

Appendix L - Subsidence Data

Information was obtained from the U. S. Geological Survey (USGS) that defined the extent of surface deformation above the accident site. USGS scientists use radar satellite images (interferometric synthetic aperture radar or InSAR) to measure small movements on the earth's surface for their research on volcanoes, earthquakes, subsidence from groundwater pumping, and other ground disturbances from natural and man-made causes. The technique has been used in Europe to study mining subsidence since 1996, but its use has been limited in the U.S. coal mining industry. USGS applied this technology in the vicinity of the Crandall Canyon Mine and were able to identify an extensive subsidence region associated with the August 2007 accident. Neva Ridge Technologies (Neva Ridge) was contracted to verify the USGS study. The Neva Ridge report is provided in Appendix M in its entirety.

InSAR Surface Deformation

The InSAR deformation measurement technology relies on bouncing radar signals off the earth from satellites orbiting over the same area at different time periods. By studying the differences in the images, InSAR can detect small changes in the distance to the ground surface relative to the satellite. InSAR detects very small movements that can not be visually noticed. InSAR shows patterns of deformation as color bands with each band representing a few centimeters (cm) of movement. The following figures from the USGS publication "*Monitoring Ground Deformation from Space*" illustrate the use of the InSAR technology. Figure 96 depicts the orbiting satellites scanning the surface of the earth with transmitted radar waves bouncing back to the satellite.

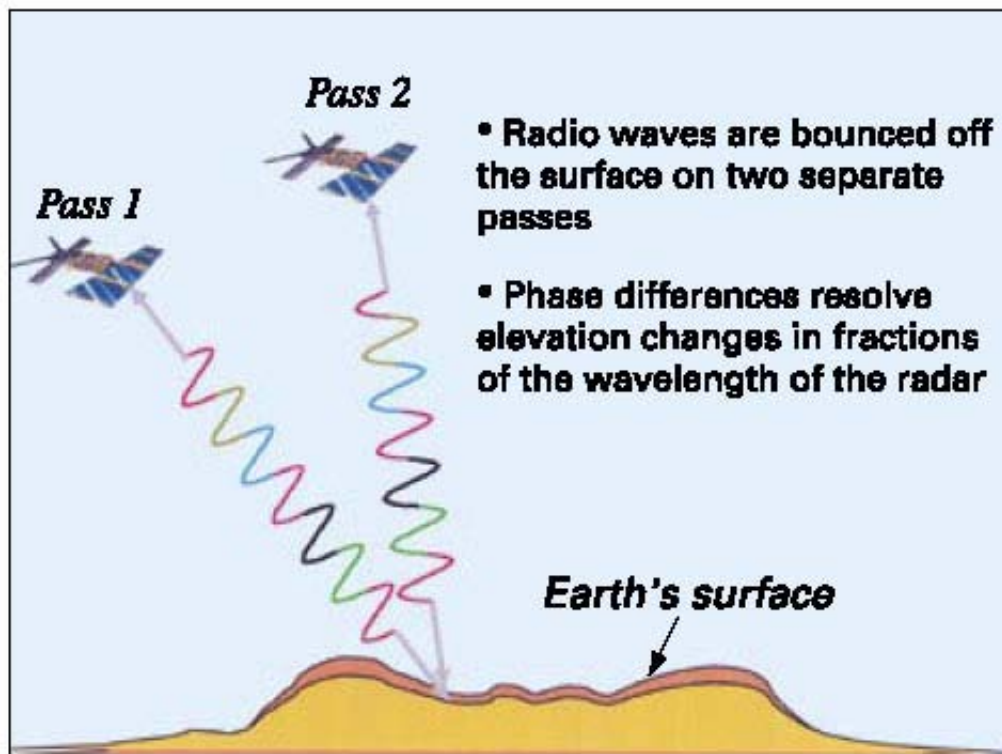


Figure 96 - How Satellites and Radar Interferometry Detect Surface Movement
from USGS Fact Sheet 2005-3025

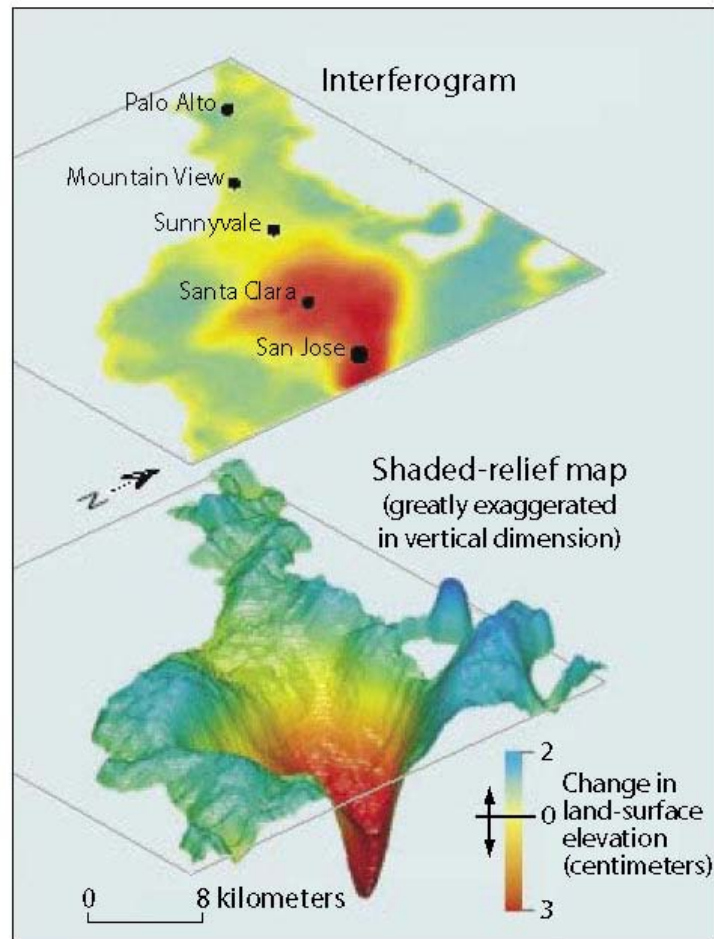
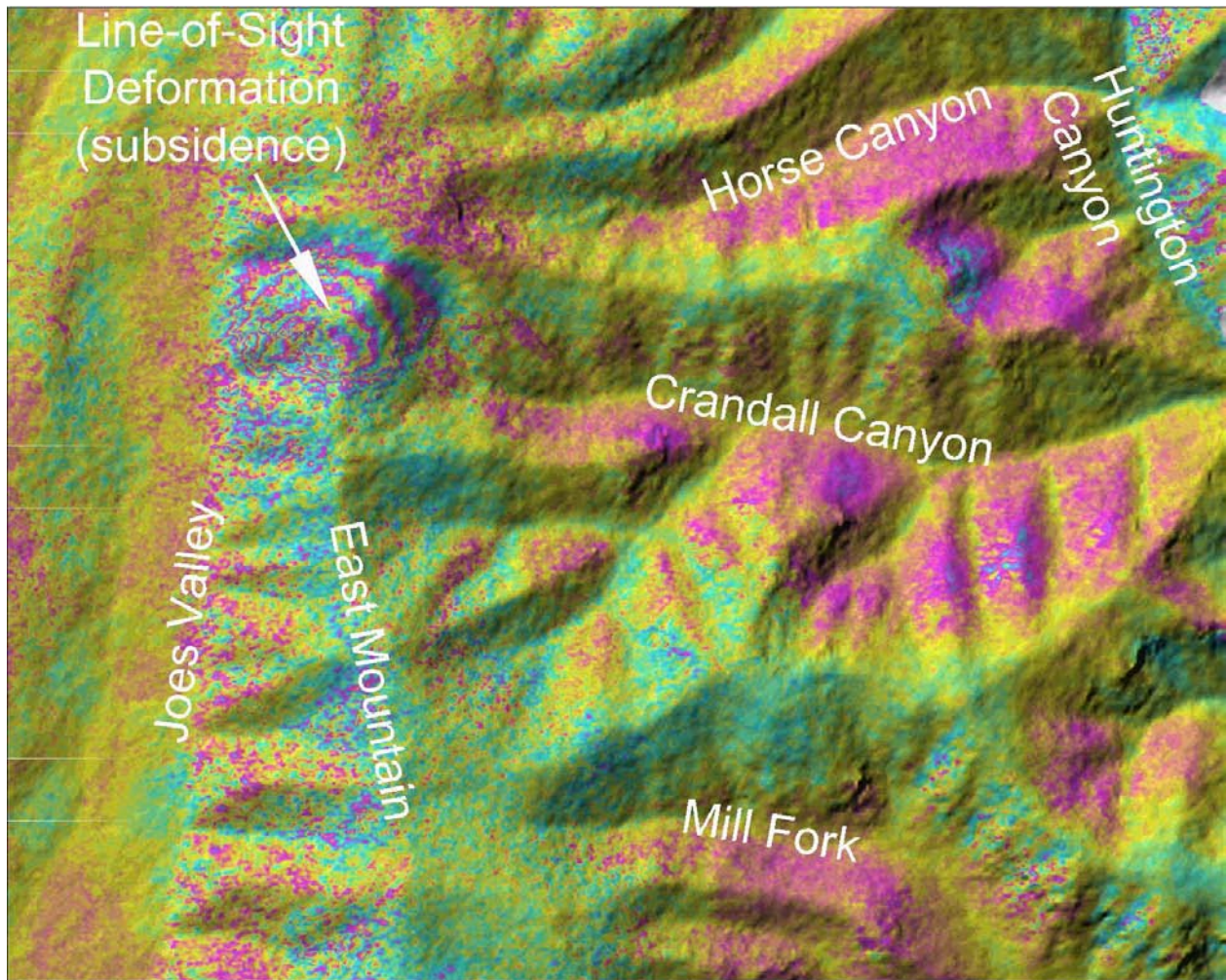


Figure 97 – Example of Interferogram Color Banding from USGS Fact Sheet 2005-3025

The radar images are processed to determine deformation. Figure 97 is an example from California showing the interferogram color banding generated from an InSAR analysis that depicts regional subsidence and localized uplift. Included in Figure 97 is the topographic detail of the subsidence and uplift for the study area with the vertical scale exaggerated.

Crandall Canyon Mine InSAR Surface Deformation.

There are only a limited number of InSAR images over the Crandall Canyon Mine area. The USGS identified a Japanese ALOS PALSAR satellite scan for June 8, 2007 (before the accident) that covered the Crandall Canyon Mine reserve area and another satellite scan on September 8, 2007 (after the accident). InSAR analysis of the radar imagery between the June and September time periods generated the InSAR deformation image shown in Figure 98. The image identifies a region of subsidence centered on the west flank of East Mountain in the vicinity of the Crandall Canyon August 2007 accident sites. Figure 98 shows the terrain surrounding the mine area, with nearby valleys identified for geographic reference. The Line-of-Sight (LOS) deformation in Figure 98 represents subsidence movement measured in a non vertical direction from the satellite. In the USGS analysis, the deformation is measured along a LOS of 39.7° from vertical. The InSAR images were processed and provided by a staff scientist of the Radar Project of Land Sciences at the USGS Earth Resources Observation and Science Center.



**Figure 98 - USGS InSAR Image of Subsidence above the Accident Site.
The surface deformation depicted occurred between June 8, 2007, and September 8, 2007.**

The InSAR image furnished by USGS was referenced by latitude and longitude, allowing conversion into state plane coordinates. The accident investigation team translated and rotated the InSAR image onto the Crandall Canyon Mine coordinate system using known state plane and corresponding mine local survey points. The InSAR deformation image with 5 cm color banding was contoured by the accident investigation team with some guidance from USGS to delineate the ground surface subsidence (see Figure 99).

The displacement contour values are Line-of-Sight (LOS) from the satellite. In Figure 99, maximum LOS subsidence contour is 20 cm (approximately 8 inches LOS). Each repetition of the color band (i.e., sequence of rainbow colors) represents 5 cm of LOS deformation with the repetitive color banding indicating successive 5 cm increments of movement. Mining subsidence is typically vertical; therefore, LOS subsidence values are multiplied by 1.29 ($1/\cos 39.7^\circ$) to determine vertical deformation. Consequently, the 20 cm LOS deformation contour converts to approximately 25 cm (approximately 10 inches) vertical surface subsidence. The movement is significant but, at a magnitude that cannot be detected visually on the mountainside.

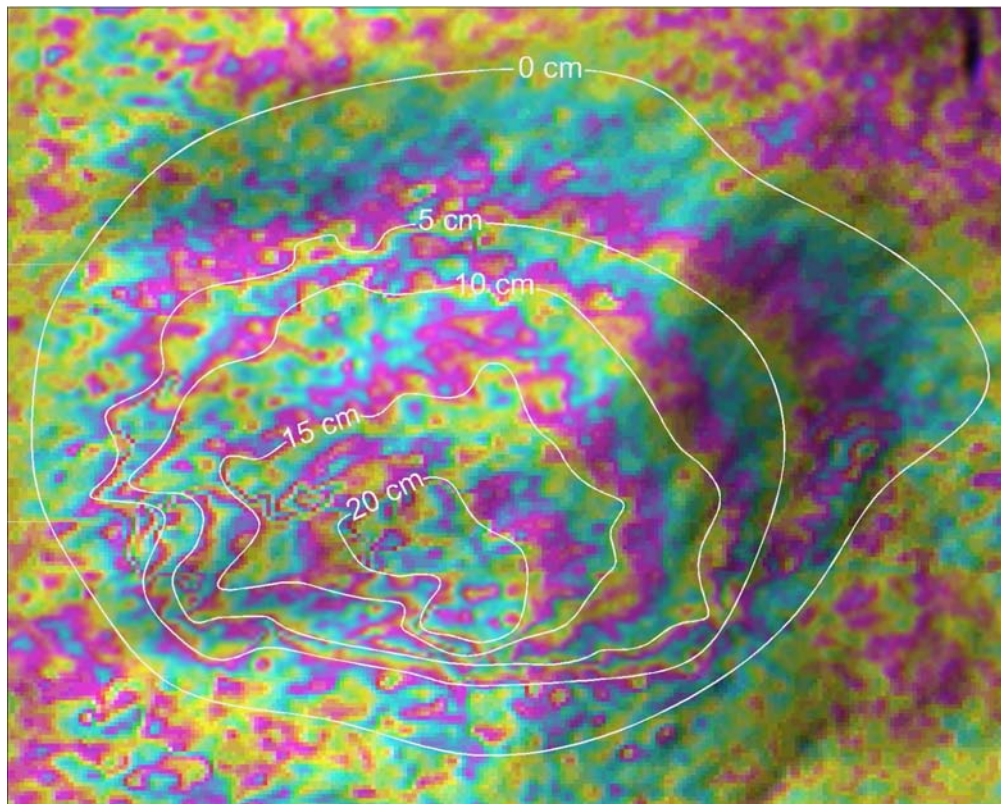


Figure 99 - Surface Deformation from USGS InSAR

Color banding contoured to delineate Line-of-Sight successive 5 cm subsidence movement. Maximum LOS movement of 20 cm (~8 inches) contoured.

The analysis performed by Neva Ridge included a contoured map of 5 cm vertical subsidence contours. The contoured map is included as Figure 100 below.

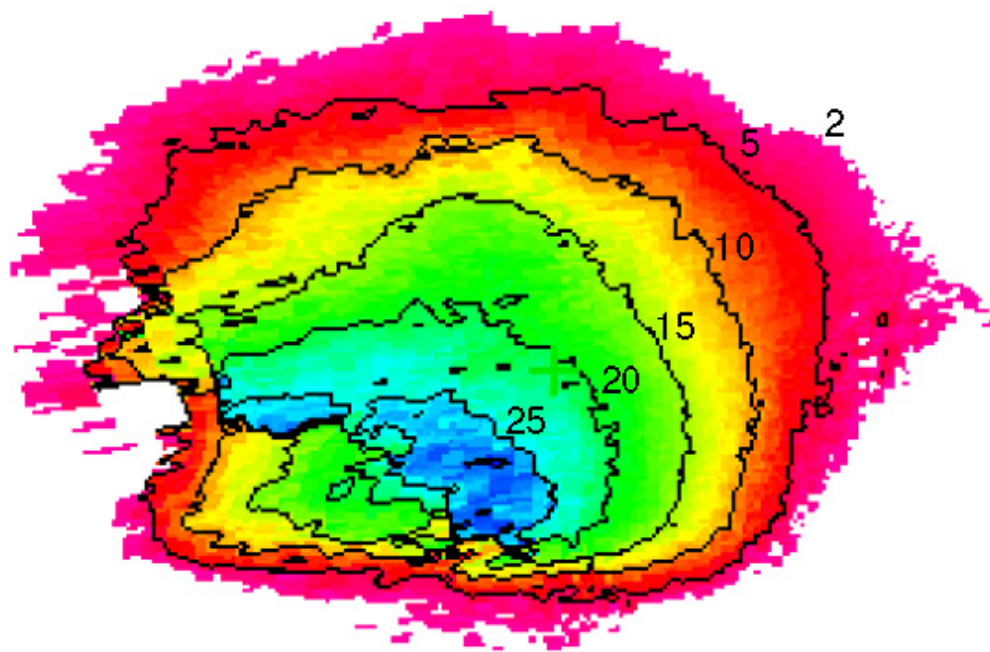


Figure 100 - InSAR Vertical Subsidence Contours (cm) from Neva Ridge

The contours on the USGS results were converted to vertical values and overlain on the Neva Ridge results for comparison. All measurements less than 2 cm were considered noise by Neva Ridge and removed from the map. The comparison of the two results is shown in Figure 101. The results are very similar except for the south-west portion of the depression. Tracing the contours of the USGS image was very difficult in this area due to the rapid rate of change, making it challenging to follow the color banding in Figure 99. The uncertainty in this area was a factor in retaining an independent analysis. The Neva Ridge contours developed by experts in InSAR analysis were therefore used throughout this report. The Neva Ridge InSAR surface subsidence contours were overlain onto the mine workings and identify a wide spread subsidence basin with the 25 cm (10-inch) vertical subsidence contour centered within the South Barrier section, roughly between crosscuts 133 and 139 (see Figure 31).

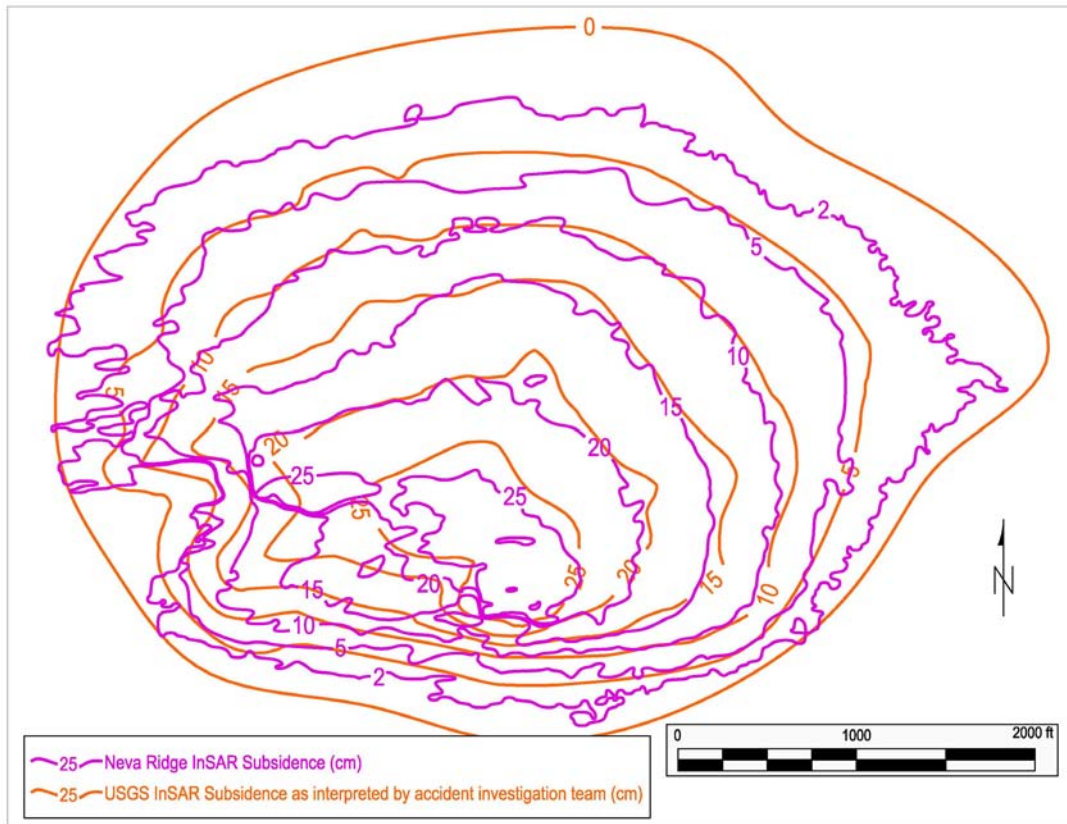


Figure 101 - Comparison of Vertical Subsidence from Interpreted USGS and Neva Ridge InSAR Results

The geometry of the InSAR surface subsidence depression indicates that the Main West and North and South Barrier sections have undergone extensive pillar failure. The knowledge that surface deformations radiate around collapse regions was used to extrapolate the extent of damage into adjoining regions that could not be traveled or investigated. Subsidence principles suggest that the extent of the collapse at seam level would be less laterally but greater vertically than the surface expression implies. The development of bed separations and other openings within the overburden can cause surface subsidence to be less than the full height of closure at mine level. Conversely, the collapse at mine level will draw the overburden downward with subsidence deformations radiating outward and laterally over an area greater than the collapsed area. Although subsidence research has primarily focused on full extraction mining, it is reasonable to expect that strata will respond similarly to a pillar collapse.

InSAR analyses were performed using satellite images from December 2006 and June 2007 specifically to determine if surface subsidence had been associated with pillar recovery in the

North Barrier section. No subsidence was detected. However, it is possible that subsidence occurred but the deformation was too small to measure or it was masked by ground surface conditions. December radar scans would be affected by snow cover and June's radar scans would not. Snow cover tends to generate data scatter (noise) that interferes with InSAR analyses.

InSAR Validation with Longwall Subsidence Monitoring Data

In 1999, a subsidence monitoring line was established on the north-to-south trending ridge of East Mountain. The survey line over a portion of Main West and Panels 13 to 17 was monitored from September 2000 to July 2004 by Ware Surveying, LLC (surveying contractor) using GPS survey technology. Surveys were performed using a Trimble GPS Total Station 4700 and Real Time Kinematics processing. The vertical accuracy of these surveys was reported to be ± 0.2 -foot (roughly ± 6 cm). The survey monuments were 5/8-inch rebar driven into the ground.

Surface monuments were resurveyed on August 17, 2007, along the portion of the line from the center of Panel 14 to just north of Panel 13. These GPS subsidence measurements are the only reliable information available for comparison with the InSAR analyses. On August 17, six of 16 survey stations had been destroyed in the area of interest. However, some of the remaining monuments lie within the deformation crater identified using InSAR. The northern end of the survey line terminates along the 20 cm (8-inch vertical) deformation contour. The southern portion of the line lies outside of the 2 cm vertical subsidence contour (see Figure 102).

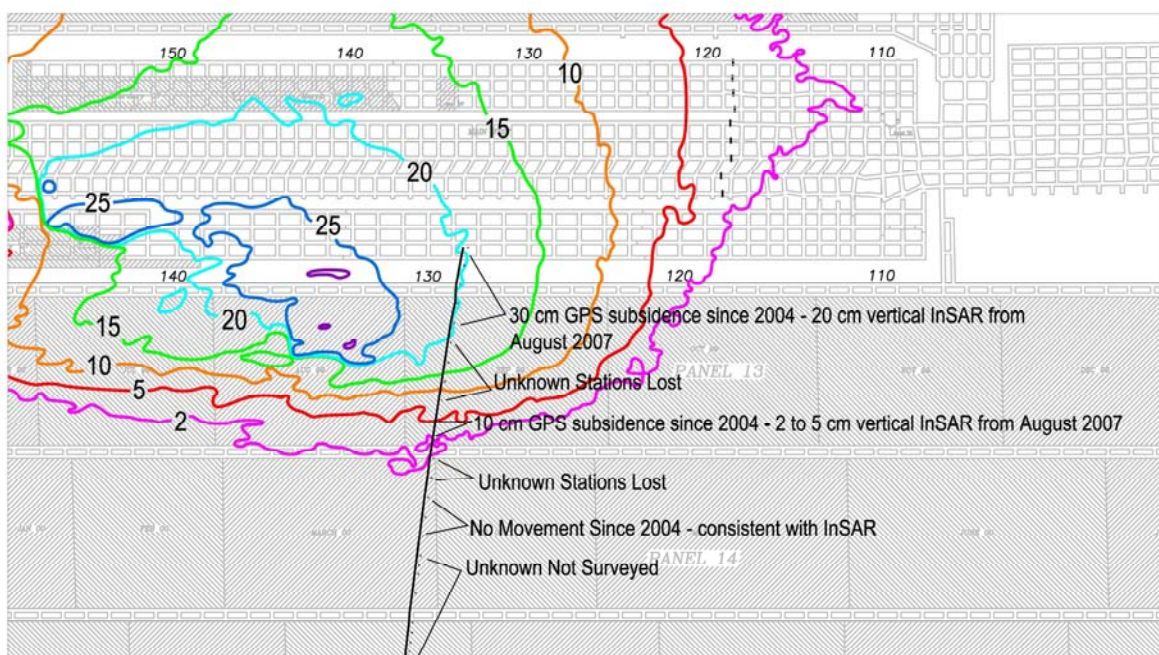


Figure 102 - InSAR Vertical Subsidence Contours & GPS Subsidence Line Data

Three stations near the southern end of the survey line showed no movement since 2004; this observation is consistent with the InSAR analysis in this area (see Figure 102). Two survey stations which showed approximately 10 cm of vertical movement (since 2004) were located within the 2 to 5 cm InSAR vertical deformation contours. Five stations at the northern end of the survey line showed 30 cm of vertical movement (since 2004) although they were located along the 20 cm InSAR vertical deformation contour.

InSAR provides a more reliable characterization of surface subsidence associated with pillar recovery in the South Barrier section since it only captures movement that occurred between June and September 2007. GPS survey data incorporates deformations that occurred over a longer time period between 2004 and August 17, 2007. For example, the five northern stations of the survey line showed remarkably similar displacements between 2004 and 2007 (i.e., 29 to 33 cm). These stations are situated near the edge of Panel 13 and the original unmined South Barrier. The data suggest that this area subsided gradually over the years between 2000 and 2004. It is possible that some amount of residual longwall subsidence and variations due to surveying precision (± 6 cm) account for the 10 cm difference between the InSAR and GPS survey data.

Longwall Mining Subsidence History

Main West and adjoining barrier pillars near the accident area are bounded to the north and also to the south by six extracted longwall panels. To establish if unanticipated or unusual subsidence from the longwall extraction affected the region, the Panels 13 to 17 subsidence information was compared to information from handbooks and references. The data suggests that the Crandall Canyon Mine subsidence is similar to that published for deep longwall districts.

Data from the subsidence surveys show the development of the subsidence trough with the extraction of successive longwall panels. As illustrated in Figure 103 surface profiles do not begin to show the formation of a critical subsidence basin²² (i.e., when subsidence reaches the maximum possible value) until 2001 when the third successive panel (Panel 15) was extracted. This delayed subsidence behavior is typical of the Wasatch Plateau where strong, thick strata in the overburden control caving characteristics. Similarly, these strong units can resist caving and form cantilevers at panel boundaries (as indicated by the absence of subsidence over more than half the width of Panel 13). Subsidence data collected elsewhere in the region indicates that the amount or extent of cantilevered strata at panel boundaries varies. These strata can be responsible for high abutment stresses and long abutment stress transfer distances.

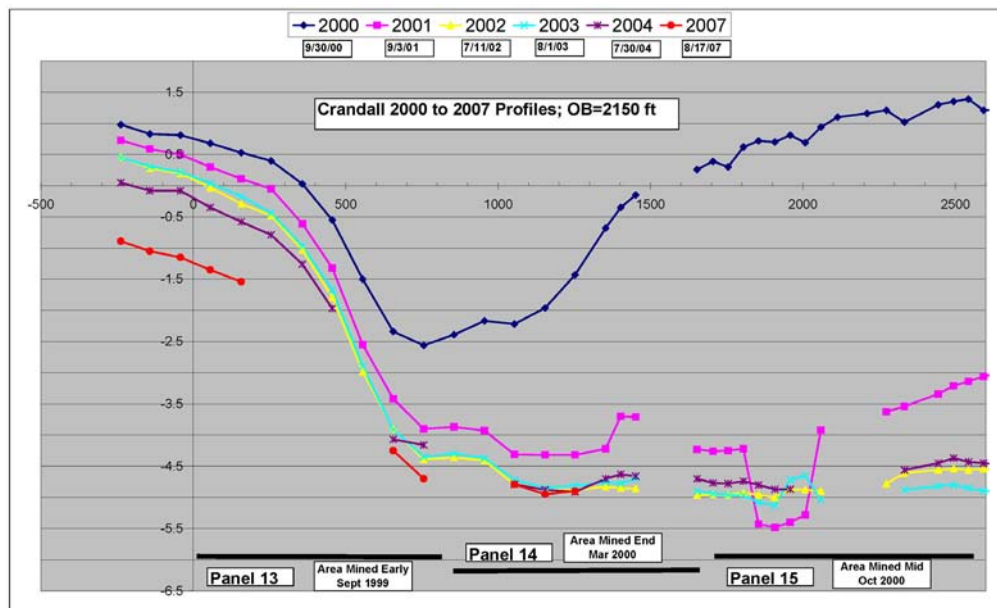


Figure 103 - Longwall Panels 13 to 15 GPS Surveyed Subsidence Profiles

Early measurements (2000 to 2002) show a surface elevation increase above the baseline from about the middle of Panel 13 to the barrier south of Main West. Cantilevered strata may be responsible for this movement. The data also suggest that the strata gradually subsided in this area over time.

Subsidence values derived from the surveyed profiles over Panels 13 to 17 are summarized in Table 14. The Panel 13 to 17 profile is supercritical in character where maximum subsidence (S_{max}) is achieved. Also, listed in Table 14 is the horizontal distance (d) from the excavation edge to the inflection point (point dividing the concave and convex portions of the subsidence profile). The supercritical width (W) for these Crandall Canyon Mine longwall panels is comparable to other Wasatch Plateau longwall panels. Also, the subsidence factor (S_{max}/m) shown in the table is typical for longwall mining.

The distance to the inflection point (d) was calculated from subsidence references using Panel 13 to 17 factors as shown in the lower portion of Table 14. This distance for the Panel 13 to 17 profile survey is roughly 500 feet. This value is similar to the values calculated from references. This information suggests that the Crandall Canyon subsidence and associated overburden bridging over extracted panels is comparable to other deep full extraction mining.

Table 14 - Crandall Canyon Longwall Subsidence Parameters, Values, and Comparisons

Parameter				Values		
Longwall Subsidence Data Source	Approx. Depth (h), ft.	Mined Height (m), ft.	Approx. Maximum Subsidence (S_{max}), ft.	Approx. Supercritical Width (W), ft.	S_{max}/m	Approx. Distance to Inflection Point (d), ft.
Crandall Canyon Mine Panels 13-17	2,150	7.9	5.0	2,300	0.63	500
Surface Subsidence Engineering Handbook ²²	2,150 used in Fig 2.4			2,300 used in chart Fig 2.4	0.63 used in Fig 2.4	495
Average Estimate from SDPS Chart ²³	2,150 used in Fig 3.2.1			2,300 used in Fig 3.2.1		505