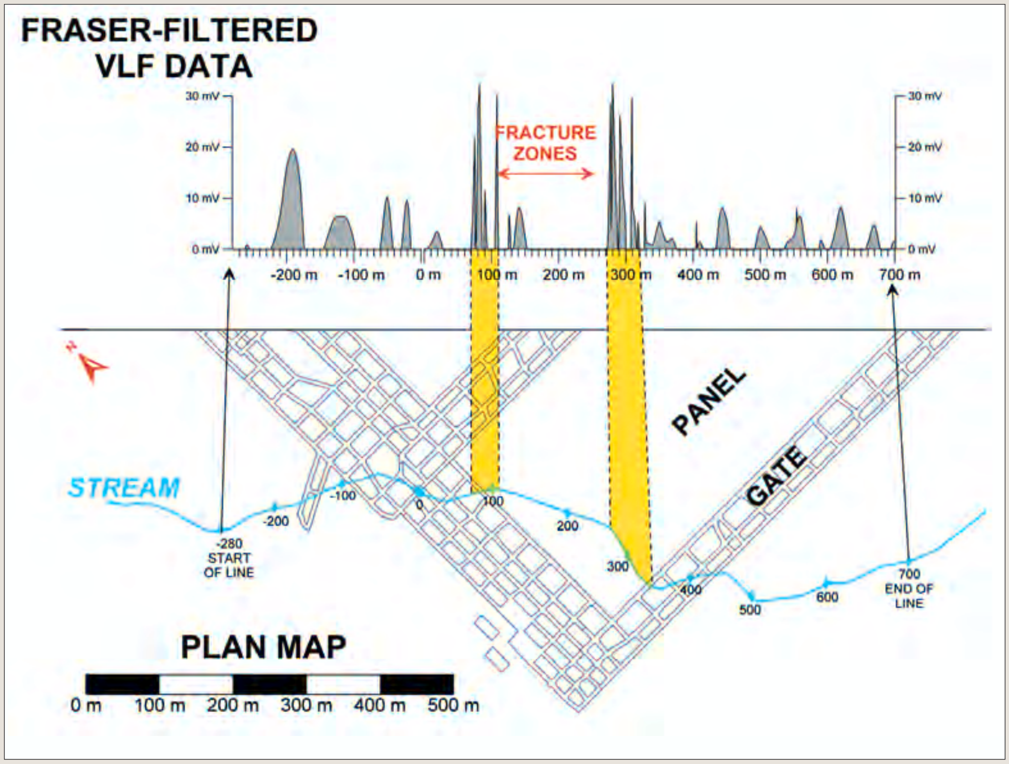

Figure 4. Plan view map of Fraser-filtered tilt-angle measurements taken along a surface stream impacted by long-wall mining activities in West Virginia. Note the intense bedrock fracturing (fracture zones) in the panel and adjacent to the gates.

fractures (50-80 m; Figure 5). The fractures appear to dip into the center of the panel due to the tailing off of the tilt-angle reading toward the center of the panel.

To attenuate the surface water loss, grouting was performed across each zone. Sealing of the fractures was completed by drilling numerous 6-inch holes to a depth of approximately 20 m below grade upstream, downstream, and across the stream channel in the area of the defined fracture, and pressure-injecting polyurethane foam into the fractured bedrock.

A VLF survey was conducted over the same area after grouting. Tilt-angle measurements were collected at the same position as the initial pregrouting survey. As with the pregrouting data, the postgrouting data were also processed using Fraser filtering.

Postgrouting data show that the fractures are poorly defined and have a very low tilt-angle response. Presumably, the grout has filled the fractures and is preventing the downward movement of surface water and groundwater. Because grouted fractures lack conductive fluids, these fractures show an attenuated tilt-angle reading. The grouted fracture at the panel edge shows almost no response. The fracture set within the panel shows a significant reduction in the tilt-angle reading for the fracture located at position 60 m (Figure 5). The fracture at position 70 m shows an attenuated tilt-angle reading, indicating that the fracture may still provide a conduit for limited loss of water from the stream.

Conclusion. VLF surveying has been deployed for decades as a useful tool in detecting steeply dipping water-filled fractures and subsequently is a useful tool to delimit fractures associated with longwall mining activities. Mine-induced fractures are usually located along the edge of a longwall panel or within the panel, are vertical or nearly vertical, and can reach the surface to intercept stream beds causing water loss. Fractures located by VLF surveying techniques along affected stream channels can be grouted by pressure-injecting polyurethane foam into the fractured bedrock. Subsequent surveying of the same area after grouting indicate a decreased VLF response.

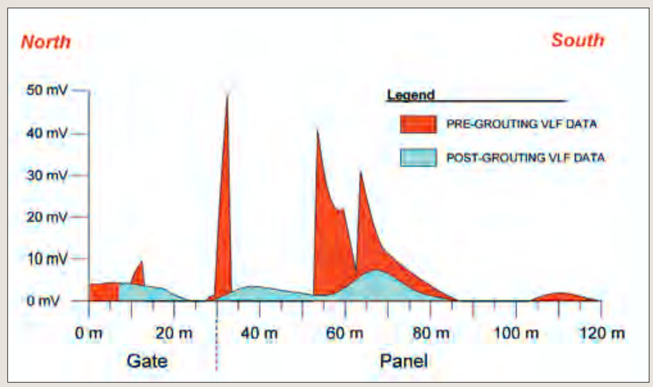

Figure 5. Fraser-filtered tilt-angle measurement of VLF anomalies collected along a deep-mine subsidence impacted a stream bed in southwestern Pennsylvania. Note the change in anomaly intensity from pre- to post-grouting.

Suggested reading. WADI VLF International Frequency List (ABEM AB printed matter No. 93062, Bromma, Sweden). *Measurement and Analysis of Random Data* by Bendat and Piersol (Wiley, New York, 1968). "Contouring of VLF-EM data" by Fraser, GEOPHYSICS, 1969. "Linear filtering of VLF dip-angle measurements" by Karous and Hjelt, *Geophysical Prospecting*, 1983. "Electromagnetics" by McNeill, in *Proceedings on the Application of Geophysics to Engineering and Environmental Problems*, 1988. "Time domain electromagnetic prospecting methods" by Nabighian and Macnae, in *Electromagnetic Methods in Applied Geophysics* (SEG, 1991). "Five years of surveying with the very low frequency electromagnetic method" by Paterson and Rönkä, *Geoexploration*, 1971. *An Introduction to Applied and Environmental Geophysics*, by Reynolds (Wiley, New York, 1998). TLE

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