Techniques To Discern Whether A Given Underground Mine Map Is Accurately Portrayed And Referenced To The Surface

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Abstract. Excluding access to underground mines or extensive geophysical testing, perhaps the most consistent method of verifying map accuracy is through the plotting of subsidence events directly onto the mine map and then comparing the shape and location of the subsidence event with respect to the mine geometries.

This paper will examine how survey precision GPS receivers combined with mobile GIS technology can utilize geo-rectified mine maps, historical aerial photography and subsidence studies that collectively can be used to qualify map accuracy and to some extent estimate map accuracy and precision.

Introduction

"In some fields of inquiry it is practically impossible to collect datum that is absolutely correct and the basis for the inquiry is either assumed or conceded. It will be readily seen that this class of statistics and the information derived will be only relatively true, but sufficiently so that valuable conclusions may be drawn from them." (Asa, 1931 p 9.)

Recent technological advances have wrought significant increases in computational power, software development, digital storage and use of satellite technology. One benefit from these evolving and merging technologies is that a wealth of spatial information is being gathered, stored, geo-rectified and combined with other spatial data to create maps that enhance public understanding and facilitate data use.

Along these lines, there are federal and state programs that are scanning mine maps of both active and abandoned coal mines and then saving them in digital format. Many of these mine maps are then being geo-rectified so that they can be used with surface maps. When dealing with

old abandoned mine maps, it should be noted that not all mine maps are created equal, and the challenges of geo-rectifying underground mine workings to surface features are many. Such challenges may include poor representation of mine geometry, insufficient quantity and/or poorly distributed map reference points, and unknown or ill-defined registry with respect to surface features. To complicate matters, many surface features contained on the mine map are frequently destroyed due to changing land use and urban development.

It is the author's belief that good faith effort was made by the mining companies to create scaled maps that visually represent the coal remnants and cavities created during the mining process and to accurately relate them to each other and to identifiable surface features. This same good faith effort has been made on the part of government to then geo-rectify these mine maps to the surface as accurately as possible. Given the number of mines that have operated nationwide and the fact that some of these mines are more than 150 years old, it is reasonable to assume mistakes will be made somewhere along the line, either in the mapping or geo-rectifying process. The end product may bear little resemblance to reality. The question becomes how best to discern whether a given map is accurately portrayed and referenced to the surface.

The only sure way to verify the accuracy and precision of abandoned underground mine maps and the relative position of the mine workings with respect to surface features would be to conduct a complete and thorough surface and mine survey. For obvious reasons such a survey in abandoned underground mines would be dangerous, expensive and perhaps not even possible. It deserves mentioning that MSHA has funded studies to develop and evaluate alternative geophysical techniques that will identify locations of underground mining activity. Usually, the geophysical techniques considered are employed to verify a relatively small portion of the mine where map information is doubtful or is missing.

Barring access to underground mines or extensive geophysical testing, perhaps the most consistent method of verifying map accuracy is through the plotting of subsidence events directly onto the mine map and then comparing the shape and location of the subsidence event with respect to the mine geometries. Implicit to using this technique is the understanding and acceptance of the fact that coal-mine subsidence is definable and that the geometry of

underground mine workings (surrounding the failed area) influences the location, size and shape of the subsidence event. It was through the work of early subsidence researchers that these conclusions are drawn. Key research and findings are presented in the 'background' section of this paper.

This paper will examine how Survey Precision GPS receivers combined with mobile GIS technology can utilize geo-rectified mine maps, historical aerial photography and subsidence studies that collectively can be used to qualify map accuracy and to some extent estimate map accuracy and precision.

Background

In 1913, Lewis Young documented the surface expression of two types of subsidence, pit and sag, and found that their form is a function of mine depth and local geology. Mr. Young had access to the mine workings thereby allowing him opportunity to examine both the mine failure and surface effects. The careful mapping of surface damage relative to the mine workings led him to conclude that surface subsidence forms directly above the mine failure. This conclusion is perhaps the most important part of his work that is relevant to the scope of this paper. Figure 1 is from Mr. Young's 1916 publication "Surface Subsidence In Illinois", and shows two sag-type subsidence events plotted on a mine map. For those unfamiliar with subsidence and Illinois terminology, sag-type subsidence refers to the large diameter, bowl-shaped depressions that form in the ground surface as the direct result of failure within the underground room and pillar mine workings. As can be seen in Figure1, the ground cracks delineate the perimeter of the sag and are contained within the panel. Not readily apparent in the diagram is the reason why. Each panel is surrounded by large blocks of unmined coal called barrier pillars. Barrier pillars located between the entries and panel range from 42 to 46 meters in thickness. Whereas, barrier pillars left between adjacent panels (not shown) are 12 to 18 meters in width. Preliminary data collected by this author suggests that sag type subsidence can override barrier pillars if they are undersized. In this particular instance, they were apparently of sufficient size and strength to contain each subsidence event and prevent outward expansion into adjacent panels.

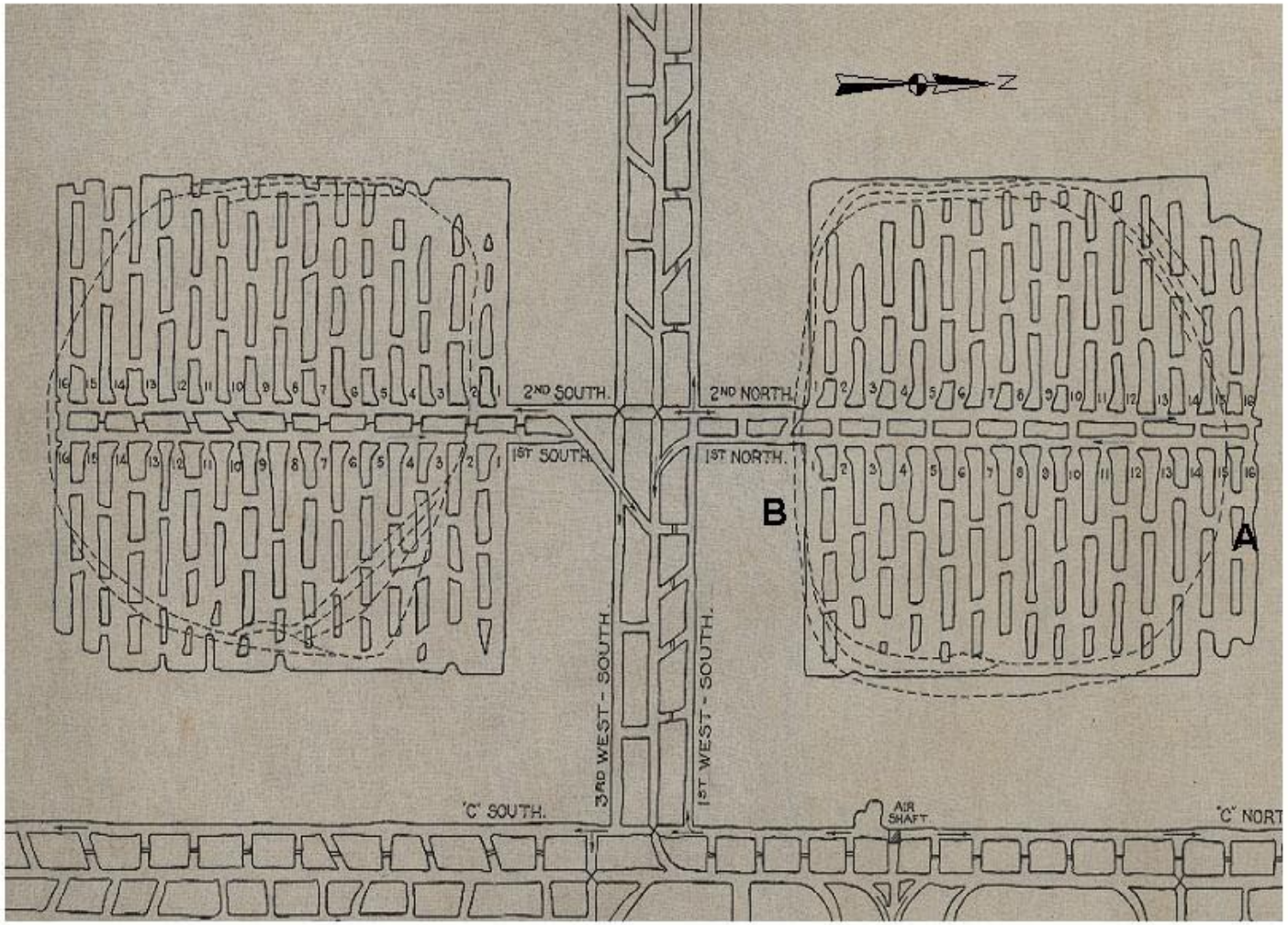


Figure 1. "Plan of two panels of a Franklin County mine, 550 feet deep. Subsidence caused surface cracks as indicated. Over the north panel at A the crack was 8 to 10 inches wide, and at B were two smaller cracks" (Young, 1916).

Herbert and Rutledge's 1927 publication, "Subsidence Due To Coal Mining In Illinois" is also an important work. The intent of the study was "to include the establishment of monuments, in order that the existence and the amount of subsidence with reference to the underlying excavation in a part or a panel of a mine could be determined." (Herbert and Rutledge, 1927). Figure 2 shows, for one of their study sites, the location of the monitoring points used to measure subsidence related ground settlement plotted relative to the mine map. Also included on the map are the ground cracks that formed as the result of the subsidence event. Note that the locations of ground cracks are within the panel thereby confirming the observations of Mr. Young. Figure 3 is a plot of differential ground settlement associated with each monitoring point through time. Together Figures 2 and 3 show that subsidence related ground movements can be measured quantitatively and that the ground directly over the mine failure is where the settlement occurs.

A more recent study conducted by Stephen Hunt (1978) entitled, "Characterization of Subsidence Profiles Over Room-and-Pillar Coal Mines In Illinois", provides a concise discussion on how geologic setting, mine depth and mining practice control and influence vertical movements associated with subsidence. His work defines the characteristics of the subsidence profile in terms of "(1) the magnitude of the vertical settlement, (2) the shape of the profile, and (3) the position of the profile relative to the ribside or edge of mining. Ribside is a barrier pillar or solid block of coal on the perimeter of the panel." Figure 4 illustrates the subsidence profile characteristics and in essence graphically summarizes and confirms the findings of Herbert and Rutledge. In his 1980 doctoral thesis, Hunt provides one of several figures that illustrate the influence large blocks of coal, or the lack thereof, on the magnitude of vertical settlement. Note in Figure 5 that the large blocks of coal on either end of the subsidence event terminate ground movement and that the barrier pillar near the center of the event also greatly reduces the amount of vertical settlement.

Philip DeMaris and Robert Bauer of the Illinois State Geological Survey evaluated, in a 1983 contract report for the U.S. Bureau of Mines, whether subsidence could be identified and differentiated from naturally occurring closed depressions associated with glaciated areas using aerial stereo pair photographs. They found that subsidence events with very pronounced and

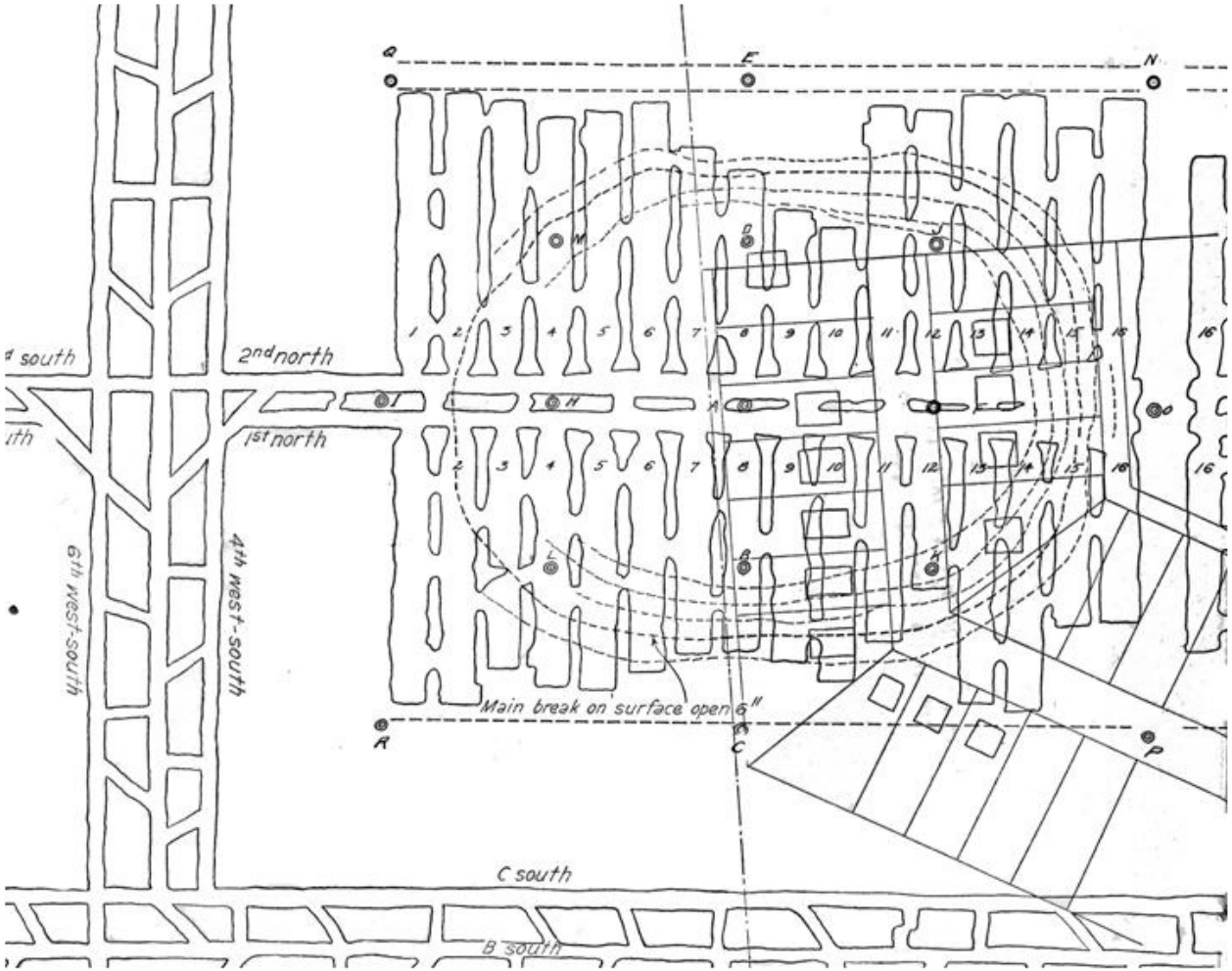


Figure 2. "Study of subsidence over first and second north panel entries off fifth west south at D. Room interval, center to center of rooms, 40 ft.; barrier pillar, 150 ft.; number of rooms on panel, 16; fire pillar, 50 ft." (Herbert and Rutledge, 1927).

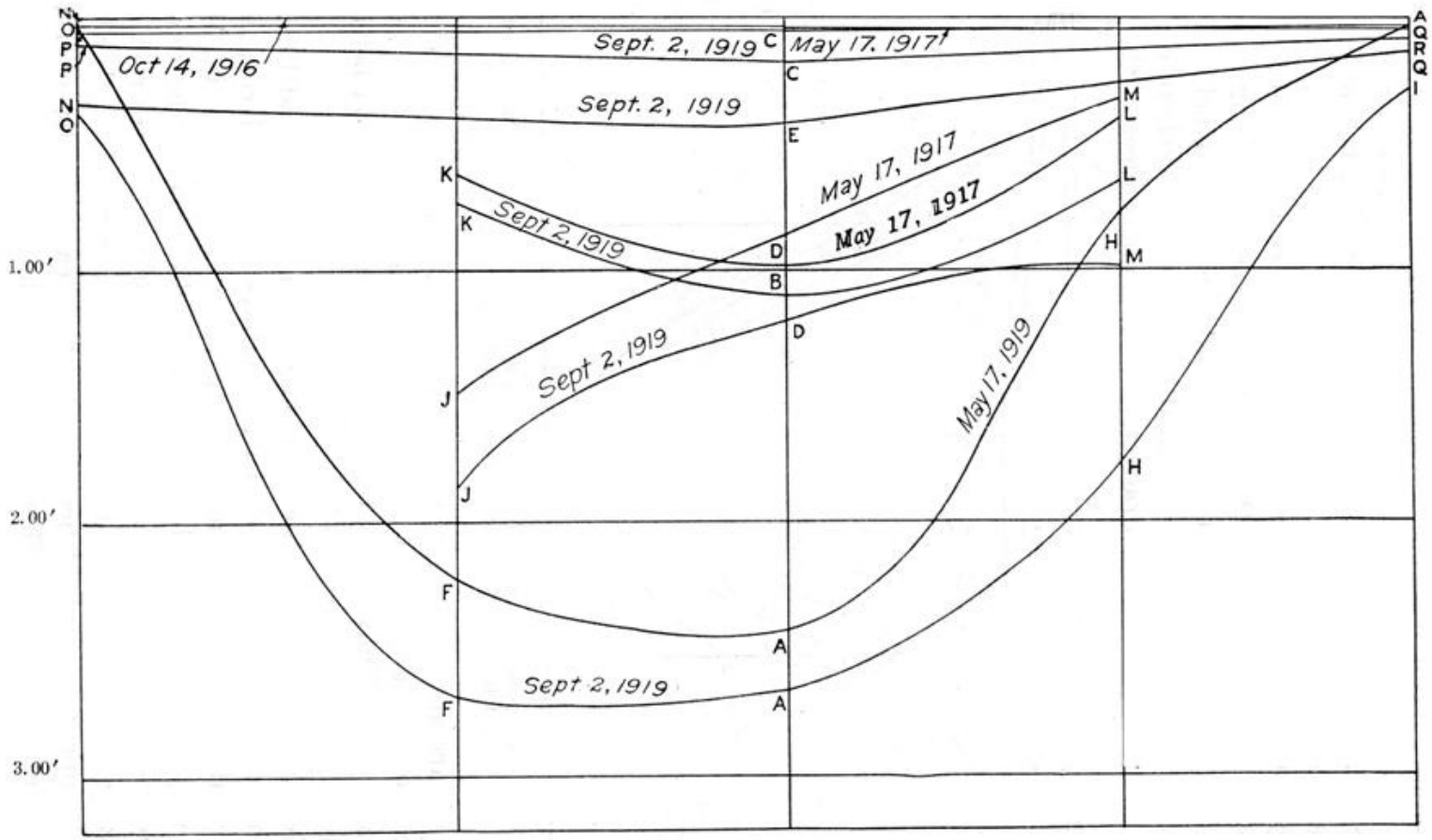


Figure 3. " Longitudinal section curves for subsidence monuments at D. Horizontal scale, 1 inch =105.5 feet; vertical scale, 1 inch =0.85 foot" (From: Herbert and Rutledge, 1927).

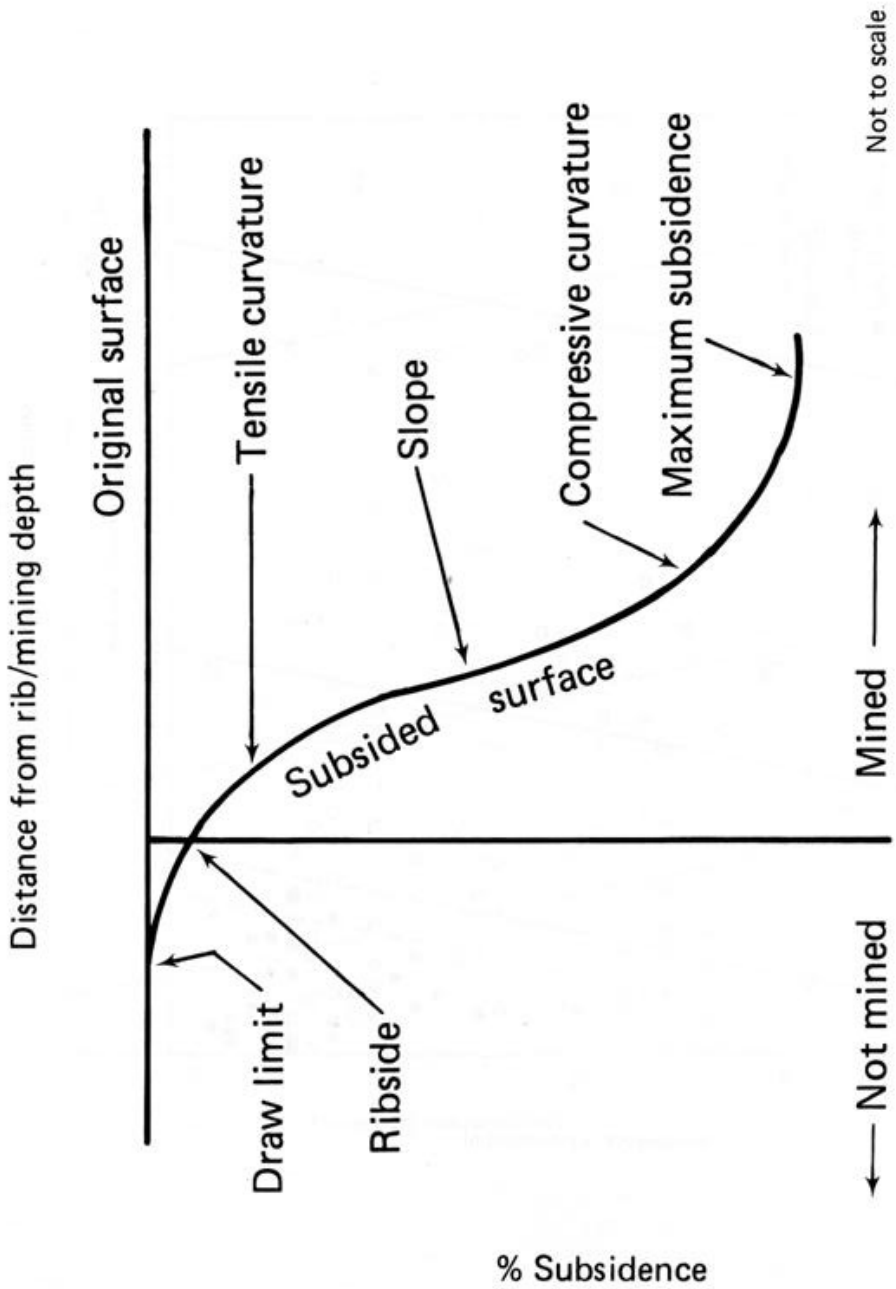


Figure 4. "Diagram showing the features common to most subsidence profiles." (From: Stephen Hunt, 1978))

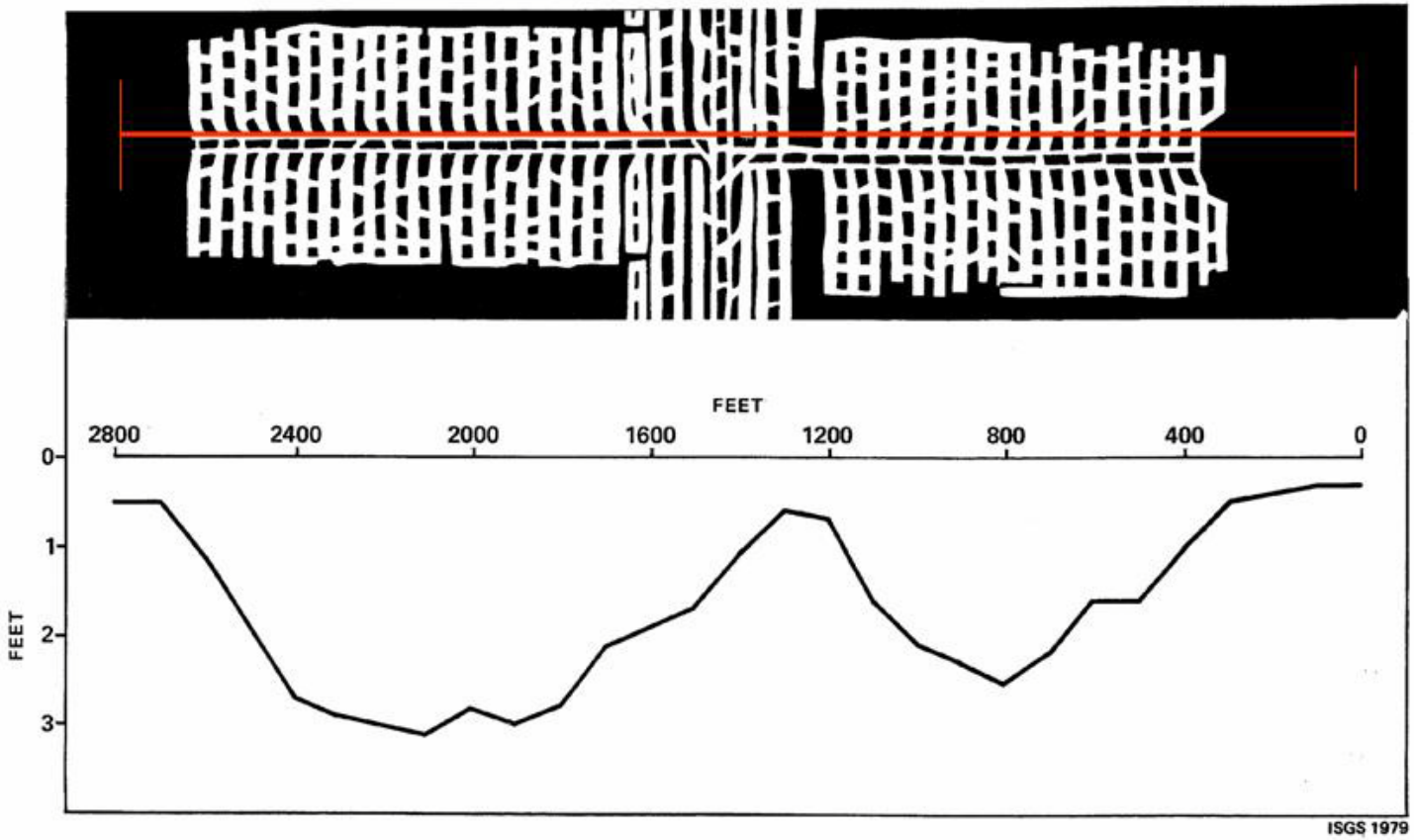


Figure 5. Subsidence profile plotted with respect to the mine workings. Note the decreased settlement associated with the barrier pillar adjacent to the entry. (After: Stephen Hunt, 1980).

sharply delineated boundaries could be reasonably identified as being subsidence. Whereas subtle subsidence events, typically smaller in size with less vertical settlement and indistinct boundaries, were difficult to identify and distinguish from naturally occurring closed depressions. In general, the ability to identify subsidence using aerial photography is enhanced when features of interest are: 1) compared using multiple sets of photography taken over time, 2) photographed when drainage pattern displays high contrast, and 3) large relative to the resolution of the photography (1:4000 to 1:10,000 is considered ideal). "Infra-red photography which emphasizes natural drainage features, would assist in picking out subsidence sites which fall by chance along natural drainage" (DeMaris and Bauer, 1983). Custom photography may be necessary in order to meet the conditions listed above.

Methodology

Attempts are made to obtain an original mine map for scanning purposes, but in most instances only 'blue line' copies of the original map are available. The best available map of the mine workings is selected and scanned at a sufficiently high resolution that will produce a digital image that is the visual equivalent of the map and according to procedures outlined in a proposal submitted by Dr. Randall Pearson to the Department of Natural Resources. If it is in color, "the map is scanned in true color with a minimum resolution of 400 dots per inch and stored in Tagged Image File Format (TIFF)". The mine map image is then geo-rectified using the USGS 7.5 minute topographic quadrangle that is closest in time to mining activity as a reference map. "The rectification process will employ the transformation method that minimizes total image distortion" (Pearson, 2007). It is accomplished by assigning X-Y coordinate information from the reference map to the common point location shown on the mine map. Such common points typically include section lines, road and railroad intersections.

In addition to the geo-rectified mine map, other imagery used in this study includes aerial photographs and Digital Orthophotography Quadrangle (DOQ). Aerial photographs were obtained from the Department of Agriculture and the Department of Transportation. The aerial photographs were scanned and geo-rectified to USGS 7.5 quadrangle maps or to DOQ's. Whereas, the digital orthophotography quandrangles were downloaded from the Illinois Natural

Resources Geospatial Data Clearinghouse hosted by the Illinois State Geological Survey. Particularly useful are the National Aerial Photography Program (NAPP) Digital Orthophotography quarter Quadrangle (DOQ) and the Illinois National Agriculture Imagery Program (NAIP) Digital Orthophotography quarter Quadrangle (DOQ) which provide black and white and color-infrared photographic coverage, respectively. All images were projected or reprojected to UTM NAD 27 zone 15 and/or zone 16 as appropriate using ERDAS Imagine 9.1.

Geo-rectified images including mine maps, topographic maps and DOQ's are combined as a series of overlays and evaluated. Software used for in-office evaluation includes ESRI ArcView 3.2 and ESRI ArcMap 9.1. Whereas field verification of subsidence events or map features is accomplished by loading the aforementioned maps onto an Explore iX104C^2 Tablet PC. Field measurement of specific features for this paper was accomplished using a Trimble ProXH receiver with signal relay via blue tooth connection with the Tablet PC. Field software includes ESRI ArcPad7.0.1. and Trimble GPScorrect software which provides real-time differential corrections. The software is pre-set to accept only sub-meter measurements and can be post processed to achieve sub-foot accuracy with Trimble GPSanalyst. In one instance, a Garmin GPSmap 76 handheld unit was used to map the ground cracks shown in Figure 14. The Garmin GPSmap 76 is reported to have sub-3 meter accuracy when WAAS enabled.

The accuracy and precision of both GPS devices and of the geo-rectified topographic maps was confirmed by field measurement of USGS benchmarks. Comparisons were then made between the predicted coordinate location as derived from the geo-rectified map, GPS field measurement (both GPS units), and the National Geodetic Survey coordinates established for each benchmark. It was determined that the measured differences of the benchmark location and its published values were 2.5 meters (averaged position) using Garmin GPSmap 76, 1.9 meters using a Trimble Pro XRS with ArcPad, and 0.36 meters 0.24 to 0.40 meters with Leica 530 (Gibson, 2005). This study uses a different and more precise Trimble GPS device and measurement of the same benchmark locations found a range of 24 to 40 cm (without post processing) using the Trimble ProXH.

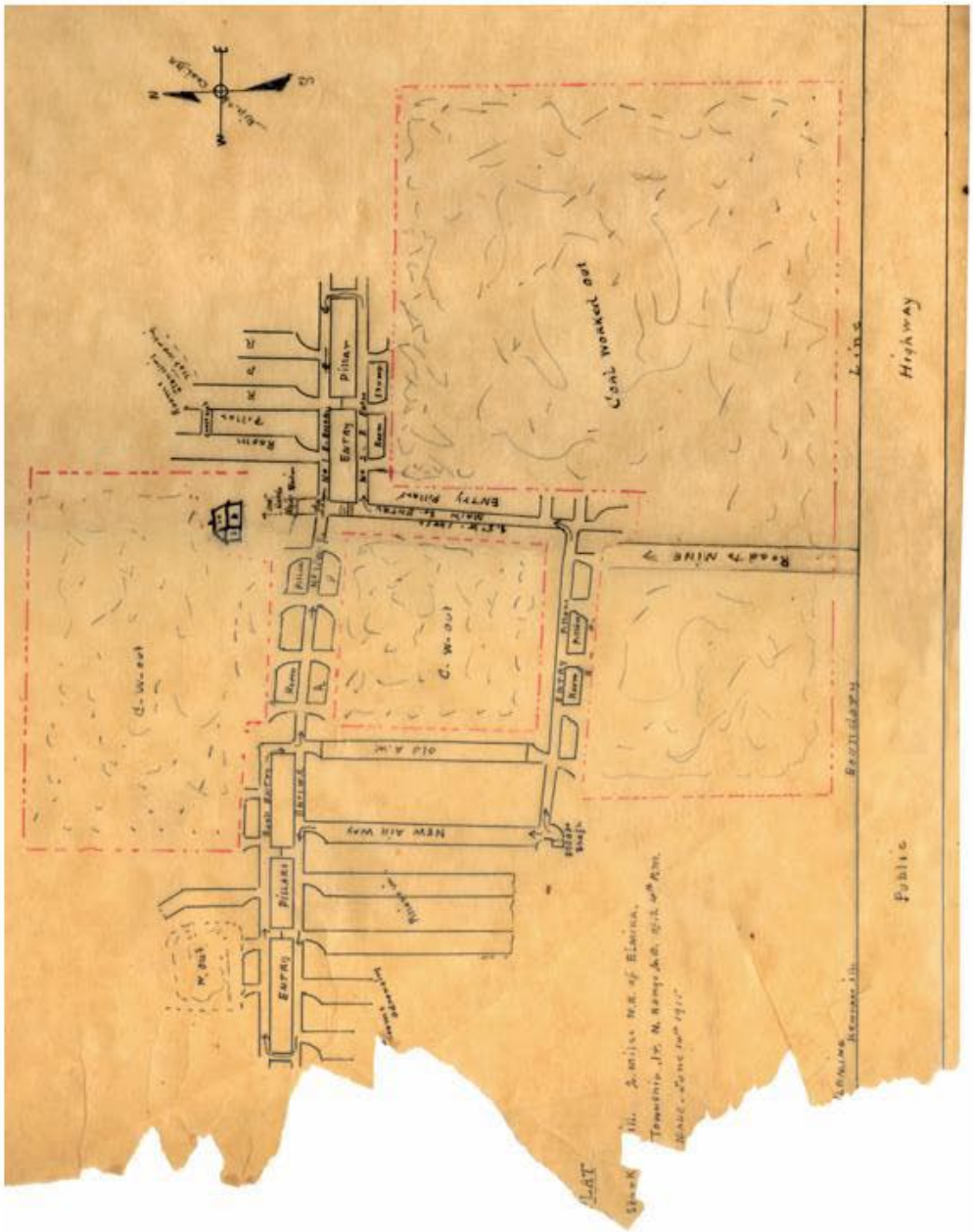
Methods of Testing Map Accuracy

The relative accuracy of any given mine map is something that is discovered rather than known at least when dealing with old abandoned mines. After having inspected a number of mine maps, one quickly realizes that map quality falls along a continuum and presumably map accuracy does as well. On one extreme are the very old maps that are essentially pictorial descriptions of mining activity. Such maps usually lack scale or sufficient information to adequately locate the map. Figure 6 is an example of such a map. On the other extreme are, perhaps, modern maps containing numerous surface features distributed across the map, pillar geometries that are accurately and precisely located with each other and with respect to the ground surface. One mine, according to it's mining engineer believes that it is realistic to routinely achieve 1:5,000 precision in underground room-and-pillars mines via closed loop traverse surveys. Greater precision can and is achieved when siting important features within or on a mine. The same official said they have drilled holes and have used inclinometers in an attempt to verify map accuracy and have found they were usually within 2.4 to 3.7 meters or less.

Fortunately many, if not most, maps in the Illinois collection contain sufficient information that allows the map to be located relative to the surface and are believed to be fairly accurate in many instances. Figure 7 is a somewhat typical example of a coal company going to considerable effort to locate surface features to the mine workings. Note that the figure includes surface survey monuments (stone), streams, streets, home address, lot and section lines and contours. Features that, if not destroyed by surface development, can be found and measured to confirm mine map positioning and top (surface) survey accuracy.

The question becomes how can mine map accuracy be estimated and where on a continuum does a particular map reside? First, it is necessary to define accuracy as used in this paper. In Illinois, 7.5 minute topographic quadrangle maps serve as the reference map to which mine maps are geo-rectified. Therefore, the best we can hope to obtain are mine maps that conform closely to the topographic map. It is our intent, that features common to both maps are of the same general size and shape and located within close proximity of each other as overlays. The closeness, or

precision, to which features are located would ideally be on the same order as the topographic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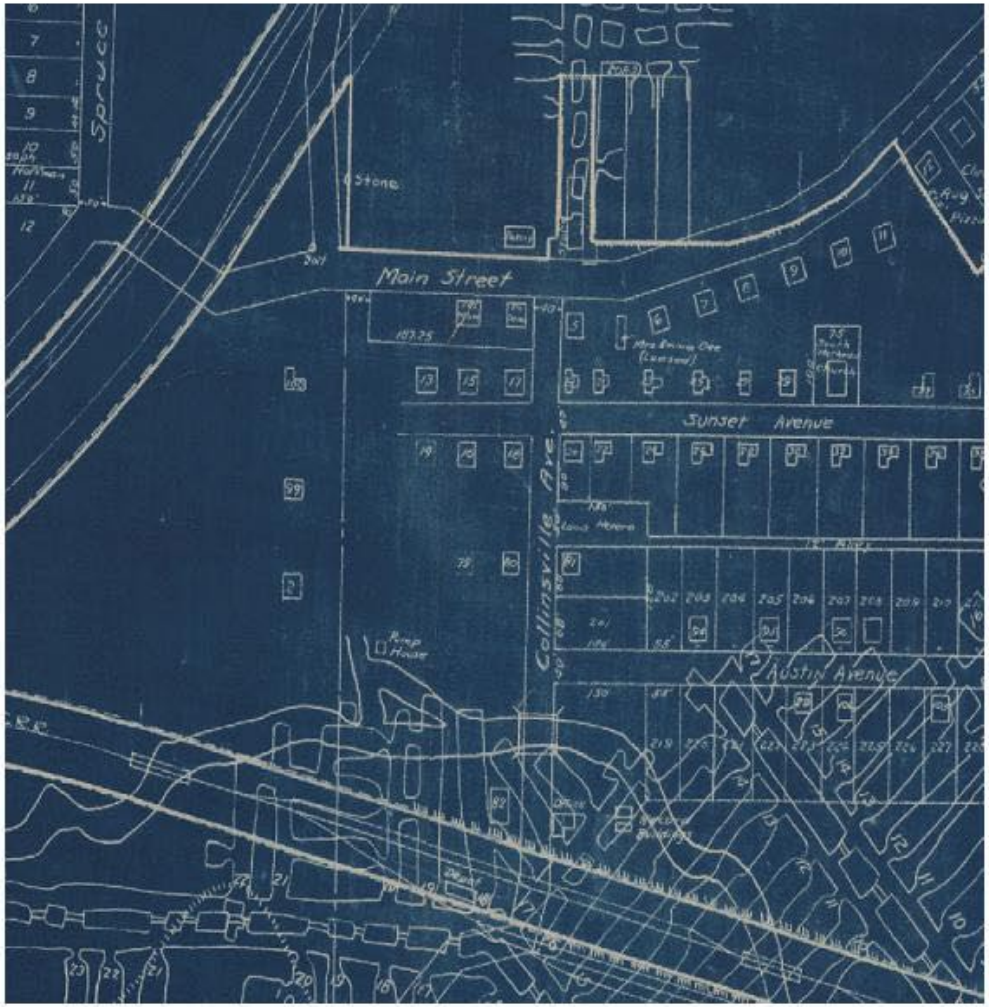

Figure 7. Example of a typical blue line mine map contained in the Illinois Mine Map Archives. This map is somewhat unusual in that it has an abundance of surface information plotted relative to the mine workings.

map which the USGS mandates that : “90% of ‘well defined points’ must be plotted to within 1/50th of an inch accuracy on a 1:24,000 scale map which is the equivalent of 40 feet (12.2 meters) on ground surface” (USGS, 1999). Since many mine maps are plotted at 1:200 or 1:400 scale, our accuracy goal should be achievable.

It will be shown in the sections below that the insights and techniques developed by early subsidence researchers can be paired with GIS, GPS and mobile technology and then collectively used to test mine map accuracy. Specifically, geo-rectified images including mine maps, topographic maps and DOQ’s when combined as a series of overlays can be used to quickly identify and locate likely subsidence features with respect to mine workings. Such images can then be loaded onto a laptop, and suspected subsidence events can then be easily found using GPS and verified through field inspection. In cases involving active coal mine subsidence, GPS can be used to locate survey monuments and ground cracks relative to the mine map in real-time.

Map Analysis

The first step is to inspect and analyze the mine map. More often than not, clues suggesting the relative accuracy of the mine map can be found on the map. Clues can be tested and combined with other information in order to complete the assessment concerning map accuracy.

For instance we expect in our modern mines, a high degree of accuracy in both the development and mapping of mine conditions. According to Mr. Daniel Barkley, Illinois Office of Mines and Minerals, the accuracy of the mine working’s orientation and location as a mine expands is critical to economic success. Often, the siting and excavation of satellite ventilation bleeder shafts must start 6 months to one year before the underground mining is anticipated to reach and intercept the completed shaft to assure uninterrupted operations. In the case of longwall entry development, satellite shaft locations could be as far as 5 to 8 kilometers from the original portal. Bleeder shafts can vary in diameter from 2.4 to 4.9 meters. When one considers 5 meter diameter shaft intercepting an 5.5 meter entry, the allowance for error is quiet small particularly given the distance involved with entry development to get to the shaft location (Barkley, 2008). Without any field measurement, one could reasonably conclude that the map for this mine is

probably accurate and exactingly representative of mining conditions. To confirm the placement of mine workings with respect to the surface, one need only precisely locate the main and bleeder shaft locations through field measurement. Simply comparing the distances between map and field measurement of shaft locations allows for a quick check.

We expect significantly less accuracy and precision for old abandoned room-and-pillar mines, but is this assumption correct? For example, consider the order of mine development shown in Figure 8. For purposes of clarity, only the entry pillars of the Madison County Mine No. 6 are provided. They are shown as closed polygon vectors created via heads-up tracing of the geo-rectified raster map image. This mine opened in 1900 and was developed by driving main entries east and west from the shaft. By 1918, a system of interconnecting east-west and north-south aligned entries was completed to form a rectangular shape 914 meters wide and 1,173 meters long. It is particularly impressive when you consider that in order to connect, the travel length along the mains was 2,016 meters in the counterclockwise direction and 2,165 meters in a clockwise direction and they meet with no apparent offset. Such an impressive feat suggests that they maintained excellent horizontal control during entry development.

The Madison County No. 6 Mine example indicates the high level of accuracy achievable in the development and mapping of mines operating in the early 1900's. It is more likely that errors reflect how maps are constructed cartographically. Some old mines laid out their top surveys and mine surveys using a unique or internal coordinate system and then referencing their map to a larger, previously existing, surface map. In some areas, property boundaries are established under very difficult physical conditions or perhaps according to an arcane survey system such as the French Long Lot and as a result may contain significant error. Yet the relative accuracy of their measurement within their local coordinate system might be quite good. If so, it may be possible to adjust the mine map accordingly in order to improve the overall 'goodness of fit' between the mine workings with respect to the surface. Such adjustments require secondary map information that has real world connections between the surface and mine. Examples would be boreholes or shaft locations and perhaps surface monuments shown on the map.

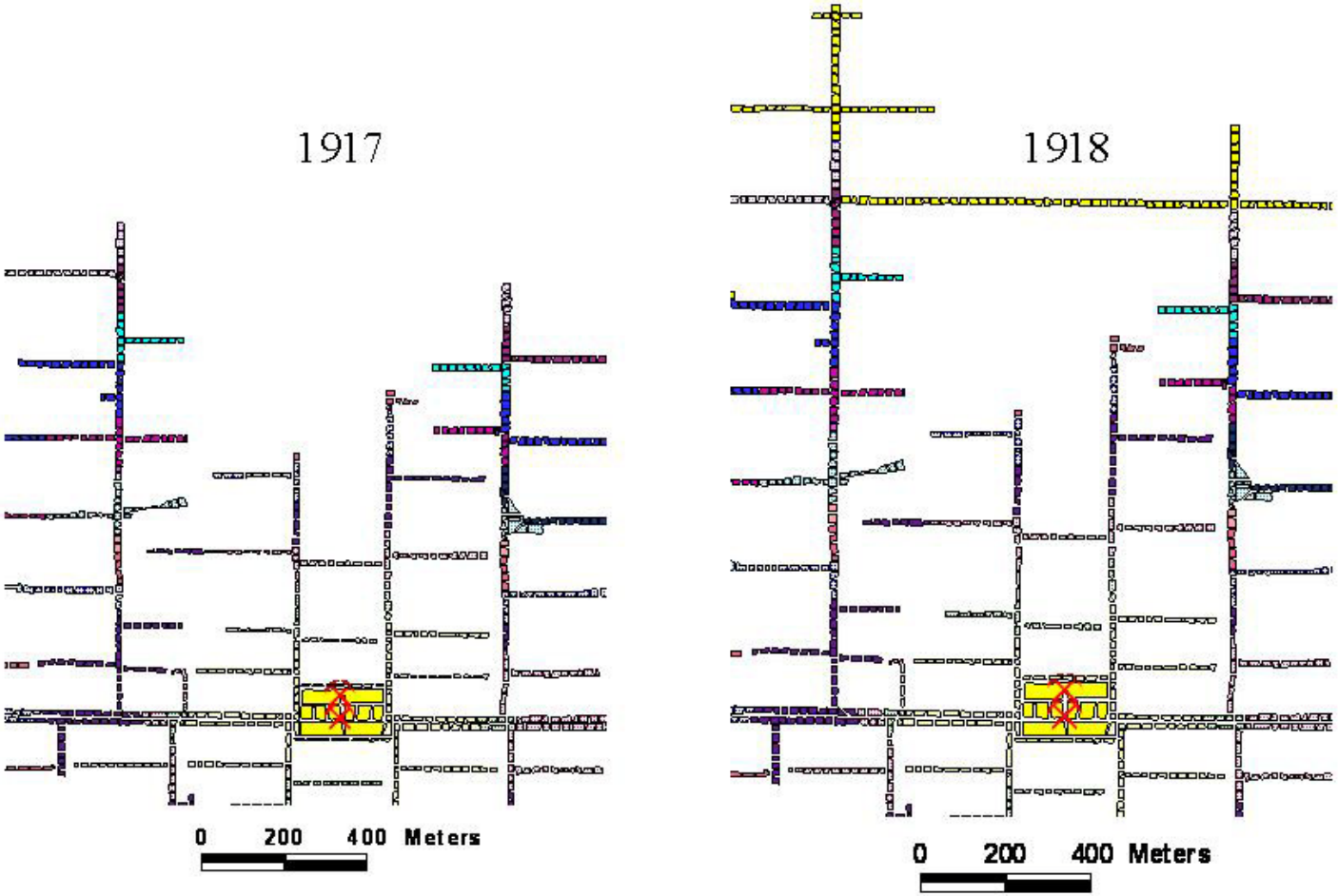

Figure 8. Example showing Entry development in the Madison County No. 6 Mine and the high level of accuracy possible in old mines.

Aerial Photography

The findings of past researchers important to this portion of the paper can be summarized as follows. Subsidence events are surface features that represent in part a subdued reflection of failures occurring at mine level in that they can delineate large blocks of coal resistant to the ongoing mine failure and map their relative location. From this perspective, subsidence events are a very useful tool in documenting the accuracy of mine maps. As an aside, the author cannot stress enough the importance of creating and maintaining subsidence databases for current and future land use considerations. The following considers the value of information collected through aerial imagery.

DOQ, both black and white and color infrared, photography are very useful in gathering preliminary subsidence information. When using aerial imagery to identify subsidence, the work of DeMaris and Bauer (1983) should be carefully considered before drawing firm conclusions as to whether any particular feature is subsidence related without supplementary supporting information. One of the conditions they recommend imposing when using aerial photography to identify subsidence is that suspected feature must fit conformably with the geometry of the coal mine. This is easily accomplished using GIS technology such as ArcView or ArcMap. There are two basic ways of collecting subsidence information from aerial photography and the choice depends on user need. One way is to create vectors by heads up tracing of suspected features identified on aerial photography and then overlaying them onto the geo-rectified mine map. Those working from a research perspective may consider this technique desirable as a means of testing and/or reducing data collection bias. A second way favors production and is accomplished by making the geo-rectified mine map somewhat translucent. Making the map "see through" allows quick comparison between the size, shape and position of the aerial feature with respect to mine geometry. This technique reduces search time by allowing the viewer to concentrate on known areas of mining. Additional time is saved by creating vectors only for those features found to be conformal with mining instead of all closed depression features. At the same time, it still allows inspection of adjacent areas for evidence of map discrepancy and a means of determining the frequency and characteristics of naturally occurring closed depressions.

Time sequencing of subsidence events becomes possible if coverage for a particular area is available through time by creating vectors of suspected subsidence from each set of aerial photographs. Figure 9 illustrates this technique. In this manner additional information concerning the suspected subsidence event can be gleaned. Ideally, there would be imagery that predates mining activity from which naturally occurring closed depressions could be identified. Successive aerial imagery thereafter would allow bracketing the time period when a particular event formed and allow crop damage and/or gauge effectiveness of remediation techniques. Figure 10 shows the suspected sags identified on 1968, 1998 and 2004 aerial photography superimposed upon a geo-rectified mine map.

If the suspected subsidence feature is consistent with the general shape of a nearby panel but is simply offset, particularly if there are a number of such features, it may be indicative of poor surface to mine referencing rather than naturally occurring features. A nesting of such features beyond or parallel to known mining merits further inspection because they may indicate a missing mine map or map segment. Field inspection of these features to confirm that they are in fact subsidence related should be conducted prior to adjusting the mine map.

Finally, it should be stated that without other sources of information documenting occurrences of subsidence, the use of aerial photography exclusively to identify subsidence events will likely produce a statistical bias that underrepresents the total population of subsidence events. Preliminary findings of the author are that subsidence events are readily identifiable on soils forming on slopes 0 to 2 percent and identifiable on slopes as high as 5 percent. Due to their low permeability characteristics, silty clay loam soils appear to present the most favorable conditions for seeing subsidence on aerial photography with silt loam soils being a close second. Perhaps under favorable moisture and photographic conditions they may be identifiable on greater slopes.

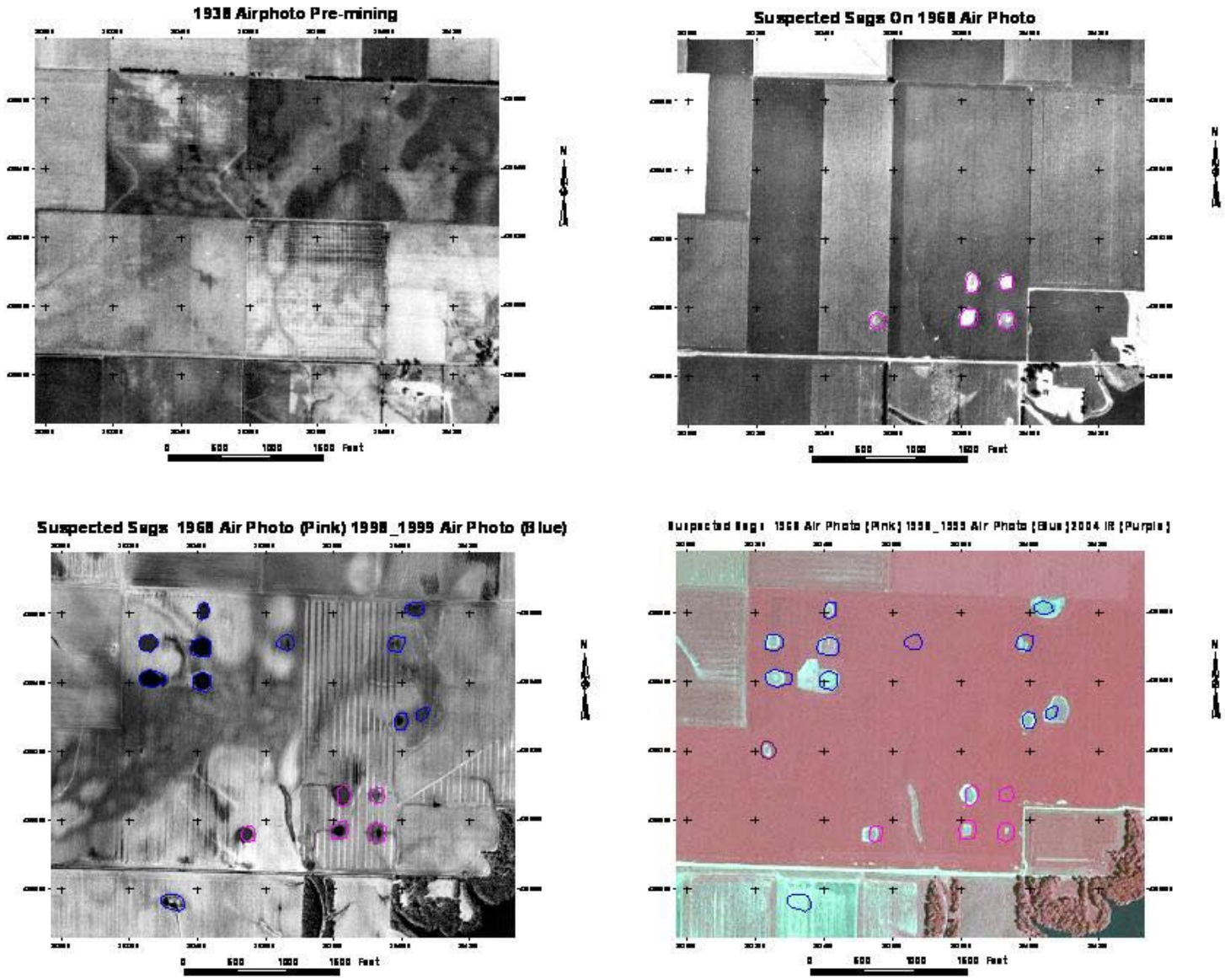

Figure 9. Suspected subsidence features identified using geo-rectified aerial photography from different time periods. Area mined post 1938.

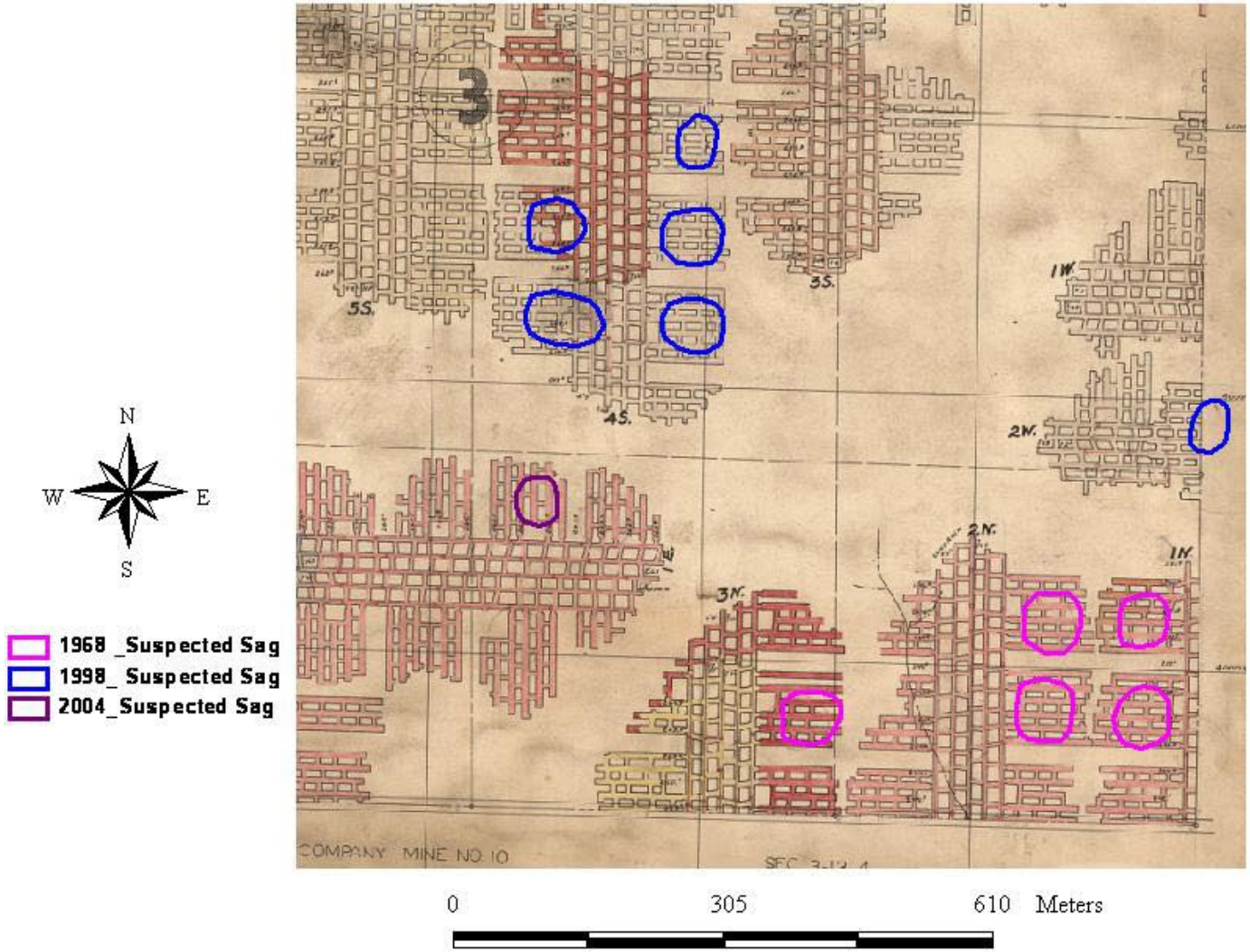

Figure 10. Sag development identified from aerial photography taken through time plotted relative to mine workings.

Direct Field Measurement

Direct field measurements include techniques that measure the X and Y coordinates of mine features such as shafts, boreholes, survey monuments and property lines as well as surface effects, namely coal mine subsidence. In the case of subsidence, it would also include change in elevation measurements (Δ Z). Unless specifically noted, all horizontal and vertical measurements are taken using GPS and level survey techniques, respectively. The focus of this discussion will be on how the XYZ measurements can be used to verify mine map accuracy.

Personal communication with one Illinois coal company mining engineer was particularly enlightening when he expressed the opinion that the largest source of error was likely to be associated with angular rather than distance measurements. As a result, rotational drift can occur in the mine layout requiring periodic adjustments to maintain orientation. It is from this perspective that 'more is better' when it comes to measuring as many discrete point locations as widely distributed across the mine map as possible. But with old abandoned mines, one can only measure what is shown on the map. Shafts, boreholes and subsidence collectively provide the best measure in verifying the accuracy and precision of a mine map and its geo-rectification with respect to ground surface. Each however, has challenges and inherent error associated with its measurement.

Shafts and borehole locations are the most useful because they are discrete point locations common to both the mine and surface. Since it is from the shaft location that subsequent underground mine surveys are predicated, measuring its location with GPS is singularly important. Typically, most mines have at least two shafts and can be used to check map registry with the surface and to confirm mine map scale. Frequently however, mine shafts are located in heavily wooded areas, covered or otherwise hidden by surface developments making their measurement exceedingly difficult. Figure 11 is a typical example showing the difficulties in locating and measuring shaft locations. Next in order of importance is believed to be the measurement of borehole locations. Boreholes were drilled for a variety of reasons but common to many boreholes used for servicing the mine, is the fact that they were drilled to intercept a

Figure 11. Surface land use development frequently obscures shaft locations making precise X-Y coordinate measurements difficult (From: Gibson, 2005).

specific room or intersection within the mine and are shown on the map accordingly. In addition, boreholes used for servicing mining operations are typically cased, which facilitates locating them long after the mine is abandoned. Unfortunately, boreholes are not always shown on the old maps or are subsequently covered through surface development making them difficult to find. Other important point source locations include oil wells and survey monuments associated with the top survey. Nearly all mine maps will show the location of oil wells situated on their mine property and reserve holdings. Whereas, only some maps will show the location and describe the composition of surface survey monuments such as stones or iron pins. Figure 12 is a photograph of the survey stone shown on the map. The horizontal difference between the stone location as shown on the geo-rectified map and its location as verified by GPS is 4 meters. A second stone was found for the same mine and was within 7 meters of its mapped location.

When found, the discrete point locations described above afford opportunity to confirm map accuracy, orientation and precision in more distant parts of the mine. As such they provide precise locations that when measured with GPS afford a check on the geo-rectification process. The horizontal difference in their location should be of the same order of magnitude of error as the reference map. In Illinois, nearly all mine maps are referenced to an USGS 7.5 minute topographic map having an allowable error of 12 meters for well-defined locations. Figure 13 is a plot showing the horizontal differences between field and mine map locations for shafts, boreholes, oil wells and survey monuments for eleven mines in west central Illinois operating between 1870 and 1980. Although the data are few, they suggest that the geo-referencing process used in Illinois to locate underground mining with respect to the surface yields reasonable accuracy and precision. As would be expected, modern mines yield the closest agreement with least amount of error. Further sampling of measurement and mapping error is ongoing and will be reported in future publications.

From the perspective of this paper, subsidence is a subdued expression of the failure occurring at mine level reflected in the ground surface. Maximum settlement coincides with the weakest mine elements associated with the mine failure and gradually diminishes in magnitude towards its perimeter thereby delineating stronger pillar and floor conditions. Typically in room-and-pillar mining, the strong subsidence resistant areas of the mine are the barrier pillars left between

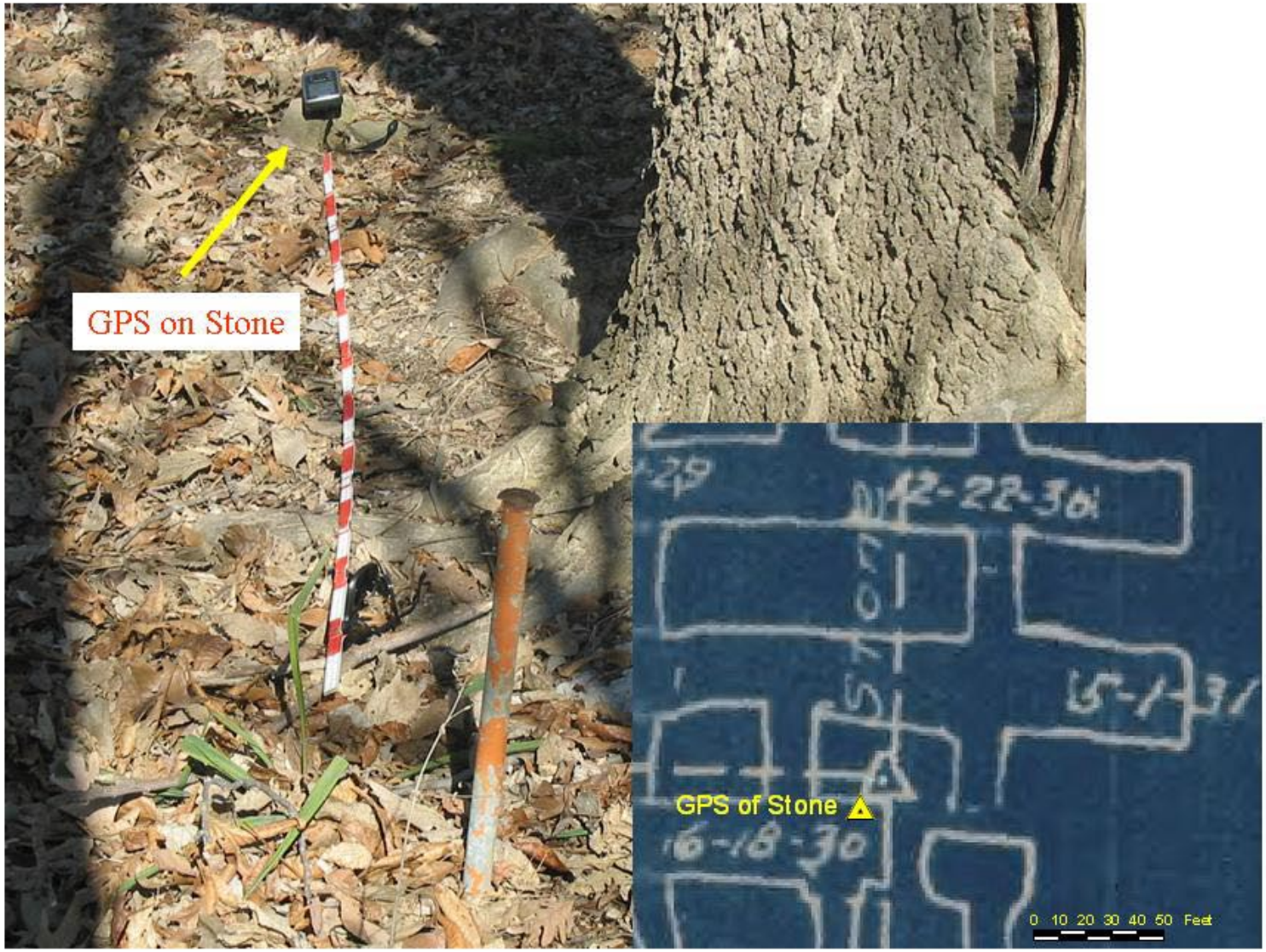

Figure 12. Photograph of stone used in mine survey shown on the mine map inset and its GPS measurement location.

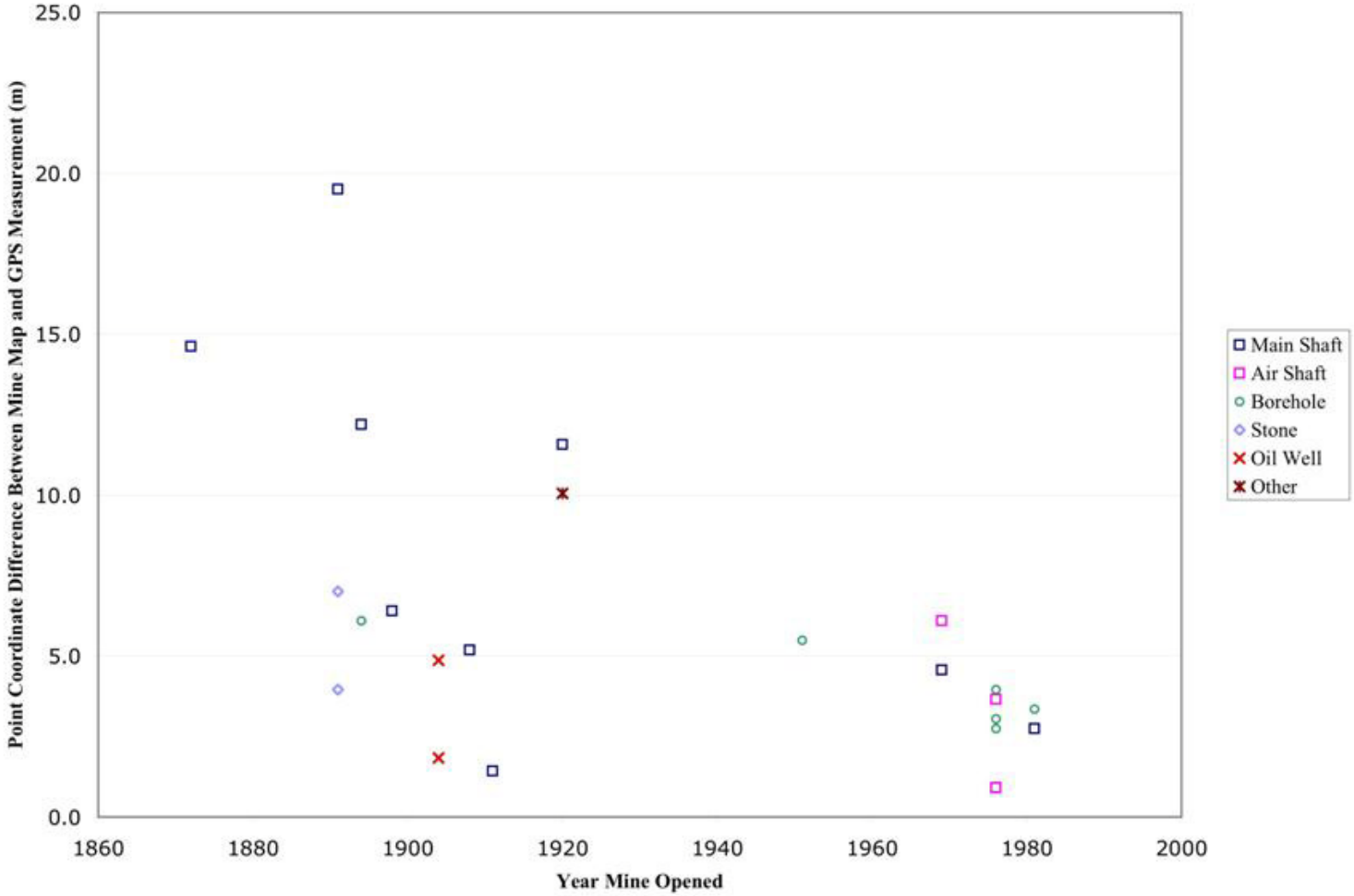

Figure 13. Plot of X-Y coordinate difference between GPS measurement and point location shown on geo-rectified mine map.

panels and panel entries. Subsidence related ground cracks, when they form, usually do so at this location. If the barrier pillars (ribside) are undersized, subsidence may override them resulting in progressive failure into the adjacent panel. In such instances the barrier pillar is represented as a topographic high between lows centered over the adjacent panels. Often when inspecting mine subsidence events, there is a concern as to whether the event will enlarge and cause damage to adjacent structures. To answer this question fully would require a considerable amount of discussion beyond the scope of this paper. Suffice it to say, the measurement of ground cracks and survey monuments distributed across the event, particularly near boundary conditions, provides useful information as to its likelihood.

GPS Measurement. When GPS is used to measure subsidence related ground cracks fairly precise measurement of the boundary conditions is possible. Assuming the GPS is used in conjunction with a mobile computer device storing the geo-rectified image of the mine map, an immediate real-time analysis of mine conditions can be made both in terms of map accuracy and likelihood of progressive failure at least in relative terms. Rarely do subsidence related ground cracks form continuously around the entire perimeter of the sag. Figure 14 shows a tracing of subsidence related ground cracks using a hand held GPS device and plotted relative to the mine workings. In urban areas when ground cracks are missing or are discontinuous, tension related damages forming in structures can be mapped to complete the sag boundary. There are several interesting features shown in Figure 14. The ground cracks were 7.6 to 12.7 centimeters wide and were more or less continuous along the west side of the panel. Their location relative to the full sized room pillars and barrier pillar seems somewhat analogous to subsidence associated with the bleeder pillars in the development of the first panel a longwall mine. There is a difference, with long wall mining the ground cracks tend to form on the inside of the bleeder pillars rather than over them as is the case in figure 14. Perhaps the reason is due to the partial support provided by the reduced pillars causing bending verses rupture of rock thereby causing an outward displacement of the ground cracks. Also note the absence of ground cracks along the east side of the panel. The east side of the panel coincides with a natural drainage area. It is believed that the stress and associated strain developing within the wet soil is accommodated through soil flow and plastic deformation rather than rupture.

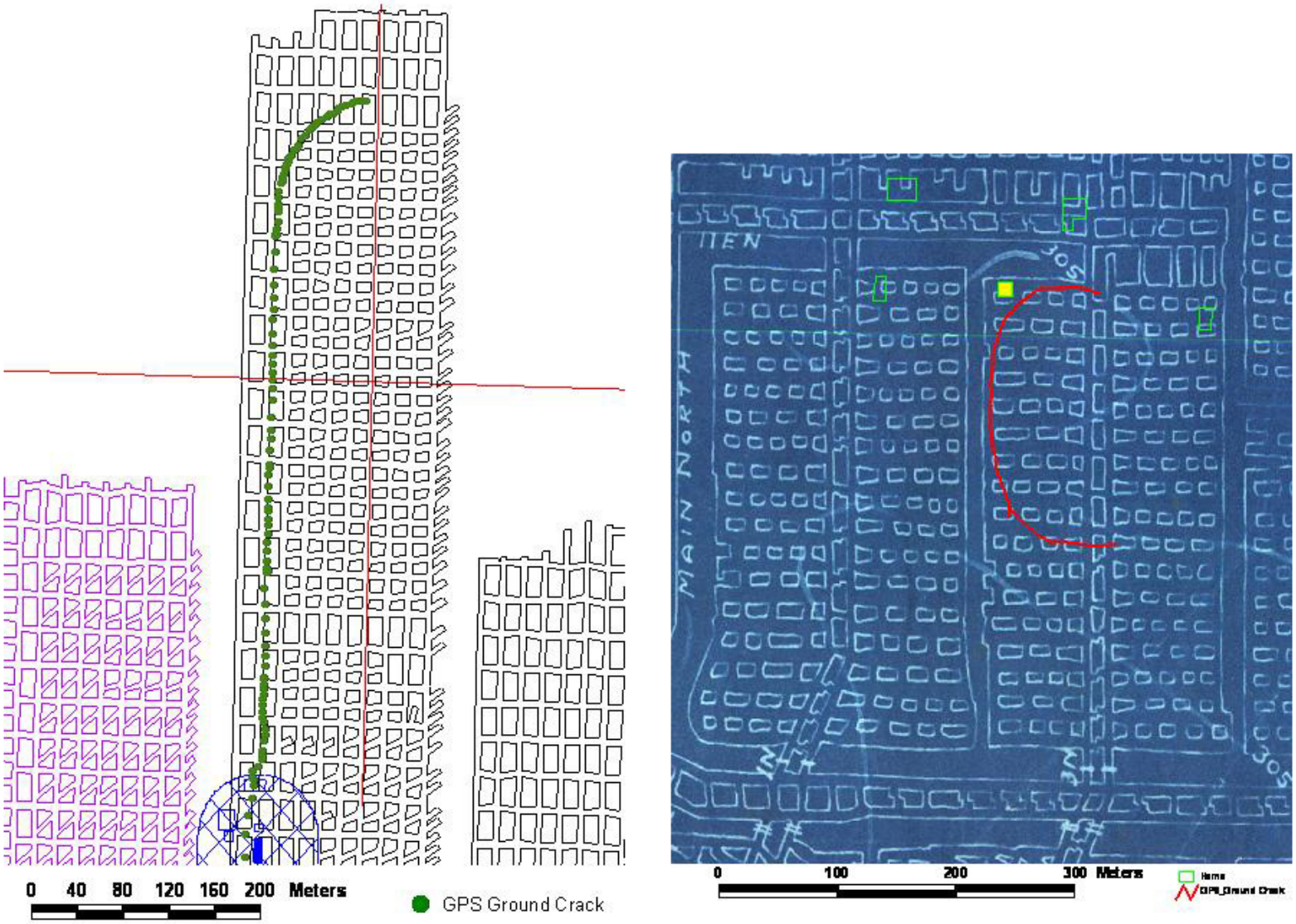

Figure 14. GPS measurement of subsidence related ground cracks plotted relative to geo-rectified mine maps for two case in central Illinois..

In instances involving older subsidence events in rural areas where structures are few or are non-existent, it may be possible to identify the subsidence boundary by mapping strandlines associated with the temporary ponding of water or damaged/stunted crops. Figure 15 is a composite image that maps May 2003 GPS measurements of a subsidence event onto 2005 DOQ (made 50% translucent) imagery and geo-rectified mine map. Also included in the figure are two photographs taken at the time of inspection. The photographs show standing water in a corn field after partial drainage has occurred as is evident by the strandline created by plant debris and stunting of crop due to wetness. Several important observations can be made from this figure. First, there is an apparent offset between the GPS measurements and the 2005 DOQ of about 11 meters. Part of the error is due to the precision of the handheld GPS unit estimated to be around 4.6 to 9.1 meters at the time. Close inspection of the DOQ with respect to the 7.5 topographic map indicates a small offset of about 4.6 meters of a road intersection located approximately 460 meters southwest of the subsidence event. The offset discrepancy, being the resultant of compounding errors, was found acceptable given reference map accuracy and intended use. Importantly, note that the location of subsidence as determined using both aerial imagery and field GPS measurement has formed exactly as expected with respect to the mine workings. In this instance, the coal left in the surrounding barrier pillars, entry pillars and room (neck) pillars was of sufficient size and strength to constrain or limit the size of the subsidence event at least for the period of time elapsing between GPS measurement and the taking of the DOQ (approximately two years). Finally, it should be noted that this particular subsidence event is located 7.3 kilometers distant from the main shaft.

Level Survey Measurement. Level survey measurements of active coal mine subsidence allow quantitative information to be gathered concerning the magnitude and rate of vertical settlements at discrete locations within the event. Bauer and Van Roosendaal (1992) suggested that when measuring vertical settlement associated with subsidence, ± 0.9 cm should be considered a practical lower limit of precision. With precise GPS measurement of survey point locations, the vertical settlements can then be related with respect to the mine workings which have a ± 12.2m (40 ft) uncertainty of measurement. Figure 16 shows partial profiles for four subsidence events plotted relative to ribside. In each of the four examples, ribside position was derived from plotting survey point location, as measured by GPS, relative to the geo-rectified mine map. All

of the subsidence profiles are from mines located in southwest Illinois and two, DN and B, are located over the same mine. The data suggest that all but the B Profile example are within the expected vertical and horizontal error of uncertainty. The ground crack in B Profile suggests a more likely ribside location.

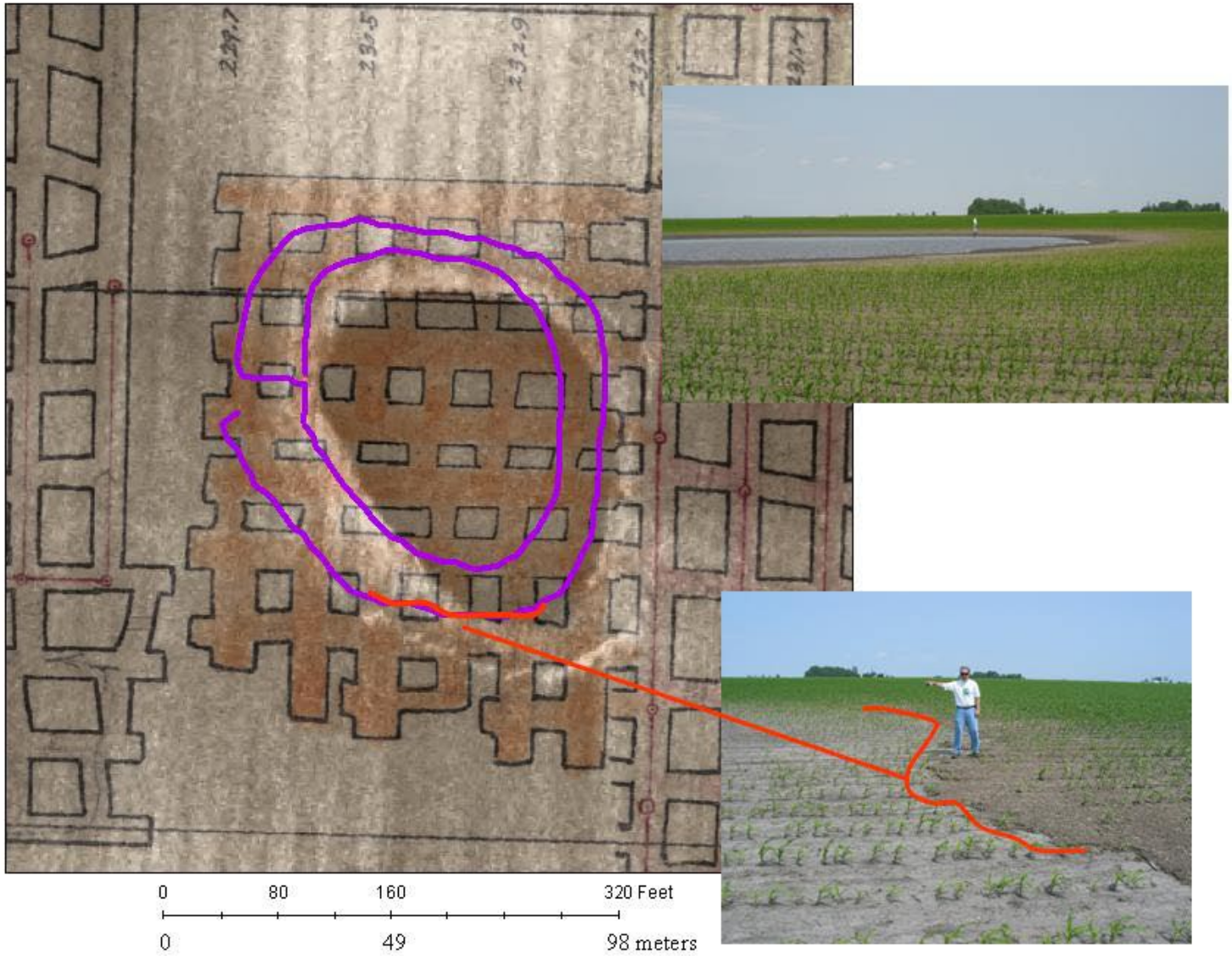

Figure 15. GPS measurement of subsidence induced ponded water and strandlines plotted relative to mine workings.

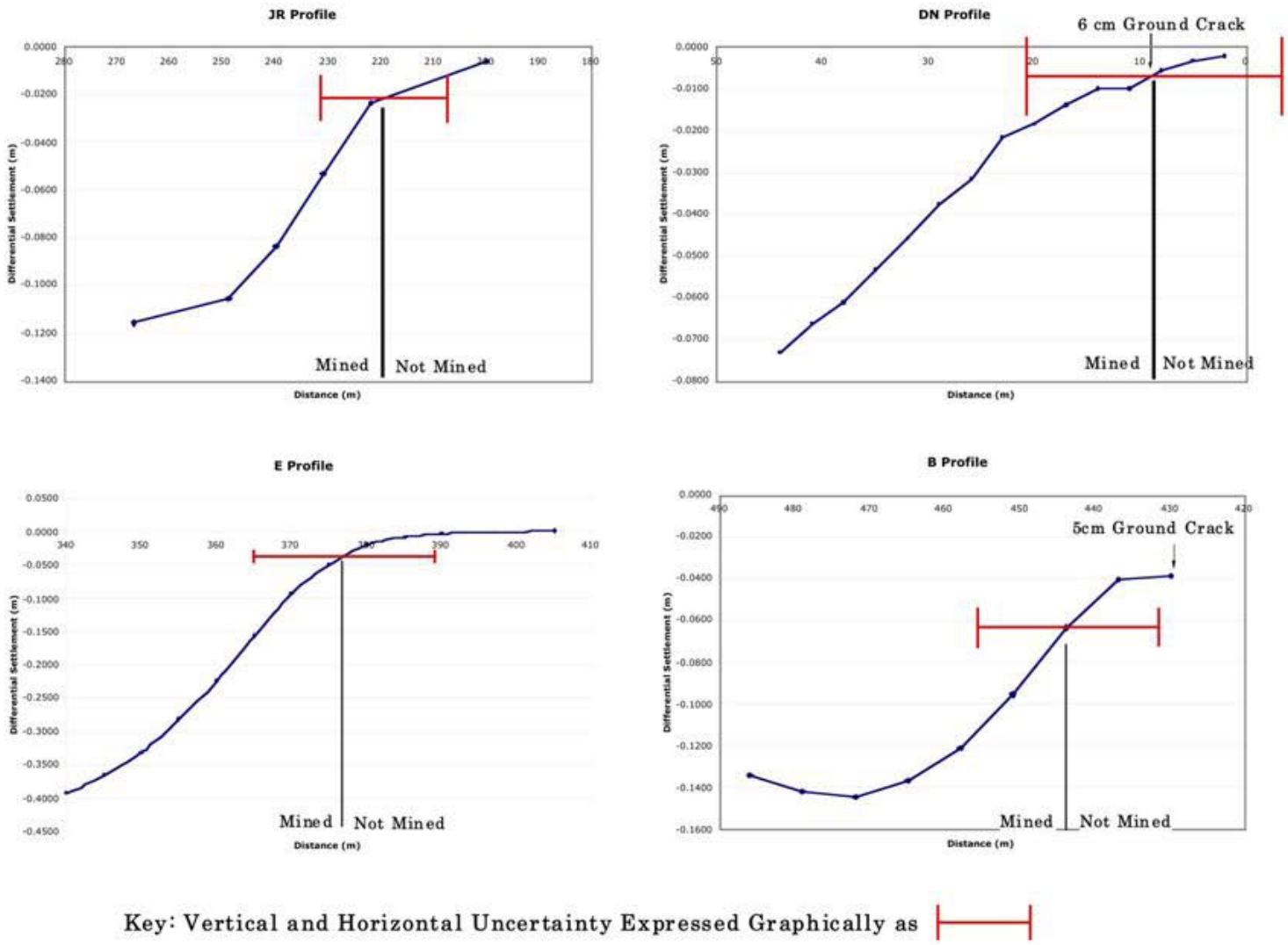

Figure 16. Subsidence profiles and ribside positioning.

Case Examples

Three examples were chosen to demonstrate a range of relative mine map accuracy that is believed to be representative of the total mine map population likely to be encountered in the Illinois map collection. This section is intended to show how the ideas, equipment and procedures described previously were used in subsidence studies and subsidence field investigations, and found useful in evaluating mine map accuracy.

Mine Study Divernon, Illinois. The Madison Coal No. 6 located near Divernon, Illinois was in operation from 1900 to 1925. It used room and pillar mining techniques to extract the Herrin No. 6 Coal seam at a depth of 300 feet below ground surface. This mine was chosen for inclusion in this paper for several reasons. The foremost reason being it was the mine over which DeMaris and Bauer identified subsidence features on aerial photographs as part of their 1983 study. They in turn relied on the work of early researchers who had documented subsidence within the mine as a means of testing their observations. Many of the features identified as subsidence by DeMaris and Bauer in 1983 are still visible on the 1998, 2004 and 2005 DOQ's. In addition, the author has measured ground movements associated with a subsidence event over this mine as well.

Earlier in this report Figure 8 was used to illustrate how a mine map can be examined for clues that may suggest its relative accuracy and precision. Recall that the meeting of entries between 1917 and 1918 without apparent offset was used as an example indicating good map accuracy. Such information alone can only be used as a relative indicator of accuracy and requires supplemental information to confirm the overall accuracy with respect to ground surface. Figure 17 shows the northern part of the mine with known subsidence events plotted relative to the mine workings. For cartographic purposes, only the entry pillars, barrier pillars and reserved coal are shown. As can be seen, each of the four subsidence events, is situated conformably with respect to the mine workings. Of particular importance is the subsidence event located farthest north of the shaft location. This sag was identified through an AML subsidence investigation of damages occurring to several homes and was confirmed as subsidence through level survey measurement of ground movements. Figure 18 shows the approximate location of survey monuments, sag

boundary, and ground settlement (NW Profile) with respect to the mine workings. The data suggests that mine at this location is properly located with respect to ground surface.

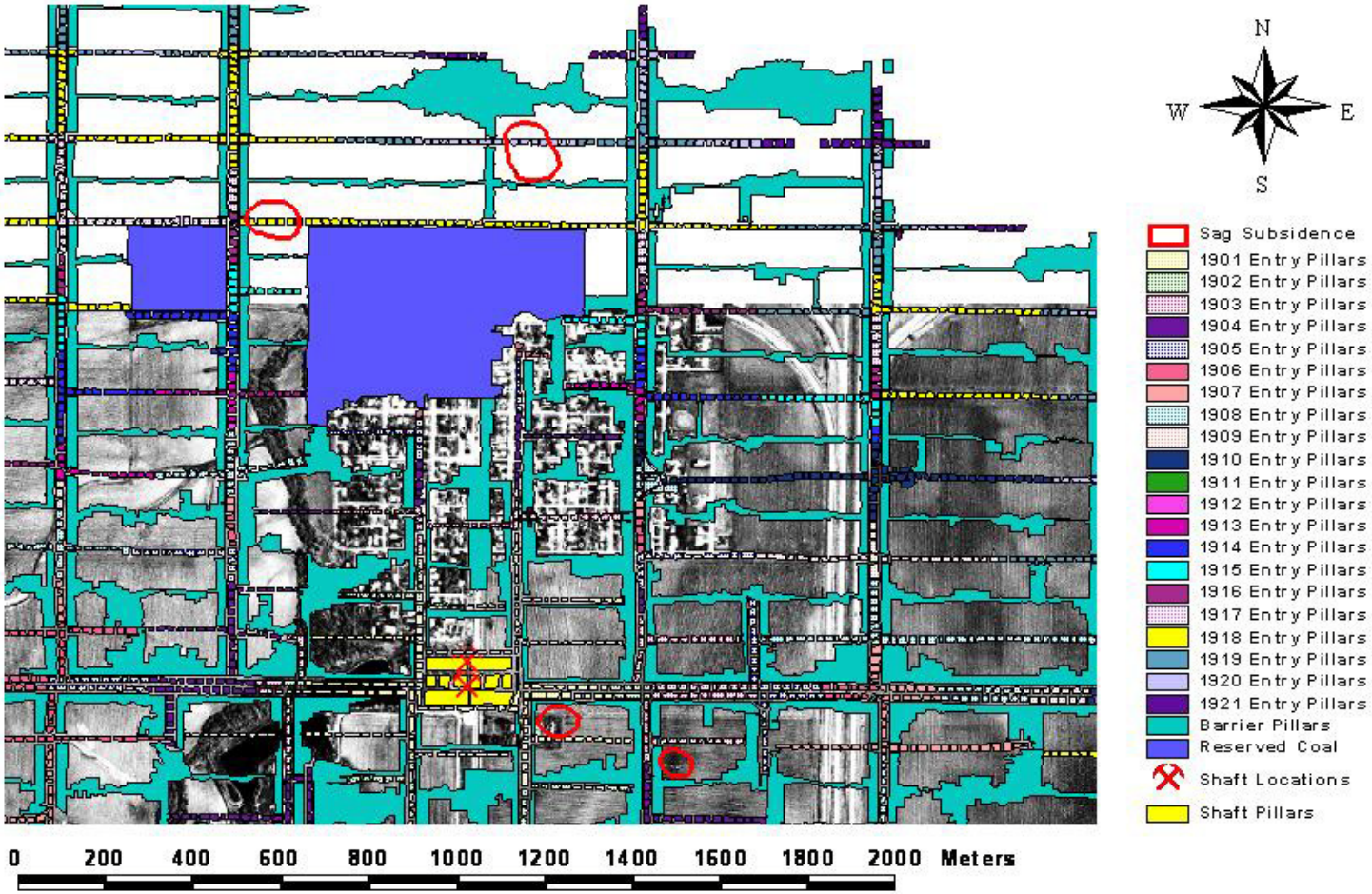

Figure 17. Subsidence events plotted relative to mine development on the north half of the mine. Northern most sag is highlighted in Figure 18.

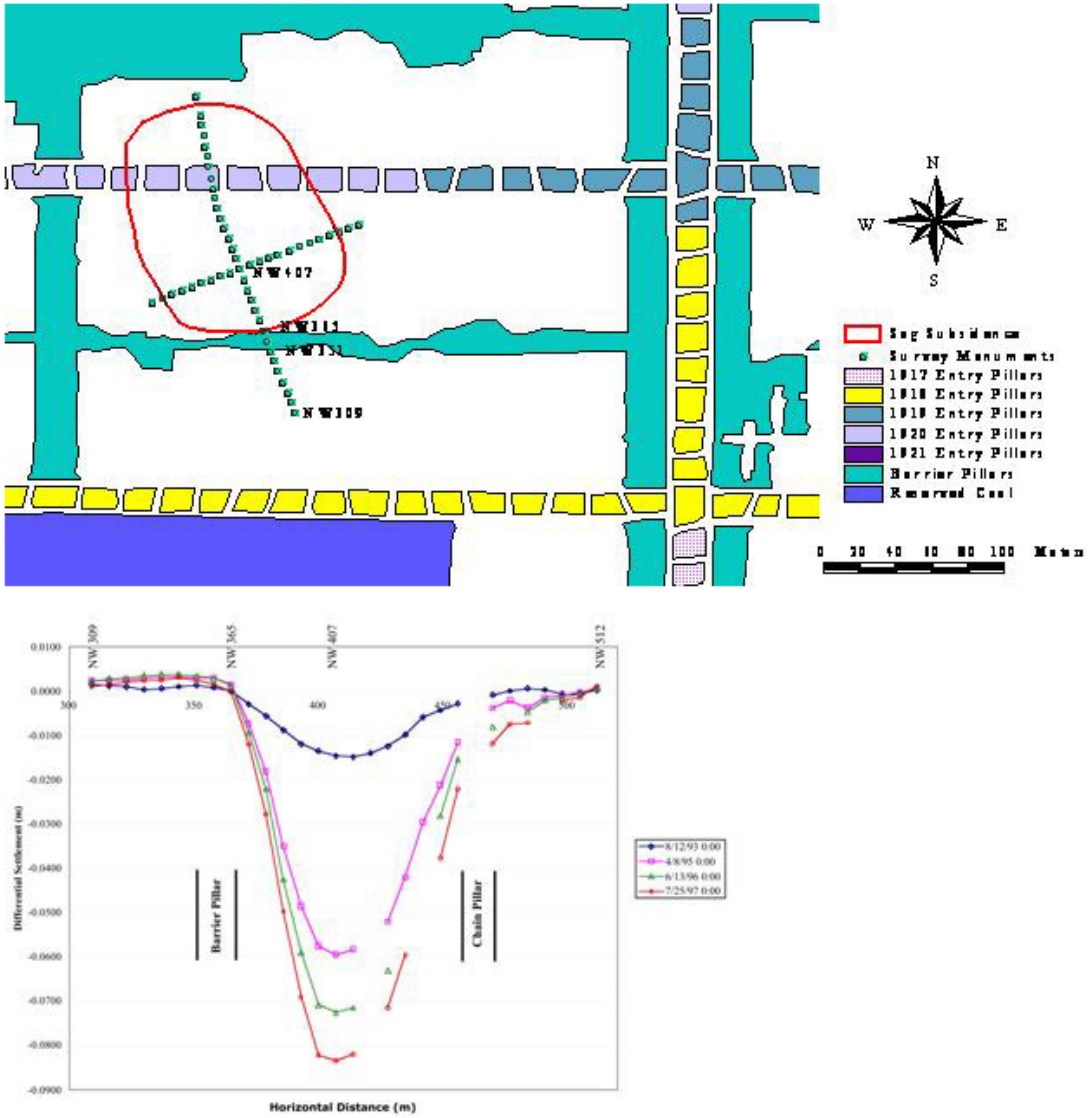

Figure 18. Approximate location of Profile NW with respect to mining. Note the influence of the barrier pillar on vertical settlement and that the 1918 entry pillars shown above are the same of those illustrated and discussed in Figure 8.

Figure 19 is a partially complete composite map that is intended to demonstrate (cartographically) the use of GIS, GPS, aerial photography and survey measurement in validating the location and geometry of mine workings as delineated by subsidence events. The subsidence events outlined in green are those that formed while the mine was active and are indicated on the mine map. Note the subsidence event delineated in purple. According to DeMaris and Bauer (1983) an engineer named J.C. Quade noted the sag in 1934 while conducting field investigations for the St. Louis Federal Land Bank. Figure 20 is a plot of the level survey measurements recorded by Quade and located with respect to the mine works. In 2004, the author traced the bounds of this event using a hand held Garmin Map76 GPS unit. Other sags that are clearly observable on the DOQ were left unmarked intentionally so that the reader can have an unobstructed view of how distinct some subsidence events are on aerial photography. For example note the subsidence events forming in the panels immediately west and to the north of the sag identified by Quade. Given the variety of subsidence information available for this mine and its distribution across the mine, one can reasonably conclude that mine workings as shown on the Madison County Coal Mine No. 6 map are represented accurately and are located correctly with respect to the ground surface.

Subsidence Event Glen Carbon, Illinois. Madison Coal Corporation Mine No. 2 located in Glen Carbon, Illinois operated from 1891 through 1932 mining the Herrin No. 6 coal seam at a depth of 61 meters. Monitoring points were installed and level surveying measurements taken as a means of tracking subsidence related ground movements and the concomitant damages to homes. Figure 21 shows the layout of the monitoring points, ground cracks, and sag boundary with respect to the mine workings. Also included in the figure are the subsidence profile measurements through time.

On the upper part of the diagram the sag boundary, as of November 17, 2005, was drawn based on survey data and GPS ground crack locations collected very early in the event. The profile data and ground crack information are conformal with the mine geometries in that the sag boundaries are temporarily constrained by the mine entry on the west and the large barrier coal on the east. Close examination along the west side of the profile near station DN122 shows that the end point

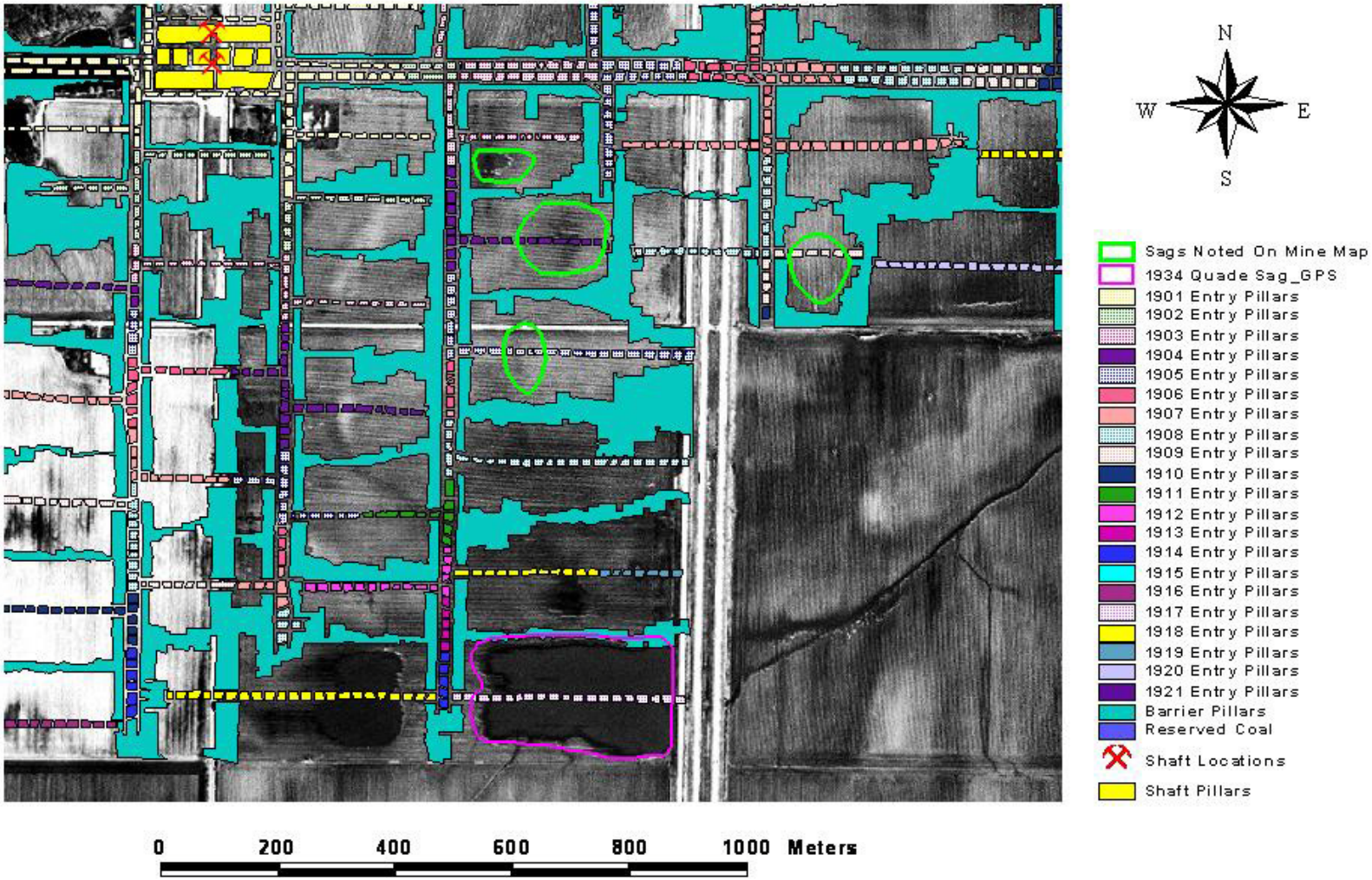

Figure 19. Shown are subsidence events, GPS measurement and mine workings plotted relative to a 1998 DOQ. Subsidences shown in green are those identified by the coal company while the mine was active (pre-1925). Subsidence shown in purple, was identified by J.C. Quade (Figure 20) in 1934 and re-mapped by the author in 2004 using GPS.

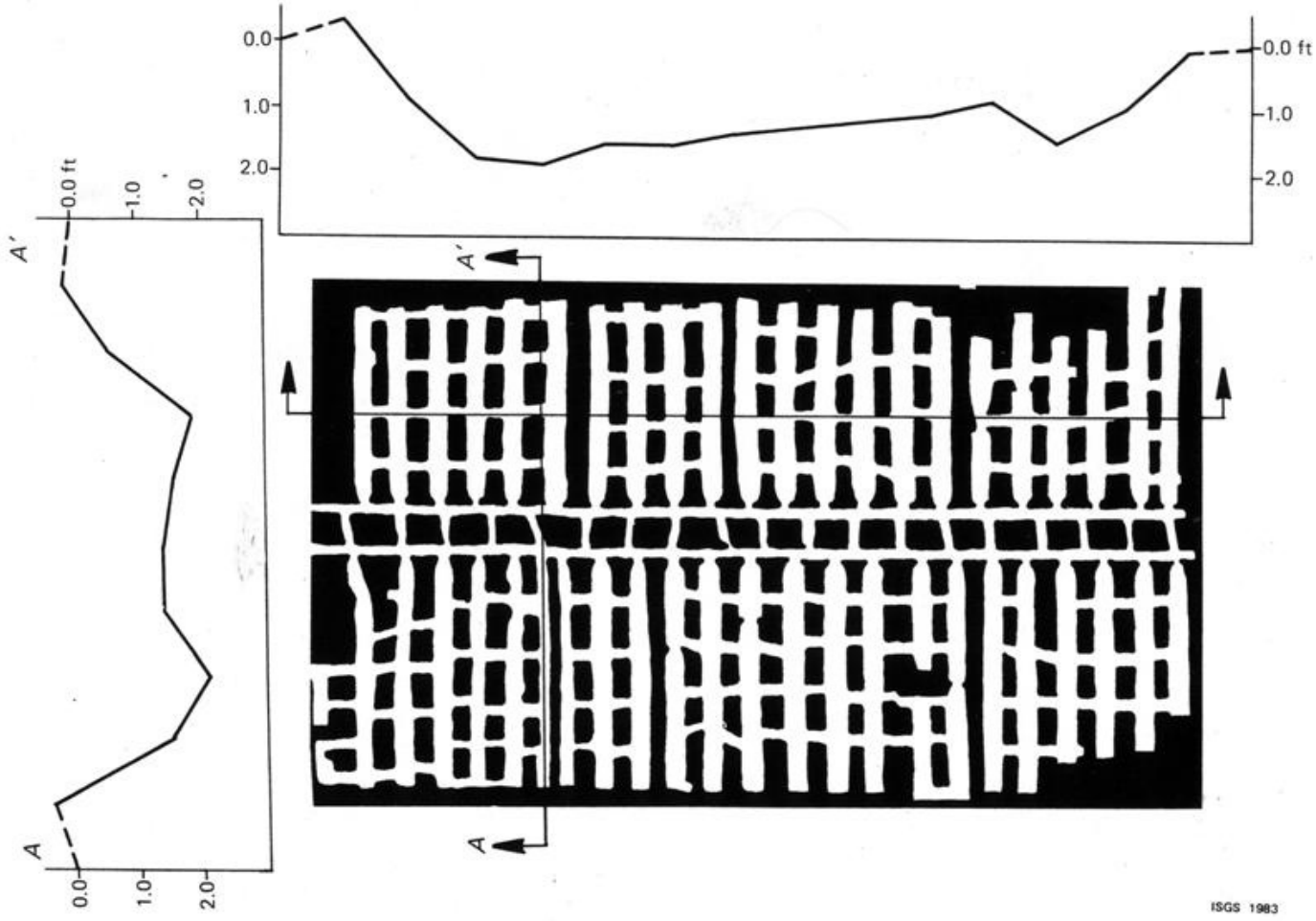

Figure 20. "Map and subsidence profiles of production panel in No. 6 Mine of the Madison Coal Corporation based on survey by Quade, 1934." (DeMaris and Bauer, 1983).

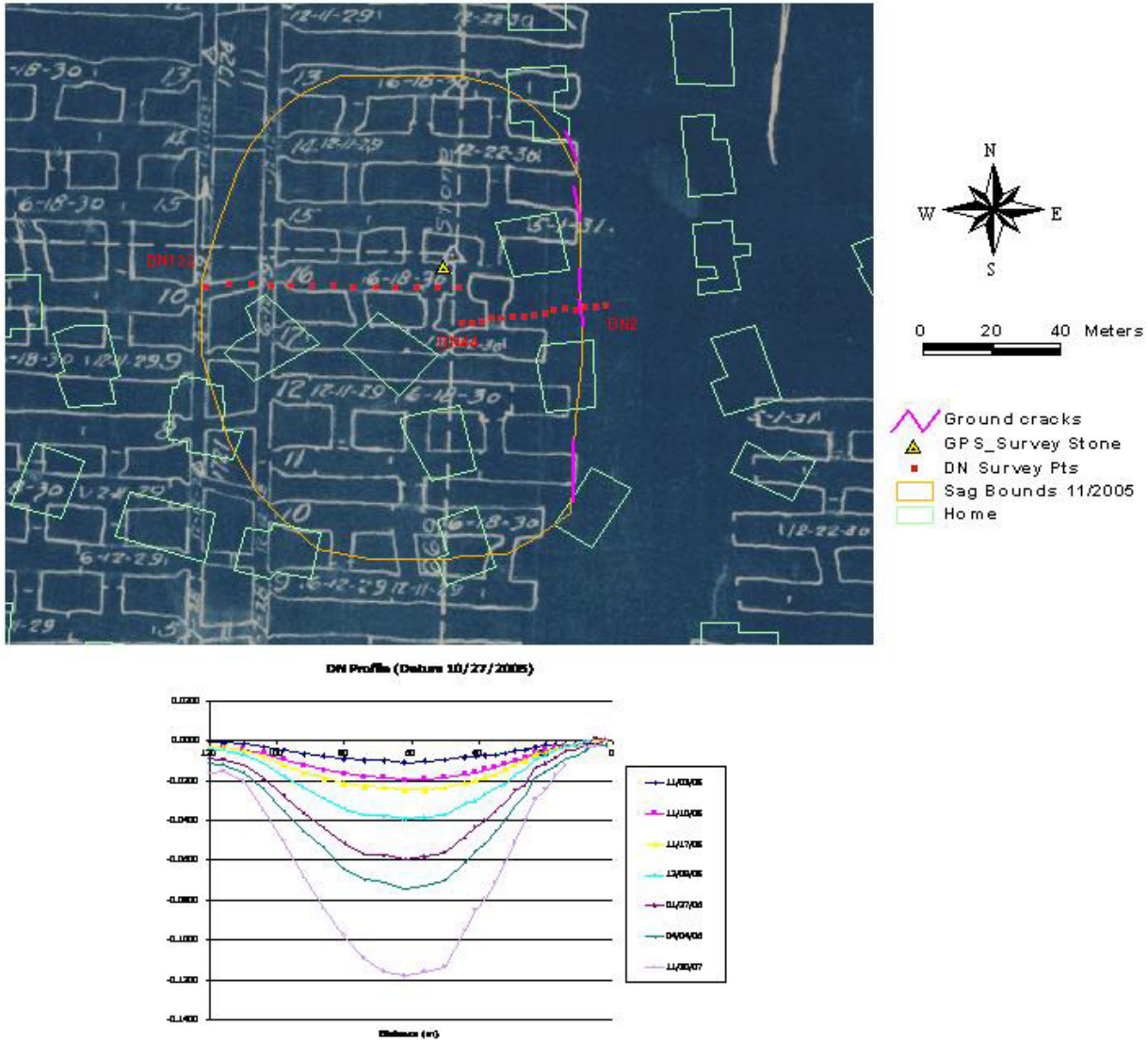

Figure 21. GPS measurement of ground cracks and DN Profile survey monuments plotted relative to a geo-rectified mine map. The differential vertical settlement measured along Profile DN is shown at the same horizontal scale as the mine map to facilitate direct comparison.

is slowly dropping. Such small movements, at or near error in measurement, are interpreted as indicating pillars yielding at mine level and are sometimes precursors to eventual large ground settlement associated with progressive failure. In this case, the entry pillars are of insufficient size to prevent westward expansion of the sag at a later date. The sag expands to the north, west and south, whereas the east boundary coincident with the barrier coal (ribside) remains fixed. An enlarged view of the east side of Profile DN with respect to ribside was shown earlier in Figure 16. Also note the close agreement between the GPS measurement and "Stone" location shown on the mine map. It is the same location shown earlier in Figure 12. The subsidence data gathered for this case indicates the mine geometry and its location with respect to ground surface is good. In practical terms, those homes shown to be located on the large barrier pillar to the east should not experience subsidence damage.

A second subsidence event located 1,800 meters to the southwest indicates that the mine map contains inaccuracies or that it is not geo-rectified correctly across the entire mine. Figure 22 shows the location of the survey monuments , ground cracks and subsidence profile information and is plotted with respect to the mine workings. The B profile was described and analyzed earlier in this report. The size and shape of the subsidence event is consistent with the mine geometry as shown on the map when the complete mine history for this particular panel is known. In 1977, the west side of this panel subsided and a very sharply defined tension crack extended north/ south through the center of the home as shown in the figure. The boundary of the 1977 event is inferred from structural damage to the homes. Whereas, B Profile represents an ongoing subsidence event that is forming over the east half of the panel, again the tension zone extends north/south through the west side of the home only this time the direction of movement is to the east. The boundary of the 2006 event is based on ground crack location and level survey measurement with horizontal control established via GPS measurement. Based on the subsidence damage that has occurred to this home through time, it seems likely the home is centered over the panel entry. Suffice it to say, from the survey data and home damage patterns, there is an apparent offset of the mine working relative to ground surface on the order of 6 to 9 meters. One possibility is that the offset represents 'drift' in the horizontal control of the original mine survey. A second possibility includes map distortion during the geo-rectification process. In this part of the mine, there are few features common to the mine map and USGS topographic map.

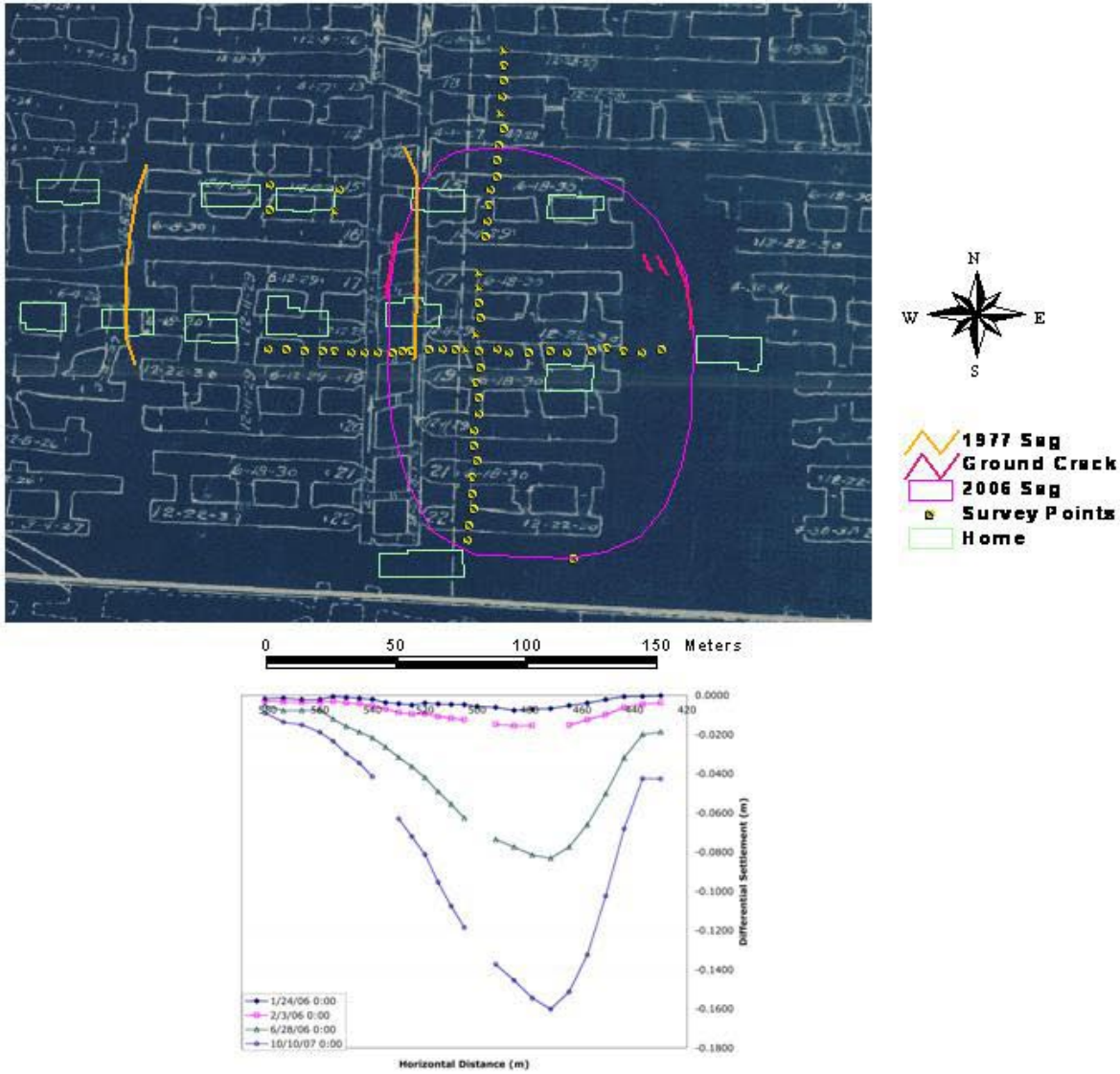

Figure 22. The boundary of two subsidence events, ground cracks, homes and survey monitoring points plotted relative to mine workings

Further the area is a wooded and rugged terrain (from an Illinoisan' perspective) factors that may have introduced horizontal control errors in the top survey layout. Until additional subsidence information is accumulated, a definitive answer is not possible. Until then, the tentative evaluation of this mine in terms of mine geometry and surface registration is suspect but judged overall to be fair to good.

Subsidence Event Shiloh, Illinois. The Saint Ellen Mine operated from 1904 to 1960 mining the Herrin No. 6 Coal seam. The Herrin Coal is nearly 2.4 meters thick and lies at depth of 76 meters below ground surface. The author has accumulated only limited data for this mine thus far, so discussion will focus on one particular panel that is currently experiencing subsidence and its implications.

The panel in question is located near the southeastern most extent of the St. Ellen Mine, nearly 5.5 kilometers from the main shaft. The initial subsidence event formed in July 2006 and was approximately 185 x 270 meters in diameter. Progressive failure was evident early on and the event expanded rapidly to the west -northwest and is now nearly 185 x 360 meters in diameter. Extensive damages have been sustained in 32 structures, many of which are duplex homes. Figure 23 shows the bounds of the subsidence event at three distinct time periods. Lately, the event appears to have stabilized in that the outermost boundary has remained in its current position for nearly 6 months while the large area contained within the bounds continues to settle. From a practical perspective, AML personnel (and nervous homeowners) are concerned that the subsidence event will expand yet even further. Nineteen additional homes located immediately west and northwest of the existing sag boundary may be threatened. A second related concern is whether the barrier pillar between panels really exists and whether it is of sufficient size to prevent the current subsidence event from overriding it and progressing into the adjacent panel to the south over which numerous homes are located. Through experiential observation of numerous subsidence events having formed over mines less than 106 meters deep, the author has yet to confirm an instance where a sag type subsidence event has overridden a barrier pillar equal to or greater than 24.4 meters in width. It is the author's belief that adjacent panels separated by large barrier pillars will eventually subside as well, but the evidence gathered thus far suggests

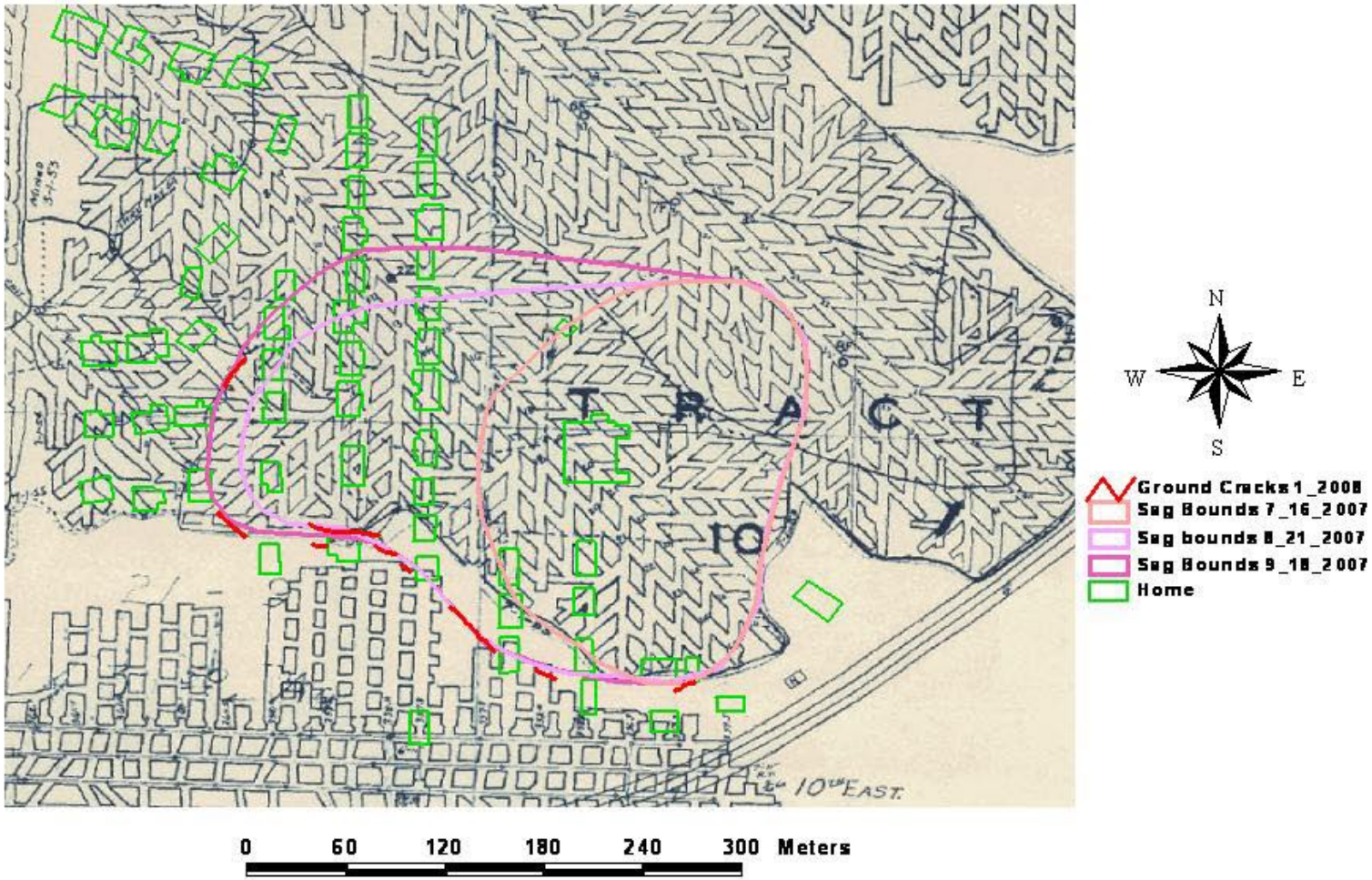

Figure 23. Example of progressive mine failure causing damage to numerous homes and potentially threatening many more.

that there is a significant time interval between events implying causative factors other than simple load transfer.

Figure 24 shows the GPS measurement of significant ground cracks plotted relative to the geo-rectified mine map. Also included on the figure are the relative locations of survey monuments established for profile EG and a plot of the surface settlement. Several observations can be made at this time. First, there exists a fairly large and continuous system of ground cracks that are offset by approximately 45.7 meters but otherwise parallel to the general shape of the south boundary of the northern panel. These cracks range from 4 to10 centimeters in width and are more or less continuous over a horizontal distance of nearly 330 meters. Second, the survey monuments were intentionally laid out to cross over the barrier pillar and extend well out over the southern panel. The distribution of survey monuments was to measure the magnitude of subsidence, verify the location of the barrier pillar and to determine whether the barrier pillar was sufficiently large to accommodate the presumed increased loads imposed upon it without yielding. We also wanted to know if the south panel was showing any signs indicating impending failure. The level survey measurements indicate that subsidence related ground movements terminate abruptly a short distance beyond the ground crack without any apparent movement occurring over the south panel. Given that such cracks typically form at or near ribside it would appear that the general shape of the panel and its orientation is more or less correct, simply offset in its position relative to ground surface. Finally, the position of the road shown on the mine map is conformal with its position as shown on the topographic map suggesting that the source of error is not associated with the geo-rectification process but rather in the mapping of the mine (Figure 25). The reader has probably noticed the difference in mining pattern between the north and south panels. The difference in mining technique reflects a change in mine ownership. Whether the subsequent mine owner attempted to verify the mine survey accuracy of the northern panel or simply accepted its map positioning is unknown. The relative position between the north and south panels may not have been particularly important at the time of mining but has practical importance now in that the barrier pillar may not be as large as shown on the map. Thus far, the survey data suggests that coal left in place is sufficiently large and strong to accommodate the load transfers that may be occurring and that progressive failure into the south panel is deemed unlikely.

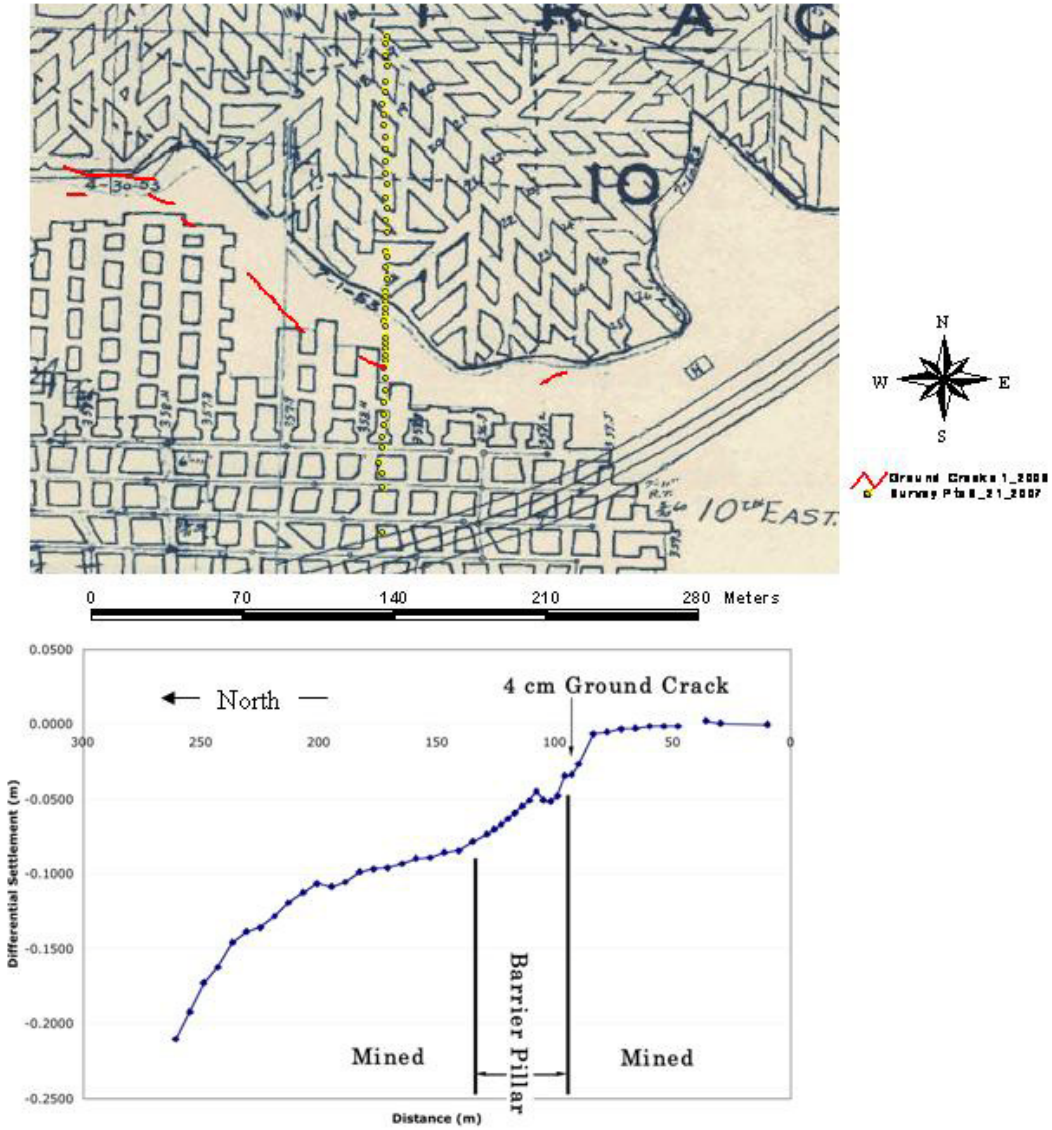

Figure 24. Large ground cracks, survey monuments and differential settlement Profile EG located relative to geo-rectified mine workings. Crack location and settlement data indicate that the mine workings are improperly located with respect to ground surface.

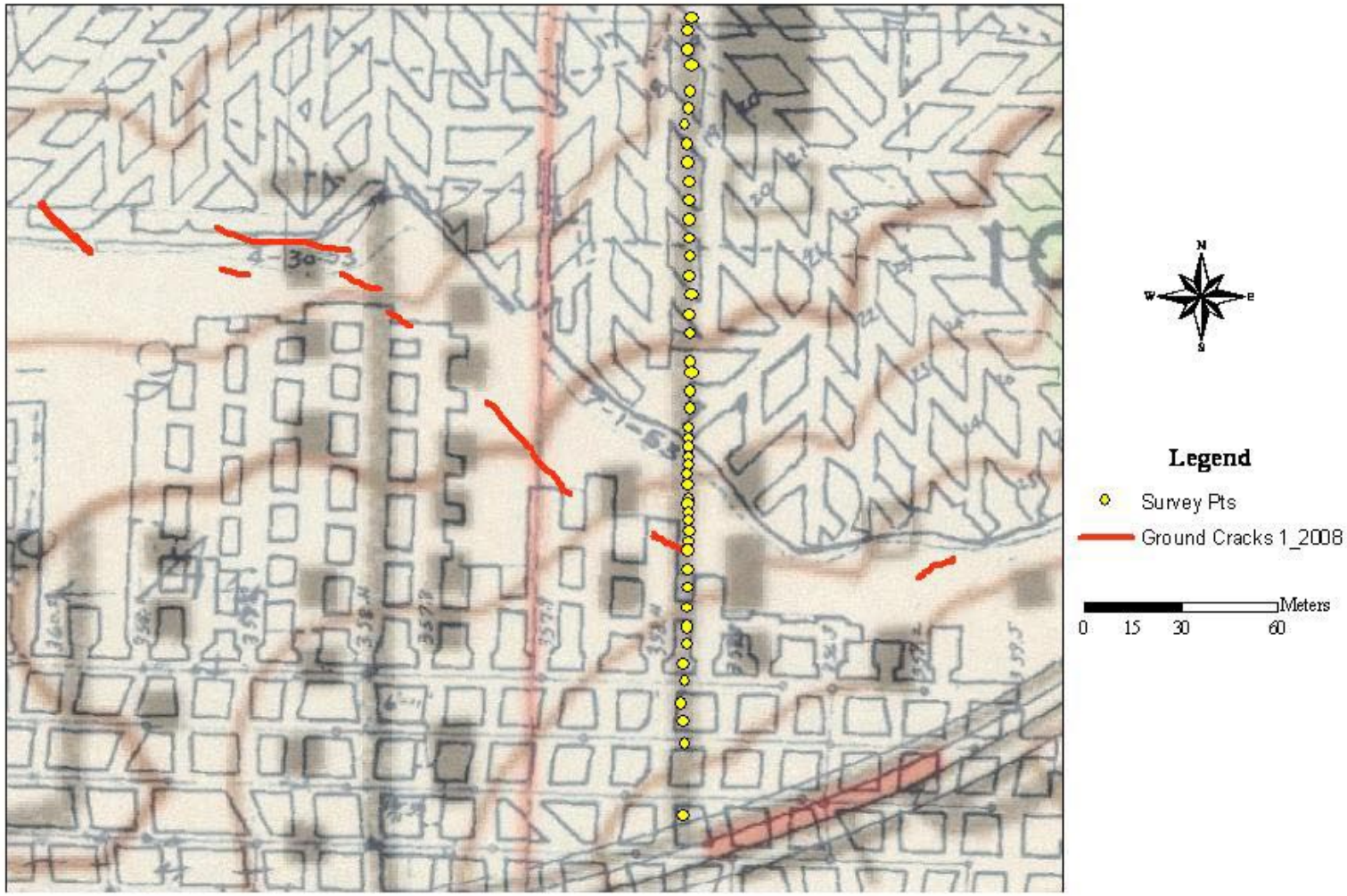

Figure 25. Ground cracks, Profile EG survey points, and geo-rectified mine map positioning with respect to the reference topographic map.

Summary and Conclusion

There is no simple direct means known to the author of determining the accuracy and precision of abandoned underground mine maps and their absolute position with respect to ground surface short of conducting an extensive drilling program and/or drilling coupled with geophysical testing. There are, however, techniques that can be employed that will allow one to determine with some measure of confidence the relative accuracy of a mine map both in terms of its pillar geometry and its position with respect to ground surface.

It has been shown that with GIS technology, a mine map can be associated with a suitable surface map provided there are sufficient point locations common to both maps. Further, the point locations common to both the underground mine map and the surface reference map can be measured with GPS thereby providing at least a partial check of the accuracy and precision of the geo-rectifying process. In most instances, there are insufficient points in common to completely confirm mine map geometry and its surface registry. However, additional information can be obtained about the mine map by plotting characteristics of sag type subsidence with respect to the mine workings.

The surface area affected by sag type subsidence is nearly coincident with the area of failure occurring within the mine. In some instances, subsidence locations can be identified using aerial photography. Subsidence is readily identifiable on aerial photography when it forms on flat low-lying areas with a high ground water table and low permeability soils. Whereas subsidence is harder to identify on aerial photography when it forms in areas of uneven terrain, high permeability soils or in highly developed urban areas. Expert interpreters of aerial photography, using high resolution images taken at opportune soil moisture conditions, may be able to identify subsidence even in rugged terrain.

Direct field measurement is the most reliable means of establishing that subsidence has occurred. Repeated level survey measurement of established monuments allows one to distinguish the boundary between subsiding and non-subsiding areas. In some instances subsidence boundaries are also delineated by ground cracks. Early researchers have shown that vertical settlement

rapidly decreases to zero and ground cracks frequently form at or near large blocks of coal. GPS can be used to establish horizontal control thereby allowing accurate positioning of survey monuments and ground cracks with respect to a geo-rectified mine map. Together, vertical and horizontal measurements of subsidence characteristics provide an opportunity to confirm mine geometry, particularly when there are large coal pillar remnants such as barrier pillars present.

Collectively, the point and area measurements mentioned above provide insight into mine map accuracy, map completeness and mine location relative to ground surface. Naturally, confidence in the mine map is proportional with the quantity of data collected and the evenness with which the data is distributed across the mine. Each new subsidence event provides additional data (point and area information) and affords yet another opportunity to validate the mine map. Subsidence occurring off the mine map provides warning of either map incompleteness or the presence of unknown or unmapped mining activity. Regardless, in many instances assessment of mine map accuracy and its location relative to ground surface can often be reasonably made. Such information is important when siting surface developments and new mines.

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