INSTALLATION OF A DIGITAL, WIRELESS, STRONG-MOTION NETWORK FOR MONITORING SEISMIC ACTIVITY IN A WESTERN COLORADO COAL MINING REGION

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Abstract

A seismic monitoring network has recently been installed in the North Fork Valley coal mining region of western Colorado as part of a NIOSH mine safety technology transfer project with two longwall coal mine operators. Data recorded with this network will be used to characterize mining related and natural seismic activity in the vicinity of the mines and examine potential hazards due to ground shaking near critical structures such as impoundment dams, reservoirs, and steep slopes. Ten triaxial strong-motion accelerometers have been installed on the surface to form the core of a network that covers approximately 250 square kilometers (100 sq. miles) of rugged canyon-mesa terrain. Spread-spectrum radio networks are used to telemeter continuous streams of seismic waveform data to a central location where they are converted to IP data streams and ported to the Internet for processing, archiving, and analysis.

Background

During underground mining operations strata respond to excavation-related stress with deformation mechanisms that sometimes include dynamic rock mass failures. Experience in western coal mines shows that such dynamic failures can produce microtremors or seismic events with magnitudes in the range of $M = 2\text{-}3$ with infrequent occurrences up to $M = 4$ (Arabasz et al., 2005). Factors affecting the susceptibility to mining-induced seismicity include mechanical properties of the local strata, amount of overburden, and size, geometry, and mining sequence of excavated areas.

In anticipation of mining near structures such as earthen dams and reservoirs, Bowie Resources LLC and Mountain Coal Company have joined together with NIOSH to develop a digital seismic monitoring network to collect background data on mining-related seismic activity and to implement a real-time hazard monitoring tool. In addition to the mine-safety technology transfer activity, NIOSH is participating in this project to gather data for use in its mine safety research program. Data collected with this network will be used to (i) identify and characterize dynamic failure mechanisms of potentially hazardous rock mass failures (e.g. coal bumps), and (ii) determine empirical relations between levels of ground shaking, seismic event magnitude, and distance to the seismic sources. The latter can then be used to help evaluate the potential responses of surface and underground structures to shaking and identify minimum distances between the seismic activity and these structures to keep levels of shaking below key damage thresholds.

Setting

The longwall coal mines are located in the rugged canyon-mesa terrain of western Colorado (Figures 1 and 2) with vertical relief up to ~ 1 km (3300 ft). The major geologic units present are representative of the Upper Cretaceous Mesa Verde Formation and include six coal seams with thickness from 2 to 6 m (6 ft to 20 ft). Overburden above longwall panels in the district extends up to ~ 0.7 km (2400 ft). Yearly production from all of the coal mines in the North Fork Valley exceeds 16 million tons per year.

Preliminary Seismic Study

Prior to the network design and installation a pilot study was carried out using a single triaxial seismic station deployed at the King Mine portal area adjacent to the Bowie Mine. Differences in arrival times of the compressional (P) and slower shear (S) waves constrain the distance between the station and the recorded events. For example, Figure 3 compares traces recorded on this instrument for a mining-related event at Bowie ($M_L \sim 2.8$, upper traces) with an S-P time of ~ 0.7 s against those for a regional earthquake ($M_L \sim 3.3$) with S-P time of ~12 s. The distances to these events are approximately 2 and 100 km, respectively.

Of the 350 events that were recorded over a two-month period and analyzed, most fell into three groups with similar S-P times (Figure 4). As there are three different coal mines operating in the North Fork Valley with workings that clustered at three different distances, the different S-P time groupings were consistent with events originating at all three of these mines.

North Fork Seismic Network

Seismic stations

Ten triaxial strong-motion seismometers (Altus K2 instruments with internal EpiSensors) and one short-period seismometer (WE1) were installed in two groups centered over the two participating mines (Figure 5) providing coverage over an area of approximately 250 square kilometers (100 sq. miles). Strong-motion seismographs, or accelerographs, are specifically designed to measure ground motions near seismic sources that are strong enough to potentially impact the integrity of engineered structures. With the nominal 24-bit resolution of their internal data recorders, they can also resolve background vibrations in the micro-g (10^{-6}) range. At each strong-motion station a fourth channel records an additional co-located 1-Hz moving-coil (L4-C) seismometer, providing higher sensitivity to smaller and/or more distant seismic events. The data recorder is configured to (i) continuously stream data at 100 samples per second, and (ii) locally trigger and save event data to compact flash cards providing backup in case of telemetry failure. Time synchronization is achieved at each digitizing/recorder unit using GPS receivers.

Seismic station sites were selected to provide suitable azimuthal coverage of the mining areas, a workable telemetry path, concealment from view, and, wherever possible, access to bedrock. Separate instrument and power vaults were installed by digging shallow holes and installing vertically-oriented corrugated steel culverts with locking lids. In the instrument vault, a flat concrete floor was poured onto exposed bedrock, onto which the strong-motion seismometer is bolted. Remote power sources consist of two 75-watt photovoltaic panels and four 115 Amp-hr batteries.

Installation of the accelerographs at the Bowie Mine was complete by October 2005. The West Elk instruments were added to the network and made operational starting July 1, 2006.

Data communications

Communication with, and data transfer from, the strong-motion seismometers is achieved with license-free 900-MHz frequency-hopping spread-spectrum radios equipped with 10dB directional Yagi antennas. With the use of three repeaters, the ten remote instrument sites are connected in four separate point-to-multipoint radio subnets operating in a bandwidth-sharing time-domain multiple-access (TDMA) mode. Radio interference issues have been experienced with other nearby 900-MHz data-comm networks associated with ventilation and methane drainage drillhole monitoring. The interference has been mitigated by appropriate antenna selection, positioning and RF power level adjustments.

Each seismic station outputs continuous digital seismic waveform data at 9600 bits per second (RS-232) and is received at a site in town with a DSL Internet connection (Figure 7). A dedicated server demultiplexes the serial data from each subnet and converts it to individual station-based IP data streams. The serial/IP data network allows complete control over the instruments from distant Internet-connected user locations. Currently this data is received, processed, and re-distributed at NIOSH's Spokane Research Laboratory.

Data Processing

A large portion of the software for data collection, processing, analysis and display is based on the U.S. Geological Survey's (USGS) Earthworm system (Earle et al., 2003). At its core are real-time TCP/IP data distribution and data processing modules interconnected by a message-passing system. The software can be configured to automatically detect, process, archive and analyze seismic events from numerous types of instruments and make the raw data and processed results available over a computer network/Internet.

At this stage of implementation, software modules have been configured to coordinate data collection from the remote seismic stations, merge and time align all of the data streams in a common buffer containing several weeks worth of data, identify both individual station triggers and network (event) triggers, save triggered event data to disk, filter traces and create helicorder/webicorder plots from individual stations. Other module functions in the process of being automated include arrival-time picking, magnitude estimation, event location, and detection and email notification of user-specified threshold acceleration levels.

Example Results

As with any new seismic network there is a period of time where the parameters that control the data acquisition and processing functions are adjusted as experience is gained with the different types of seismic sources of interest. In the case of mine seismicity, the occurrence rate and magnitude of the activity can vary tremendously over relatively short periods of time as working areas encounter variable geologic and mining conditions. Both of these mines have gone through long periods of time without experiencing any seismic activity that is noted on regional seismic networks, only to have, for example, 5 or more seismic events with magnitudes between 2.5 and 3.0 occur within a single one-month period of time. One goal of this joint effort is to document these mining and geologic conditions so that we are better able to identify, and anticipate, circumstances that may lead to dynamic rock mass failures.

Data Visualization

Webicorder plots provide the digital equivalent of the old pen and ink and/or smoked-paper seismograph drum (helicorder) records and provide a convenient way of evaluating overall levels of seismic activity on a daily basis. Raw and/or filtered seismic records are plotted in continuously updated GIF image files (Figure 8) that are accessible via a web interface. Waveform data satisfying a user-controlled triggering condition (i.e. events, Figure 9) are saved in separate files and can be viewed with a number of different software utilities.

Comparison with USGS/NEIC Locations

During the time period between July 1 and December 1, 2006 the USGS's National Earthquake Information Center (NEIC) in Golden, CO reported 7 seismic events in the North Fork Valley area with local magnitudes (M_L) between 2.5 and 2.9. Figure 10 compares NEIC locations, calculated with data from available regional network stations and using a generic global earth model, with those determined using data strictly from the local network. Event locations determined using local network data were calculated using Hypoinverse (Klein, 2002) with a layered velocity model (Swanson and Koontz, 2006). The average difference between the two calculated locations is 8.5 km (5.3 mi). Event locations based on the local network data coincide closely with areas of mining activity underway at those times. Six events clustered in one group over a one-month period of time. The event locations correspond to an area of multi-seam mining (mining below a previously mined seam separated vertically by 90 m (300 ft)) where an unusually thick sandstone channel was encountered in the roof.

Conclusions

NIOSH, Bowie Resources LLC and Mountain Coal Company have cooperated on a joint project to develop a digital wireless seismic monitoring network to collect background data on mining-related seismic activity in western Colorado and to implement a hazard monitoring tool. The ten station strong-motion array provides real-time monitoring capability using wireless serial and IP communications networksData collected with this network will also be used to (i) identify and characterize dynamic failure mechanisms of potentially hazardous rock mass failures, and (ii) determine empirical relations between levels of ground shaking, seismic event magnitude, and distance to the seismic sources.

References

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Klein, F., 2002, *User's guide to HYPOINVERSE-2000, a Fortran program to solve for earthquake locations and magnitudes*, USGS Open-File Report 02-171, vers. 1, 123 pp.

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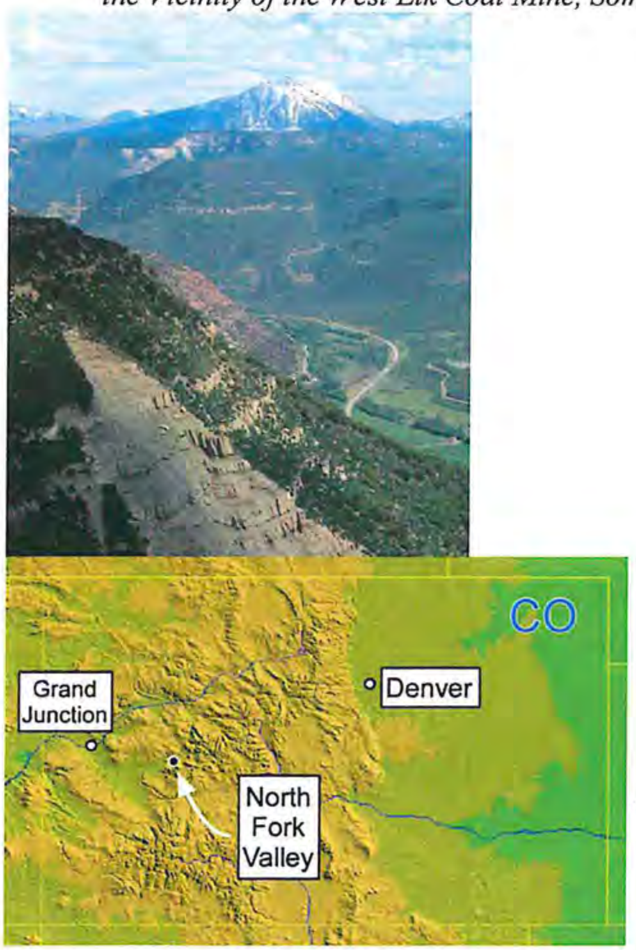

Figure 1: Location of North Fork Valley Mining Region.

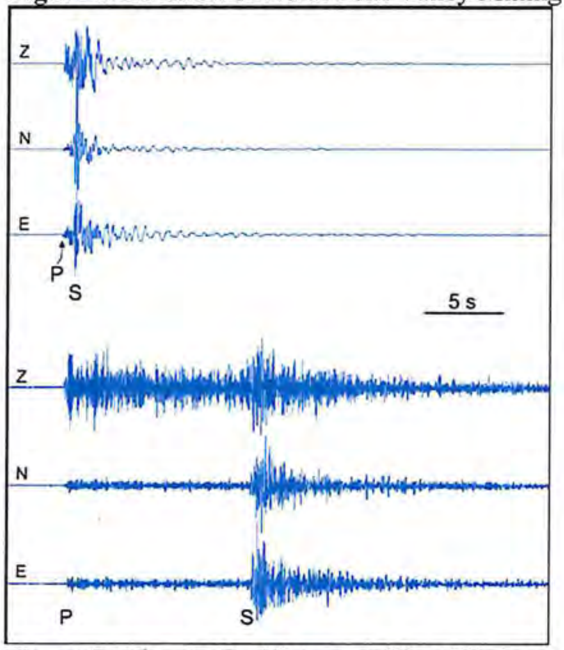

Figure 2: View to the SE toward West Elk property from Bowie Mine.

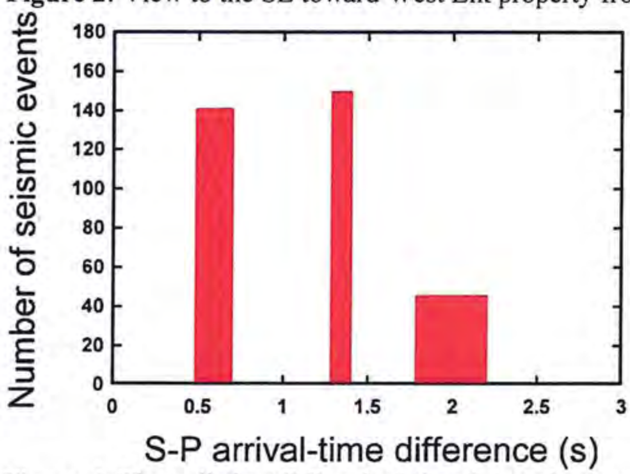

Figure 4: Three distinct S-P arrival-time intervals observed with single-station monitoring at the King Mine portal area.
Figure 3: S-P arrival-time intervals observed on triaxial sensor for events at 2 and 100 km distance.

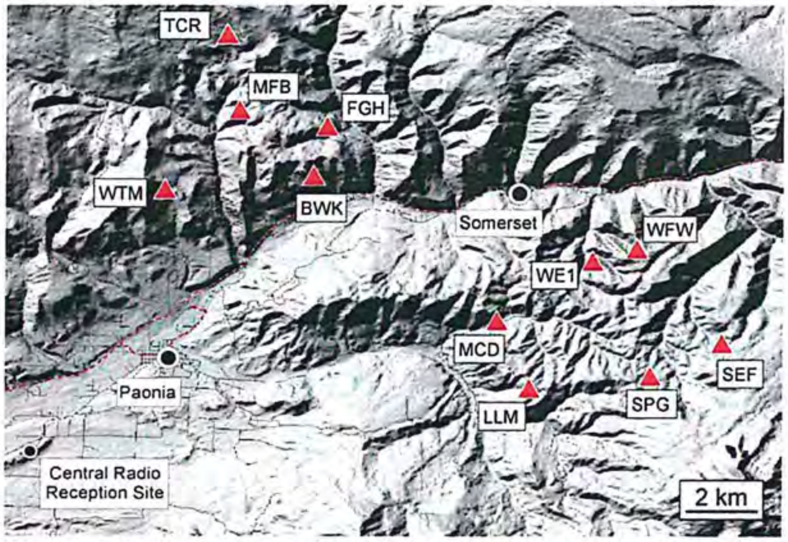

Figure 5: Stations of the seismic montoring network. Stations north and south of the North Fork river are centered on Bowie and West Elk workings respectively.

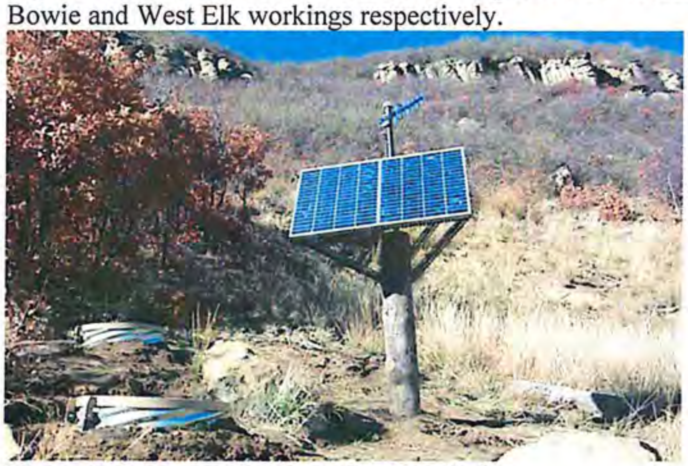

Figure 6: Remote seismic station installation

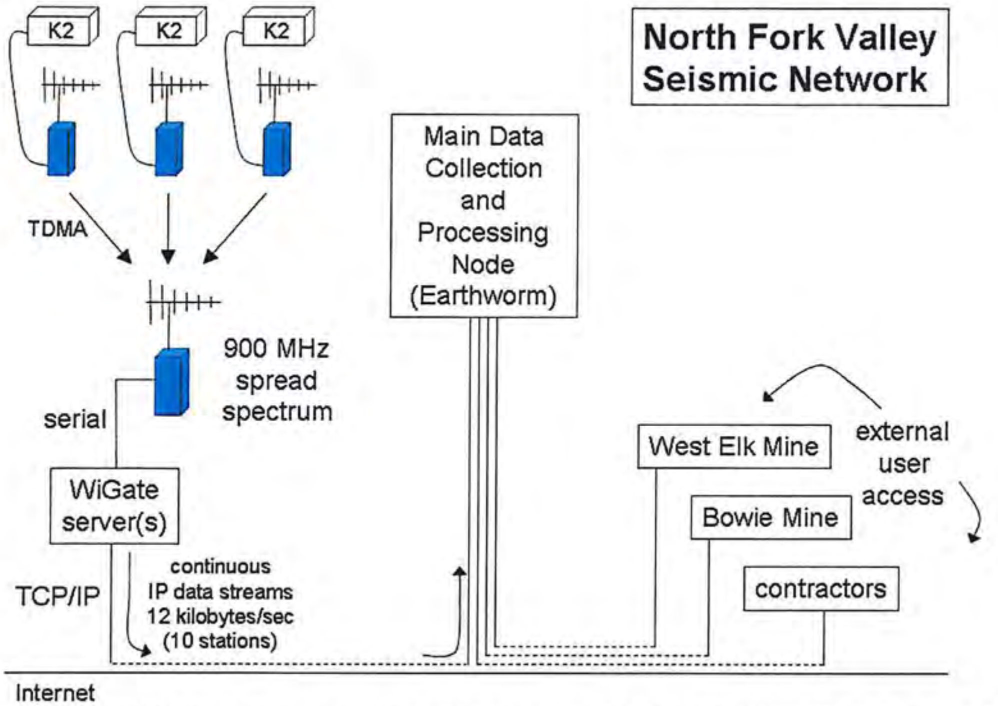

Figure 7: Serial/IP data communications network. Example of radio telemetry link shown for one radio subnet serving three remote seismic stations.

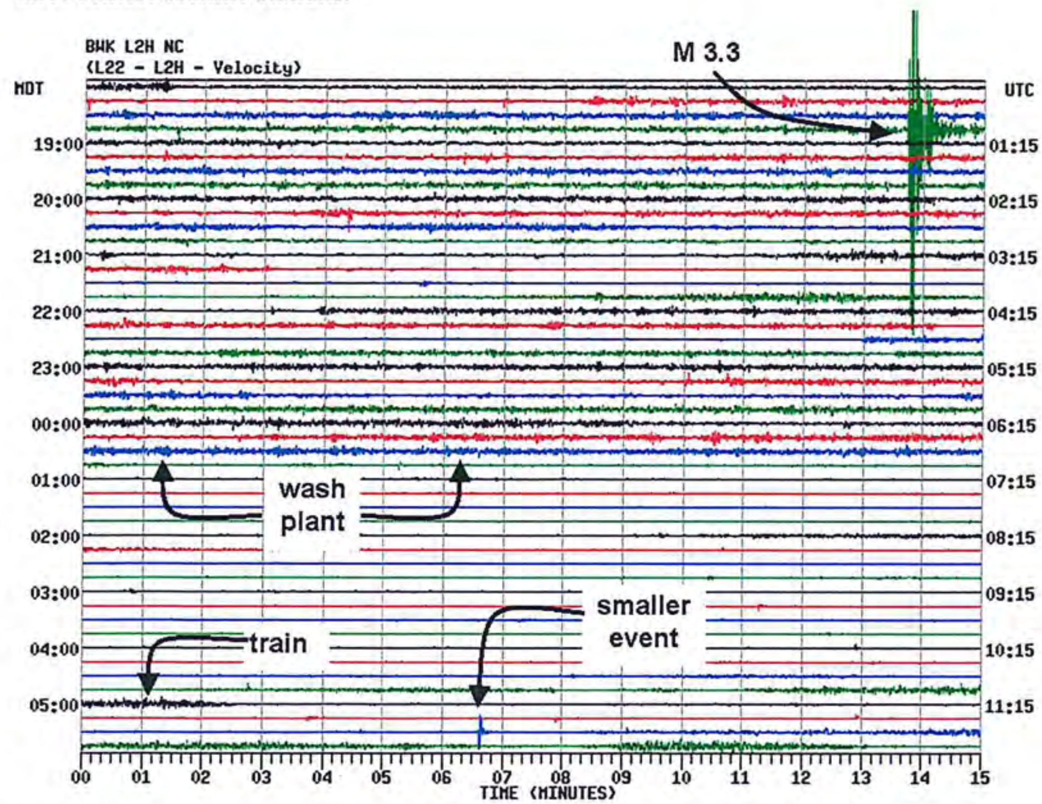

Figure 8: 12-hour long webicorder style plot for vertical component at station BWK.

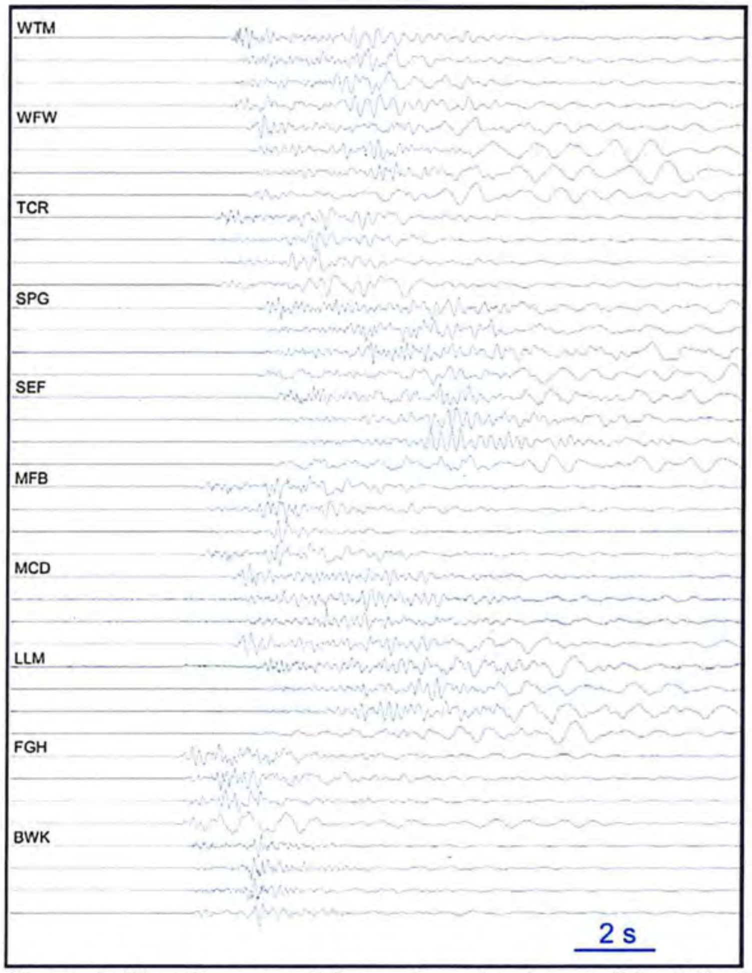

Figure 9: Waveform record from mine-related event (M ~ 2.8). Each station shows accelerometer components Z, N, E, and short-period vertical Z.

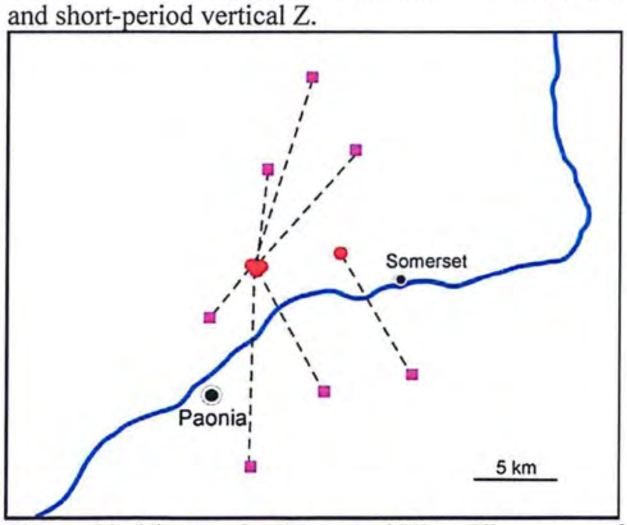

Figure 10: View to the SE toward West Elk property from Bowie Mine.