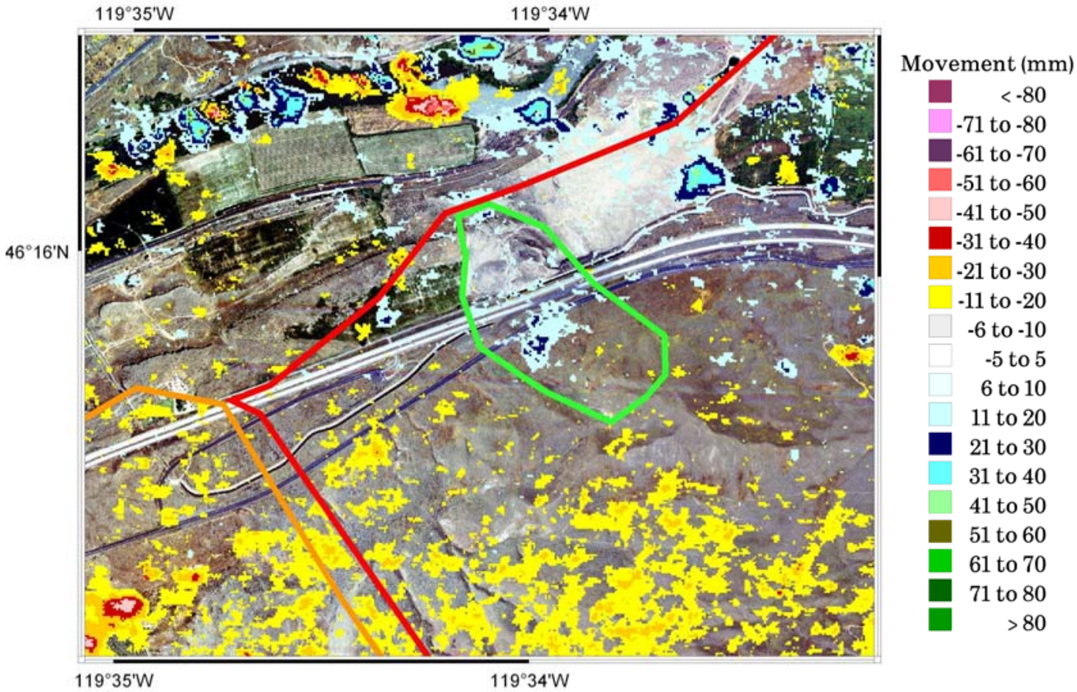

Figure 33. Graph. InSAR derived cumulative height change for January 15, 2003 to May 28, 2005.

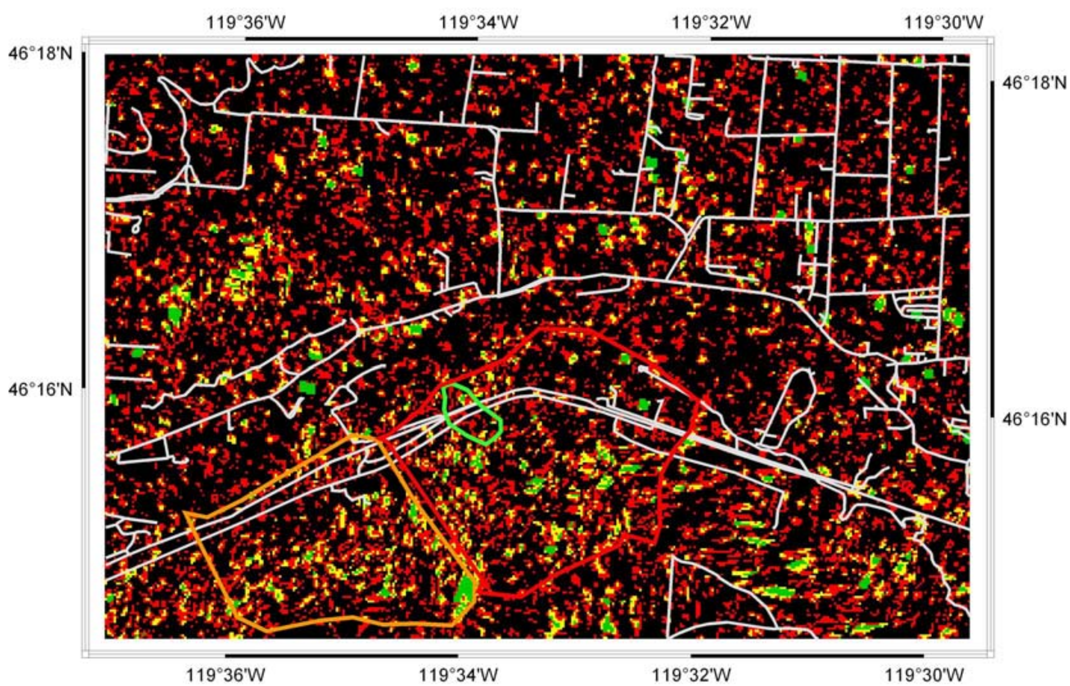

Figure 34. Graph. ERS SAR coherence for acquisitions on January 9 and September 11, 1999.

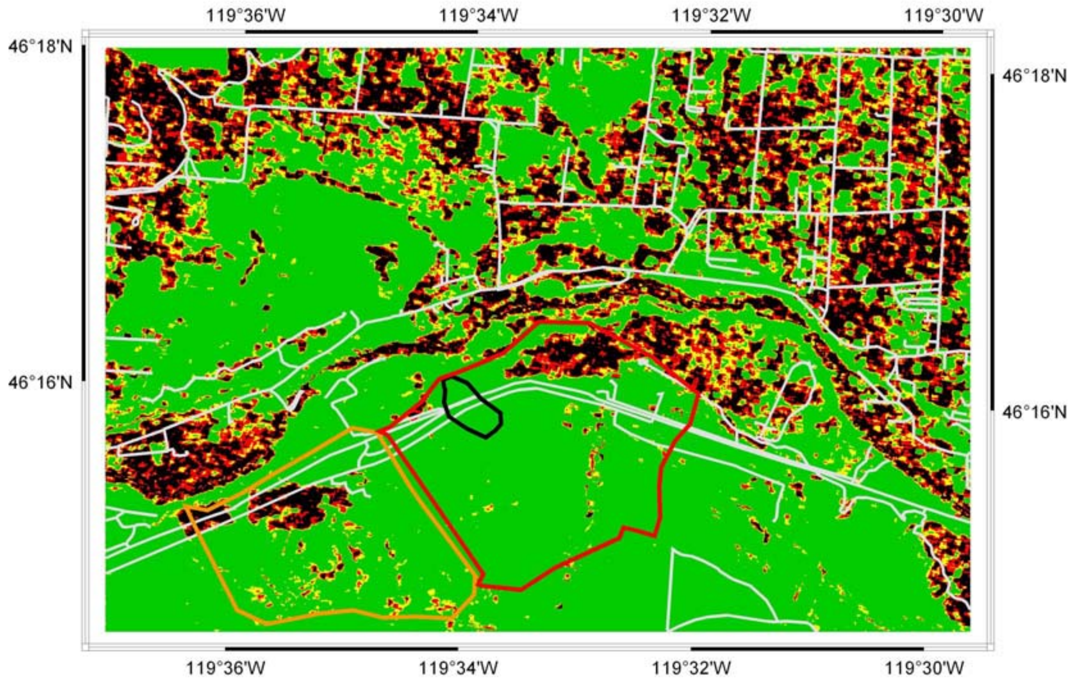

Figure 35. Graph. RADARSAT SAR coherence for acquisitions on October 6 and October 30, 2003.

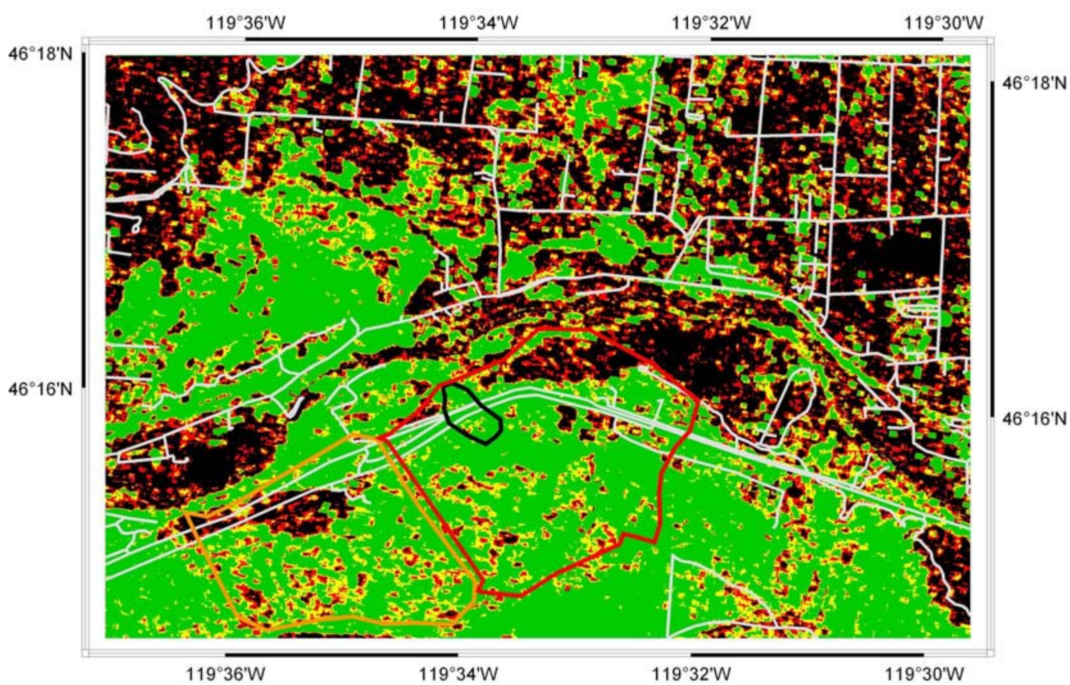

Figure 36. Graph. RADARSAT SAR coherence for acquisitions on October 30, 2003 and April 15, 2004.

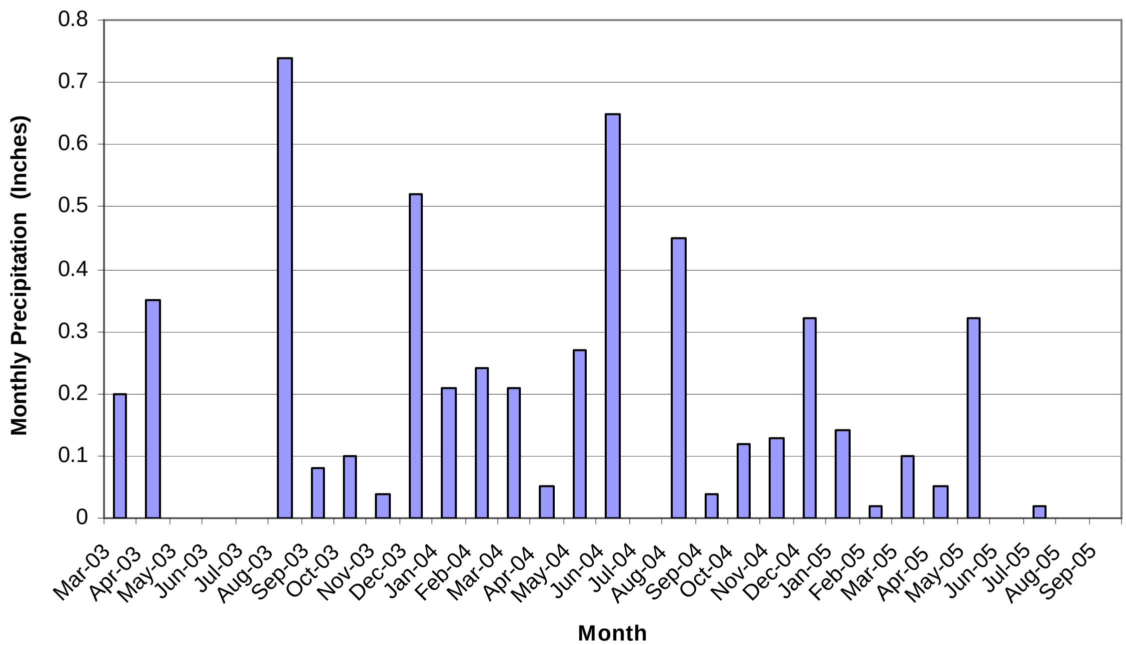

Figure 37. Graph. Monthly precipitation from March 2003 to September 2005 for the Prosser site.

Interpretation

Within the uncertainty associated with the InSAR analysis of the Prosser slide area, no obvious movement was measured. The most recent slope inclinometer data from H5-02 located at the base of the rock buttress indicated that the lateral movement was around 25 mm (1 inch) at 7° west of north over the timeframe from November 2002 to August 2004. The direction of the slope movement shifted from a generally westerly direction as measured further up the slope in 1987. For the current slope movement direction of slightly west of north, the SAR look-direction is poor, being about 10° north of east, at this latitude, for the ascending satellite pass. To further understand the InSAR results, a geotechnical analysis was undertaken to determine the potential movement mechanisms and the likely magnitude of any potential slope movement.(17)

Geotechnical data supplied by WSDOT was reviewed to develop a suitable geometric and material model for the analysis. The data consisted of borehole logs from a number of site investigations, readings from slope inclinometers installed within the slope area and reports prepared over a period of time that discuss the potential movement regime. The soil conditions consist of interlayered, silty clay and gravel, overlying conglomerate or basalt bedrock. It was established that the lower gravel layer could potentially act as a confined aquifer, and a likely mode of slope instability could be attributed to groundwater level variations acting to reduce the soil strength directly above the confined gravel layer. Movement records obtained from slope inclinometers indicated a seasonal correlation between observed movement and rainfall data for the area.

Two methods were employed to perform the geotechnical analysis; limit equilibrium techniques that allow a factor of safety to be calculated for a slope under particular conditions, and finite element analysis, which determines soil stresses and potential strain effects, and indicate the development of tensile and shear forces within the soil matrix. The analyses were performed with essentially the same soil models, with a range of soil strengths and groundwater conditions being considered to reflect the uncertainty in these parameters and provide some understanding of the sensitivity of the various parameters. The issue of the use of residual strength parameters was also considered in some detail.

The results of the geotechnical analyses suggest that the slope is essentially stable using both analysis techniques. Slope instability could be simulated by considering particularly low residual shear strength, or high (above-artesian) water levels within the lower gravel layer. The large movements initiated during highway construction works in the 1980s were attributed to toe excavation and were simulated using the finite element analysis. Thus, the InSAR and geotechnical analysis results both imply that the slope is essentially stable. The slight cumulative movement indicated by the InSAR results for January 2003 to May 2005 should be confirmed. Given that there is ongoing deformation of the highway in this area, it is recommended that InSAR and in-situ monitoring be continued to determine the actual movement.

CIMARRON

Acquisitions

For the Cimarron slide, ERS-1/2 acquisitions are most plentiful along Ascending Track 141, Frame 2835. In this location, there are 11 ERS-1 images from 1992 to 1996, and a further 37 ERS-2 images between 1995 and 2001. Within the scope of this project, six ERS images, as listed in Table 4, having suitable satellite baseline were procured in the 1995-1997 timeframe to coincide with the timeframe of "just prior to" and "during" the active slide of 1997. A tandem mode pair was also selected in the 1996 timeframe to facilitate the generation of a DEM for the InSAR analysis. A DEM was generated using this pair, however, a more recent SRTM DEM from 2000 was used in its place.

As part of the image selection process, precipitation and temperature information were gathered to allow the selection of scenes acquired outside of precipitation periods or when snow was present on the ground. The weather data for the acquired SAR scenes are presented in Table 4. Unfortunately, the closest weather station to Cimarron, which readily provided historical data, is approximately 50 miles (80 km) away in the city of Gunnison. Cimarron's elevation is also higher than that of Gunnison, and consequently the weather conditions (in particular the temperature) may be different at the slide site from that at the weather station. As shown in Table 4, precipitation occurred during the time of each ERS acquisition in 1997. However, given the importance of this data set to the study according to the slide movement that is known to have occurred, the satellite baseline data were judged to be sufficient to justify the data procurement even though precipitation was recorded on the day of each acquisition.

Like the Prosser site, there are sufficient data for Cimarron in the archive to perform interferometric point target analysis (IPTA). The IPTA technique requires a large stack of images (15 minimum, 25-35 preferred), which was beyond the scope of this project. The IPTA technique is used to isolate ground movement from atmospheric and topographic effects, and to mitigate phase unwrapping issues associated with spotty coherence. Therefore, this technique may be considered for application to this site at some future date.

Table 4. Cimarron ERS images procured for analysis.

Date	Temperature ° Celsius	Meteorological Conditions, Gunnison Weather Station
November 11, 1995	No Data	No Data
May 8, 1996	~11°	(clear) Tandem Pair for DEM
May 9, 1996	~11°	(clear) Tandem Pair for DEM
September 26, 1996	7°	Precipitation
April 24, 1997	8°	Precipitation
July 03, 1997	15°	Precipitation
August 07, 1997	16°	Precipitation
September 11, 1997	21°	Precipitation

In the case of RADARSAT-1, acquisition planning began for this area in August 2003, with an Ascending Fine Mode F2F scene chosen for acquisition. In total, 26 acquisitions were captured over the site on this beam mode between August 2002 and June 2005.

Within the scope of this project, scene selection was made on roughly a quarterly basis over the duration of the contract from September 2003 to June 2005. The scenes were collected with particular emphasis on minimizing the baseline (to less than 500 meters (1600 ft)) and choosing scenes on days without precipitation. The list of RADARSAT-1 scenes that were procured is given in Table 5.

Table 5. Cimarron RADARSAT images procured for analysis.

Date	Temperature ° Celsius	Meteorological Conditions, Gunnison Weather Station
September 03, 2003	21°	cloudy
September 27, 2003	19°	clear
November 14, 2003	1°	clear
March 13, 2004	2°	clear
April 06, 2004	9°	clear
June 17, 2004	20°	clear
July 11, 2004	24°	cloudy
September 21, 2004	16°	cloudy
October 15, 2004	12°	clear
December 02, 2004	-23°	clear
April 25, 2005	8°	cloudy
June 12, 2005	13°	cloudy

Analysis

Differential interferograms were computed for ERS and RADARSAT image pairs with perpendicular baselines around 600 m (1,980 ft) or less, and with timeframes no longer than seven months. Five ERS and eleven RADARSAT interferograms, as listed in Table 6, were generated.

The generation of the SAR interferograms was performed mainly through the use of the Gamma SAR processing software. The SAR signal data were first processed to yield image data, which were then co-registered so that all images were aligned in the SAR acquisition geometry. An external DEM was obtained for the study area from the 30 m (100 ft) SRTM DEM data available from the USGS. This DEM was co-registered to the SAR data as well, and then used to determine the topographic phase contribution for each interferogram. Both the curved-Earth and topographic phase were calculated based on the SAR acquisition geometry, and initially relied on the intrinsic satellite orbit information. The orbit baseline information was then refined by using the curved-Earth fringe rate evident in the differential interferogram, and/or by using ground control points with accurate horizontal and vertical information. The differential interferogram is generally spatially filtered to reduce phase noise. The phase of the differential interferogram is unwrapped to remove the 2π discontinuities inherent in the measured values. The unwrapped phase is directly proportional to the change in distance along the look vector of the radar and can be converted to ground movement assuming either vertical displacement or a principal direction of motion. The conversion of the measured movements to an absolute scale, that is, removing any offsets or simple trends in the data, relied on identifying known stable areas that can be used to define the zero displacement level.

Table 6. Cimarron SAR interferometric image pairs.

Figure	Acquisition Dates	SAR Sensor	Perpen-dicular Baseline (m)	Δ Time (days)	Mean Coherence	Standard Deviation
38	Sep 26, 1996–Apr 24, 1997	ERS-2	-339	210	12%	6%
39	Apr 24, 1997–Jul 03, 1997	ERS-2	188	70	15%	8%
40	Jul 03, 1997–Aug 07, 1997	ERS-2	304	35	15%	8%
41	Aug 07, 1997–Sep 11, 1997	ERS-2	232	35	20%	12%
42	Jul 27, 2000–Oct 05, 2000	ERS-2	320	70	8%	4%
43	Sep 03, 2003–Sep 27, 2003	RSAT	-143	24	39%	19%
44	Jun 17, 2004–Jul 11, 2004	RSAT	611	24	29%	15%
45	Jul 11, 2004–Sep 21, 2004	RSAT	-364	72	31%	15%
46	Sep 21, 2004–Oct 15, 2004	RSAT	193	24	45%	21%
47	Apr 25, 2005–Jun 12, 2005	RSAT	-128	48	28%	14%

Results

The resulting ground movement maps as derived from the ERS and RADARSAT SAR interferograms are shown in Figure 38 to Figure 42 and Figure 43 to Figure 47, respectively (negative values denote subsidence). For individual interferograms, displacements that are less than 10 mm (0.4 inch) are considered to be within uncertainty levels and therefore are transparent in the above figures. Movement greater than 10 mm (0.4 inch) should be interpreted within the constraints associated with the phase variations and systematic uncertainties. Since areas of low temporal coherence stem from changes in the radar-scattering characteristics of the ground, such areas produce noisy interferometric phase. Further, systematic uncertainties may arise due to residual inaccuracies in the orbit modeling, atmospheric variations between the two acquisition times, and inaccuracies in the DEM and / or its co-registration to the SAR images. Except for small-scale atmospheric effects, these systematic variations will generally be aligned with the topography and can therefore be identified.

From Table 6, it is evident that all the ERS interferograms suffer from poor coherence, with mean values ranging from 8% to 20%, as illustrated by the example shown in Figure 48. The displacement derived from these interferograms appears to contain mostly small areas of noise that fluctuates by up to 20 to 30 mm (0.8 – 1.2 inch). Given the poor coherence and the absence of any consistent displacement signatures, one can only conclude that no movement has been detected.

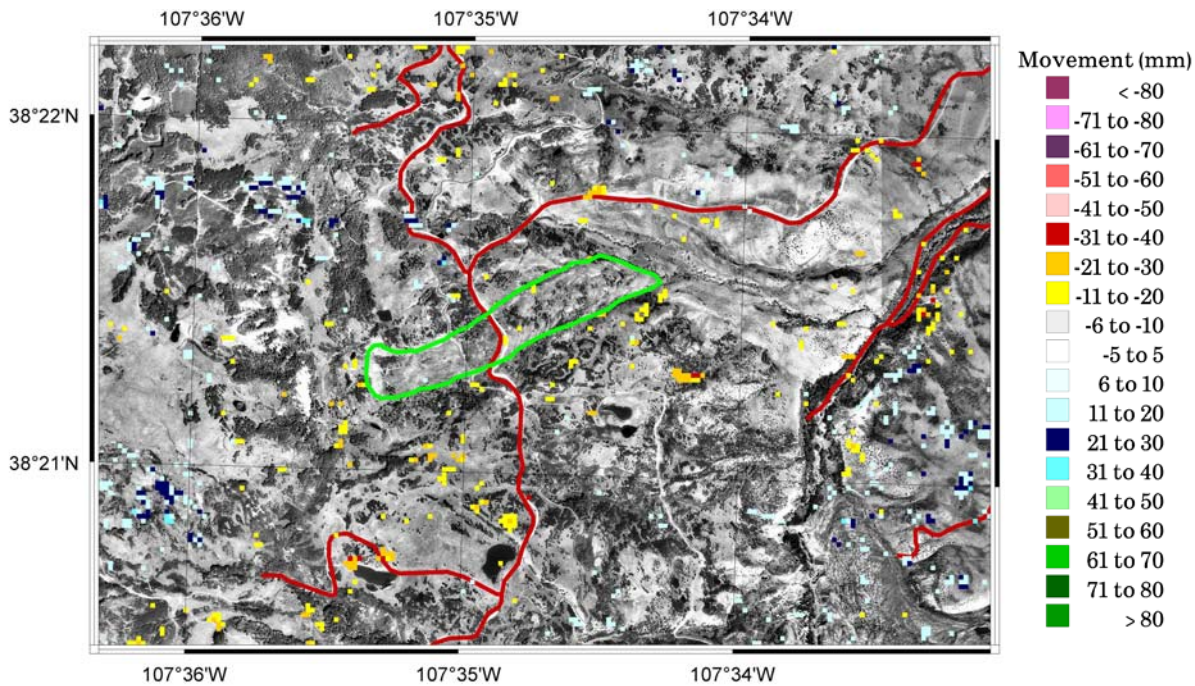

Figure 38. Graph. ERS InSAR derived height change for September 26, 1996 to April 24, 1997.

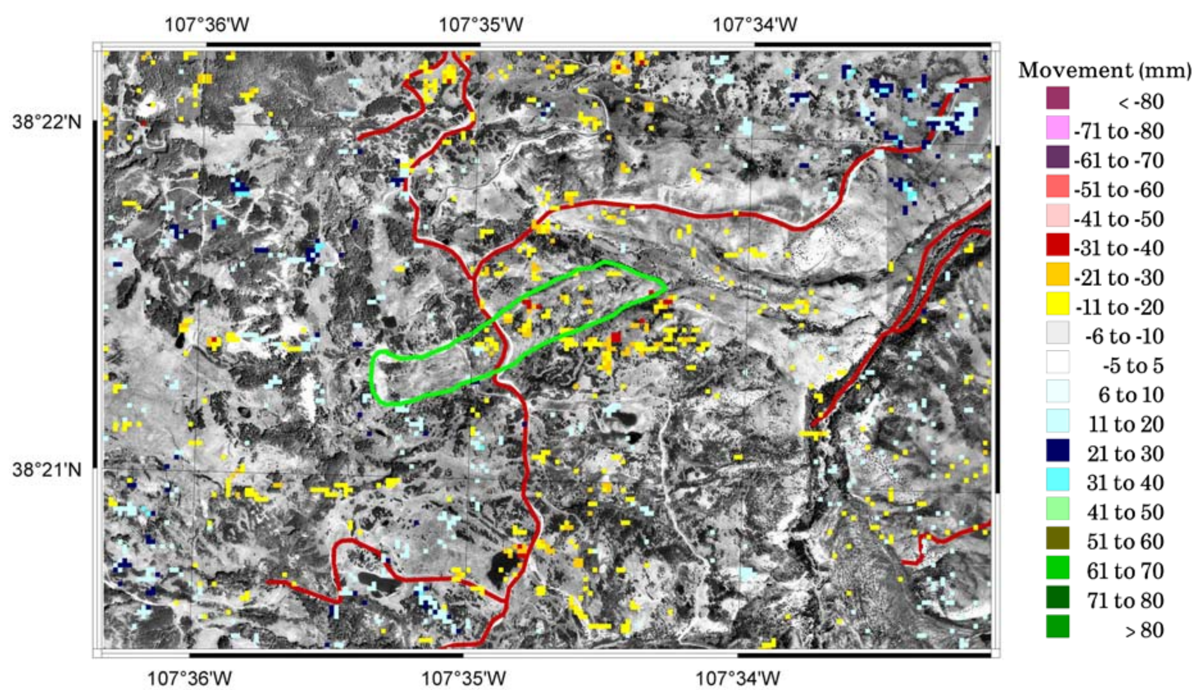

Figure 39. Graph. ERS InSAR derived height change for April 24 to July 3, 1997.