Geohazard Mapping and Evaluation using Softcopy and LiDAR Technologies

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ABSTRACT
Traditional methods of aerial photograph interpretation are limited; however their value is more on regional scale projects. Advances in both photogrammetry and GIS software have created new viewing and analysis tools, including softcopy mapping and Global Mapper, and new datasets including LiDAR and dINSAR. Using a combination of both these tools allow for the better delineation and classification of geohazards, especially on the local and operational scales where subtle landscape features often play a large role in geohazard identification and ultimately management. Numerous examples from a variety of pipeline, rail and mining projects are presented showing the value of using these complimentary technologies and data sets to enhance geohazard identification and mapping.

RÉSUMÉ
Les méthodes traditionnelles de photo-interprétation sont limitées dans leur portée et leur valeur est de plus en plus restreinte aux analyses régionales à petite échelle. Les avancées récentes en photogrammétrie et en développement de systèmes d'informations géographiques apportent de nouvelles perspectives d'applications et de nouveaux outils d'analyses. La photo-interprétation numérique tridimensionnelle, la venue de logiciel tel que Global Mapper ainsi que l'utilisation des données LiDAR and DInSAR sont quelques exemples d'outils qui permettent une meilleure précision et facilitent la classification des géorisques, particulièrement à l'échelle locale où les formes du relief jouent un rôle déterminant dans l'identification des risques naturels. Plusieurs exemples d'application provenant de divers projets d'oléoduc, de chemins de fer et de projets miniers seront présentés afin de démontrer la valeur de l'utilisation de ces technologies complémentaires et des ensembles de données afin d'améliorer l'identification et la cartographie risques géologiques.

1 INTRODUCTION

A geohazard is defined by the International Centre for Geohazards as a geological state that may lead to widespread damage or risk. Geohazards are geological and environmental conditions and involve long-term or short-term geological processes.

A number of geohazards present risk or damage to today's infrastructure, including:

1. Mass movements (e.g, debris slides, rock fall, snow avalanches, etc.);
2. Liquefaction;
3. Subsidence;
4. Erosion and hydrologic processes (e.g., stream avulsion, gullying, etc.); and
5. Freeze/thaw (e.g., thermokarst)

Today there is a prolific growth in infrastructure development including road, pipeline and rail to support resource development. Roads, pipelines and railways are being constructed at a rapid pace to transport raw resources from Arctic environments, across rugged mountainous terrain and ecologically sensitive environments to processing facilities and ultimately, end users.

For the development of today's infrastructure including roads, rail, pipeline and facilities, it is critical to identify and locate these hazardous features so that routes or sites can be avoided (Figure 1). If they cannot be avoided, additional detailed geotechnical investigations need to occur to ascertain specific features of these geohazards to develop sound construction and management practices to limit risk and potential damage.

Figure 1 Landslide in northern Alberta near town of Peace River

Traditionally, geohazards such as mass movements are associated with steep valley side slopes and river crossings. Geotechnical investigations generally focus on these areas, however mass movements are known to occur on low angle slopes (e.g., 3 – 5^{o}) (Morgan et al 2012). Areas subject to liquefaction, subsidence, and thermokarst processes are not generally associated with steep topography.

Detailed terrain mapping should always occur prior to any development, including infrastructure siting (e.g., transmission towers, pump stations, well pads). Not only will it assist in identifying areas of potential geohazards, but the use of such tools allows for proactive re-routing or siting of linear corridors and facilities to better areas. It also results in better siting of more costly geotechnical investigations, thereby reducing the costs of geotechnical investigations. For the purpose of this paper, detailed mapping is generally considered to be mapping at scales greater than 1:10,000 (e.g., 1:5,000, 1:2,500, etc.).

Mapping is generally completed using stereo aerial photographs and a stereoscope (Figure 2). Traditional aerial photograph interpretation is limited by (1) the scale of the aerial photograph, (2) the magnification provided by the stereoscope, and (3) the abilities of the aerial photograph interpreter. Most aerial photographs are acquired at scales of 1:15,000 to 1:50,000, hence mapping is generally completed at such scales. Mapping at these scales is generally considered to be of local to regional scales and hence the data needs to be applied accordingly (e.g., local and regional planning). Data created from 1:20,000 scale aerial photographs should not be used for detailed work at 1:5,000 scale.

Figure 2 Traditional approach to aerial photograph interpretation using stereoscope and hardcopy aerial photographs.

Advances in photogrammetric technologies from the early to mid-1990s have provided new tools to complete aerial photograph interpretation. Traditionally, mapping has been completed using a combination of hardcopy aerial photographs and a stereoscope. This approach to aerial photograph interpretation has been used since World War I (Campbell 2008) and unfortunately, is still the case today with many engineering and environmental companies as well as educational institutions. Today, numerous digital tools and datasets are available to provide advanced interpretation of geohazards including tools such as softcopy mapping (e.g., PurVIEW, DatEM) and Global Mapper as well as LiDAR data.

2 HD-MAPP

Stantec Consulting Ltd. has incorporated the functionality of ArcGIS and PurVIEW software as well as other tools including Global Mapper and dINSAR to create a tool known as HD-MAPP (Figures 3a and 3b). HD-MAPP provides our terrain scientists and geohazard specialists with tools to complete detailed mapping at scales as large as 1:500 from 1:12,000 scale digital imagery. This obviously has significant advantages when identifying, delineating and classifying geohazards and when these tools are combined, provides for better identification of geohazards and solutions.

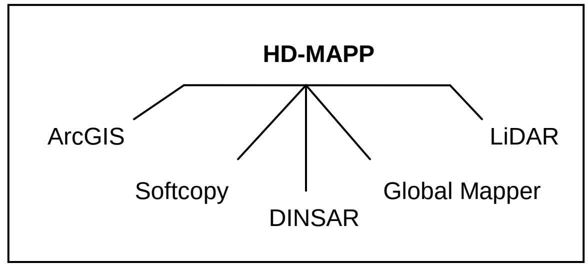


Figure 3a HD-MAPP

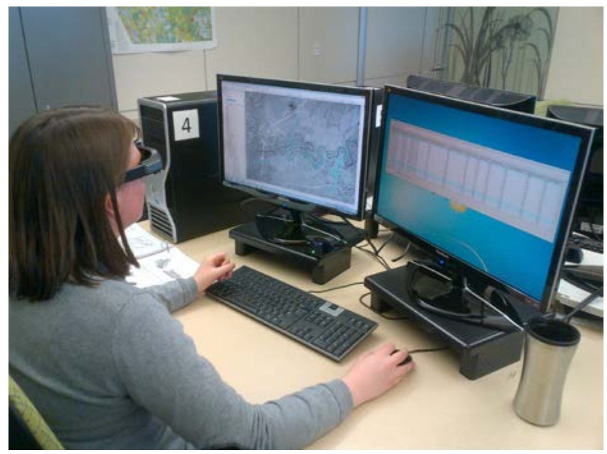


Figure 3b Softcopy mapping using HD-MAPP

2.1 Softcopy

Softcopy mapping has been around since the mid-1990s when a number of suppliers stripped of the viewing packages of digital photogrammetric workstations. As an “add on” to ArcGIS, packages such as PurVIEW and DatEM allow mappers to view digital imagery on a computer monitor with the aid of specialized 3D glasses.

Using traditional hardcopy aerial photographs for softcopy mapping requires that the photographs be scanned at high resolution (10 – 15 microns) and merged with DEM data to create digital files that can be seen in 3D on a computer monitor with the aid of specialized 3D glasses. Because the data is merged with DEM data, x, y and z coordinates are parts of the final dataset and can be used to calculate slope length and percent slope. Traditional hardcopy aerial photographs are available for much of the world.

Digital imagery is now being flown by a number of providers. This kind of data is already digital, does not requiring scanning and has been georectified; it has a much higher resolution than is found with traditional imagery and hence the quality of this kind of imagery is superior to imagery obtained by scanning.

Softcopy mapping has a number of advantages, including:

- Mapping can often be completed at scales as large as 1:5,000 to 1:2,000 from traditional scales of 1:20,000 to 1:50,000. This allows the mapper to zoom down into the data (e.g., data mining) to see and interpret features that are not possible with hardcopy aerial photographs and a stereoscope. For examples, small landslides that are not discernable at 1:20,000 can be identified and delineated; likewise, mappers are able to better estimate the depth to bedrock below the surface, a key requirement in any infrastructure project.
- Mapping is completed by the terrain scientist or geohazards specialist. Using a mouse, the mapper digitizes critical landscape features (e.g., headwall scarps, run-out zones, springs, bedrock outcrops, etc.) and provides corresponding attribute data (e.g., rapid or slow mass movement, mass movement subprocesses (e.g., debris slide, debris flow, rock fall, etc.), slope, drainage, etc. This eliminates the need for costly digitizing from aerial photographs by a GIS technician and likewise, data entry by a data entry specialist. The mapper is in control of the linework and the data attributes.
- Measurements are able to be made of individual features. For example, area of the runout zone, length of a headwall scarp or distance to a pipeline or transmission tower.
- Being able to identify features at up to 1:2,000, allows for better targeting of field investigations. For example, small landslides that are not discernable at 1:20,000 can be identified and delineated with corresponding GPS coordinates to allow for more targeted field investigations. This ultimately results in reduced field costs and better data. Sites for further geotechnical investigation can be better identified and targeted resulting in reduced overall costs.
- Using a 3D projector, HD-MAPP can be used in public meetings and boardrooms to help with the planning and public consultation process.

The advantages of HD-MAPP are clearly shown in Figures 4a, b, c and d. They show an area characterized by dense forest canopy outside of Cancun Mexico. Figure 4a is of the initial 1:20,000 scale aerial photograph while figures 4b, 4c and 4d are from the same image however the interpreter has zoomed in to scales as large as 1:2,500 to better identify and delineate and classify features. In Figure 4a, one can make out the cleared land in the northeast corner of the image as well as a road running in a northeast/southwest direction. In Figures 4b (1:10,000) and 4c (1:2,500), better definition of the infrastructure is clearly visible. In Figure 4d (1:2,500), a quarry is visible along with a vehicle on the road; using ArcGIS tools, the quarry is approximately 188 m in width and overlaying materials appear to be thin.

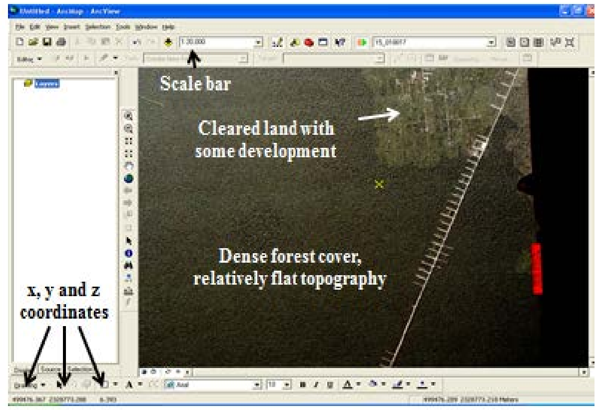


Figure 4a 1:20,000 scale

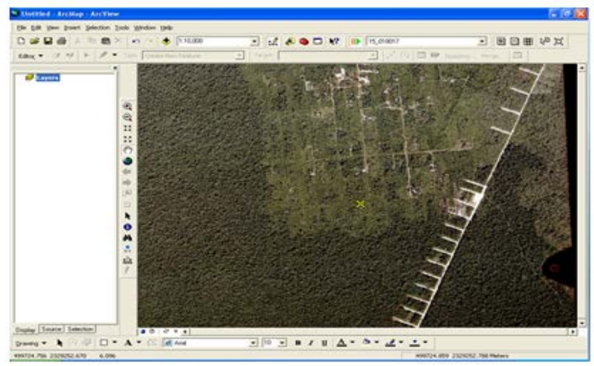


Figure 4b 1:10,000 scale

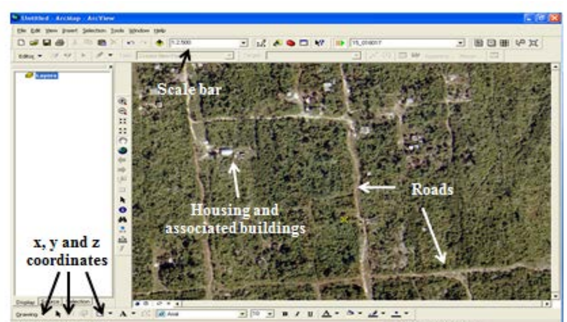


Figure 4c 1:2,500 scale

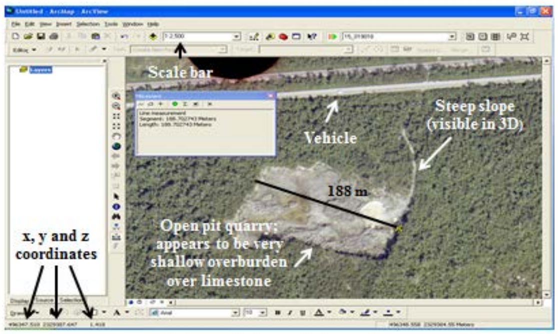


Figure 4d 1:2,500 scale

Softcopy can use a variety of data acquired from fixed-wing aircraft (e.g, hardcopy and digital aerial photographs) and satellites (e.g, IKONOS, Quick Bird, ASTER and OrbView). While these satellites maintain the dominant spectral advantages demonstrated by lower resolution satellite imaging systems such as Landsat TM and SPOT, they provide strong geometric capabilities including high resolution photogrammetric stereo capability and revisit rate (Li 1998). In addition, radar data has been brought into 3D for use in HD-MAPP. GeoSAR, dual band (X- and P-band) single-pass interferometric synthetic aperture radar (IFSAR) provides data that has been incorporated into HD-MAPP to map terrain features and geohazards in the Peruvian jungle where aerial photographs and LiDAR data cannot penetrate jungle canopies.

2.2 LiDAR

LiDAR is submeter scale point data obtained from either ground based, fixed-wing or helicopter mounted platforms. Two types of LiDAR data are collected, "full earth" and "bare earth". The former provides vegetation data while in the latter, the vegetation is stripped off and provides valuable data for the identification of geohazards.

Submeter LiDAR data allows for the creation of 1 m contours as well as the accurate portrayal of landforms through hillshade "models" (Figure 5). By "zooming" into the data, the terrain scientist is better able to identify and delineate landslides that may not be visible on aerial photographs due to forest cover.

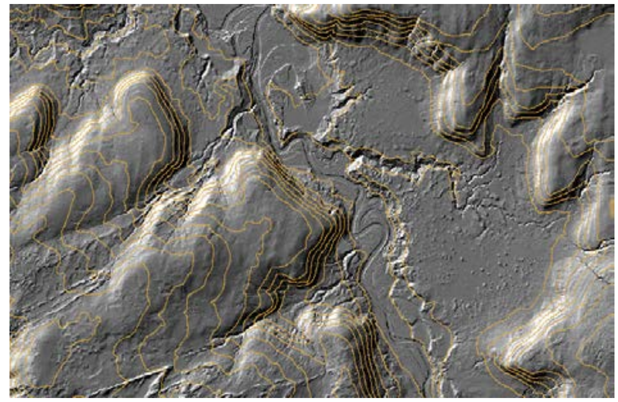


Figure 5 "Bare earth" hillshade LiDAR data with contours.

2.3 Aerial photographs and LiDAR as Complementary Data Sources

Aerial photographs and LiDAR data provide a snapshot in time. In completing geohazards studies, LiDAR data should be used in conjunction with aerial photographs when available. LiDAR data provides valuable submeter DEM data and when viewed in a hillshade model, geohazards such as deep-seated and shallow landslides are readily apparent. However, LiDAR data does not provide any data on soil moisture. Moisture data is critical in geohazard analysis, especially in determining wet areas on planar landscapes and seepage areas on slopes. The moisture data is important in identifying areas where buoyancy issues may be of concern, and seepage areas are important on slopes that show no evidence of failure, but when disturbed may fail.

2.4 Global Mapper

Global Mapper is a utility, stand-alone GIS program that has wide application to the handling of vector, raster, and elevation data, and can be easily integrated into real-time data capture and GPS-based field studies. While it shares many similarities and capabilities with other larger GIS packages, it is renowned as an easy-to-use tool (particularly by non-GIS specialists) that can be integrated with other software, or used as a stand-alone resource. It also has a tremendous capacity for integrating and converting different file types, formats, and projections, and has an active on-line discussion forum where questions can be posted or searched. The power and ease of manipulating, viewing, and processing digital elevation data (e.g., SRTM, LiDAR) is a particular strength of Global Mapper that we use in terrain mapping. Simple tools are used to manipulate sun angles and altitudes, providing quick illumination of terrain that is shadowed in lee-side slopes. The ability to quickly alternate sun azimuth allows us to discern geomorphic features that may otherwise be masked by an azimuth-parallel orientation (e.g., low amplitude flutings can be poorly discerned when illuminated from parallel orientations, but are immediately apparent when illuminated from perpendicular sun angles). Other tools of note are its "3D Path Profile" which on digital elevation data sets allows you to quickly measure slope angles, elevation changes, and lengths of slopes and geomorphic features. In low relief areas, we use Global Mapper's "Water Display" tool to flood terrain up to different elevations, thereby allowing you to more accurately determine limits of past glacial lakes, shorelines, and former breach points. The "3D View" tool quickly projects images that can be rotated, pitched, and differentially shaded by a number of different options to give perspective views of terrain or individual geomorphic features in order to better illustrate/explain details.

2.5 SAR Differential Interferometry (D-InSAR)

SAR Interferometric data along with different (D-InSAR) processing techniques can be used to assist in detecting and monitoring ground deformations as a result of the measurement of the signal phase shift at different times creating an interference pattern called interferogram. Once infrastructure (e.g., rail, pipeline) has been developed, it is important to measure and monitor ground movement (upheaval and/or subsidence) to identify areas where reclamation work is required or to identify anomalies associated with geohazards. Minimal shifts in the ground can cause significant effects to pipelines, roads and rail infrastructure.

3 APPLICATIONS

These tools and datasets have been used for numerous applications, including pipeline, road and transmission line planning, railroad routing, and facility siting. The following provides a listing of some projects and results.

3.1 Pipelines

A study was completed to assist in the re-opening of a pipeline that had been ruptured due to massive deep-seated landsliding following abnormal rainfall events. Initial mapping of mass movements along a 100 km stretch of the pipeline using traditional hardcopy aerial photographs and a stereoscope identified 153 landslides (1.5 landslides per kilometer). More detailed mapping at 1:500 scale using HD-MAPP with 1:24,000 scale color digital imagery and LiDAR data identified over four times as many landslides (704) over the same distance, resulting in an average of 7.0 landslides per kilometre. These included earth slides, earth flows, slumps and rockfall. Using HD-MAPP, statistics were identified for each type of slide, including area, length of runnout zones, height and length of headscarps (where visible) and width of slides.

Each landslide was rated on a five-class system for Potential Feature Hazard based on a number of factors, including distance from the pipeline to the landslide and the relative age of the landslide. Features were initially rated while viewing the features in stereo in HD-MAPP. Following field investigations the ratings for certain features were downgraded to reflect site specific conditions.

Of the 704 landslides, 84 were rated as having recent slide movement with (1) the pipeline either in the body or headscarp of the slide; (2) the pipeline exposed due to active gully or slope erosion (3) the pipeline either in the stream bed or stream bank, or (4), the pipeline was exposed by a cut slope. These features identified as having a high potential hazard that occur along the existing corridor required immediate attention prior to the pipeline being commissioned.

Because of the detailed nature of the imagery that was used with HD-MAPP, re-route options were developed for a number of the most problematic areas (Figure 6). Using HD-MAPP, a re-route option was identified and subsequently used where the line did not pass through any landslides.

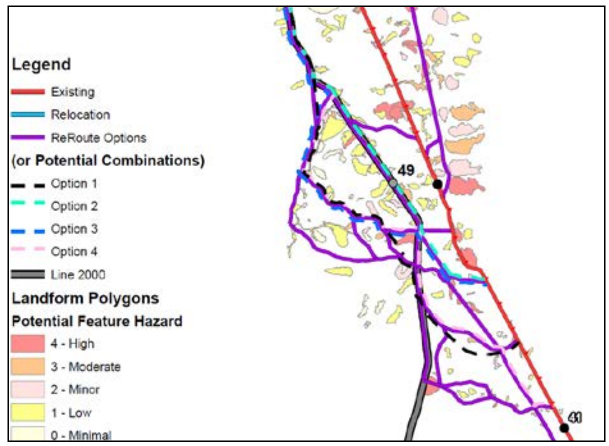


Figure 6 Small section of pipeline route (red) along with a number of potential re-routes.

3.2 Rail

HD-MAPP was used to help evaluate three possible rail options across a highly eroded and dissected plateau area. The topography varied from level fluvial plains to rugged, highly eroded and failed plateau side slopes to an undulating plateau some 300 m above the surrounding plains. The area is characterized by low magnitude earthquakes. The probability of a magnitude 5 or higher earthquake occurring in the next 50 years, within 50 km of the project site is six (6) percent. The likelihood of damage is mostly associated with secondary hazards including landslides and sinkholes.

Detailed mapping using HD-MAPP was completed at a scale of 1:5,000 from a series of 1:24,000 color and color infrared aerial photographs to identify the 'best possible route'. A total of 64,300 hectares of land was mapped. Weathered bedrock and colluvial materials were the two most common materials mapped.

A review of Route Options 1 and 2 showed that they had more than double the amount of terrain instability that Route Option 3 exhibited; 40% and 38% of Options 1 and 2 exhibited strong evidence of instability (e.g. landsliding) as compared to only 15% of Option 3. The Option 3 route however, had a higher percentage of "potentially unstable" terrain as compared to the former two routes due to the amount of weathered bedrock on the slopes that do not exhibit signs of mass movement, but show similar lithology and slope gradients to areas that have previously failed and are now identified as colluvial materials.

3.3 Pipeline and Facility Siting

HD-MAPP was used to assist in both pipeline and facility siting in an area characterized by steep, highly eroded and failed Cretaceous bedrock dominated with mesa-like remnant plateaus and valley bottoms infilled with thick glaciolacustrine sediments with seasonally high water tables. Relief across the area was in excess of 500 m.

Initially, all linear infrastructure including roads and pipelines and facilities (pump stations) were located by the lease holder using 1:20,000 TRIM maps with 20 m contours, DEM data with a 5 – 10 m accuracy and existing small scale (e.g., 1:250,000) surficial geology and bedrock geology maps.

Detailed mapping of surficial materials and geological modifying processes (e.g., mass movement, gullying, and seepage) was subsequently completed using HD-MAPP at a scale of 1:5,000 from 1:30,000 black and white aerial photographs and LiDAR data. Colluvial materials were the most dominant material mapped with lesser amounts of bedrock, glaciolacustrine and till materials.

Overlaying the initial infrastructure and facilities on the newly created 1:5,000 scale detailed terrain and geohazards map resulted in the relocation of over 67% of all features (Figure 7); this was done in a downtown boardroom with engineers, planners and project managers all wearing 3D glasses and viewing the imagery and mapping. Detailed mapping indicated that many of the proposed well pads were situated on runout zones of debris slides, that portions of the pipeline were located on active landslides and steep, avalanche-prone bedrock slopes and many of the facilities were located on very poorly to poorly drained valley bottom sites.

One very critical activity in this exercise was locating the crossing of a stream. The lease holder had sent two engineers into the field to determine the location of the crossing, spending two days in transit, two days in the field and using a helicopter to gain access to the site. Using HD-MAPP, the individuals in the boardroom identified the crossing site within 30 minutes using a combination of the digital stereo aerial photography and LiDAR data. The GPS data from the site identified through the field investigations were uploaded into HD-MAPP – the site was within 10 m of the site chosen through the use of HD-MAPP and LiDAR.

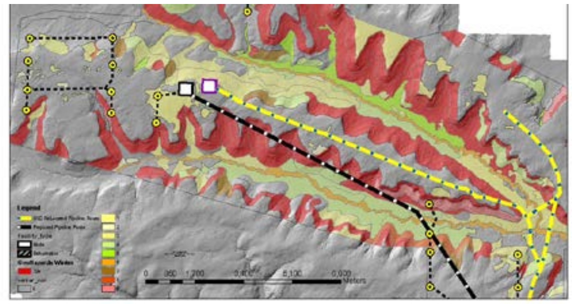
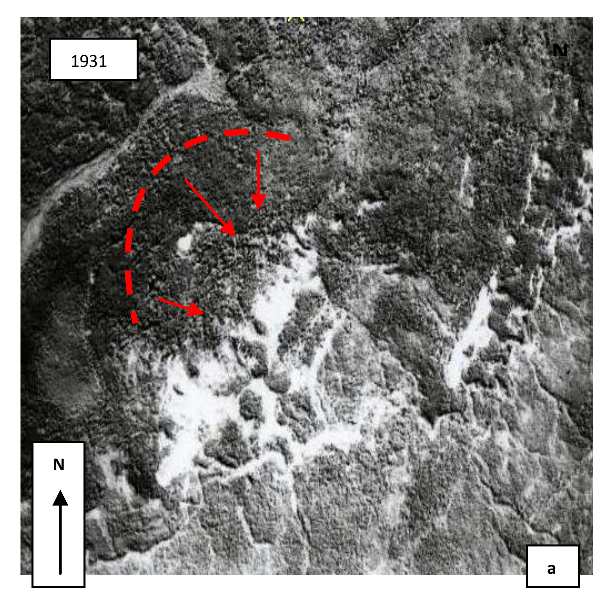


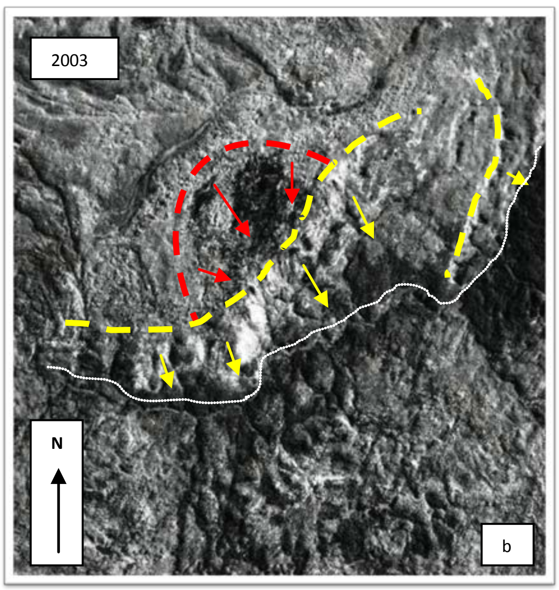
Figure 7 Initial linear infrastructures including pipelines, roads and facilities in black, proposed well pads shown as yellow circles; recommended locations shown in yellow. Red areas (steep slopes, landslides, seepage, exposed bedrock and rock fall) are most problematic in terms of geohazards followed by pink, orange and green (areas with seasonally high water tables).

3.4 Historical Landslide Analysis

Using a series of historical aerial photographs from 1931 to 2003, HD-MAPP allowed for the delineation of landslide features (e.g., headwall scarps, sag ponds) to try and estimate movement over a period of over 70 years. Hardcopy aerial photographs were scanned and merged with DEM data and subsequently controlled so that the results from each year could be overlain on other years to see changes along the slope.

The results suggest that there was no movement in the deep-seated landslides over the time period in question, but stratigraphic and morphologic evidence does suggest that the landslides were formed post-glacially. There is, however, evidence of shallow slides on the aerial photographs, and the extent of the active scarp faces did change over the time period (Figures 8a and 8b). Some areas showed revegetation of exposed material and others showed denudation of the vegetation and erosion of surficial material. Fieldwork confirmed the active nature of the surface deposits through the identification of tension cracks which split two living trees. Tree ring analysis suggests that the trees were split approximately 20-25 years ago.





Figures 8a and 8b The main scarp faces (yellow dashed lines) are south facing and are undercut by a creek (white dashed line). The extent of exposed material on these main scarp faces has changed over the time period, with some areas showing signs of revegetation. The red dashed line and arrows show an old but very active sliding unit. The samples for the tree ring analysis were taken in this area.

4 CONCLUSIONS

The use of new digital tools such as softcopy mapping and Global Mapper and new datasets such as LiDAR and DINSAR allow for better assessment and analysis of geohazards. These tools are readily available today and are simple to use. Data such as LiDAR and DINSAR are providing very detailed submeter data that can be brought into the analysis to improve upon standard analysis of geohazards. Like the tools, they too are very common or can be acquired readily.

These tools need to be incorporated into any resource development project. They are cost-effective and easy to use.

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