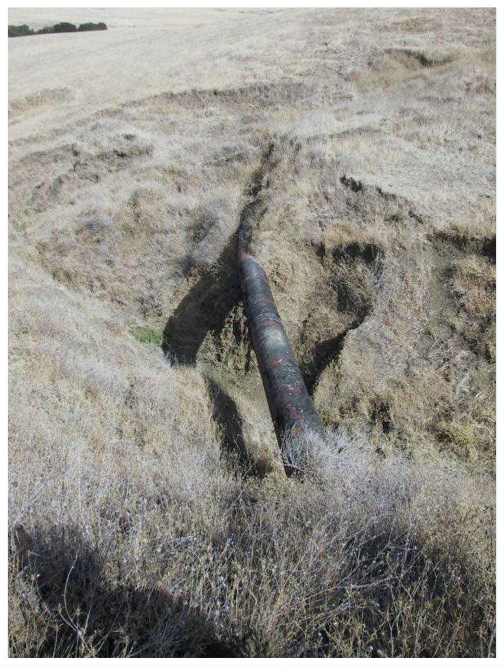
Environmental Impact and Risk Modeling of Petroleum and Gas Transmission Lines Using High Resolution Imagery from Satellite and Airborne-Based Remote Sensing Systems



Digital Globe Inc., PG&E, LLNL, and Chevron Texaco

Donald G. Price, PG&E

The Problem

Soil deformation (including landslides, gullying, Headward erosion, etc.) endangers transmission lines

Enforcing or re-routing transmission lines is done, but an area prone to the above types of deformation will continue to erode through time

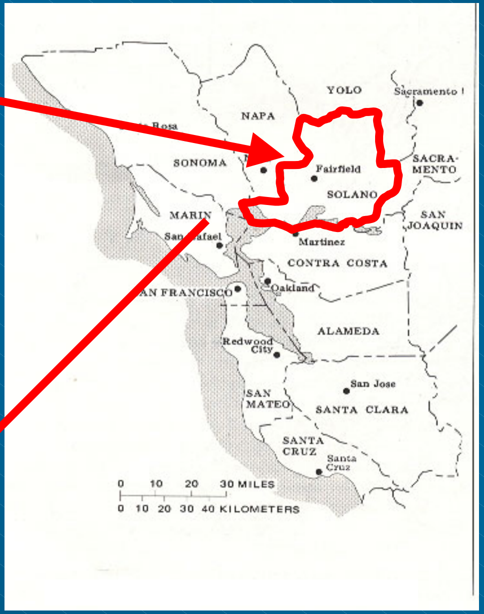
A way to monitor such erosion activity in transmission corridors is needed

Traditional monitoring and assessment methods can prove to be costly and time consuming

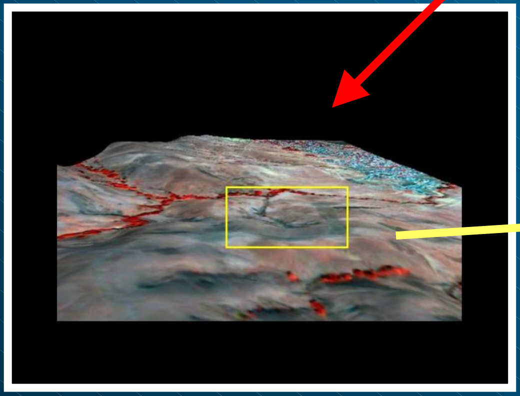
Objective

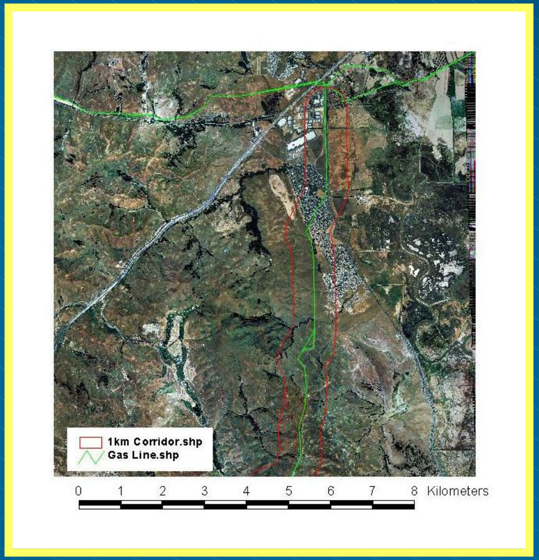
Develop processes and associated techniques to model and interpret InSAR data and high-resolution multispectral imagery in support of synoptic risk assessment of petroleum and gas transmission lines.

Study Area – Solano County, CA



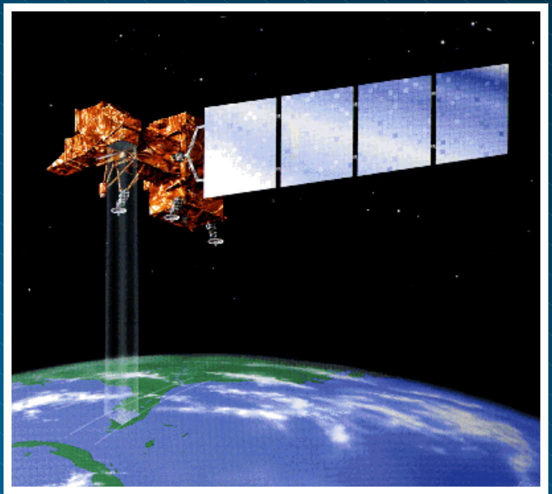
A section of pipeline located in Solano County, CA north of San Francisco Bay, near the town of Cordelia. The transmission corridor is shown below in red lines with the pipeline in green.





3D image – air photo draped over high resolution DEM
Cordelia, California

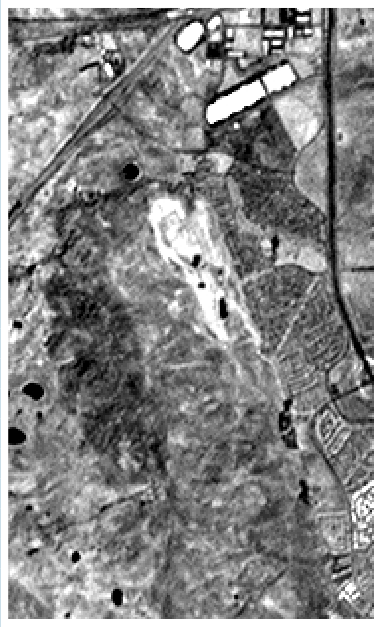
Datasets



Landsat ETM+
NASA-USGS-NOAA

Panchromatic – 1 band (0.52-0.90)
15 meter pixel

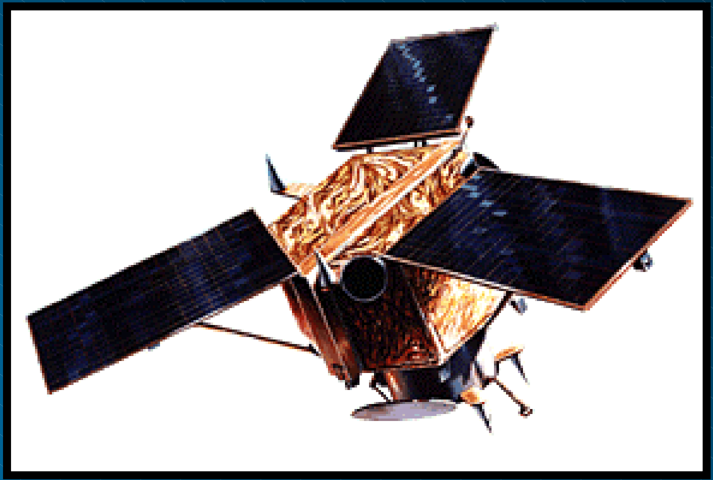
Multispectral – 6 bands (0.525-2.35)
30 meter pixel
1 band (10.40-12.50)
60 meter pixel



Subset of Landsat Panchromatic 15 meter data taken over study area

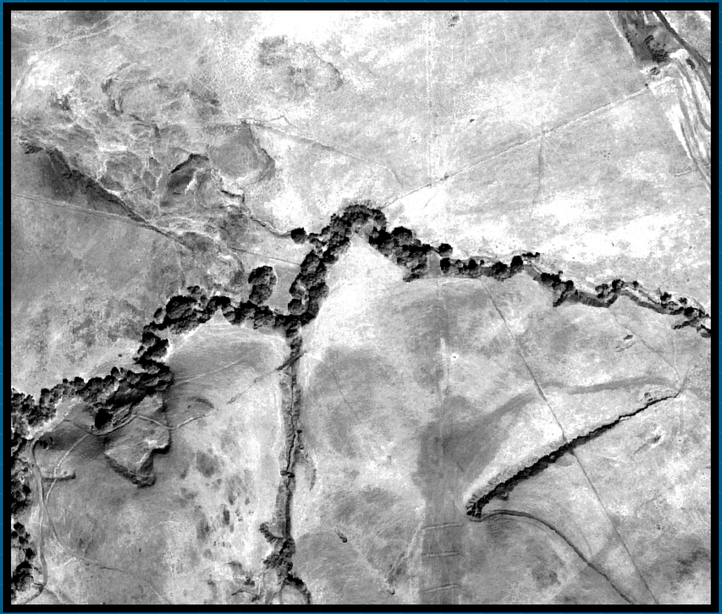
Datasets

IKONOS - Space Imaging Inc.



Panchromatic – 1 band (0.45-0.90 um)
1 meter pixel

Multispectral – 4 bands (0.45-0.90 um)
4 meter pixel



Subset of IKONOS Panchromatic 1 meter data taken over study area

Datasets

QuickBird – DigitalGlobe Inc.

Panchromatic – 1 band (0.45-0.90 um)
0.61 meter pixel

Multispectral – 4 bands (0.45-0.90 um)
2.44 meter pixel

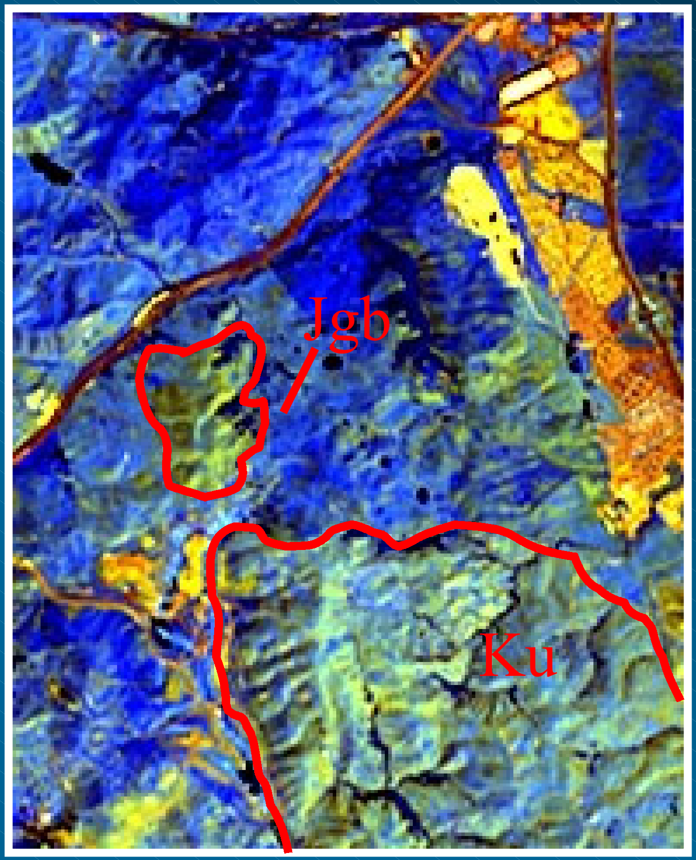
Subset of QuickBird Multispectral 2.44 meter data taken over study area in May of 2002

Landsat Analysis – Regional Geology

Landsat Bands 3,2,1 - RGB

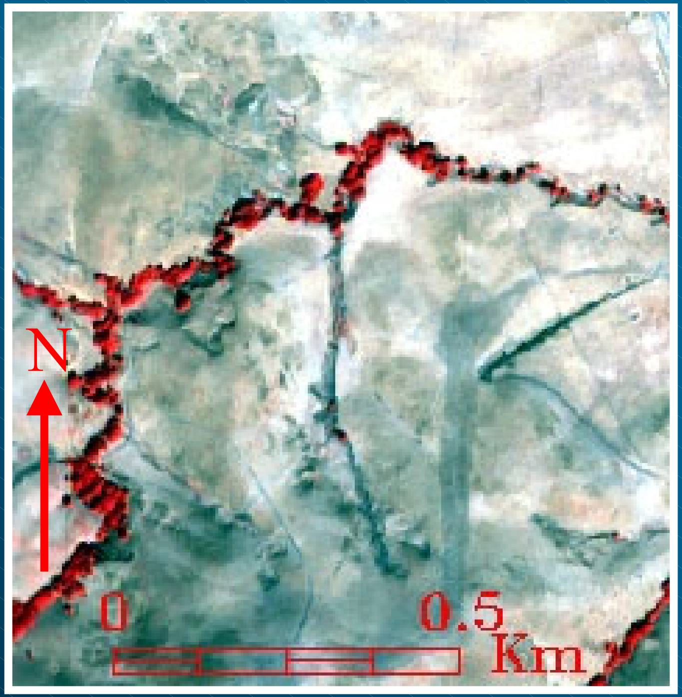
Some rock units are more susceptible to slope failure (i.e. landsliding activity) than other rock units

Simple analysis enhances major rock units – Linear Stretching



- Major rock units are identified including Jgb, a gabbro which is NOT highly susceptible to sliding and
- Ku, sandstone and shale, which IS highly susceptible to sliding

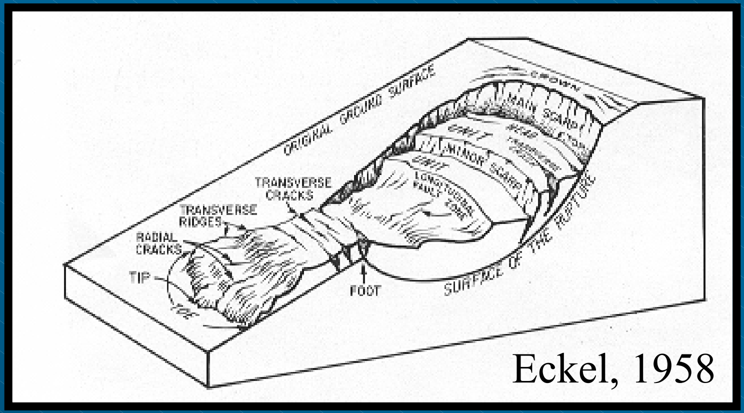
IKONOS Multispectral Analysis for Mapping Landslides



Landsliding activity disturbs and deforms the landscape in distinctive ways producing a set of unique morphologies

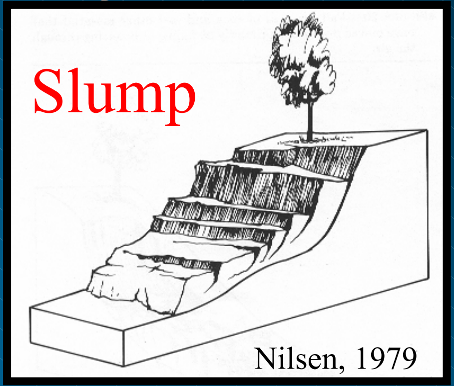
Landslide Morphologies

possible textural features seen by remotely sensed data

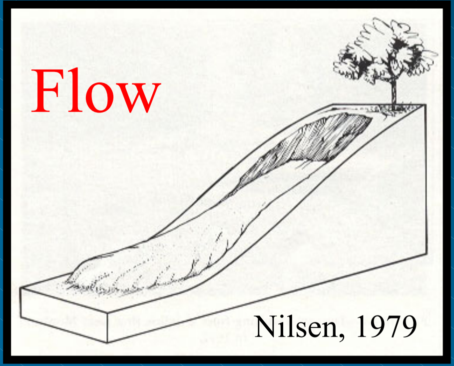


Eckel, 1958

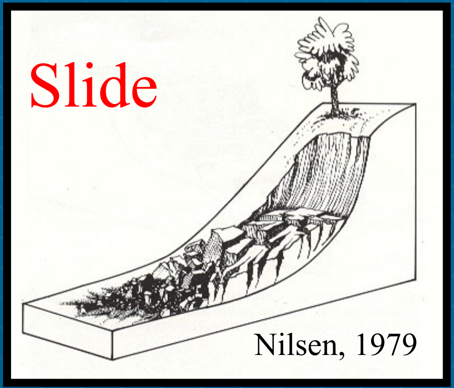
- Main head scarp
- Minor scarps internal to the slide
- Longitudinal fault zones
- Transverse cracks
- Transverse ridges
- General "hummocky topography"



Nilsen, 1979



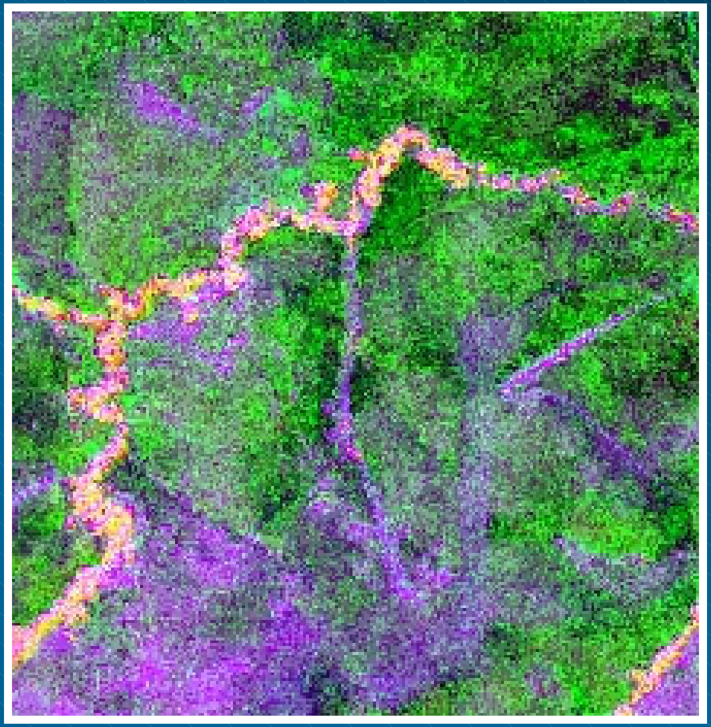
Nilsen, 1979



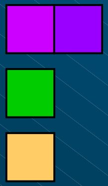
Nilsen, 1979

Landslide mapping using principle components like algorithm

IKONOS 4m color-infrared, bands 4,3,2



Minimum Noise Fraction image



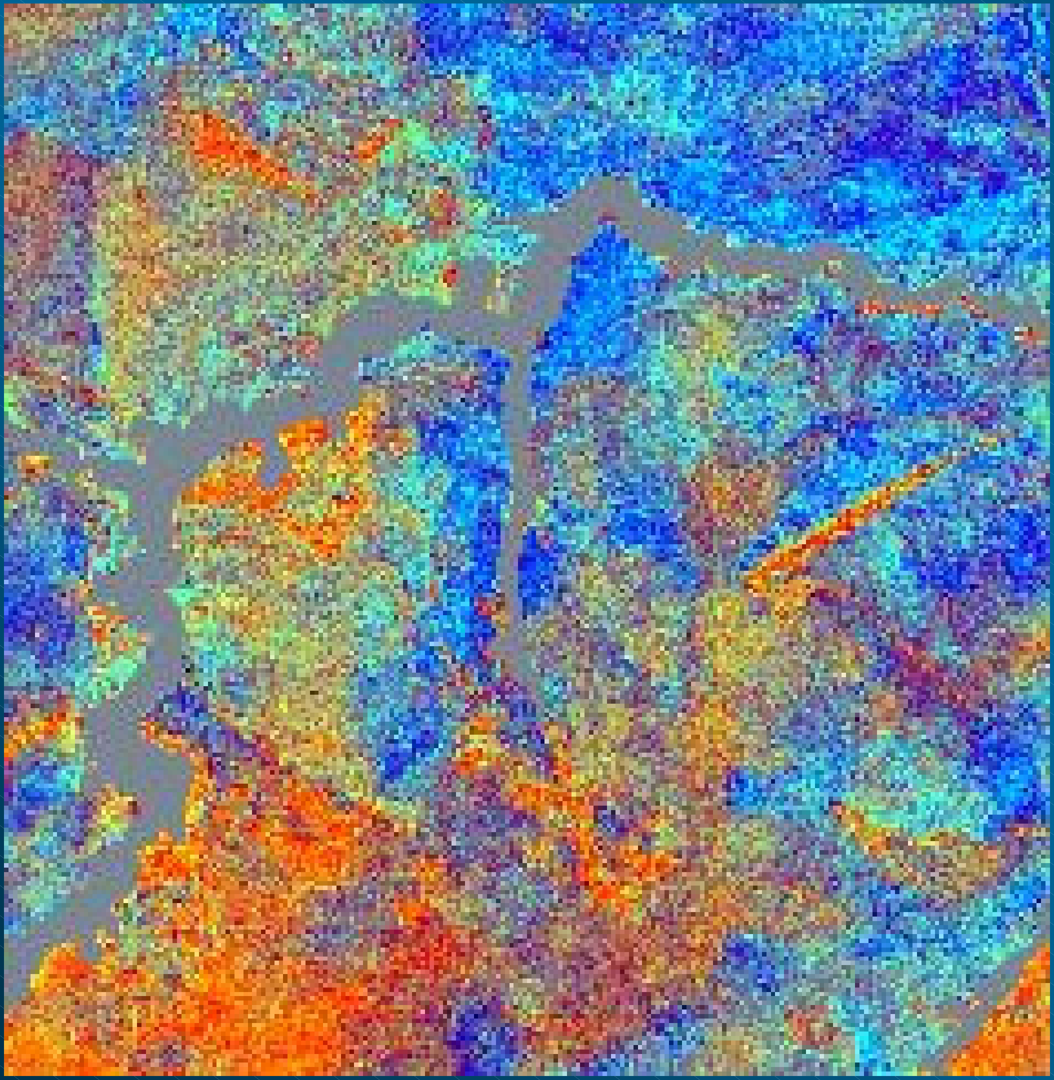
ANALYSIS

In order to reduce the spectral variability encountered by the Selective PCA and enhance landslide detection, a mask was prepared that attempts to remove the tree populations in this field area.

The next slide shows this mask and the resultant Selective PCA.

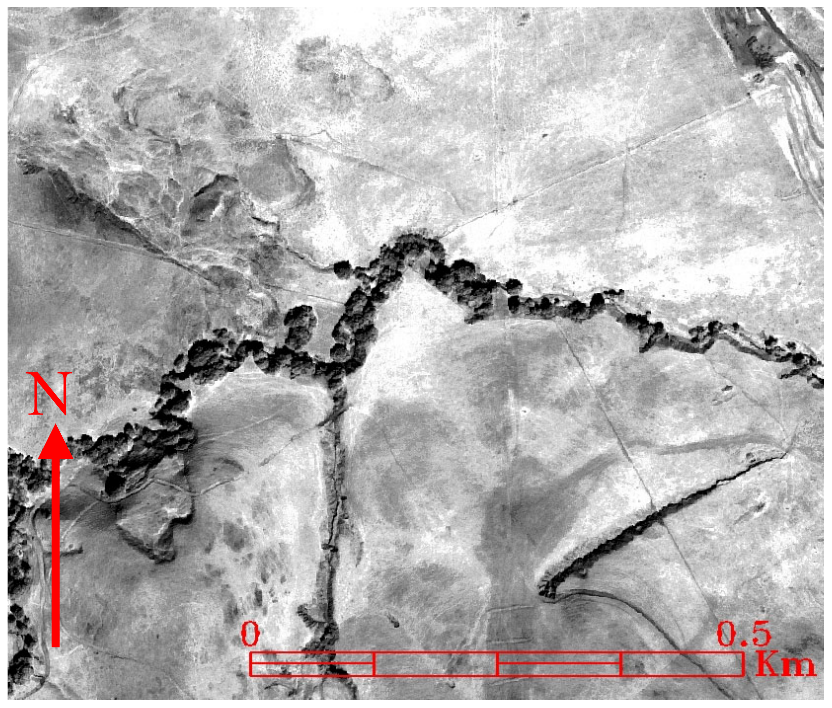
This result is used to create a vectorized landslide distribution map that can be fully integrated into a GIS domain.

Selective PCA Analysis



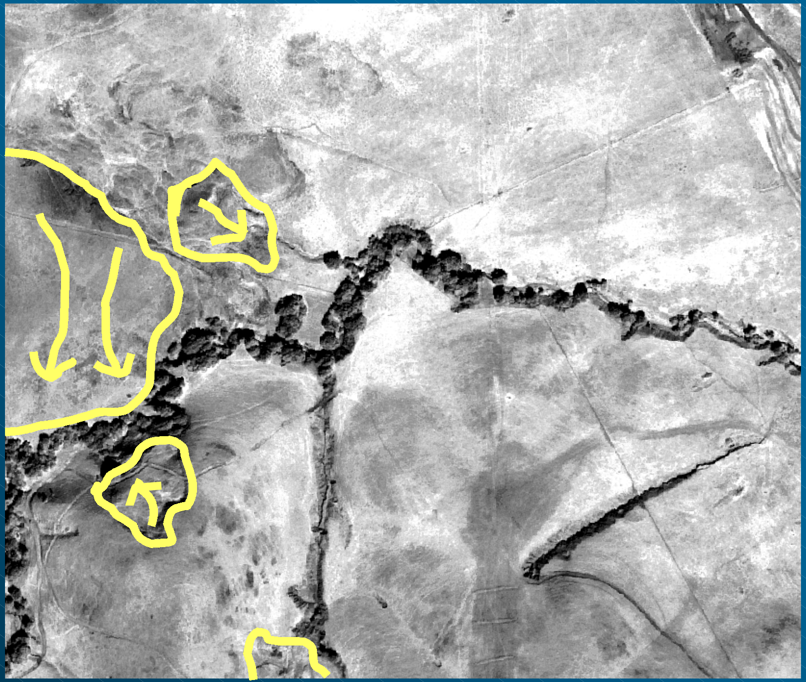
Results of the Selective PCA on the IKONOS 4 meter satellite imagery with a tree mask applied before analysis. Erosional features are more emphasized in this image. Orange and red colors correspond to erosional features (landslides and gullies), while the blues are undisturbed soil and bedrock.

IKONOS Panchromatic Analysis for Mapping Landslides

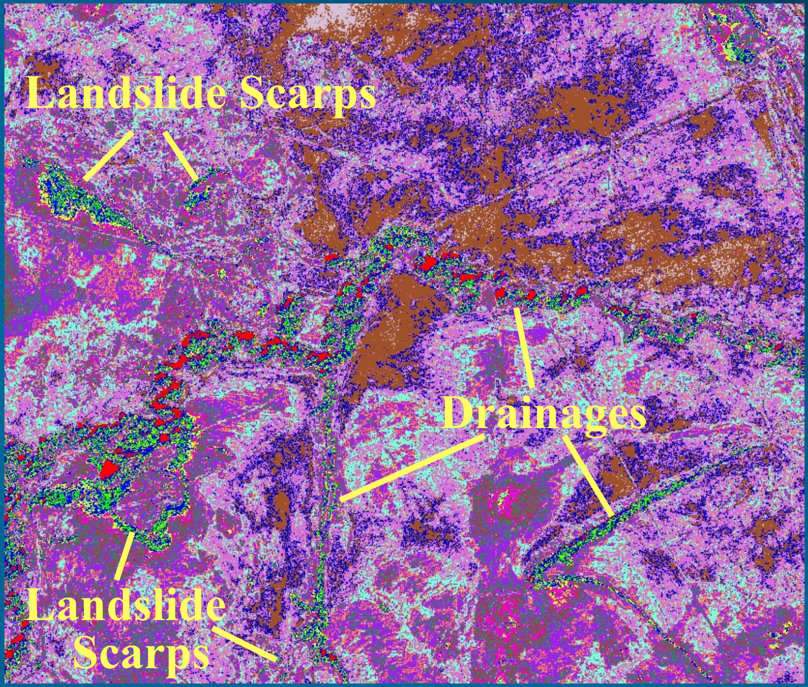


Some of the most distinctive morphologies observed include scarps, cracks, faults, and gullies

Landslide mapping – Edge detection



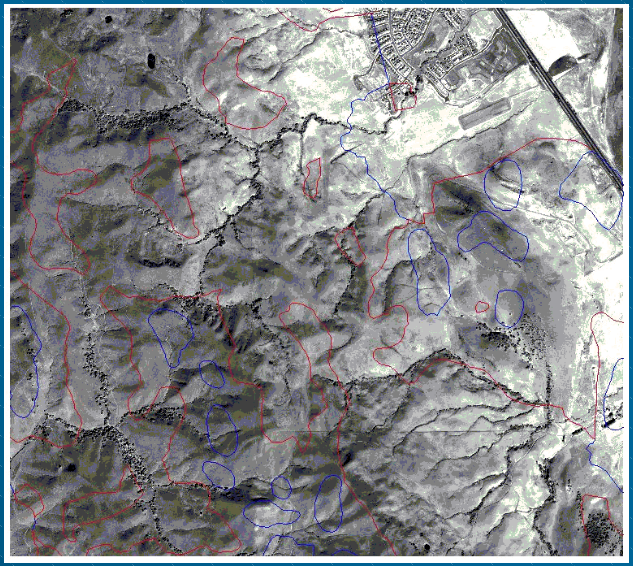
IKONOS 1 m data shown in greyscale



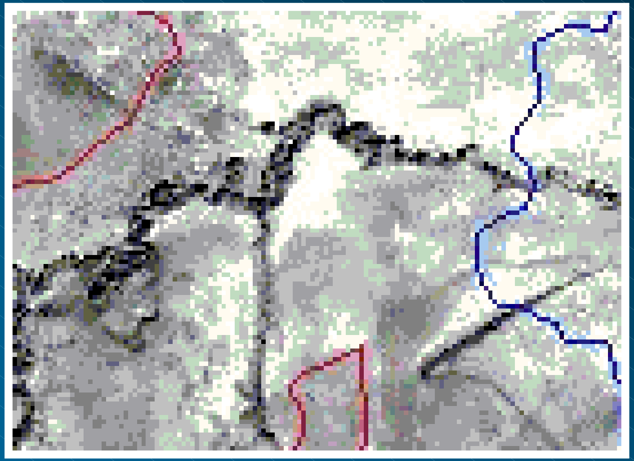
Edge-enhanced unsupervised classification

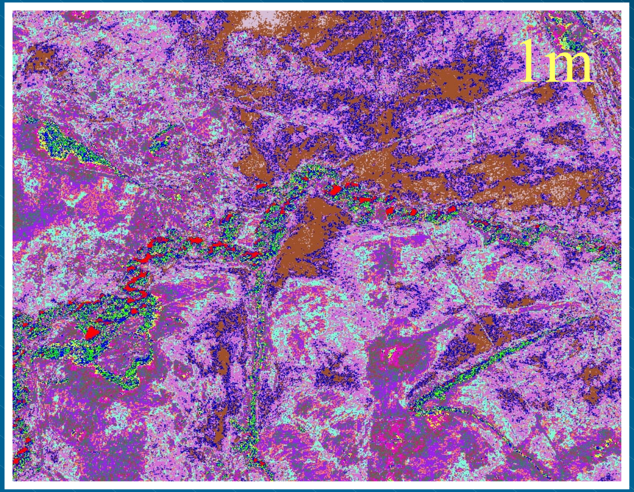
Edges, including landslides, gullies, roads and trees

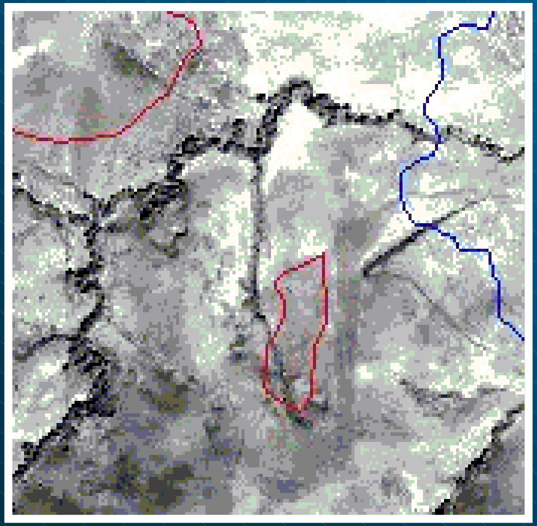
Initial Validation

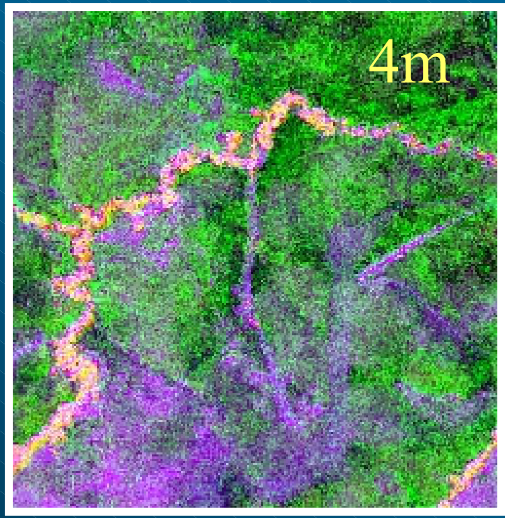


Vector overlay of landslide distribution (Nilsen and Wright, 1979)



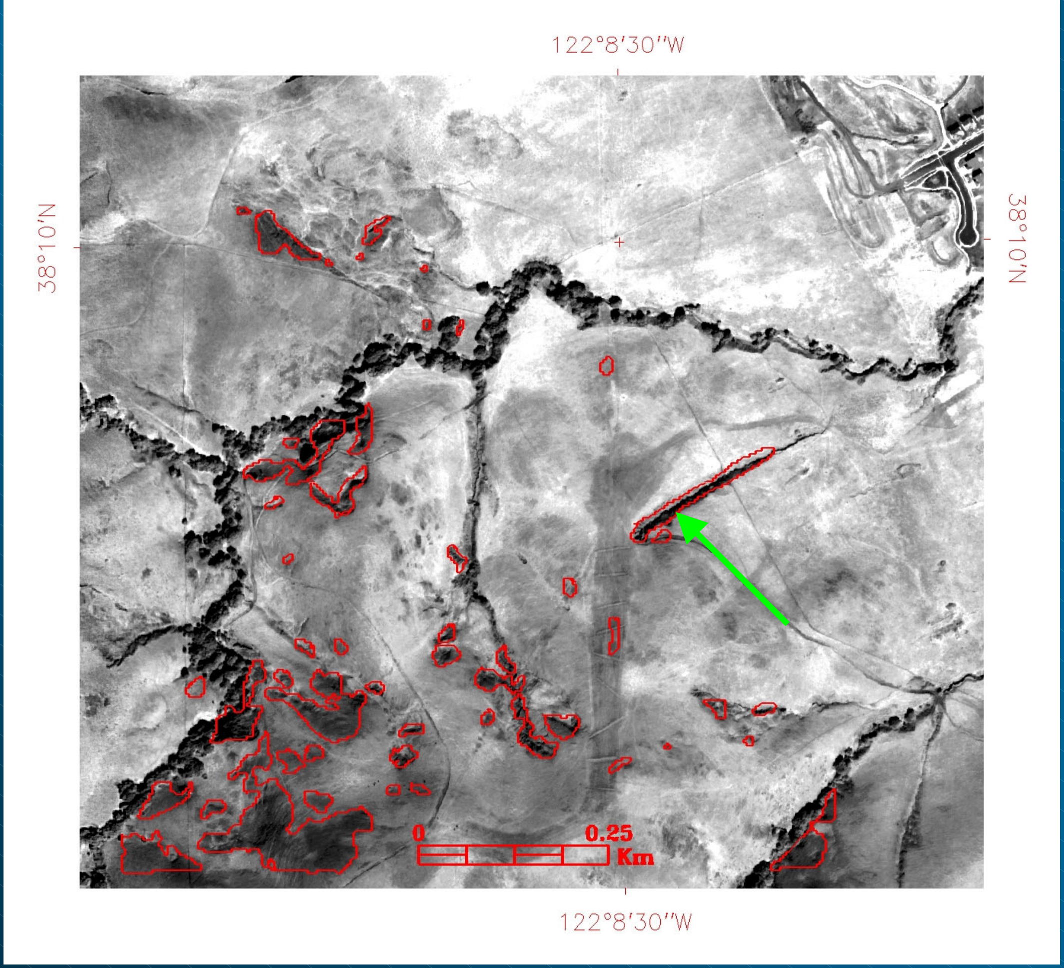






Spectral landslide mapping compared to previous aerial photo-based landslide mapping

Vectorized landslide distribution maps



The ROI of landslide distribution overlaid on 1m Panchromatic IKONOS imagery. A major gully in the field area is highlighted and indicated by the green arrow.

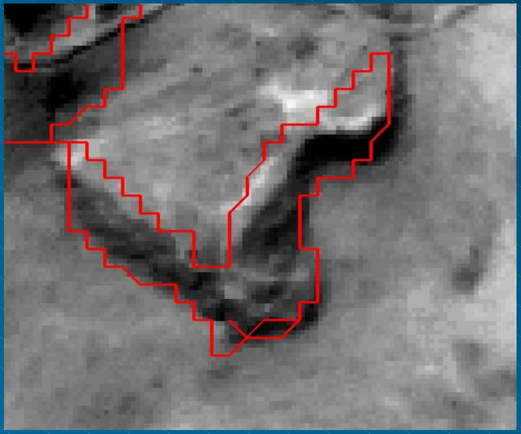
The resultant Selective PCA image shown in the last slide was then thresholded to emphasize those values in the digital image analysis that correspond to erosional features, especially landslides. Interactive density slicing was used within the ENVI software program to complete this thresholding. Those regions with values falling into the thresholds that appeared to correspond to landslides, were exported to a region of interest (ROI) file and overlaid on the original 1 m panchromatic gray-scale image.

Landslide Distribution Map Matches Known Deformation

For example, a small landslide that was previously visited in the field, was located in the imagery and analysis results. The landslide was spatially small (~12.5m in length), but was mapped quite well by the Selective PCA.

Field photo of the landslide.

1 m IKONOS imagery subset.



The image ROI of the landslide superimposed on top of the 1 m image.

Text Editor – ls_ik4m_spca_wtreemask.txt

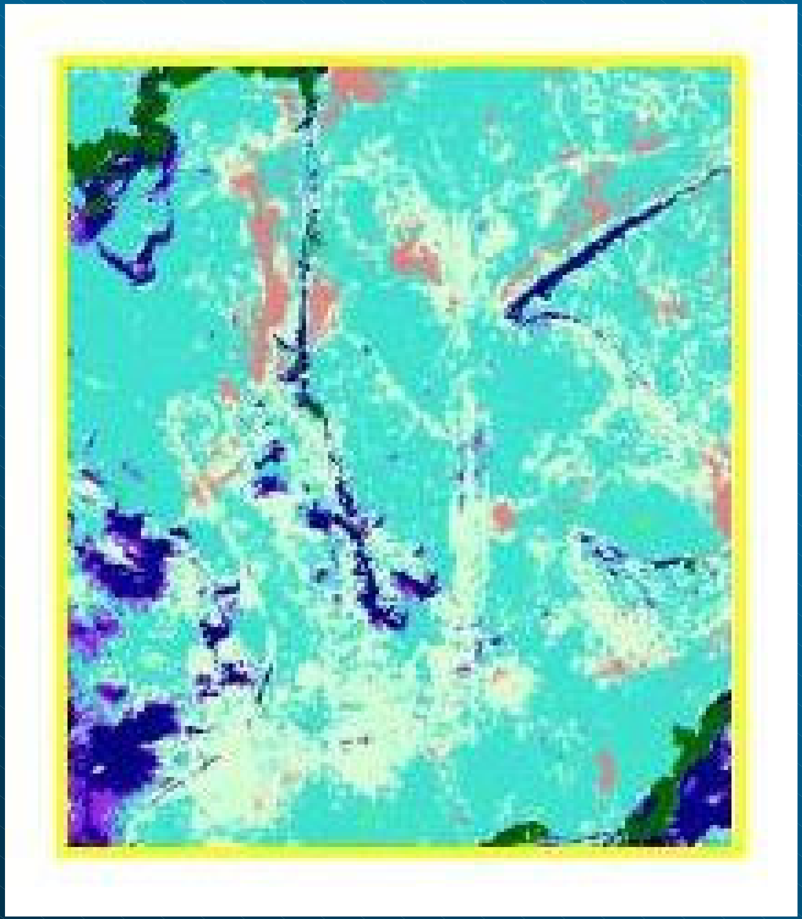
File Edit Format Options Help

```
; ENVI Output of ROIs (3.4) [Thu Feb 28 19:31:27 2002]
; Number of ROIs: 1
; File Dimension: 236 x 242
;
; ROI name: Region #1
; ROI rgb value: {255, 0, 0}
; ROI npts: 3752
;    ID    X    Y      Map X       Map Y        Lat          Lon          B1          B2
      1   40   24  574691.00  4224500.00  38.167165  -122.147369     5.6123     -0.9562
      2   41   24  574695.00  4224500.00  38.167165  -122.147323     4.9183      0.7322
      3   39   24  574687.00  4224500.00  38.167166  -122.147415     3.9610     -2.3910
      4   41   25  574695.00  4224496.00  38.167129  -122.147324     5.6123     -0.9562
      5   39   25  574687.00  4224496.00  38.167130  -122.147415     3.2670     -0.7025
      6   40   25  574691.00  4224496.00  38.167129  -122.147370     6.7850     -1.0831
      7   47   25  574719.00  4224496.00  38.167127  -122.147050     5.2653     -0.1120
      8   48   25  574723.00  4224496.00  38.167127  -122.147004     4.0926      0.0148
      9   42   25  574699.00  4224496.00  38.167129  -122.147278     5.6123     -0.9562
     10   49   25  574727.00  4224496.00  38.167126  -122.146959     1.7473      0.2685
     11   46   26  574715.00  4224492.00  38.167091  -122.147096     6.3064     -2.6447
     12   50   26  574731.00  4224492.00  38.167090  -122.146913     1.4002      1.1127
     13   45   26  574711.00  4224492.00  38.167092  -122.147142     5.2653     -0.1120
     14   48   26  574723.00  4224492.00  38.167091  -122.147005     6.4379     -0.2389
     15   49   26  574727.00  4224492.00  38.167090  -122.146959     5.2653     -0.1120
     16   47   26  574719.00  4224492.00  38.167091  -122.147050     4.7867     -1.6736
     17   48   27  574723.00  4224488.00  38.167055  -122.147005     5.6123     -0.9562
     18   45   27  574711.00  4224488.00  38.167056  -122.147142     4.9183      0.7322
     19   46   27  574715.00  4224488.00  38.167055  -122.147096     7.1320     -1.9273
     20   88   27  574883.00  4224488.00  38.167041  -122.145179     6.7850     -1.0831
     21   47   27  574719.00  4224488.00  38.167055  -122.147051     6.4379     -0.2389
     22   50   27  574731.00  4224488.00  38.167054  -122.146914     6.3064     -2.6447
     23   86   27  574875.00  4224488.00  38.167042  -122.145270     1.1371     -3.6988
     24   49   27  574727.00  4224488.00  38.167054  -122.146959     6.7850     -1.0831
     25   87   27  574879.00  4224488.00  38.167042  -122.145224     6.7850     -1.0831
     26   51   28  574735.00  4224484.00  38.167018  -122.146869     3.2670     -0.7025
     27   47   28  574719.00  4224484.00  38.167019  -122.147051     7.1320     -1.9273
     28   46   28  574715.00  4224484.00  38.167019  -122.147097     6.3064     -2.6447
     29   45   28  574711.00  4224484.00  38.167020  -122.147143     5.7439      1.4495
     30   48   28  574723.00  4224484.00  38.167019  -122.147006     6.7850     -1.0831
     31   84   28  574867.00  4224484.00  38.167007  -122.145362    -0.2510     -0.3220
```

The ROIs of the landslides were exported to both text files (for extraction of latitude-longitude information) and to vector shape files compatible with Arcview GIS software.

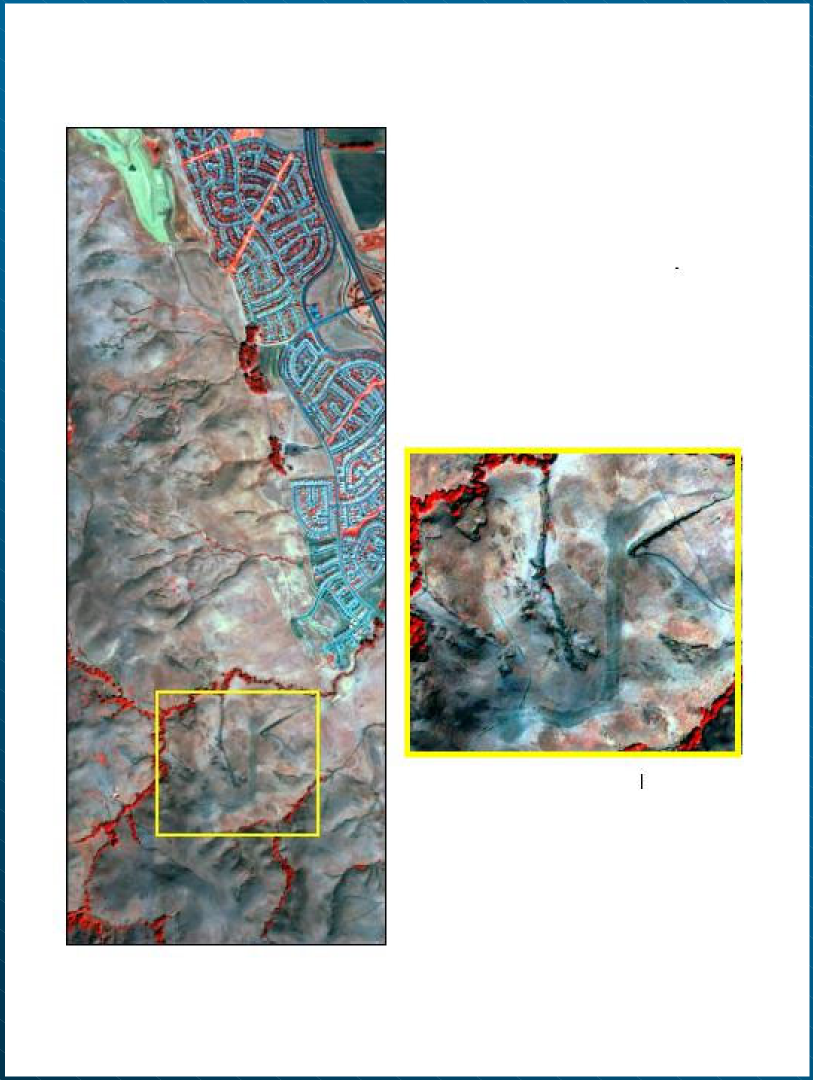
Example text output of ROI points that make up the polygons that define the landslides. Each point has an ID number as well as an x-y location within the image subset. The eastings-northings and latitude-longitude are also give for each point.

IKONOS Multispectral-based Mapping of Vegetation Distribution

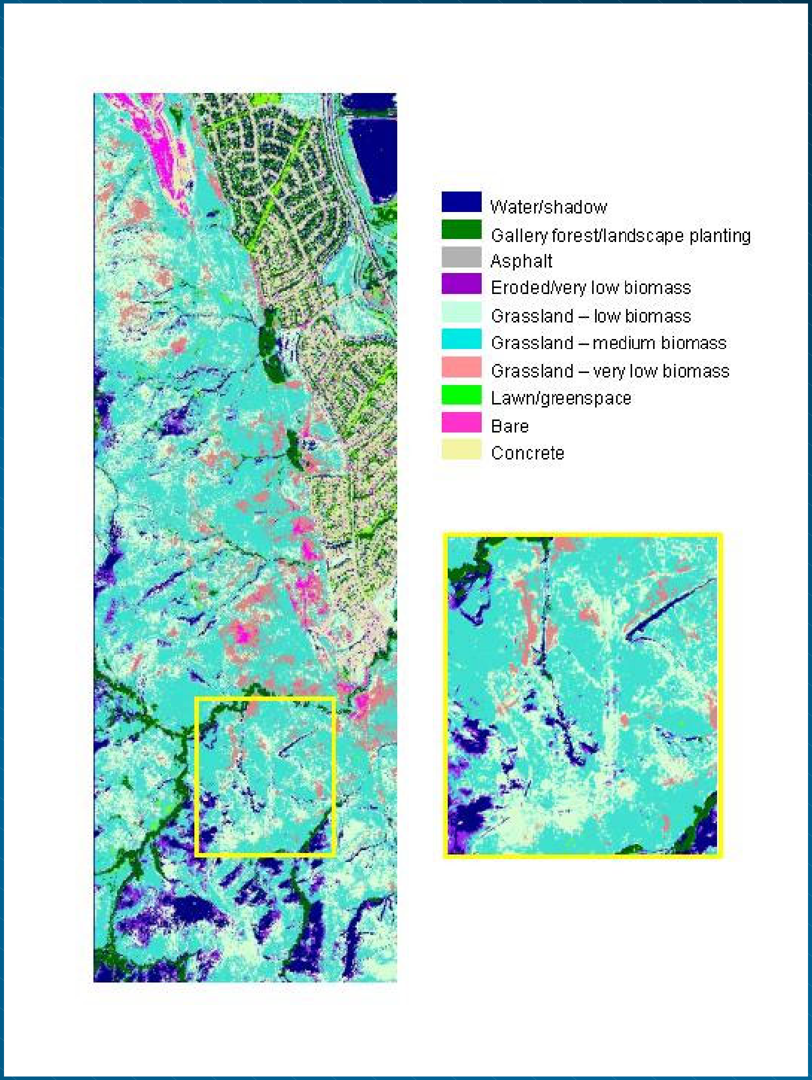


Vegetation distribution may be used as a proxy for slope stability

Vegetation distribution – Simple Unsupervised Classification



Color-infrared IKONOS multispectral



Unsupervised classification

Variables Affecting Erosional Susceptibility

- The mapping of the current distribution of landslides is obviously an important first step in characterizing the risk in a pipeline corridor.

- Such maps indicate areas for immediate concern as well as highlighting regions likely to fail again by such erosional processes.

- However, there are other important variables to consider when assessing the stability and landsliding/erosional susceptibility of a region.

- The three major variables are: geology (including rock and soil types as well as structure), slope, and biomass (both location of and relative abundance).

Geology

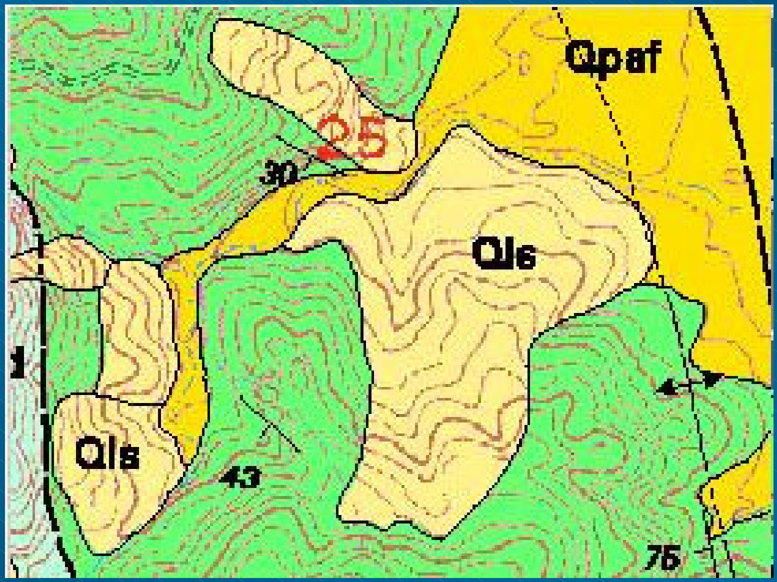
- There are certain bedrock and soil types that are more susceptible to landsliding and erosion than others.

- Knowing the identity and distribution of these units is an important step for determining sites of greatest landslide susceptibility.

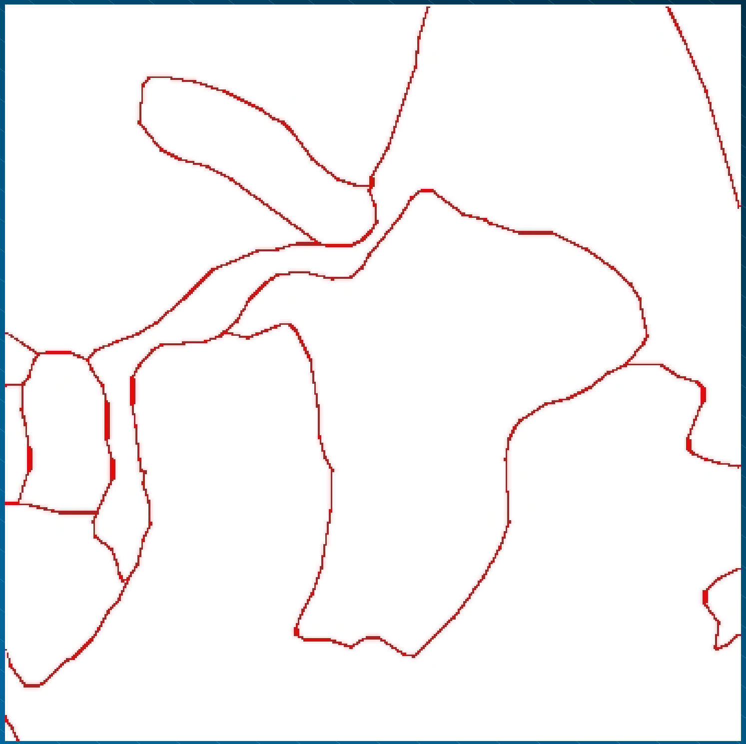
- Four major rock/sediment units outcrop in the test field area including Pleistocene aged alluvial fan and fluvial deposits (Qpaf), Pleistocene-Holocene aged landslide deposits (Qls), Eocene aged sandstones (Td), and Cretaceous aged sandstone and shale units of the Great Valley Sequence (Ku).

- All four of these units are quite susceptible to landsliding activity, though the Eocene sandstones are the least susceptible.

- Vectorized geologic unit boundaries will be combined with other vectorized information to contribute to risk assessment decisions.



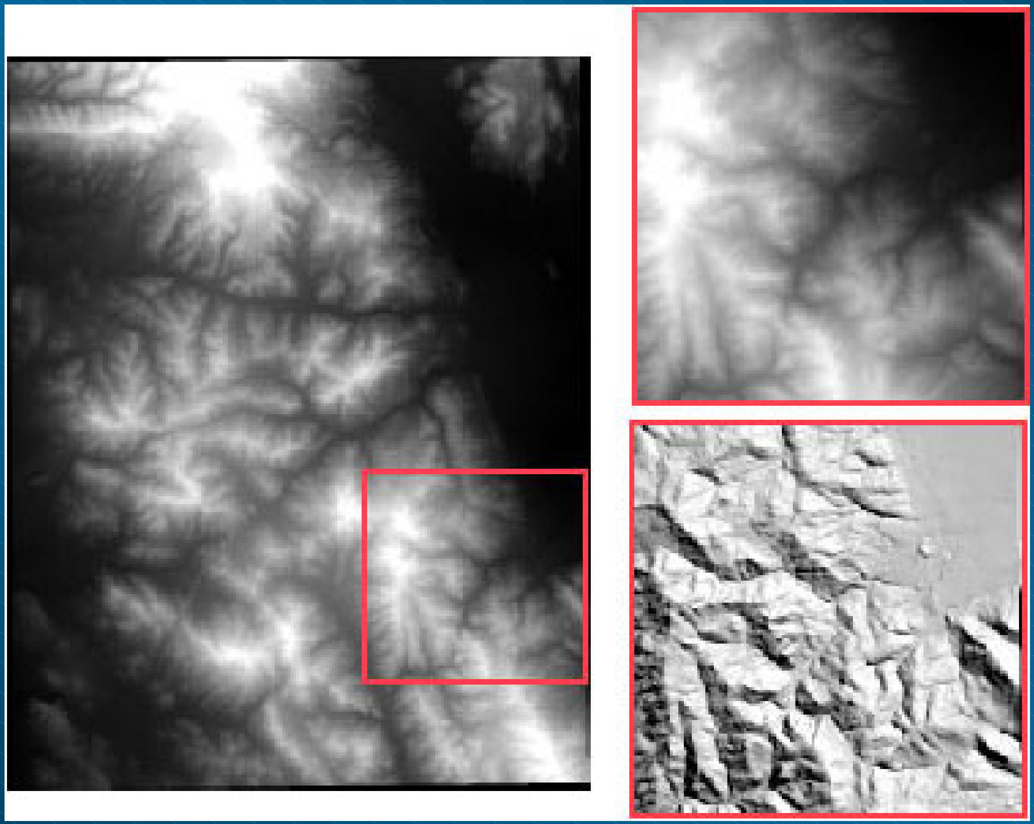
This figure shows a subset of the USGS geological map (Graymer, 1999) that covers the study area. All four units shown in this map are susceptible to landsliding, though of special note are the abundant Qls units which are mapped landslides that may or may not be currently active.



This figure is the vector shapefile from the adjacent geologic map. This vector file can be directly input into the GIS database with other vector layers such as the IKONOS-based landslide distribution map.

Slope

- Slope plays an integral role in landslide susceptibility determinations.
- Landslides tend to occur on slopes greater than approximately 15 % or about 8.5°.
- Slope threshold is still dependent on other factors including those mentioned previously (prior landsliding activity, geology).
- Hence, landslides may occur on slopes less than 15% if other mitigating factors are present (such as highly susceptible rock types or sparse vegetation).
- Conversely, landslides may not occur on slopes much greater than 15% if there are very resistant and stable rock types and abundant vegetation.

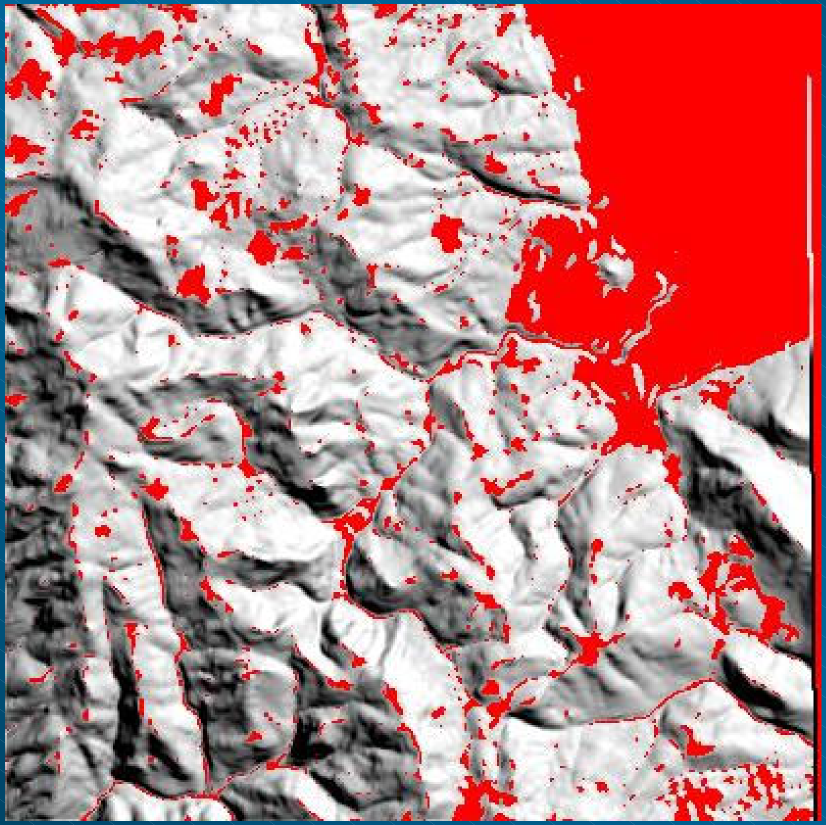


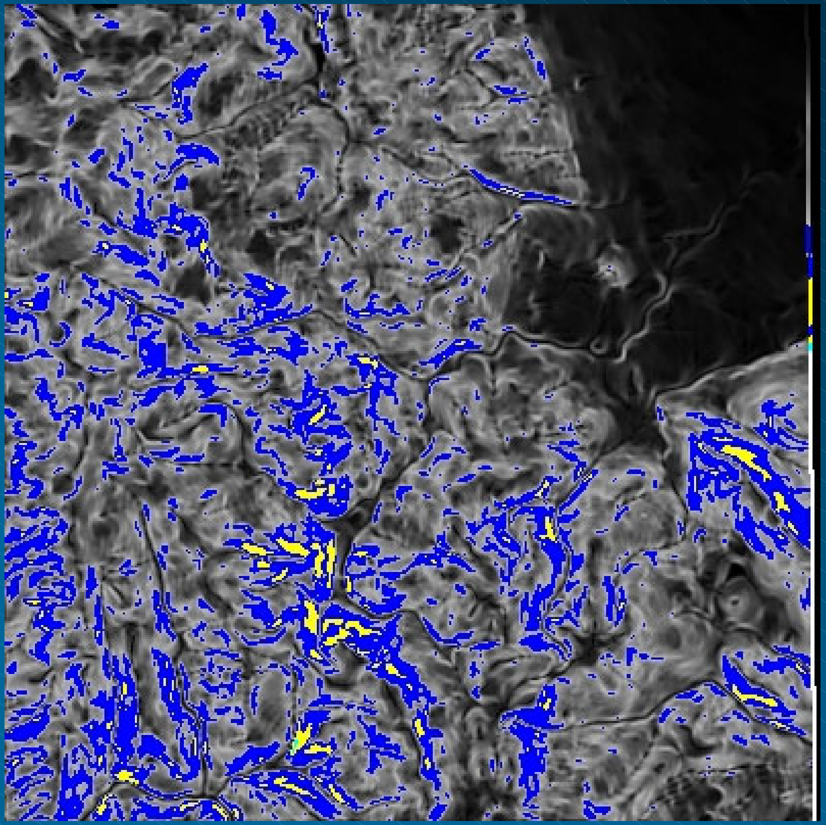
USGS 10 meter DEM of the Cordelia, CA region shown on the left. On the right are subsets of the DEM showing the test study area both in its raw form (top), and with a grayscale shaded relief drape (bottom). Sun is at 45° from nadir and coming from 045° azimuth in the bottom shaded relief version.

As a first step, we constructed slope maps that generally speak to regions more susceptible to landsliding (independent of other factors such as geology or vegetation).

Those regions with a high percentage slope can be earmarked in a risk analysis as contributing to greater slope instability.

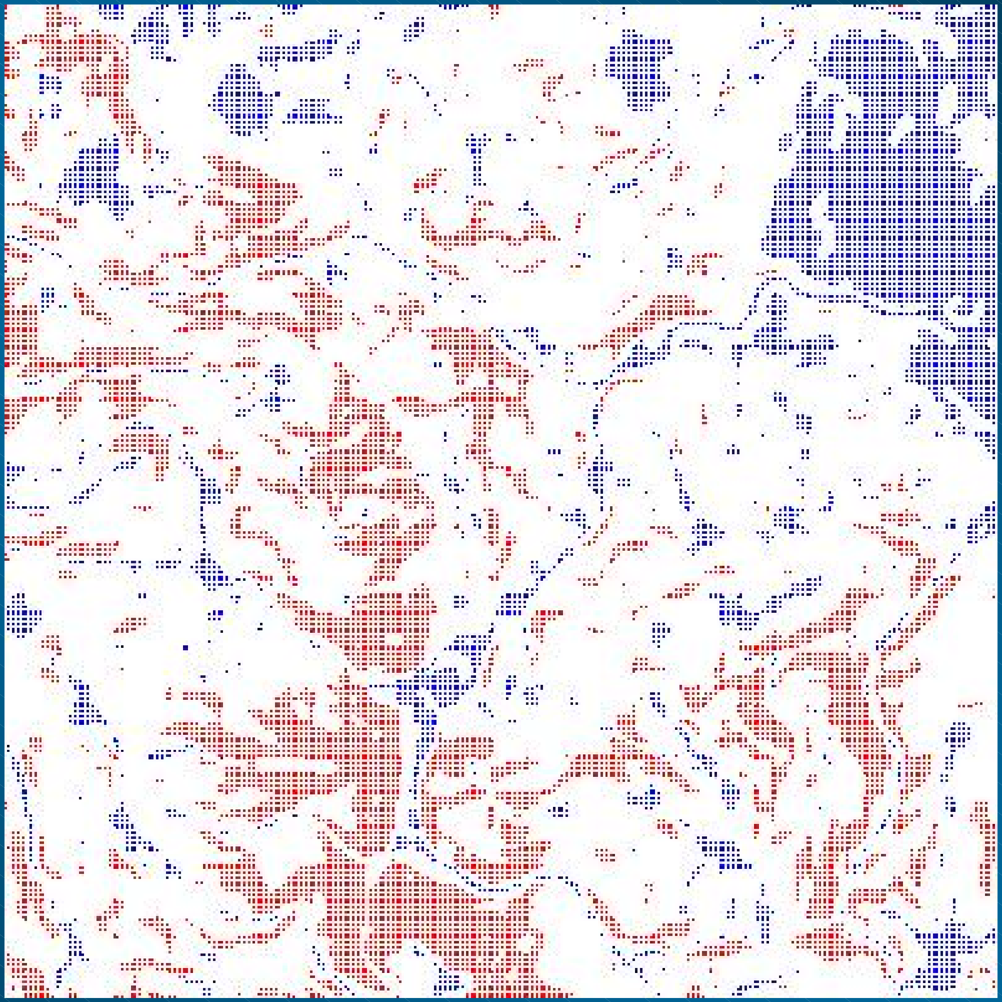
Conversely, those regions with slopes less than 15% can be effectively masked out of further analysis efforts.





The image on the left shows regions in red where the slope is less than 15%. For most analyses, these regions would be masked and removed in order to cut down data storage size requirements and processing time.

The image on the right shows those regions with slopes higher than 30%. These are the slopes most likely to fail given other conducive landsliding variables (such as sparse vegetation).



This is a vectorized version of the highest (in red) and the lowest (in blue) slopes. Such vector files can be integrated as shape files into a GIS domain with other vector files such as the geology, path of the pipeline, biomass estimates, etc.

Relative Biomass Measurement

- **Vegetation is a prime stabilizer of slopes.**

- **The lack of vegetation encourages sheet flow of water and increased rates of erosion including both gullying and landslide activity.**

- **The roots of live, healthy vegetation communities anchor the soil and rock units and inhibit their movements, though not completely negating it.**

- **The less vegetation on a slope, and the less healthy those communities are, the less inherent slope stability.**

One way to characterize this variable, is to make relative biomass measurements using the simple Normalized Difference Vegetation Index (NDVI) ratio analysis.

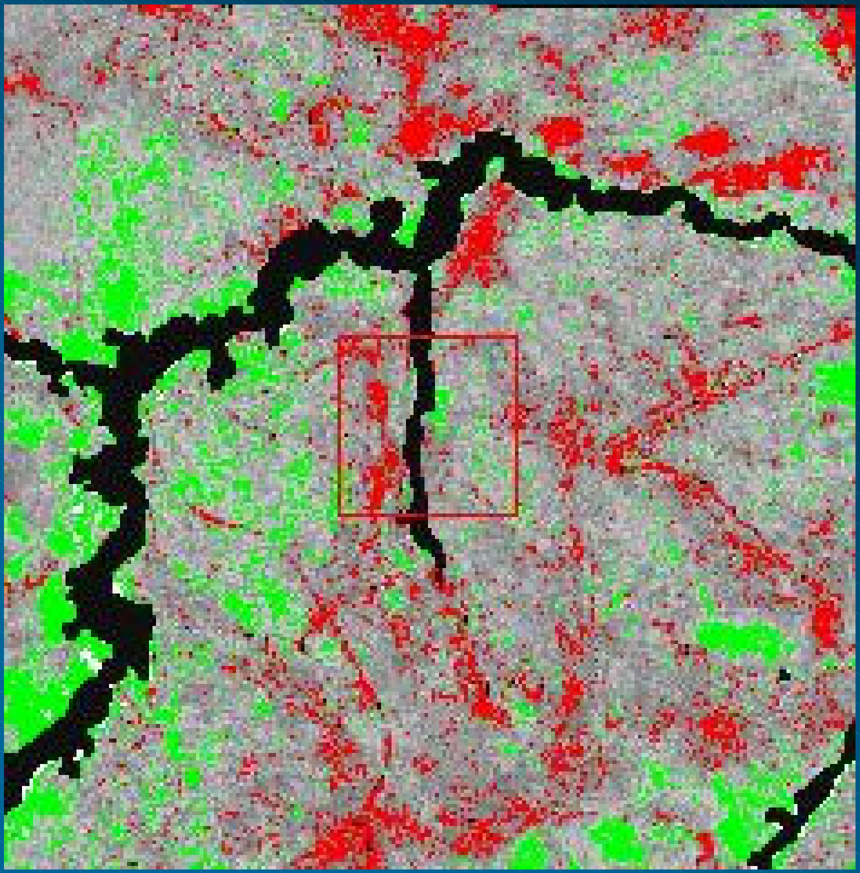
NDVI =Near-Infrared – Visible Red/ Near-Infrared + Visible Red

With IKONOS imagery, the above equation would then be:

NDVI = Band 4 – Band 3 / Band 4 + Band 3

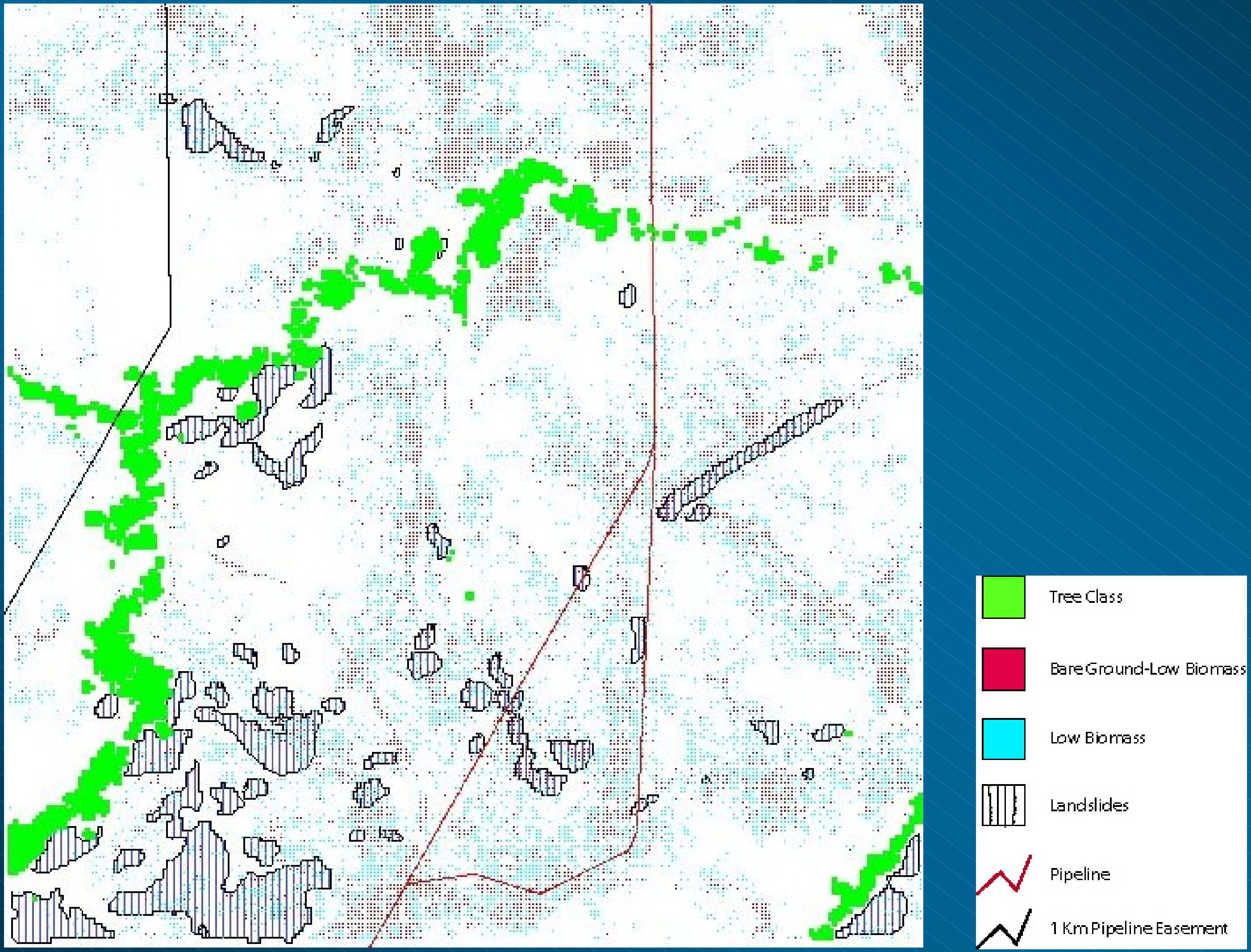
NDVI is, in effect, measuring the abundance and relative health of vegetation by analyzing the dynamics of the wavelength region spanned from the visible red wavelengths to the near-infrared wavelengths. This region is often referred to as the "red-edge".

This is the near-infrared color image of the field test area.

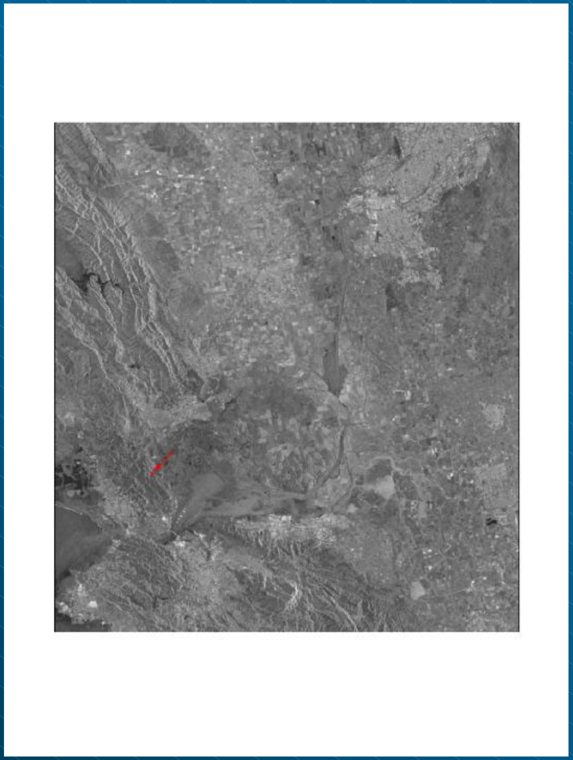


This shows two separate biomass classes. The red represents areas of bare ground to very low biomass (NDVI values of 0.01 to 0.04). Conversely, the green represents areas of much higher relative biomass (NDVI values of 0.08 to 0.12).

Example showing six of the twelve vector variables used in landslide susceptibility determinations for pipeline risk assessment.

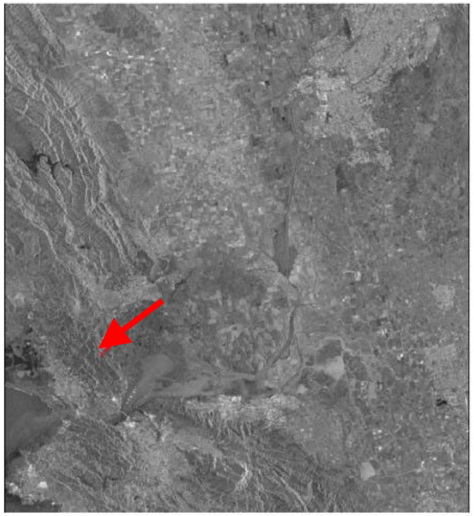


InSAR Mapping of Small-scale Deformation

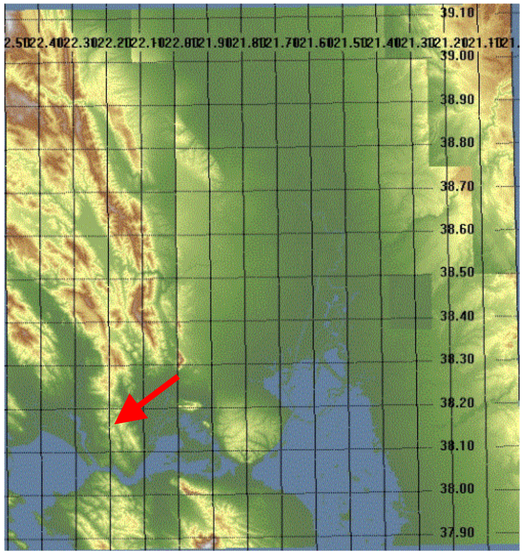


Detection and mapping of centimeter scale deformation in petroleum and gas transmission line corridors

Initial Processing of Radar Interferometry Pairs



Raw data has been processed to backscatter intensity and phase images for four summer pairs



Final interferometric processing requires the removal of topography.

First Orbit Pair Interferogram of Study Site

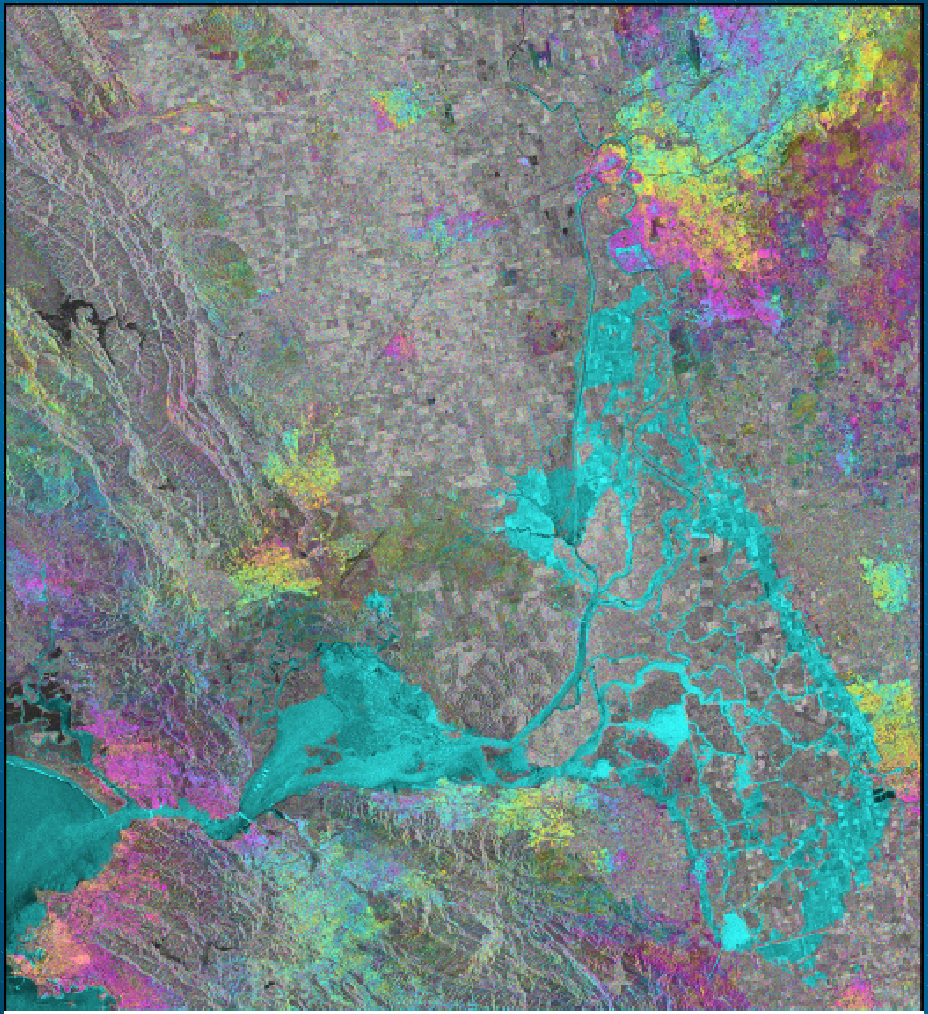


Figure 3: Orbits 17960-22469 differential (topography removed) interferogram (color) superimposed on backscatter intensity; radar coordinates. One color cycle (red-violet) represents 2π difference in phase.

Geo-referenced Interferogram for Data Fusion Analysis

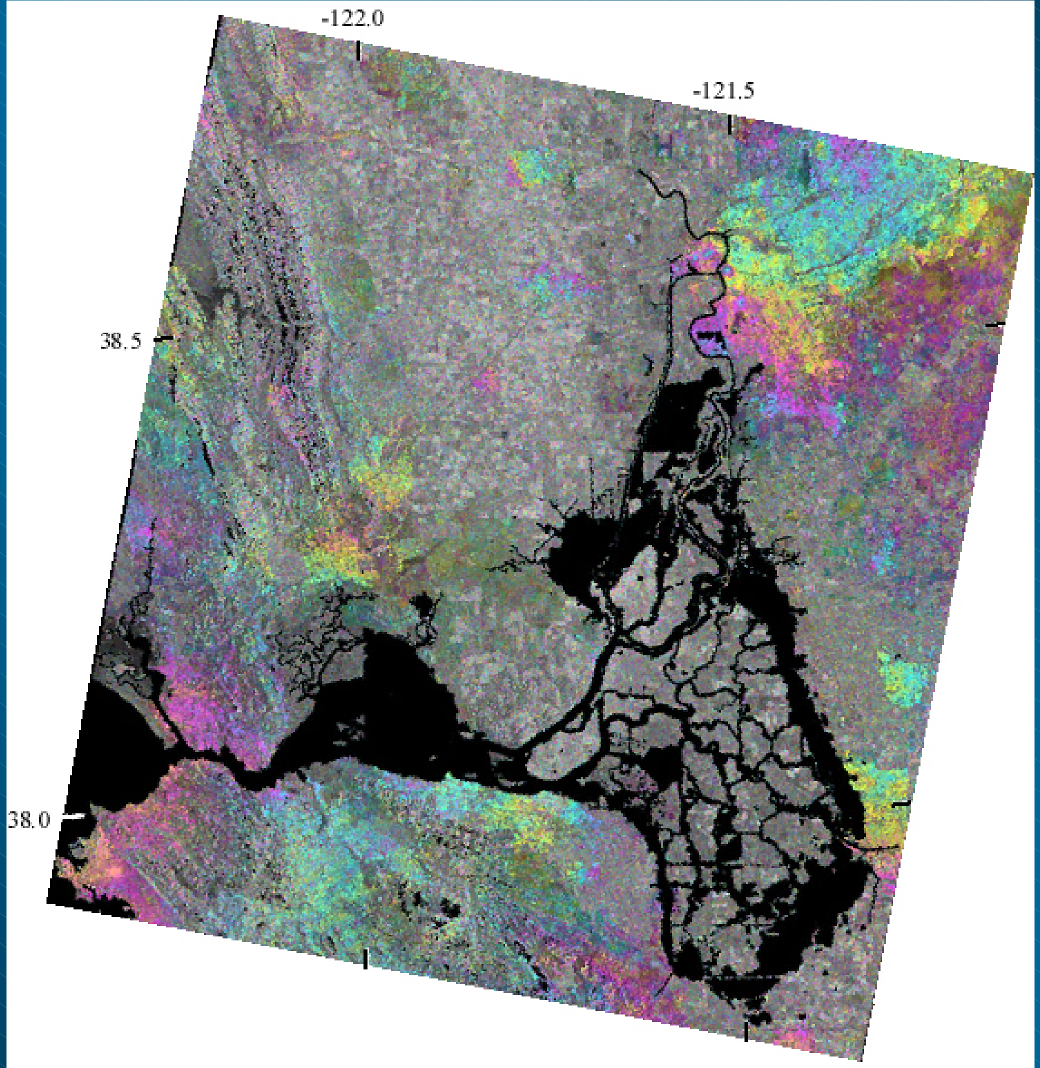


Figure 4: Orbits 17960-22469 differential interferogram geo-referenced to UTM coordinates (North American Datum 1927, Zone 10). Color scale as in Figure 3.

Second Orbit Pair Interferogram

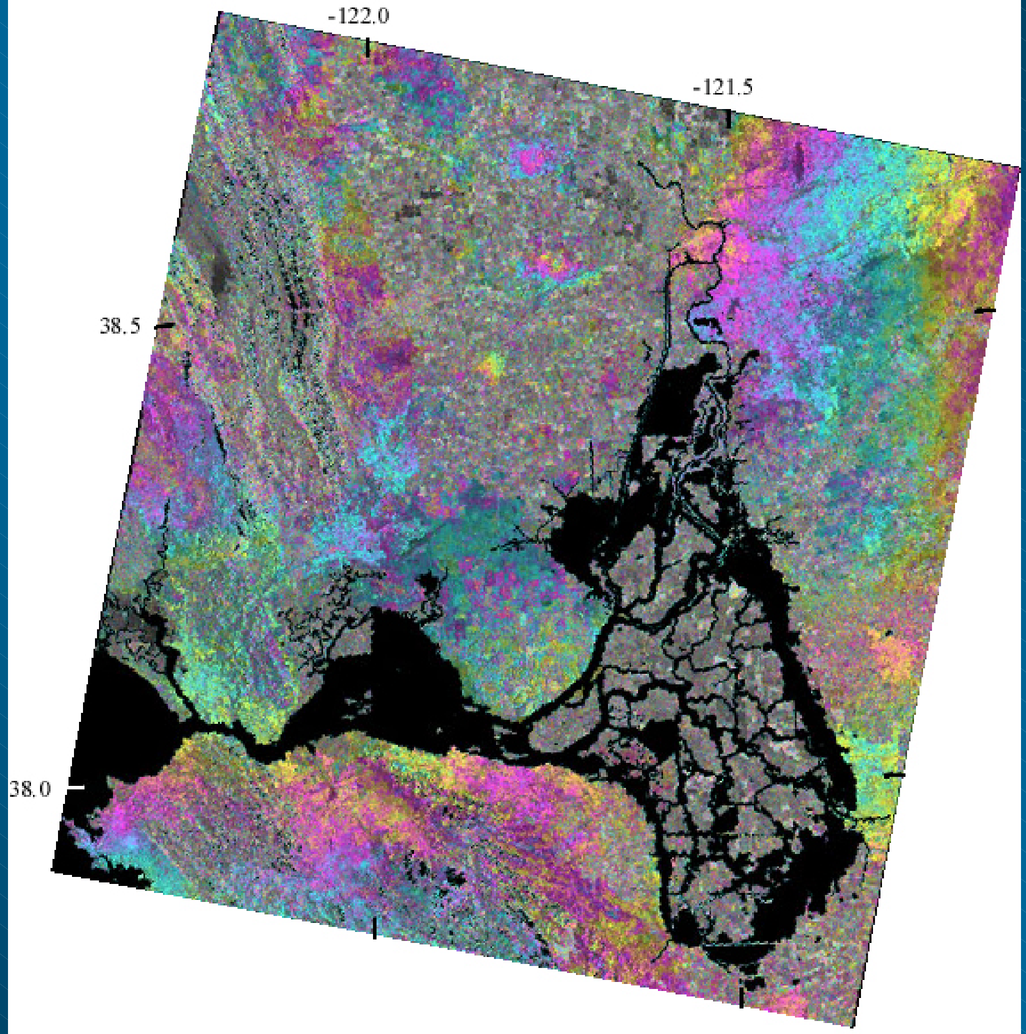


Figure 6: Orbits 21467-22469 differential interferogram; UTM. Color scale as in Figure 3.

Initial Results

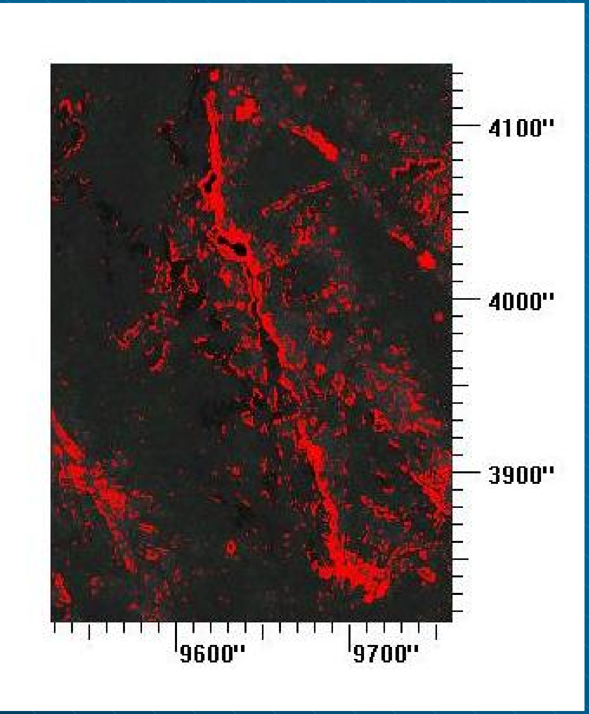
- The results of this evaluation study indicate that InSAR is not a viable technique for detecting landslide movement in an environment subject to seasonal growth of vegetation like that at the target landslide location.

- While the temporal decorrelation from one summer to the next might be expected, it is somewhat surprising that decorrelation also occurred over a two-month interval during an arid northern California summer.

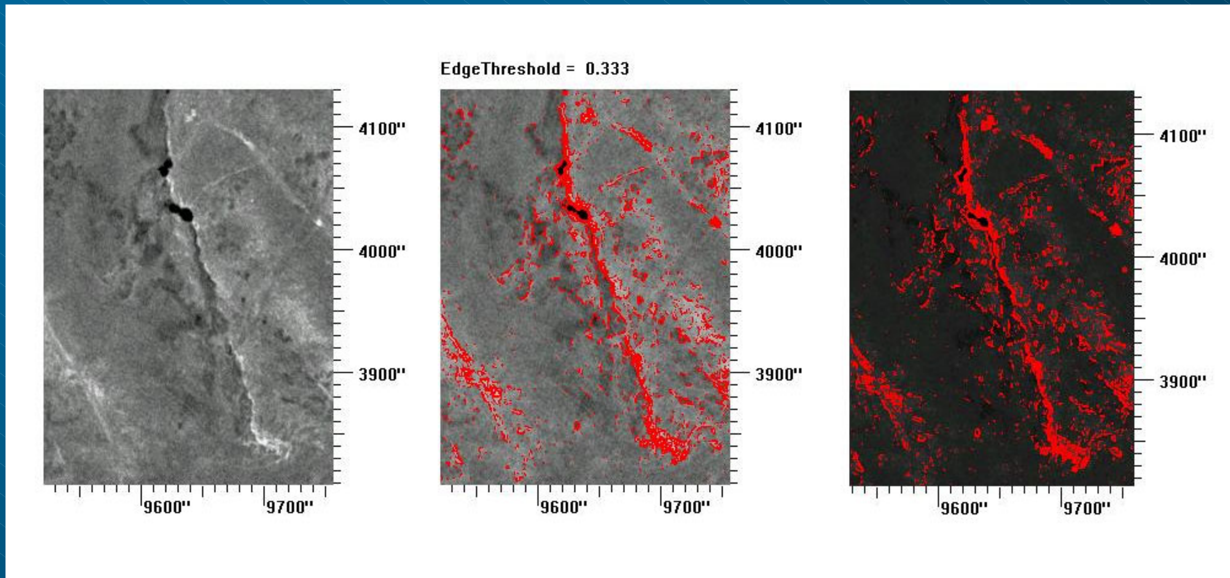
- While the results are discouraging for this particular site, they demonstrate that good coherence can be preserved within non-vegetated environments for periods up to several years.

- Therefore, the potential of InSAR for monitoring land deformation along pipeline corridors within arid regions or built-up areas remains very promising.

ImageProc – Edge Enhancement



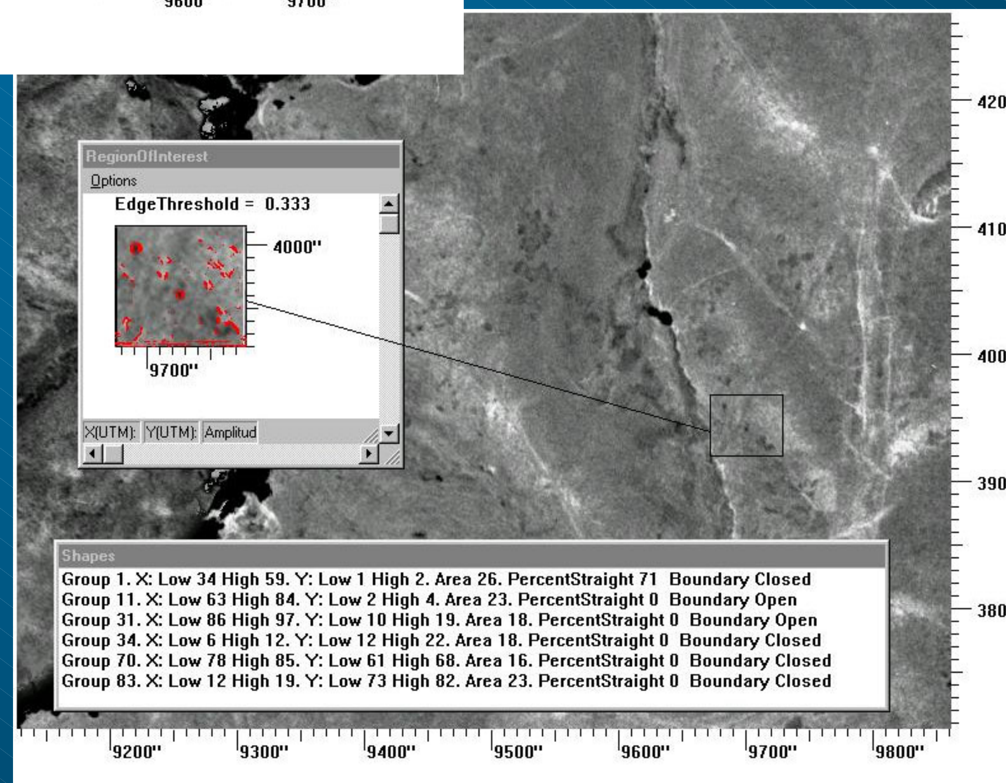
Automated extraction of features in frequency, time, and shape domains



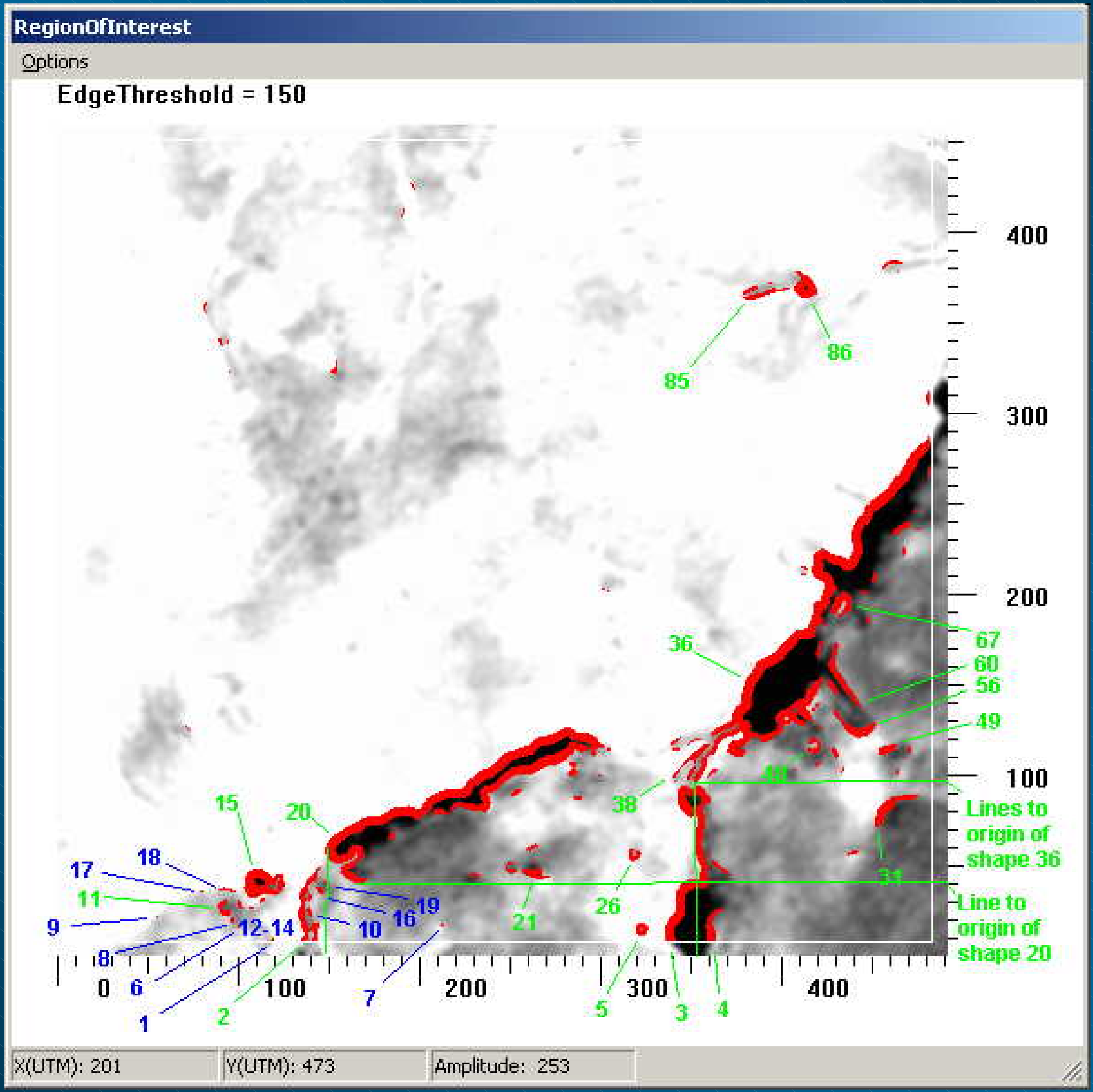
Bounding boxes are automatically put around connecting pixels with similar features. Features of interest include edges associated with erosion (landslides, gullies, etc.)

The size of boxes, skew angle, Appearance, etc. are recorded and numerical values extracted For each feature.

A database of these features is used for further numerical analysis.



Various shapes and edge features are reviewed during post processing



Conceptual Approach for Assessing Pipeline Vulnerabilities

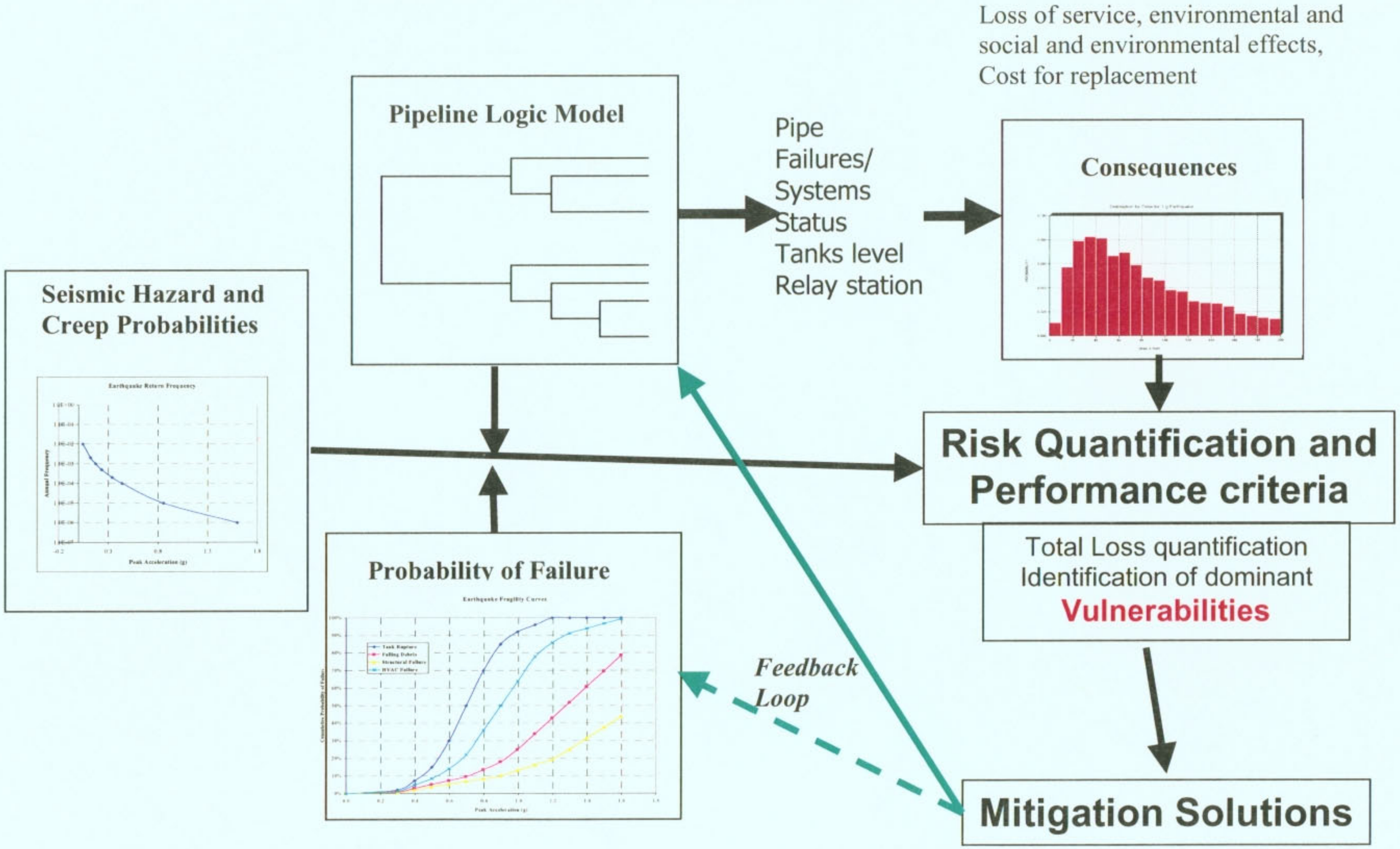


Figure X*.1 Conceptual Approach for estimating losses, identifying vulnerabilities and proposing mitigation solutions

Conclusions

- Increased spectral resolution allows for gross geological mapping and mapping of disturbed ground
- Increased spatial resolution allows for mapping of discrete erosional features including faults, scarps, and gullies
- General vegetation maps provide useful information. Their use as proxies for slope stability appear justified in this location. Conversly, masking of vegetation for edge detection provides alternative analysis methods.
- InSAR was determined to be not applicable in this study area due to vegetation initiated temporal decorrelation. InSAR shows promise in arid regions for quantitative measures of small scale slope movement.
- ImageProc is a prototype tool that can automate detection of edges in imagery. Its functionallity will be continue to be improved in the coming months