AER/AGS Special Report 105

Runout Analyses of Potential Landslides of South and Third Peaks; Turtle Mountain, Alberta

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September 2017

ISBN 978-1-4601-0171-1

Publications in this series have undergone only limited review and are released essentially as submitted by the author.

If you use information from this publication in other publications or presentations, please acknowledge the AER/AGS. We recommend the following reference format:

Hungr, O. (2017): Runout analyses of potential landslides of South and Third Peaks; Turtle Mountain, Alberta; Alberta Energy Regulator, AER/AGS Special Report 105, 68 p.

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Published September 2017 by:
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Acknowledgements

Funding for this report was provided by the Energy Resource Conservation Board (ERCB), now the Alberta Energy Regulator in 2008.

Foreword

This Special Report contains two reports from O. Hungr Geotechnical Research Inc. provided to the Alberta Geological Survey in April and November, 2008. These reports provide a description of the runout analyses for potential landslides on the South and Third peaks of Turtle Mountain. Turtle Mountain is the location of the April 29, 1903, Frank Slide. Since 2005 the Alberta Geological Survey has been managing the Turtle Mountain Monitoring Program.

Much of the content of this report has been published previously in a series of Alberta Geological Survey reports that include the following:

1) Open File Report 2008-07**:** Turtle Mountain Field Laboratory: 2007 Data and Activity Summary; http://ags.aer.ca/publications/OFR_2009_06.html

2) Open File Report 2009-06: ERCB/AGS Roles and Responsibilities Manual for the Turtle Mountain Monitoring Project, Alberta; http://ags.aer.ca/publications/OFR_2009_06.html

3) Open File Report 2009-15: Turtle Mountain Field Laboratory, Alberta (NTS 82G): 2008 Data and Activity Summary; http://ags.aer.ca/publications/OFR_2009_15.html

4) Open File Report 2012-03: Turtle Mountain Field Laboratory, Alberta (NTS 82G): 2010 Data and Activity Summary; http://ags.aer.ca/publications/OFR_2012_03.html

5) Open File Report 2015-10: Turtle Mountain Field Laboratory, Alberta (NTS 82G): 2014 Data and Activity Summary; http://ags.aer.ca/publications/OFR_2015_10.htm

The purpose of this Special Report is to make available to the public the original consultant reports.

1 Report One: Runout Analyses of Potential Landslides on South Peak: Turtle Mountain, Frank, Alberta

SOUTH PEAK OF TURTLE MOUNTAIN, FRANK, ALBERTA
RUNOUT ANALYSES OF POTENTIAL LANDSLIDES

Report to:
Environmental Geology Section
Alberta Geological Survey/Energy and Utilities Board
4th Floor, Twin Atria Building
4999 - 98 Avenue, Edmonton, Alberta, T6B 2X3

by:
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April 18, 2008

Abstract

Two existing computer runout models have been used to predict the runout distance of potential rock avalanches for the disturbed rock mass on top of the South Peak of Turtle Mountain, near Frank, Alberta. One of the models is two-dimensional and the second three-dimensional. Both give similar results, when the same parameters are used. The models were first calibrated by back-analysis of the 36 million m^3 1903 Frank Slide and two smaller rock avalanches from the Rocky Mountains. Forward analyses were then completed of two potential rock slides from South Peak, a planar slide with a volume of 6.7 million m^3 and a deeper rock slide with a volume of 13.8 million m^3. Potential runout lines were constructed representing several different conditions and conditional probabilities (probabilities of runout given detachment) were subjectively assigned to them.

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1. Introduction

Following a proposal of July 25, 2006, we carried out a dynamic analysis of a potential rock slide, involving disturbed rock mass on the South Peak of Turtle Mountain near the town of Frank, Alberta. The purpose of the analyses was to calibrate two existing landslide dynamics models against the historical 1903 Frank Slide and other case histories and then apply the models to a prediction of runout of potential future rock slides from the disturbed rock mass of the South Peak.

2. Site Description

The Frank Slide of 1903 was the deadliest landslide disaster of Canadian history, having destroyed a portion of the town of Frank with a loss of approximately 70 lives McConnell and Brock (1904). Immediately following the slide, it was found that the South Peak of Turtme Mountain, adjacent to the southern margin of the 1903 landslide source, was disturbed by numerous scarps and tension cracks. This "disturbed area" is still present on the mountain and has been the subject of continuing studies for nearly 100 years. An intensive research effort with the purpose of assessing hazards posed by the presence of the disturbed area has been undertaken recently by the Alberta Government. The present study forms a part of this work.

The Frank Slide was a typical rock avalanche (for classification see Hungr et al., 2001), involving approximately 36 million m^3 of limestone rock (Cruden and Krahn, 1978). The rock detached from the ridge of Turtle Mountain over a front about 700 m wide, disintegrated into fragments, descended the 800 m high slope, crossed talus aprons and glacial drift benches and covered the floodplain of Crowsnest River and the opposite hillside in a deposit about 1.7 km wide almost 2 km long. The deposit is approximately 18 m thick on average. It exhibits well-developed inverse grading, with mean grain sizes ranging from sandy gravel at the base to boulders several metres in diameter at the surface (Cruden and Hungr, 1986). The debris caused only minor damming of the Crowsnest River, indicating that the landslide eroded some material from the floodplain, but also that the maximum thickness of the deposit does not coincide with its proximal sector.

The South Peak disturbed rock mass is situated directly above the south-east margin of the 1903 deposit. The valley in front of the slope is occupied by a highway, the CP rail track and a community.

3. Work Completed

A site visit was made by Dr. Scott McDougall on July 18 to 20, 2006. During the site visit, Dr. McDougall examined the 1903 deposit, the potential South Peak runout zone and the summit area of the South Peak.

We were provided with a "bare earth" Digital Elevation Model (DEM) obtained by a LiDAR survey with 1 m resolution in terms of elevation. The data was supplemented by additional survey points obtained from AGS. The model was then converted into a Golden Software Surfer grid files with 10 m and 20 m grid spacings in both directions.

A rectified orthophoto of the area at a resolution of 600 dots per inch was obtained and registered with the DEM.

For the purpose of back-analysis of the 1903 slide, the DEM was modified to approximate the pre-1903 conditions, using evidence from the literature and the observation that the Crowsnest River did not change course significantly. The pre-slide slope surface in the source area was reconstructed approximately using historic photographs. The source volume was adjusted so as to account for 20% "bulking" due to fragmentation during the landslide. The DEM's were smoothed using the Surfer program, to improve numerical efficiency of the model (in our experience, limited degree of smoothing has negligible effects on the results).

A central cross-section of the model was constructed for use in the two-dimensional DAN-W analyses.

Back-analyses of the 1903 slide were carried out using the two models. Altogether, approximately 30 trial analyses were done in 2 dimensions and 30 in 3 dimensions. All of the analyses use two models, which we know from experience to provide the best results for rock avalanches (cf. Hungr et al., 2005): The frictional model and the Voellmy model. Most of the analyses used single model for the entire path. Some used a combination of frictional rheology within the source area of the rock slide and Voellmy on the path downslope, where entrainment of saturated soil from the path could be expected. No allowance was made for entrainment of material from the path, other than using reduced flow resistance parameters. We are of the opinion that the volume of material entrained in the Frank Slide is not significant in terms of changing the dynamics of the landslide.

Results of selected analyses are included in summary plots in this report. The input parameters in all back-analyses were adjusted so as to obtain the correct overall runout distance. The individual results were then classified with consideration of their ability to simulate a realistic distribution of debris and duration of travel.

We conducted limited research regarding similar, but smaller rock avalanches from the Rocky Mountain region. Our main sources were Ph.D. theses by Bruce (1978) and Couture (1998). We identified the Jonas Creek Slide (Bruce, 1978) as a suitable example of a relatively small rock avalanche produced by planar failure of limestone, across a glacial valley. The profile of the landslide was digitized from the NTS topographic map, with the help pf airphotos. Back-analyses were carried out using the 2-dimensional analysis. Similar, but less detailed back-analysis was carried out of the Slide Mountain case (Couture, 1998).

The forward analyses of the potential South Peak failure were based on the unadjusted (smoothed) DEM of the study area. The shape and volume of the source was derived from analysis carried out by Prof. M. Jaboyedoff for AGS. Two alternative sources were considered: A planar failure, with a bulked source volume of 6.7 Million m^3 (potential "Slide A") and a deeper rock failure with a bulked volume of 13.8 million m^3 (potential "Slide B").

A number of both 2D and 3D forward analyses were carried out, using a selection of input parameters and model configurations derived from the back-analyses. The results are summarized and discussed in this report.

4. The Dynamic Models and Previous Calibration

Most dynamic models are based on established hydrodynamic theory, with some landslide-specific modifications. The model proposed by Hungr (1995), DAN-W, simulates motion along a user-prescribed 2D path and includes several unique features to account for the most important characteristics of extremely rapid landslides, including the effects of internal strength, material entrainment and variations in rheology both within the slide mass and along the path. It is based on a highly efficient Lagrangian solution of the depth-averaged equations of motion for an "equivalent fluid" (Hungr 1995), a hypothetical material governed by simple internal and basal rheologies. The equivalent fluid represents an idealization of the actual landslide material, which in reality may be very complex and difficult to model.

DAN-W is a calibration-based model, which means that the appropriate rheological parameters must be constrained by trial-and-error back-analysis of previous real landslides. The trials are judged in terms of their ability to simulate the bulk characteristics of the prototype event, including the total travel distance, the distribution of deposits and the velocities estimated along the path. A large number of case studies have been analyzed and a valuable database of calibrated parameters has been created (e.g., Hungr and Evans 1996). For landslides of similar type and scale, the calibrated parameters are generally well-constrained, suggesting that accurate, first-order runout prediction is possible.

The new computer model, DAN3D, is a 3-D extension of DAN-W due to Mc Dougall (2006). The new model retains the key features of the original model, including the ability to account for both mass and momentum transfer between the landslide and an erodible bed and an open rheological kernel that allows the simulation of a variety of geological materials.

In addition, the new model utilizes a meshless numerical method, based on smoothed particle hydrodynamics which permits the simulation of motion across complex 3-D terrain without mesh distortion problems, making it suitable for the analysis of long-runout landslides. Consistent with the "equivalent fluid" approach formalized by Hungr (1995), simulation of an event is achieved through trial and error by systematically modifying the parameters that govern the basal resistance until the characteristics of the simulated landslide (i.e., velocity, extent, and depth of deposits) approximately match those of the real event. Further details, as well as results of verification testing of the model, are provided in McDougall and Hungr (2004 and 2005). A recent description of the two models appears in Hungr and McDougall (2008), reproduced in Appendix A.

DAN 3D requires the input of three files containing the following data at nodal locations on a fixed grid: (1) the initial elevation of the sliding surface, (2) the initial depth of the source failure, and (3) the initial depth of erodible material in the path.

Both models were used with two alternative rheologies (Hungr, 1995):

1) In the frictional rheology, the basal resistance is governed by a frictional model with pore pressure:

$$\tau = \sigma(1 - r_u)\tan\phi \qquad [1]$$

where τ is the basal shear stress, σ is the total bed–normal stress, r_u is the ratio of pore fluid pressure to total bed–normal stress and φ is the dynamic basal friction angle of the material

Equation [1] can be simplified by assuming a constant pore pressure ratio ru, making φb the only adjustable parameter.

$$\tau = \sigma \tan\phi_b \qquad [2]$$

where the "bulk friction angle φ_b includes the effect of pore-pressure.

$$\phi_b = atn(1 - r_u)\tan\phi \qquad [3]$$

In cases where loose, saturated soils are present in the path, the Voellmy resistance model is used (Hungr, 1995):

$$\tau = \sigma f + \frac{\gamma V^2}{\zeta} \qquad [4]$$

Here, *f* is the friction coefficient (equivalent to $\tan\sigma_b$), γ is the material unit weight, V is the mean flow velocity, and ξ is the so-called turbulence parameter. The first term on the right side accounts for any frictional component of resistance and is based on Eq. 1. The second term accounts for velocity-dependent flow resistance

Hungr & Evans (1996) reported back-analyses of 23 well-known large rock avalanches, using DAN-W with three alternative rheological kernels: frictional, Voellmy and Bingham. The model parameters were adjusted in each case so as to obtain a perfect fit in terms total runout distance and the best possible fit in terms of velocities. In terms of velocities, a good fit could only be obtained with the Voellmy rheology. Both frictional and Bingham consistently overestimated the velocities.

The same study found that the Voellmy rheology produces the best approximation of deposit length and thickness; it tends to concentrate the deposits forward into the distal zone. In contrast, the frictional rheology predicts thin tapering fronts. This is appropriate only for dry, granular landslides and model tests.

Hungr & Evans (1996) further found that 70% of cases of large rock avalanches conform reasonably well to the Voellmy model, with an f of 0.1 and a ξ of 500 m/sec2. Of the remaining 30% some were relatively dry rock avalanches, behaving as frictional fluids. The remainder were more mobile due to major entrainment of snow, ice or loose saturated soil and were analysed by the Voellmy model.with lower bulk friction angles. These findings were further substantiated by other back-analyses, as described by Hungr et al. (2005).

5. Results of back-analyses.

5.1 The Frank Slide of 1903.

The result of the "best fit" analysis of the 1903 slide appears in Appendix B. In a summary, the best results in terms of overall runout distance and debris distribution is obtained with the Voellmy rheology, using an f of 0.1 and a ξ of 500 m/s^2 (see Figure 1). Unfortunately, information regarding movement velocity is not available. However, based on eyewitness interviews, McConnell and Brock (1904) conclude that the "time that elapsed between the first crash and complete rest did not exceed 100 seconds, and may have been somewhat less". The Voellmy model shown in Figure 1 demonstrates an overall movement duration of less than 100 seconds.

A uniform frictional analysis was also attempted, with a result shown in Figure 2. The constant "bulk friction angle, φ_b of 17° had to be used, to obtain the requisite runout distance. The frictional model is not as satisfactory as the Voellmy result for two reasons: 1) The travel time is considerably shorter (about 40 seconds), although not out of the range suggested by McConnell and Brock (1904). 2) The frictional results shows the typical forward-tapering deposit distribution, predicting considerable thickness of deposits in the proximal region, near the Crowsnest River. The Voellmy model predicts greater thickness in the distal region, near the highway and this is closer to reality.

The back-calculated friction parameters give some indication of the average pore-pressure conditions during the landslide motion. Assuming that the dynamic effective friction angle of rapidly shearing rock fragments is about 30°, the friction coefficient of 0.1 used in the Voellmy solution implies an average pore-pressure ratio of 0.83. The mean bulk friction angle of 17° corresponds to an r_u of 0.47.

High pore-pressure ratios are certainly possible in those parts of the path where the landslide over-rides saturated soils of glacial, colluvial or alluvial origin. They are not likely to exist on the upper slopes and, especially within the source area of the rock slide. As the failing rock mass fragments, it expands in volume. The large new void space generated by fragmentation must be initially dry. To account for this, we attempted some analyses where the source area was modeled using a dry frictional sliding model, transferring to the Voellmy model on the path below. It was found that, in order to obtain the requisite runout distance with this model, the mean friction angle in the source area would have to be as low as 15º. With such a provision, the model produces results similar to the uniform Voellmy analysis mentioned above.

The low friction angle is justified, considering the conclusions of Cruden and Krahn, 1978, who found that highly polished pre-sheared joints bedding planes in the Turtle limestone could have friction angles as low as this value. Rapid shearing of a discontinuity plane under normal stresses corresponding to more than 100 m column of rock would, presumably, lead to intensive polishing of the surface, especially if pre-sheared by previous flexural slip.

Three-dimensional back-analyses of the 1903 slide were also conducted, using the program DAN3D. In general, for a given rheology and resistance parameters, the 3D results are very similar to the 2D in terms of runout distance, velocity and distribution of deposits although, of course, the 3D model predicts the lateral extent of the path and deposits. An example of a complete 3D run is given in Appendix B and the final predicted distribution of deposits is shown in Figure 3. The deposit is similar to that produced by DAN-W for the same set of parameters.

The three-dimensional model over-predicts lateral spreading of the path to some extent, as seen by a comparison of the actual and predicted extent of the debris in Figure 3. This is a common observation with DAN3D. The model assumes that the rock slide block expands and becomes fluid-like instantly at the onset of movement. In reality, the landslide mass probably remains somewhat coherent initially, and its disintegration is completed only after some distance of travel. This effect must result in reduced lateral spreading, when compared with the idealized behaviour of the model. Comparison with the 2D solution shows, however, that this error has negligible influence on the longitudinal motion of the landslide.

5.2 Other Rock Avalanches

One argument against using the parameters derived from the back-analysis of the 1903 slide is that a potential failure of the South Peak is likely to be significantly smaller. For this reason, we back-analysed two smaller rock avalanches from the Canadian Rocky Mountains, the Jonas Creek North slide (Bruce, 1978) and the Slide Mountain case (Couture, 1998) using DAN-W. These are “small” rock avalanches of approximately 5 and 10 million m^3 respectively, both of which initiated as dip-slope planar rock slides. Back-analyses show similar behaviour as the 1903 slide, although the Voellmy parameters are increased to $f=0.1$ and $\xi=500$ m/s^2, while the constant frictional φ_b is of the order of 20º. This increased movement resistance in both models, in our opinion, represents the effect of smaller magnitude of the rock avalanches.

5.3 Summary of back-analyses

The results of the back-analyses can be summarized as follows:

1) Satisfactory results are produced using the constant Voellmy model, with f=0.1 and ξ=500 m/s^2 for the large 1903 rock avalanche. This is in agreement with previous studies reported by Hungr and Evans (1996).

2) For smaller rock avalanches, as characterized by the Jonas Creek and Slide mountain events (less than approximately 10 million m^3 in volume), it appears justified to increase the Voellmy resistance parameters to f=0.15 and ξ=500 m/s^2.

3) Assumption of frictional rheology in the rock slide source area, followed by Voellmy on the soil-lined path below, does not materially change the results, unless a fairly high friction angle is used.

4) Constant frictional rheology produces results that are less satisfactory in terms of velocity and debris distribution. The calibrated values of the bulk friction angle, φ_b, range from 17º for the large 1903 avalanche to 20º for smaller rock avalanches.

5) The 2D and 3D models give similar results in terms of longitudinal travel, when consistently applied.

6) Based on the back-analyses, in combination with our previous experience with the models, we can assign subjective reliability rating to the various parameter sets. Unfortunately, our calibration data base is not yet sufficiently large to permit assigning objective numerical probability values to them.

6. Forward Predictions, Potential South Peak Failures.

6.1 Presentation of Results

Two potential rock slides from the South Peak of Turtle Mountain have been outlinee, based on a structural analysis by Prof. M. Jaboyedoff:

- Planar rock slide (“Slide A”), involving 6.7 million m^3 of fragmented rock.
- Deep-seated rock slide (“Slide B”), involving 13.8 million m^3 of fragmented rock.

Both 2D and 3D analyses were carried out, using calibrated parameters as described in Section 5.3 above. A complete list of all forward analyses is given in Table 2. The “preferred” results from the 2D analyses for both Slide A and Slide B are shown in Figures 4 and 5 respectively. The distribution of debris from corresponding 3D analyses is shown in Figures 6 and 7.

A range of further analyses have been carried out using DAN-W.

6.2 Results Discussion and Summary.

Runout of a potential rock avalanche from South Peak depends on several conditions, including:

- The magnitude (volume) of the initial slide.
- Manner of failure: sudden detachment of the entire mass, or gradual piecemeal detachment of several smaller fragments, over the course of time (may be only minutes apart).
- Condition of the substrate: high saturation following a relatively wet period or with snow on the ground, or relatively dry conditions.

In our judgment, the various calibration scenarios as mentioned in Section 5.3 result in the following range of predictive models, the results of which are summarized in Figures 8 and 9:

1) The Most Likely Prediction (red). For the relatively small magnitude of the potential South Peak detachments, we consider the most likely prediction to be based on the Voellmy model with $f=0.15$ and $\xi=500\ m/s^2$. It would correspond to a sudden detachment under saturated conditions.

2) Alternative Prediction (purple). For potential South Peak detachments, this is the frictional model, with a φ_b of 20º. This corresponds to a sudden detachment under unusually dry conditions.

3) The Extreme Runout Prediction (yellow,dashed). This is based on the use of the 1903 slide Voellmy parameters $f=0.1$ and $\xi=500\ m/s^2$. We believe that this is an unlikely scenario for the relatively small potential detachments from South Peak, but it is included as the upper bound of possible results.

4) Piecemeal Detachment Prediction (turquoise). This prediction considers that the detachment would not occur simultaneously. The highly frictional motion of the rock masses has been simulated using the frictional model, with a bulk friction angle of 30º (“dry slide condition).

The resulting runout outlines for the various predictions are shown in Figures 8 and 9 for the potential Slide A (6.7 M m^3) and Slide B (14.8 M m^3) respectively.

For the purposes of quantitative hazard or risk analysis, the probability of landslide impact at any of the lines shown in Figures 8 and 9 can be calculated as follows:

$$P_{impact} = P_h P_d P_r \qquad [5]$$

Here P_h is the probability of occurrence of a rock slide of given magnitude (A or B), P_d os the conditional probability of sudden (or piecemeal) detachment, given the occurrence of the slide and P_r is the conditional probability of runout to the outline shown, given that the specific volume and detachment type occurs. The probability P_h and the conditional probability P_d must be evaluated based on an analysis of the stability of South Peak, aided by monitoring observations. The conditional probabilities of runout P_r have been subjectively assigned as follows:

Given a failure occurs with sudden detachment of the entire mass, the runout corresponding to the Most Likely Prediction (red line) has a conditional probability of $P_r = 0.7$. The Alternative Prediction (purple line) has a conditional probability $P_r = 0.2$ The Extreme Runout Prediction result is associated with a conditional probability of less than $P_r < 0.1$.

Given a piecemeal failure of either slide, the Piecemeal Detachment Prediction runout is considered to have a conditional probability of $P_r = 1.0$.

The present analyses could not directly account for the possible influence of the presence of the 1903 debris on parts of the runout zone. We estimate that the coarse, dry debris would increase the flow resistance of that part of the rock avalanche passing over it. Thus, the runout of the left half of the rick avalanche stream would be moderated and the Alternative Prediction line is more likely to be applicable in that part of the runout zone than the Most Likely Prediction, which is applicable to the uncovered ground outside the debris zone.

7. Conclusion

The runout of two potential sizes of rock avalanches from South Peak of Turtle Mountain have been estimated for a range of conditions and probabilities. It is to be understood that landslide runout prediction is at present a developing subject and that the results of all analyses must be assessed through the use of experienced judgment. Any administrative or engineering decisions using the results of these analyses should be reviewed by qualified expert reviewers.

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FIGURES

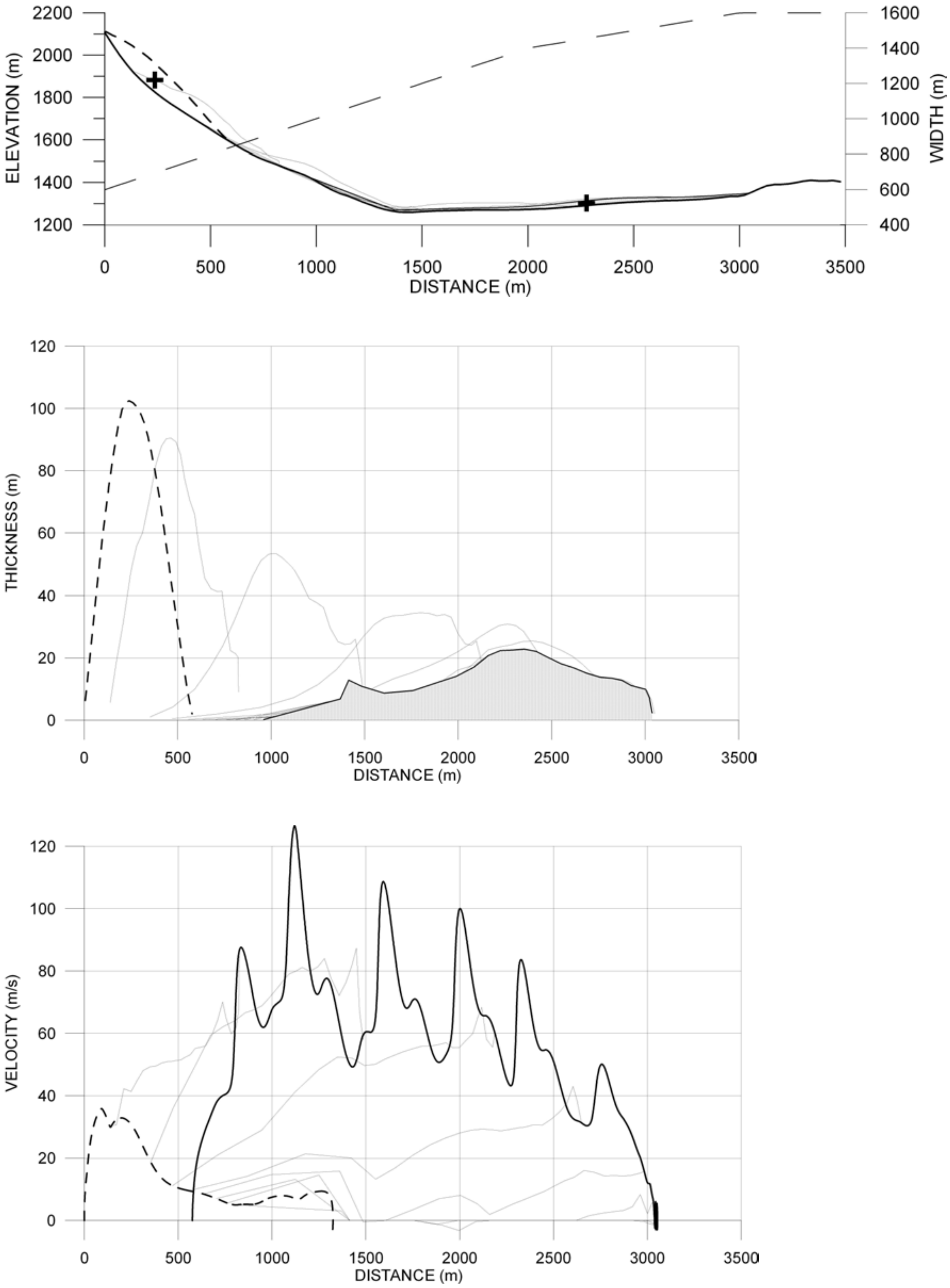
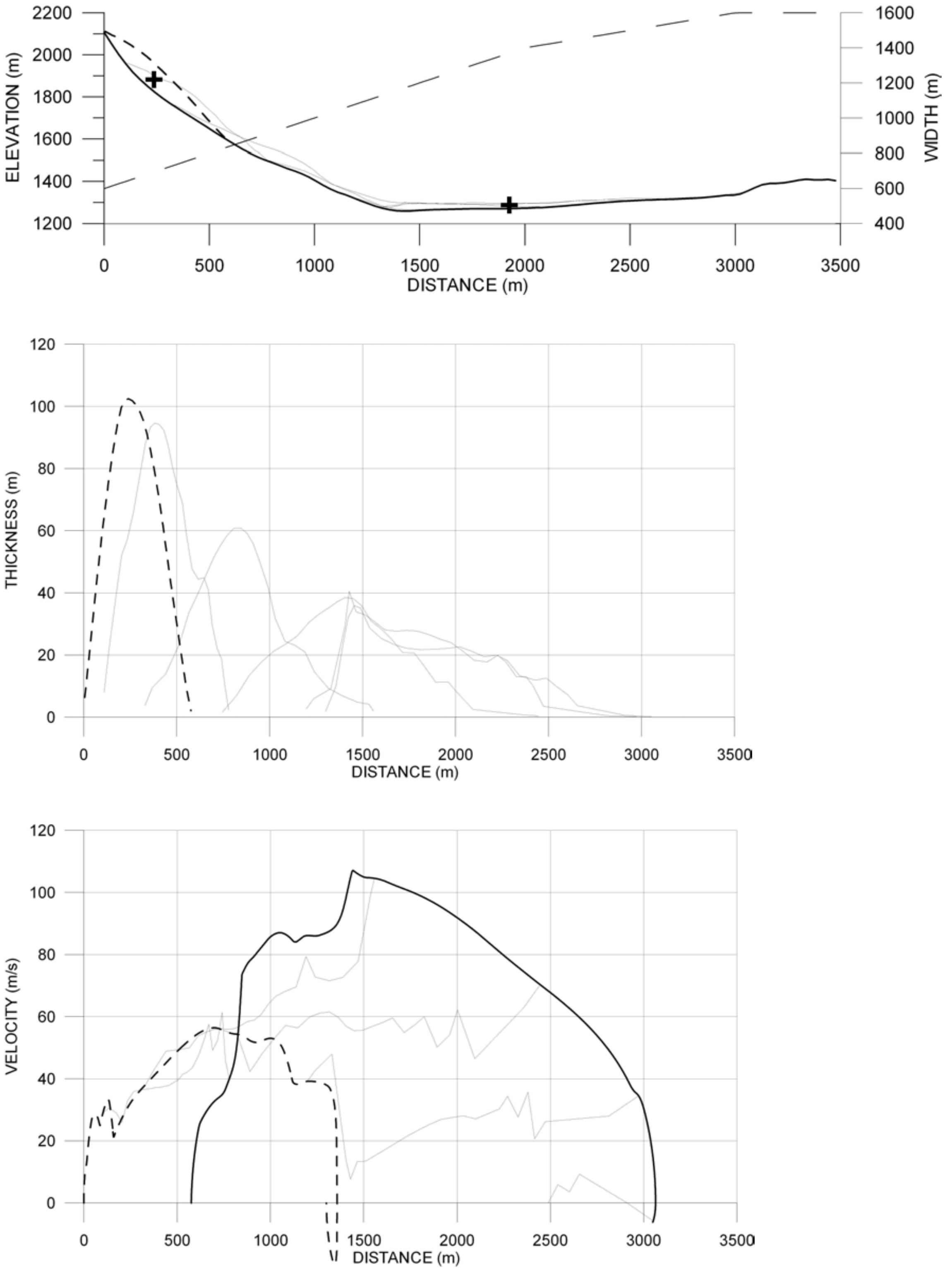


Figure 1. DAN-W two-dimensional back analysis of the 1903 Frank Slide, using constant Voellmy rheology, with f=0.1 and ξ=500 m/s^2.



2. DAN-W two-dimensional back analysis of the 1903 Frank Slide, using constant frictional rheology with a φ_b of 17º.

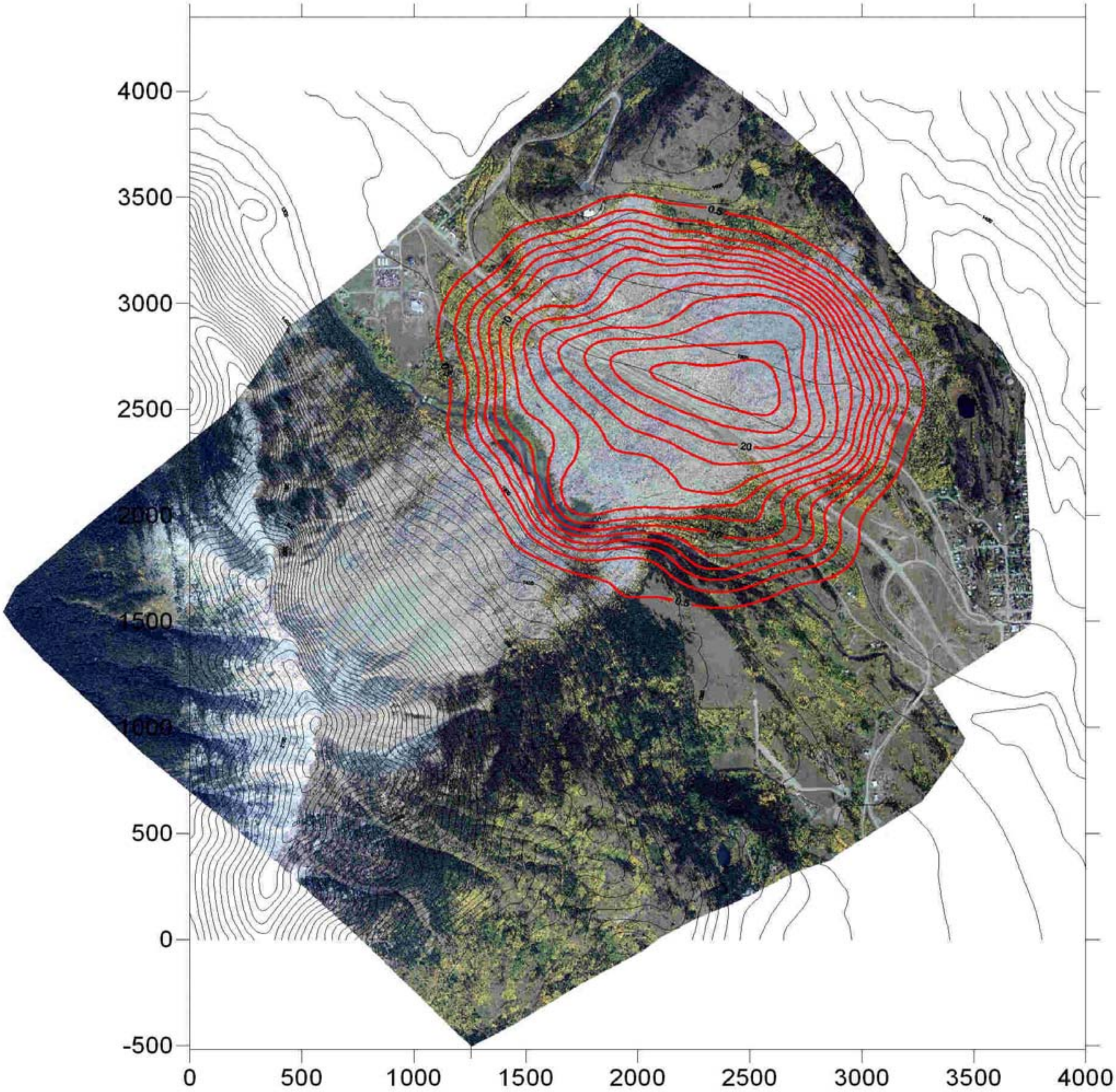


Figure 3. DAN3D three-dimensional back analysis of the 1903 Frank Slide. Final debris distribution, using frictional resistance in the source area, with a $\varphi_b = 15^o$ and Voellmy rheology in the path with f=0.1 and ξ=500 m/s^2.

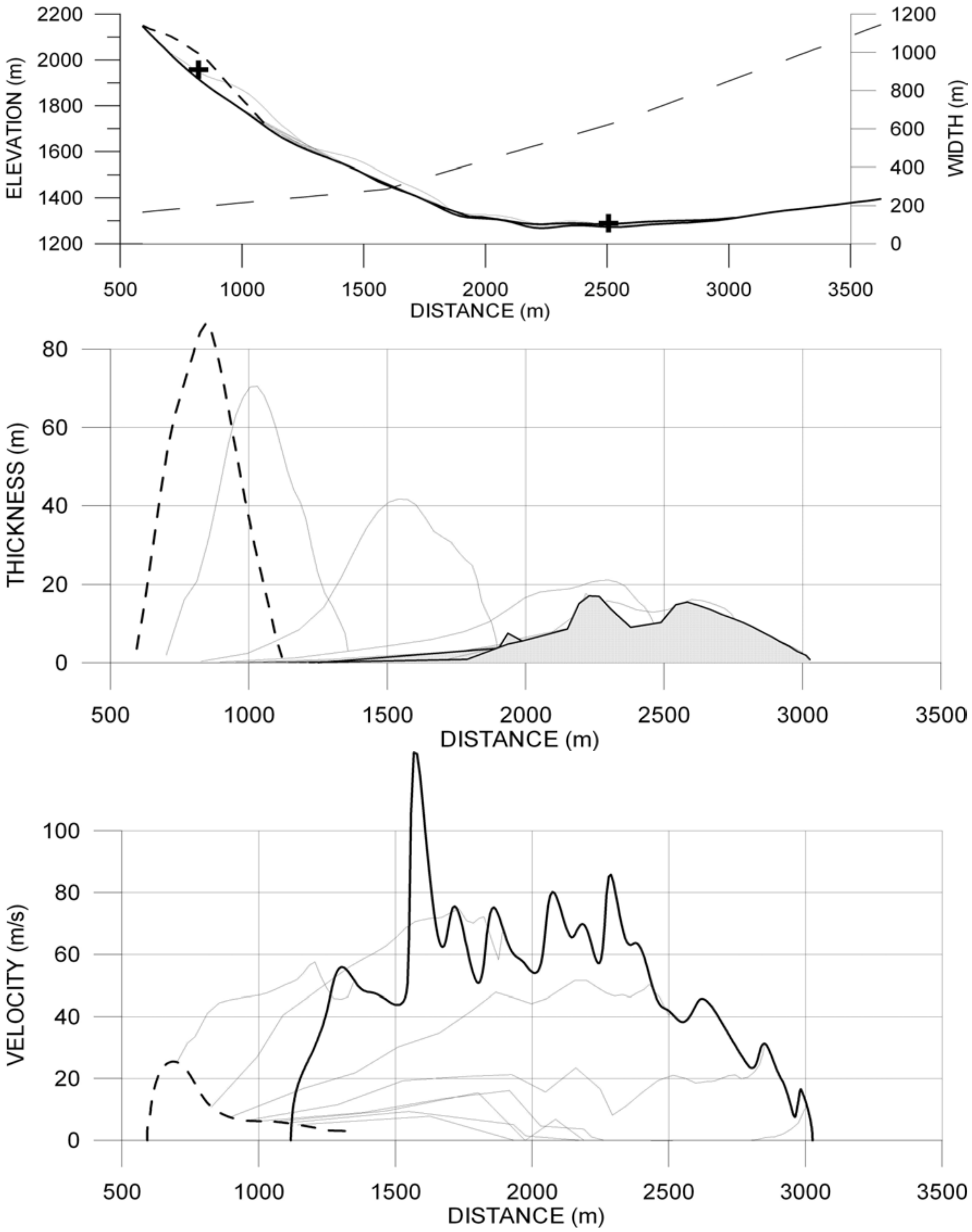


Figure 4. DAN-W two-dimensional forward prediction of the 6.7 million m^3 Slide A from South Peak, using constant Voellmy rheology, with f=0.15 and ξ=500 m/s^2.

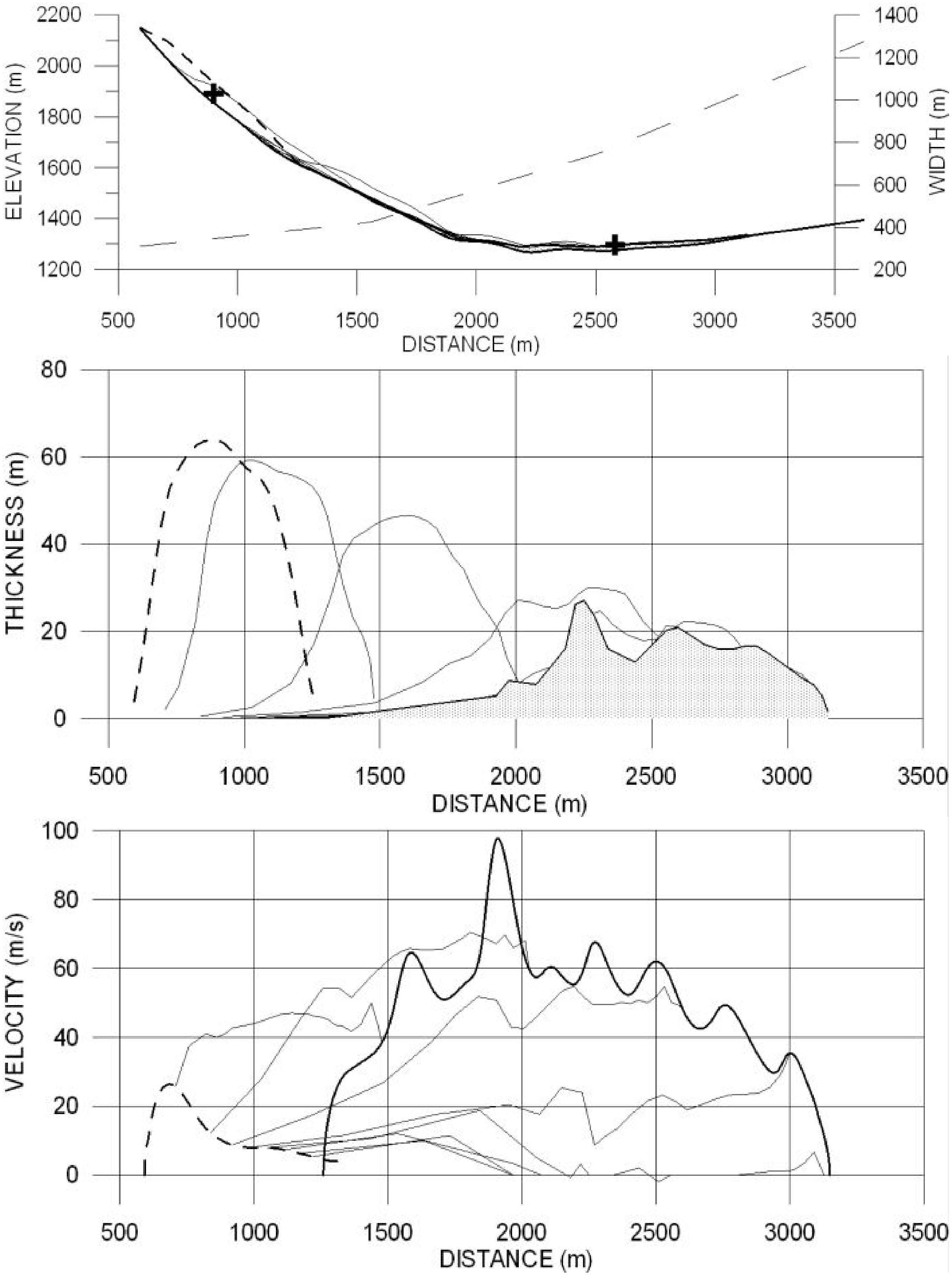


Figure 5. DAN-W two-dimensional forward prediction of the 13.8 million m^3 Slide B from South Peak, using constant Voellmy rheology, with f=0.15 and ξ=500 m/s^2.

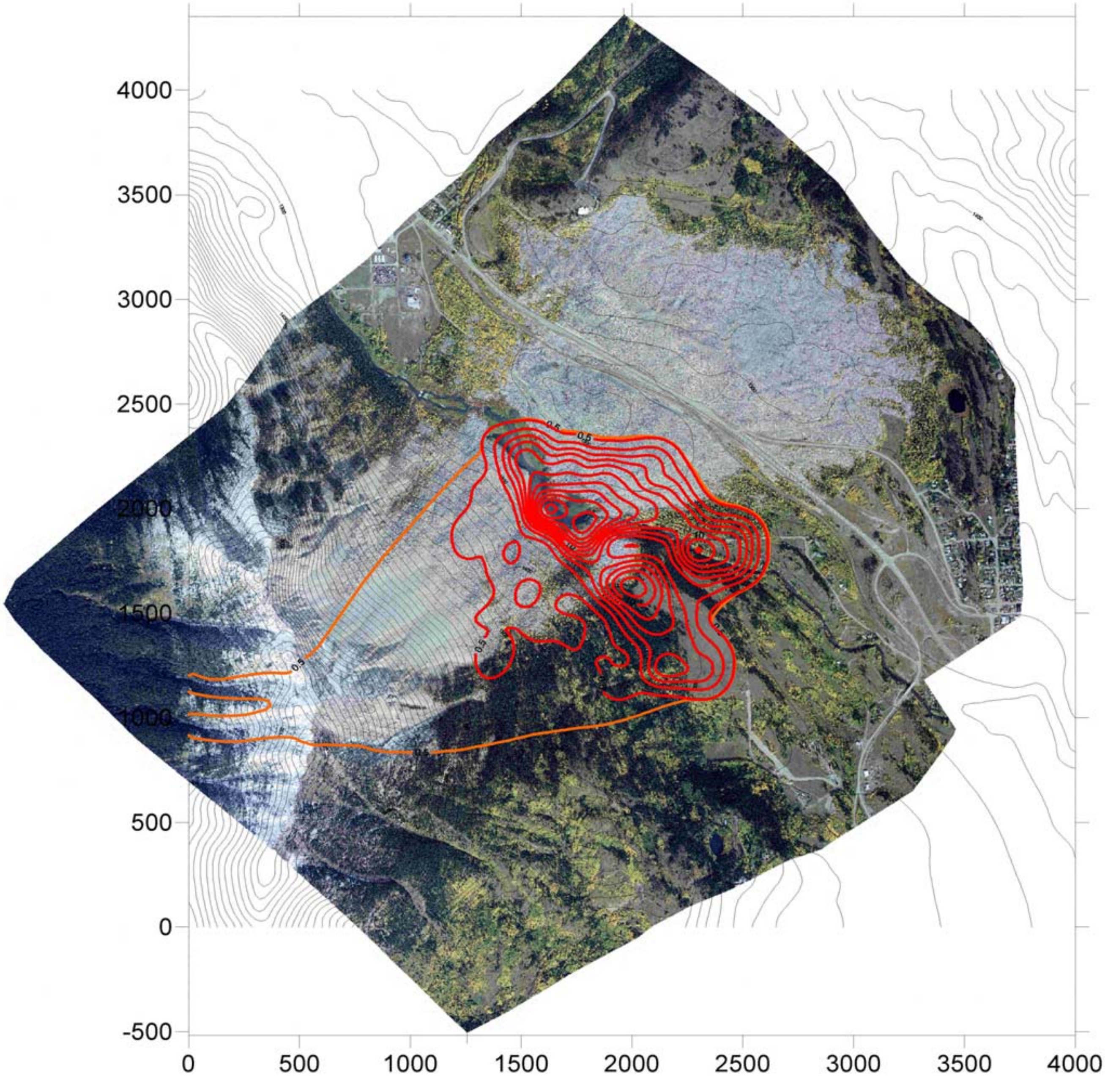


Figure 6. DAN3D three-dimensional forward prediction of the 6.7 million m^3 Slide A from South Peak. Final debris distribution, using constant Voellmy rheology in the path with f=0.15 and ξ=500 m/s^2.

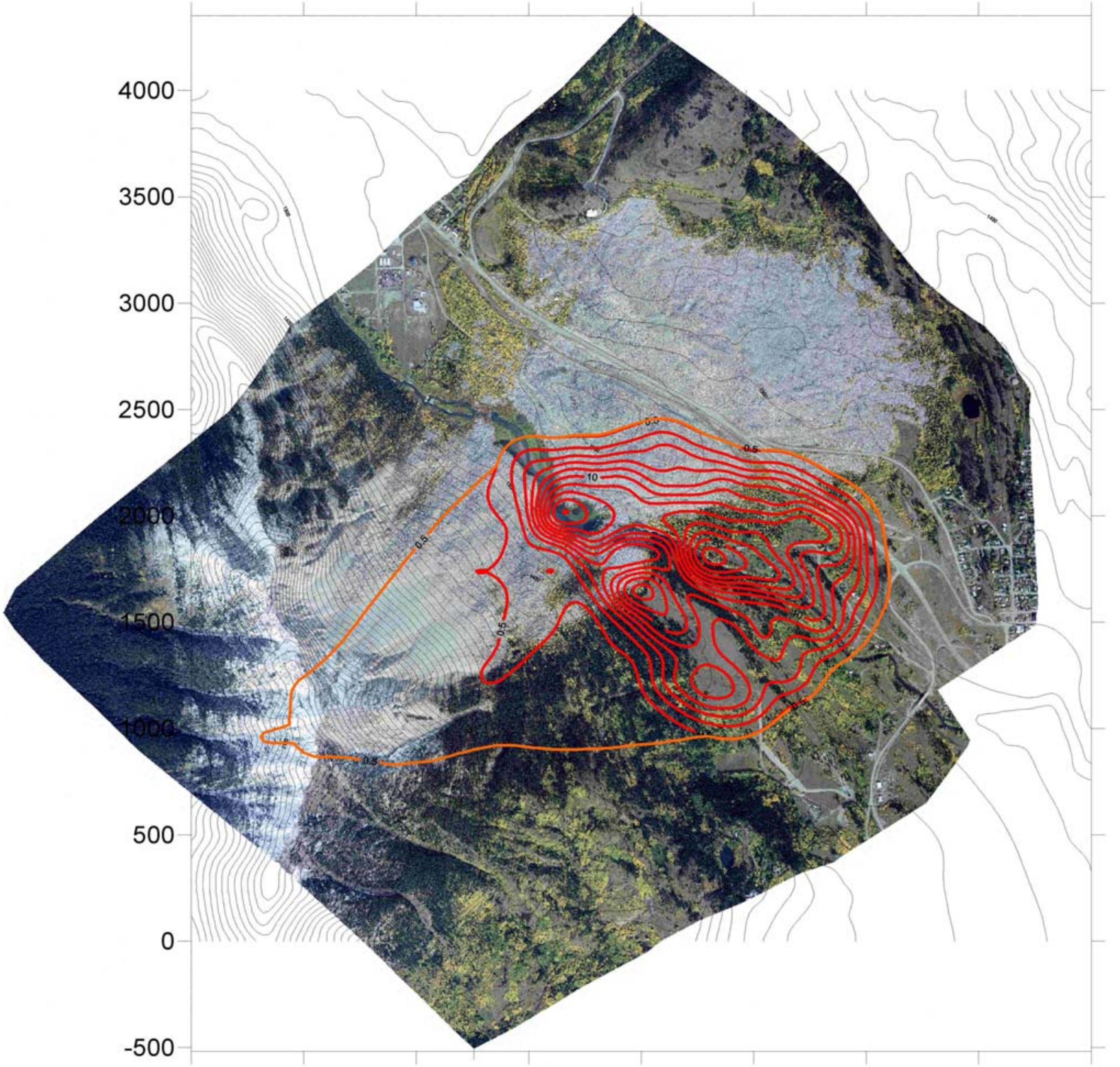


Figure 7. DAN3D three-dimensional forward prediction of the 13.8 million m^3 Slide B from South Peak. Final debris distribution, using constant Voellmy rheology in the path with f=0.15 and ξ=500 m/s^2.

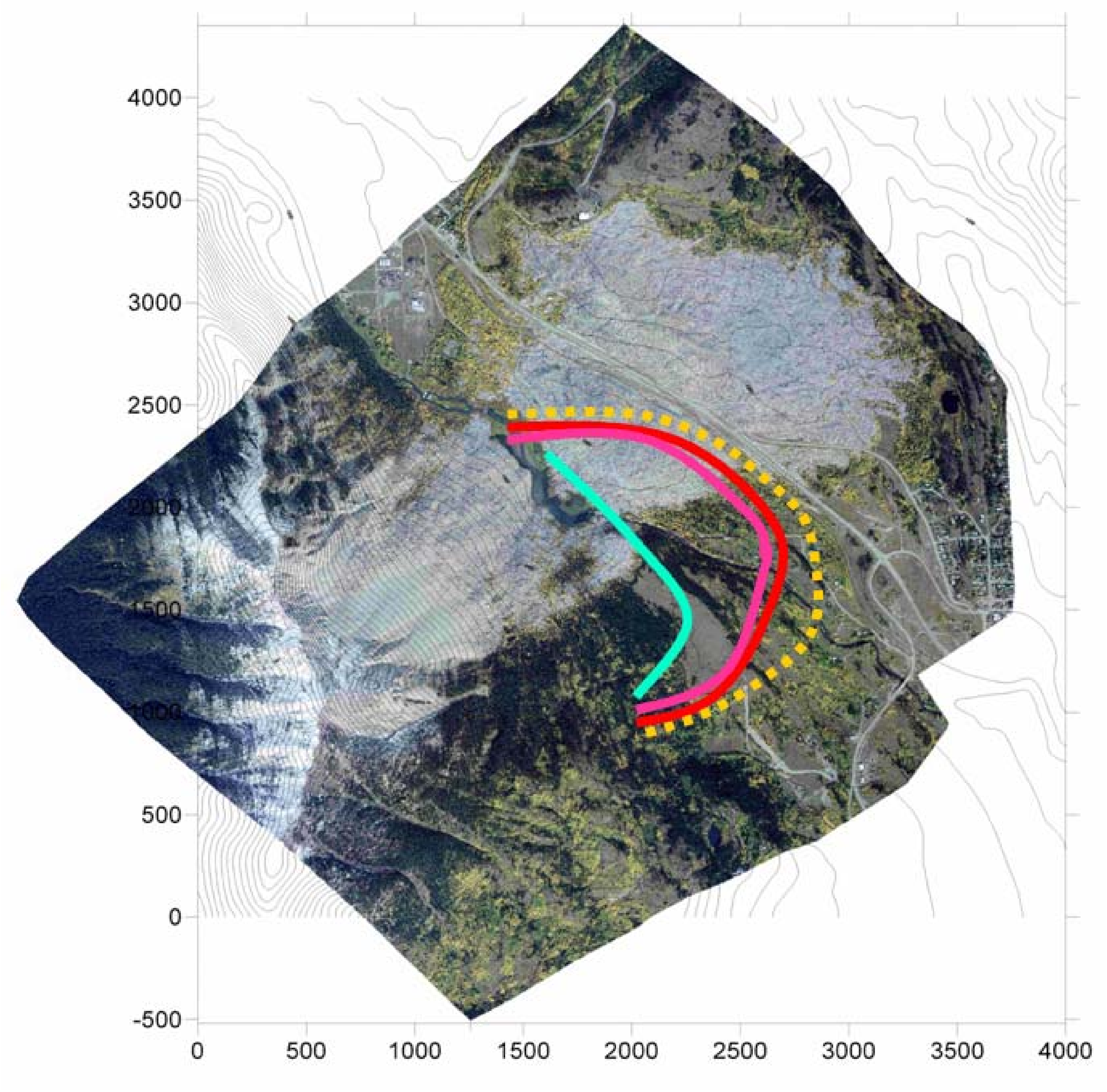


Figure 8. Summary of runout predictions, 6.7 million m^3 Slide A from South Peak.

Red:	Most Likely Prediction
Purple:	Alternative Prediction
Yellow:	The Extreme Runout Prediction
Turqoise:	Piecemeal Detachment Prediction

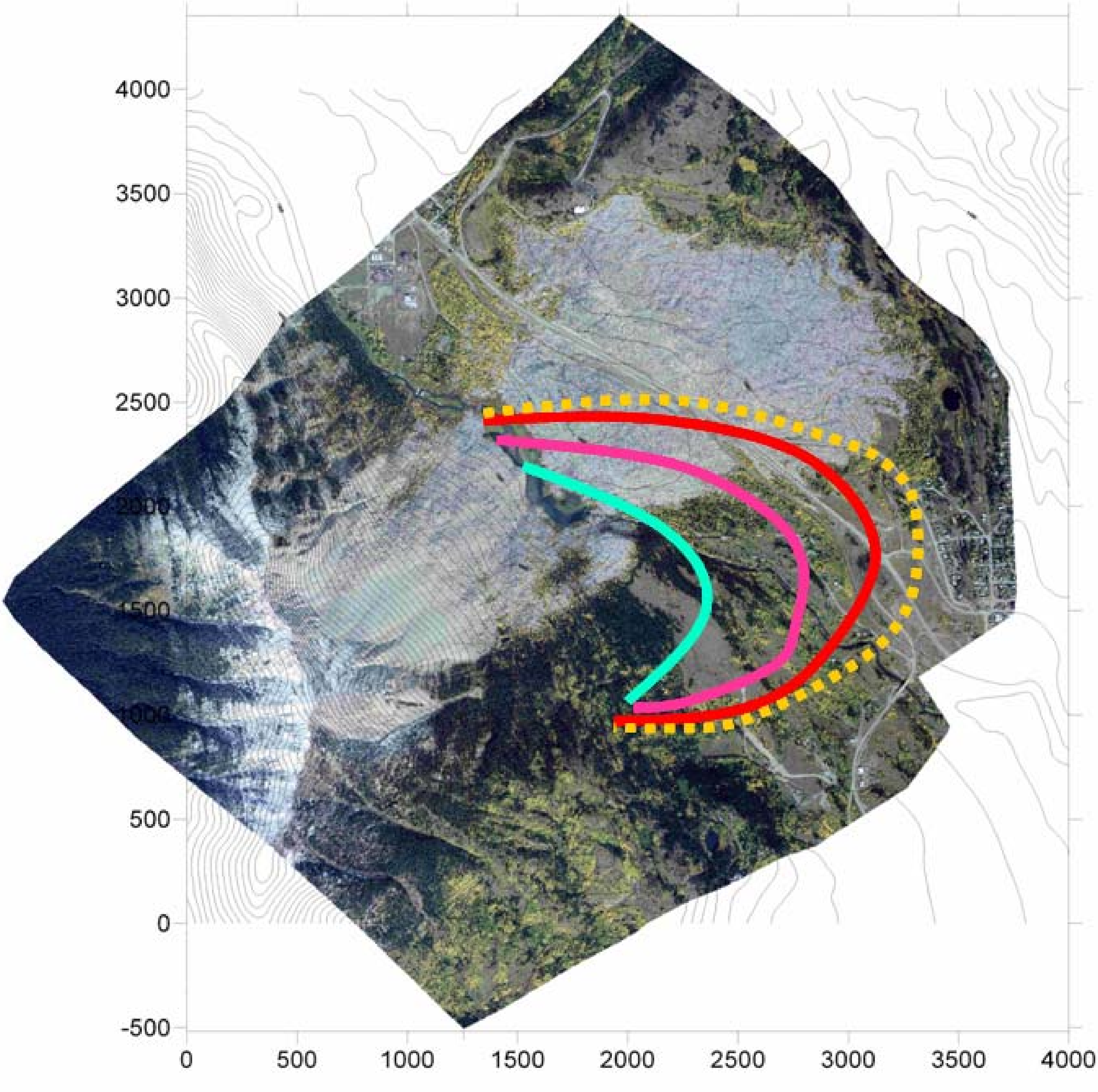


Figure 9. Summary of runout predictions, 13.8 million m^3 Slide B from South Peak.

Red:	Most Likely Prediction
Purple:	Alternative Prediction
Yellow:	The Extreme Runout Prediction
Turqoise:	Piecemeal Detachment Prediction

Appendix A
Description of models used.

Hungr, O. _1b McDougall, S., 0. . 9, Two numerical models for landslide dynamic analysis. Computers and Geosciences, v. 35, no. 5, p. 978-992, doi: 10.1016/j.cageo.2007.12.003.

Appendix B

DAN3D three-dimensional back analysis of the 1903 Frank Slide, using frictional resistance in the source area, with a φ_b = 15º and Voellmy rheology in the path with f=0.1 and ξ=500 m/s^2.

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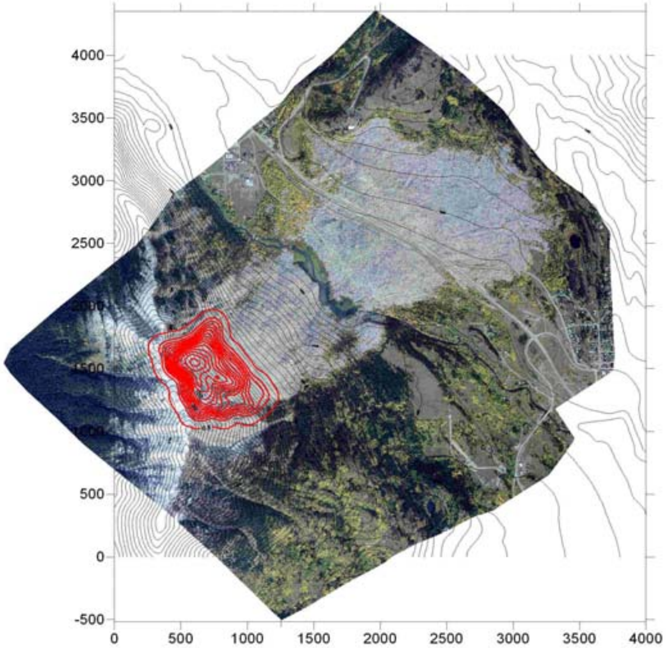

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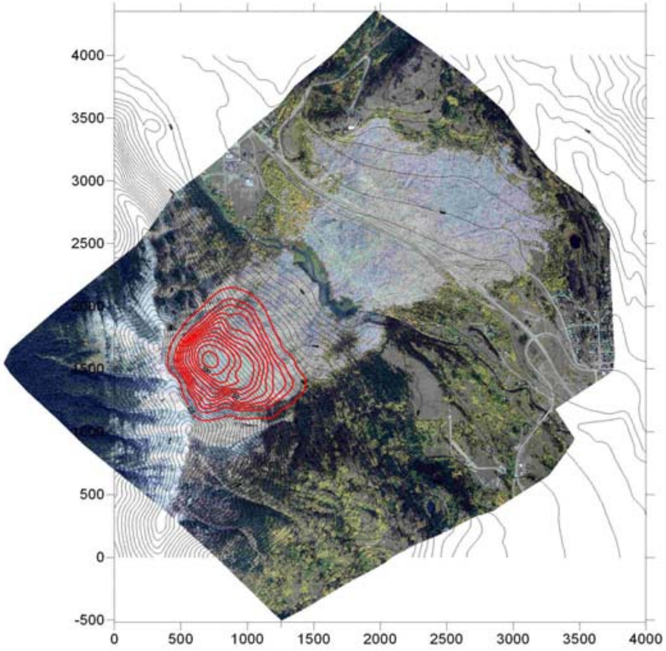

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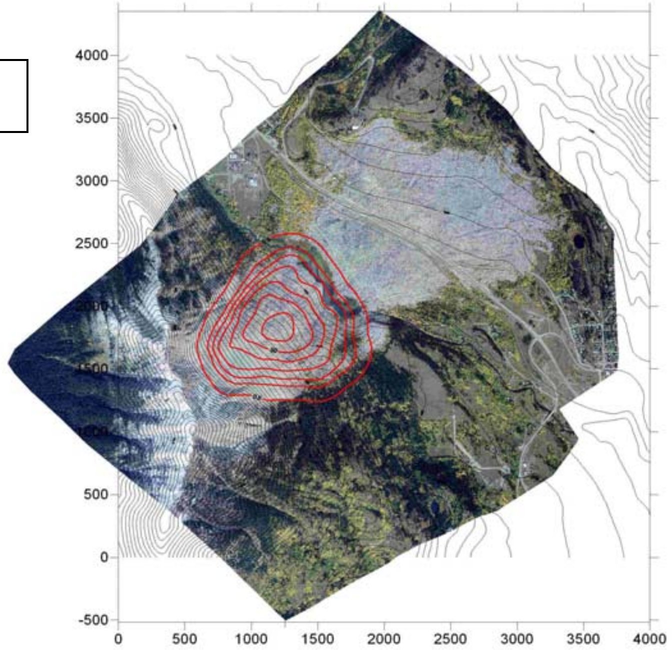

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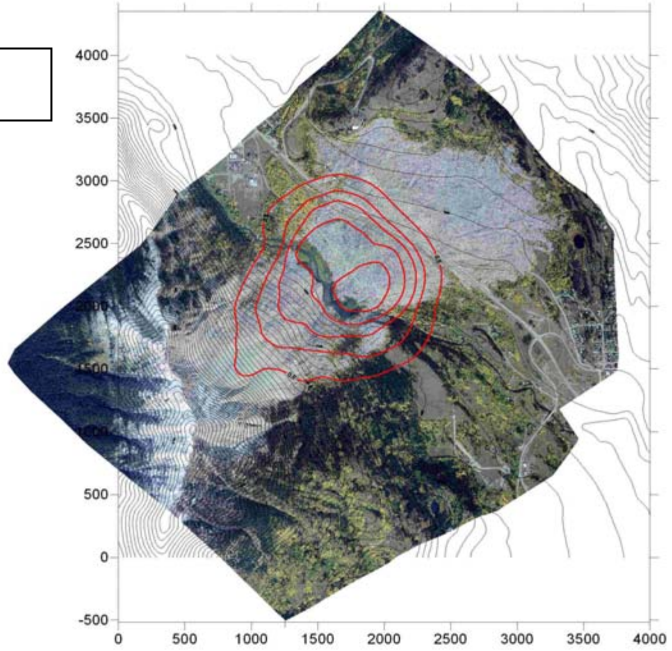

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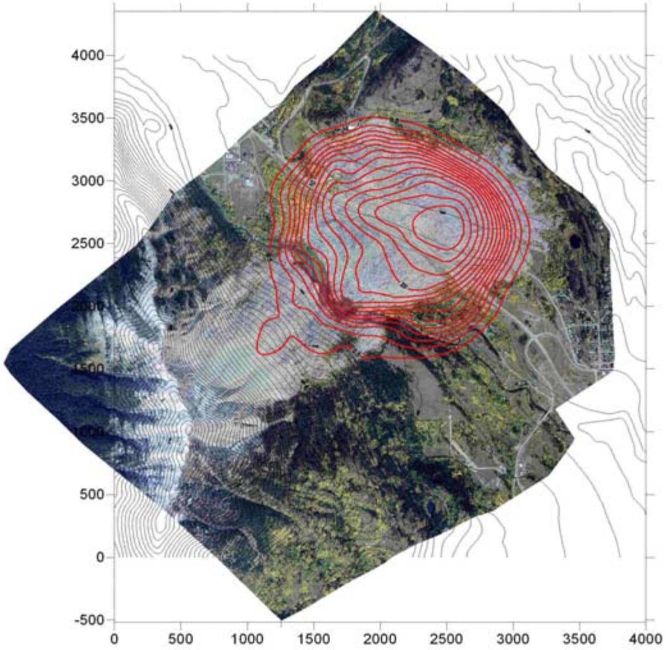

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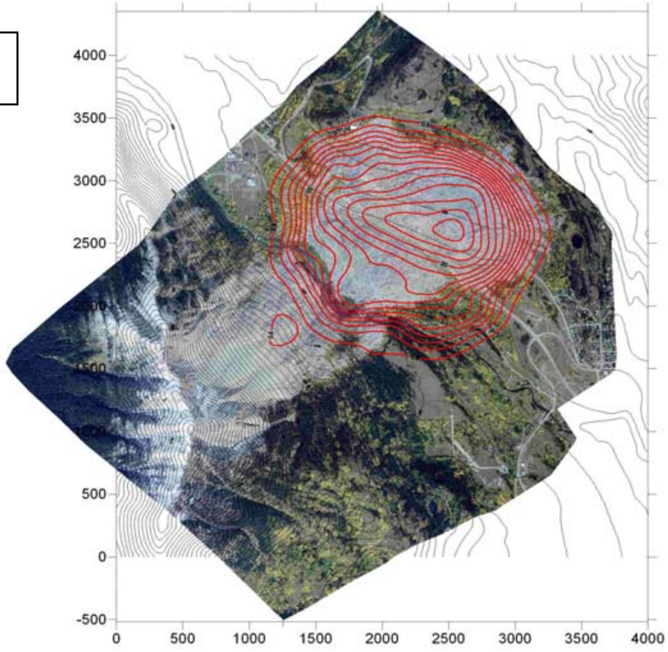

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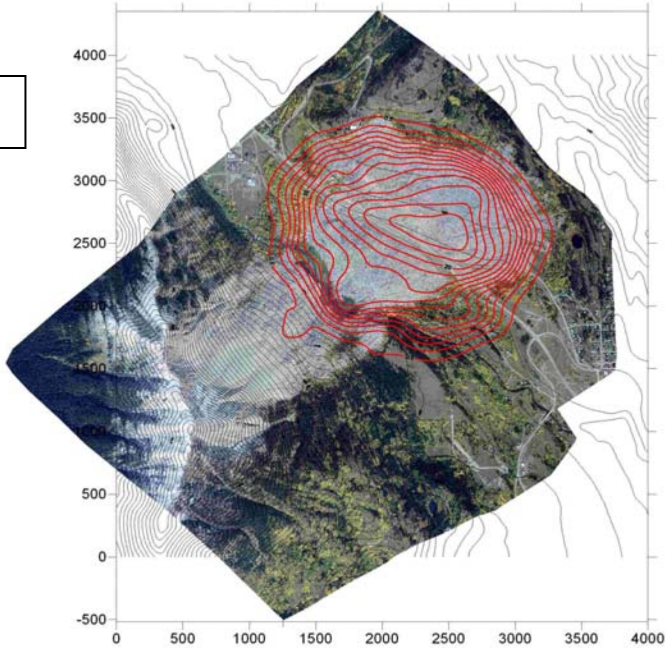

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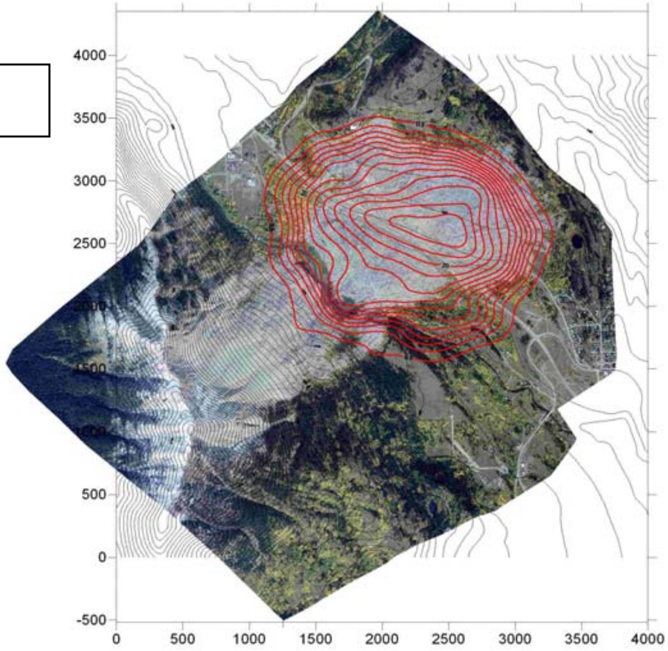

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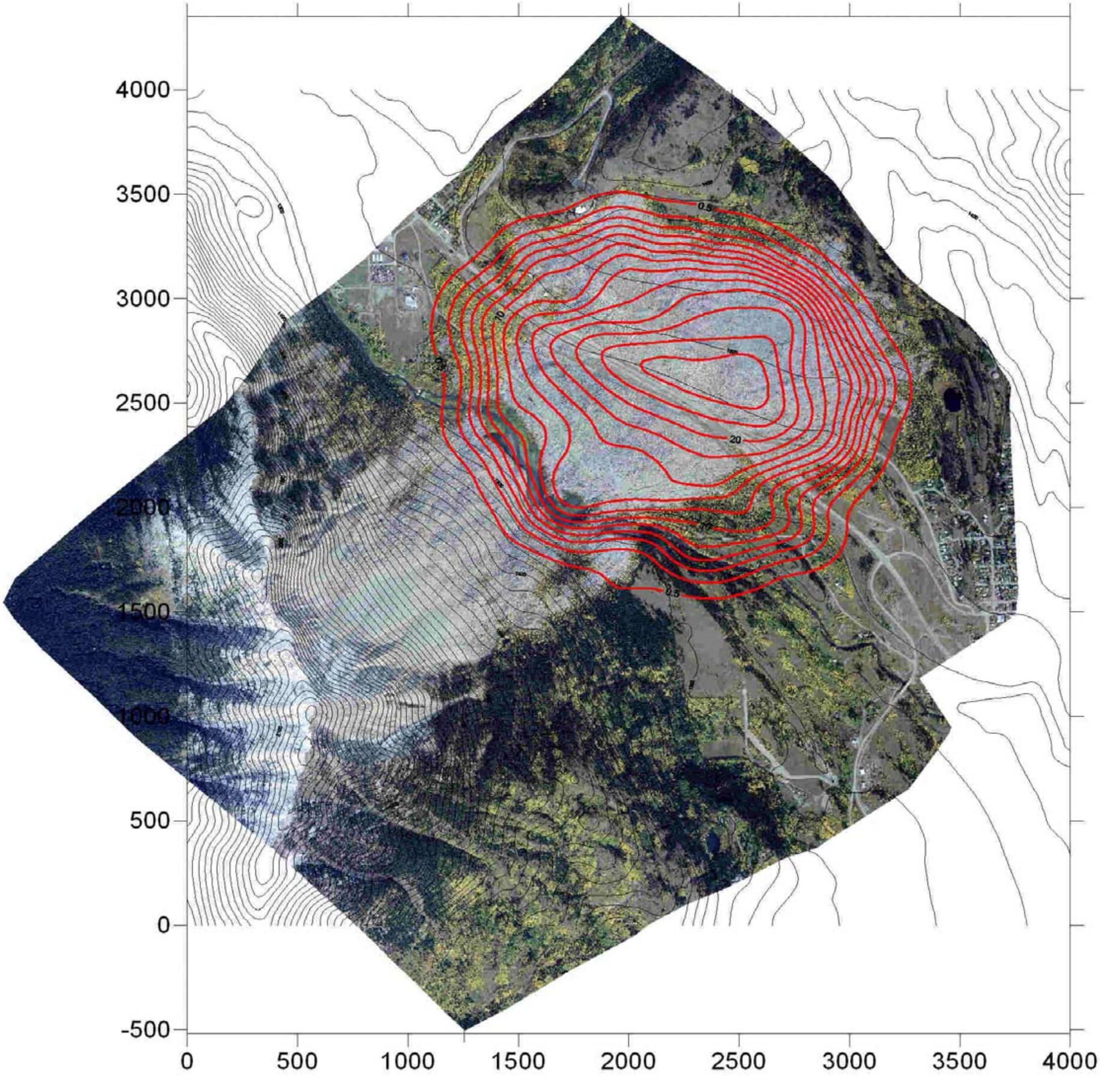

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2 Report Two: Runout Analyses of Potential Landslides on South and Third Peaks: Turtle Mountain, Frank, Alberta

TURTLE MOUNTAIN, FRANK, ALBERTA
RUNOUT ANALYSES OF POTENTIAL LANDSLIDES ON SOUTH AND THIRD PEAKS

Report to:
Environmental Geology Section
Alberta Geological Survey/Energy and Utilities Board
4th Floor, Twin Atria Building
4999 - 98 Avenue, Edmonton, Alberta, T6B 2X3

by:
O.Hungr Geotechnical Research, Inc.
4195 Almondel Rd., West Vancouver, B.C., V7V 3L6

November 15, 2008

Abstract

The runout of twelve potential rock avalanches from the South Peak and Third Peak of Turtle Mountain have been analysed using two independent software codes, DAN-W in two dimensions (2D) and DAN3D in three dimensions (3D). The input for the analyses used a detailed digital terrain model, derived from a LiDAR survey. The locations and volumes of potential rock slide sources on the Turtle Mountain were provided by a separate structural-geological study of the slopes by a group from the University of Lausanne, Switzerland. The dynamic flow resistance properties required by the models were derived by means of calibration back-analysis of nine known rock avalanche cases from different parts of the world. The results of the analyses are summarized in Appendix 1. In general, the hazard areas corresponding to the 12 landslide events analysed in this study do not exceed the hazard limits established previously for possible full-scale failures from the South Peak, as shown in our report of April 18, 2008.

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1. Introduction

Turtle Mountain, the origin of Canada's worst landslide disaster, the 1903 Frank Slide, still represents a potential hazard to areas near the present town of Frank. Alberta Geological Survey (AGS) is studying and monitoring an extensive zone of cracks on the ridge extending south of the 1903 scar, including South Peak and Third peak of the mountain. In 2007 we carried out analyses, commissioned by AGS, of runout of two potential landslides from the South Peak. The analyses outlined hazard areas that could potentially be impacted in the event that rock detachments 6.8 or 13.7 million m^3 took place (O.Hungr Geotechnical Research, April 18, 2008). More recently, AGS consultants from the University of Lausanne (UL) defined 12 other zones of potential instability on South and Third peaks, ranging in volume from 40,000 to 6 million m^3. The source volumes of these potential rock avalanches were defined based on detailed structural analysis of the Turtle Mountain slopes (Pedrazzini and Jaboyedoff, 2008). Following a request by AGS, we carried out dynamic analyses of the 12 identified potential landslide detachments, in order to define hazard areas that could potentially be impacted in the event of failure.

2. Site Description

The site involves an extension of the Turtle Mountain ridge south from the 1903 scar and including the South Peak (2195 m asl) and Third Peak (2205 m asl), see Figure 1. Prominent crack systems and discontinuity configurations that could lead to instability have been identified and analysed by the University of Lausanne group (Pedrazzini and Jaboyedoff, 2008). Table 1 lists the potential instabilities that have been analysed.

All of the potential landslides are smaller than the two major South Peak detachments that were analysed in our April, 2008 report. As a result and based on our previous experience with analysis of rock avalanches (e.g. Hungr et al., 2005), we expect that the dynamic behaviour of these landslides is likely to be dominated by frictional behaviour, given the absence of large quantities of unconsolidated, saturated soils on the upper and middle slopes of the mountain. This observation guided our selection of rheological equations used for the calibration of the model.

3. Work Completed

A site visit was conducted by Dr. O.Hungr in company of Mr. C. Froese and Prof. M. Jaboyedoff in August, 2008 and included a helicopter and ground inspection of the two peaks. We were provided with a "bare earth" Digital Elevation Model (DEM) obtained by a LiDAR survey with 1 m resolution in terms of elevation. Depth files outlining the structurally-defined potential detachment volumes have been provided by the UL group.

The Digital Terrain model was converted into Golden Software Surfer grid files with 10 m grid spacings in both directions. The "runout surfaces" were obtained by subtracting the depth grid files from the "existing" surface grids and passing the grid files through a smoothing filter. The source volumes were increased uniformly by 20% to account for fragmentation bulking. Profiles of the slope were constructed for use in two-dimensional modeling.

The dynamic analyses were conducted using two independent programs: DAN-W in two dimensions and DAN3D in three dimensions. The two codes are described in Appendix 2. Calibration runs were first completed using DAN-W, as described in the next section.

4. Model Calibration

Nine rock avalanche cases have been selected for calibration back-analysis, as listed in Table 2. Four of these originated in limestone rock and five in strong igneous or metamorphic rocks. All the cases ran out over steep mountain slopes, but only those larger than 10 million m^3 reached valley bottoms. Table 2 gives the (bulked) volumes of the rock avalanches and the Bulk Friction Angle values (see Hungr, 1995) required to produce the observed runout in each case. The back-analysis clearly indicates an inverse relationship between volume and the friction angle, as shown in Figure 2. Such a trend has been observed in previous analyses. The reasons for it are presently not clear, but may include: 1) increased likelihood for the slide to encounter unconsolidated saturated material on lower slopes, 2) greater intensity of possible undrained loading of material over-run by a larger slide, 3) more intensive grain crushing and destruction of rock asperities in the larger events. A linear lower-limit envelope was drawn to the calibration data in Figure 2. This envelope was used to select bulk friction angles used in forward analysis, given the volume of each detachment. As a result, the larger rock avalanches are more mobile.

5. Results of Analyses.

The results of all analyses appear in Appendix 1. For each of the 12 potential rock avalanches listed in Table 1, the Appendix gives the final distribution of debris predicted by DAN 3D analysis and a graphical summary of the corresponding 2D analysis carried out by DAN-W. All of the rock avalanches are essentially completed in less than 1.5 minutes, similar to the Frank slide. The maximum velocities are in excess of 50 m/s (180 km/h). The deposit thickness, shown in 5 m contour intervals, is typically up to 10 m, but ranges up to 20 m. Animations of the largest landslide from each of the three alternative areas have been prepared, with a time frame 5 times shorter than that of the actual potential slide.

The 2D maximum runout distances are typically somewhat larger than the 3D results. The reason for this is that the 2D analyses were conservatively forced to travel on relatively narrow paths and therefore, their energy is more confined. Such a situation could actually arise in reality, as the rock slide mass may remain somewhat coherent in the initial stages of its movement, in contrast to the 3D model that assumes instant, fluid-like lateral spreading. The direction of the 3D slide and the assumed 2D profile did not often agree.

In Figure 3, the maximum extent of the rock avalanche runout is summarized by runout envelopes compiled from the figures of Appendix 1. Over most of the area, the largest runout is determined by LSP-2, the total failure of Lower South Peak, with a volume of 6.6 m^3. The 2D runouts, marked by a dotted line, are somewhat larger than the 3D envelope (full line). None of the predicted runouts exceed the previously-determined reach of the two large failure from the South Peak, as analysed in the April, 18, 2008 report (O.Hungr Geotechnical Research, April 18, 2008).

6. Discussion

Dynamic modeling of landslide motion is a relatively new field of analysis, that cannot be considered routine. The geotechnical research group at the Department of Earth Sciences at the University of British Columbia has done more practically-oriented work on this subject than almost any other group in the world and our software can be considered as state-of-the-art. In particular, the large number of back-analyses of real rock avalanche cases gives us a fair degree of confidence in our predictive results. Nevertheless, it is still impossible to place reliable error limits on our runout predictions. We believe that our analysis is conservative, given a selection of relatively large and mobile events for calibration and representing the friction angle by a lower-limit envelope to the calibration data in Figure 2. We have also allowed for possible model error by employing two independent algorithms, one of which removes the possible influence of excessive lateral spreading. It is our belief that the runout estimates provided in this report are reasonably conservative. However, an additional safety margin should be considered, if our predictions are to be used for conducting risk estimates.

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Table 1

1. Potential source volumes identified by the UL group.

Symbol	**Location (UL)**	**Expanded Volume (m^3)**	**Bulk friction angle (°)**
LSP-1	South Peak, Lower Instability	1.89 M	25.0
LSP-2	Lower South Peak, Total	6.59 M	20.0
LSP-3	South Peak, Slice 1	0.12 M	36.0
LSP-4	South Peak, Slice 2	0.46 M	30.4
LSP-5	South Peak, Slice 3	0.63 M	29.7
LSP-6	South Peak, Slice 4	1.44 M	26.2
USP-1	Upper South Peak, Subsidence Zone	1.99 M	24.5
USP-2	Upper South Peak, Toppling Zone	0.30 M	31.0
USP-3	Upper South Peak, Wedge Zone	1.37 M	26.3
3dP-1	Third peak, DSGSD	2.59 M	23.2
3dP-2	Third peak, GPS Station	54 000	37.0
3dP-3	Third peak, Sackung Zone	1.37 M	26.3

Table 2

Rock avalanche cases selected for calibration

Location	**Volume (m^3)**	**Bulk Friction Angle (°)**	**Reference**
Afternoon Ck.	0.7 M	35	Strouth et al., 2006
Thurwieser	1.9 M	26	Sosio et al., 2008
Jonas North	2.4 M	25	Bruce, 1978
Jonas South	3.7 M	26	Bruce, 1978
Madison	33 M	15	Hungr and Evans, 1996
Frank, 1903	36 M	14	Cruden and Krahn, 1978
ValPola	59 M	18	Hungr and Evans, 1996
Hope, 1965	64 M	22	Hungr and Evans, 1996
Diablerets	73 M	17	Hungr and Evans, 1996

Figure 1
View of the Turtle Mountain ridge from the east. The Third Peak and the South Peak are the two highest points in the photo.

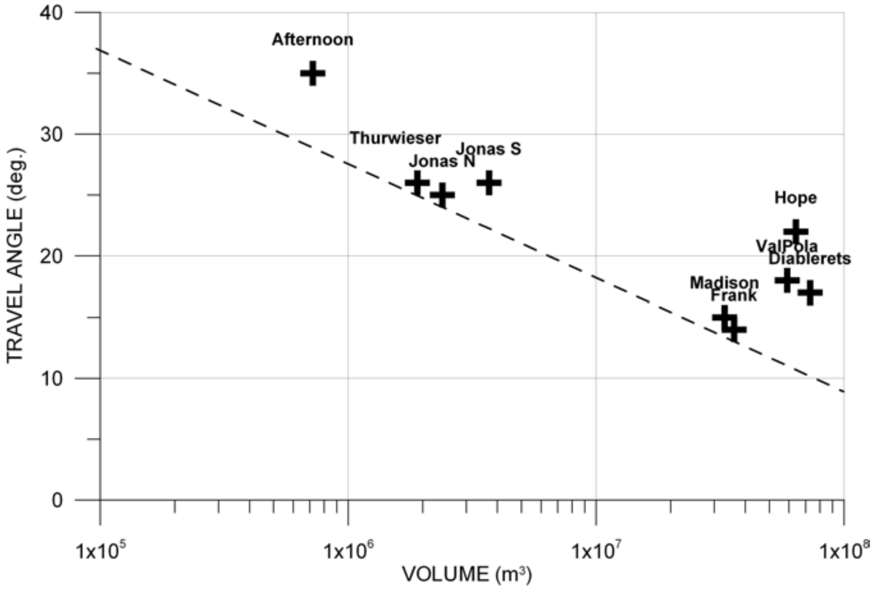


Figure 2
Calibration analysis: Correlation between landslide volume and the back-calculated Bulk Friction Angle (including pore-pressure effects), based on Table 2.

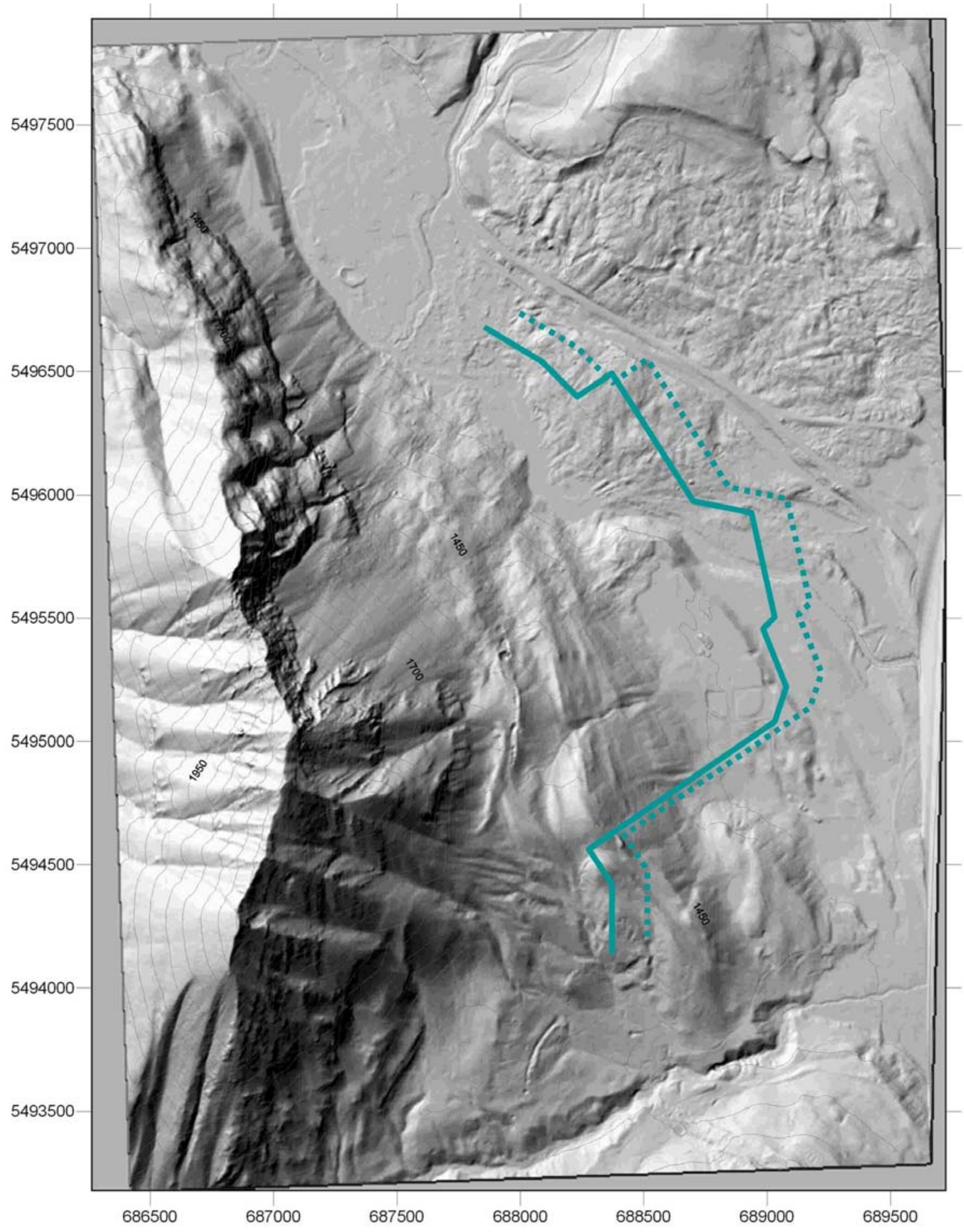


Figure 3
Envelope of Hazard Areas for 12 potential rock avalanches from the South Peak and Third Peak of Turtle Mountain. Full line: 3D analyses. Dotted line: 2D analyses.

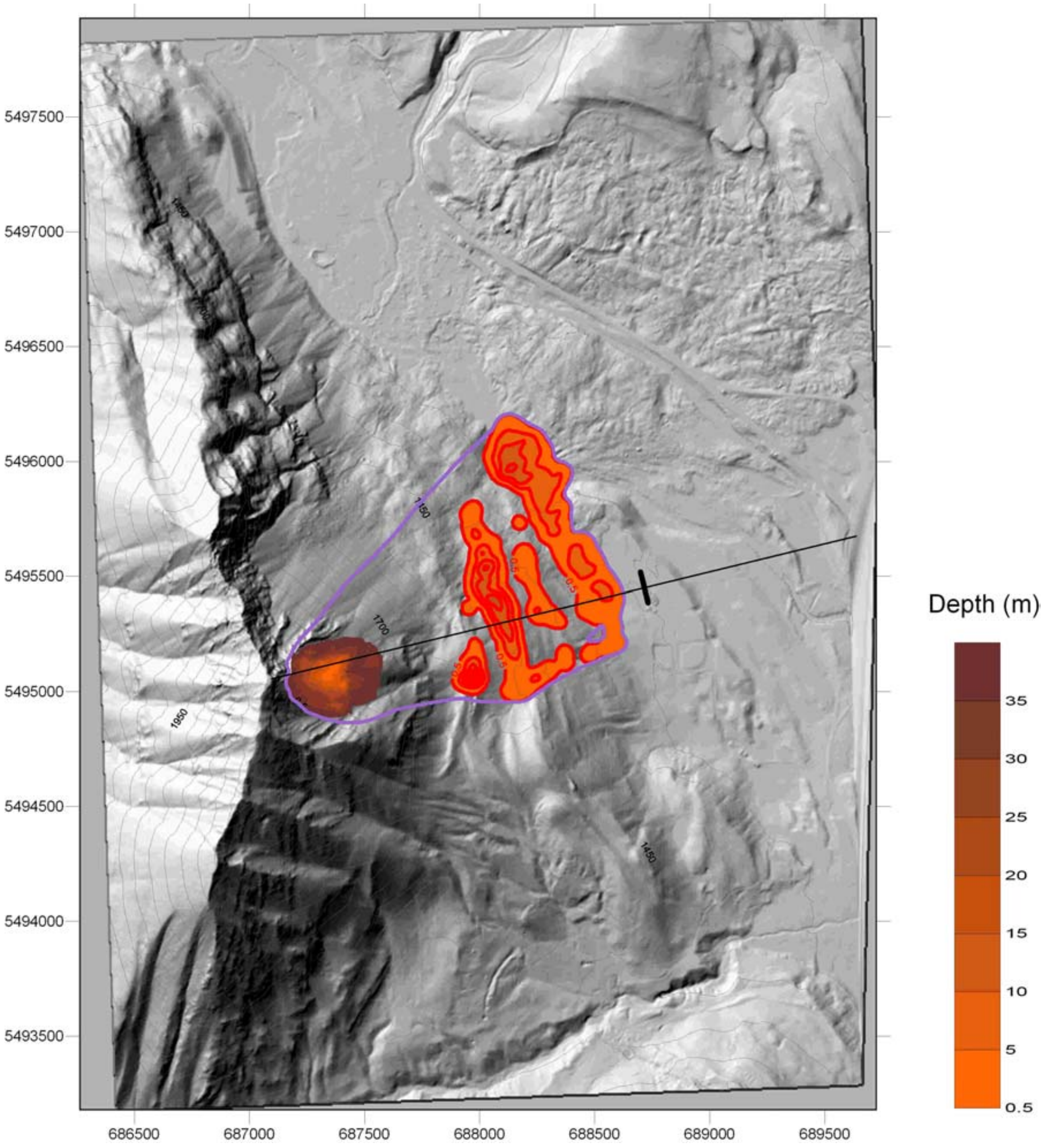
APPENDIX 1

Results of the runout analyses.

Notes:

1) The red areas indicate the final position of the 3D deposit, with 5 m contours.
2) The black line on the map shows the location of the profile used in the 2D analysis.
3) The thick, short black line shows the 2D runout.

LSP-1, Lower South Peak, Lower Instability



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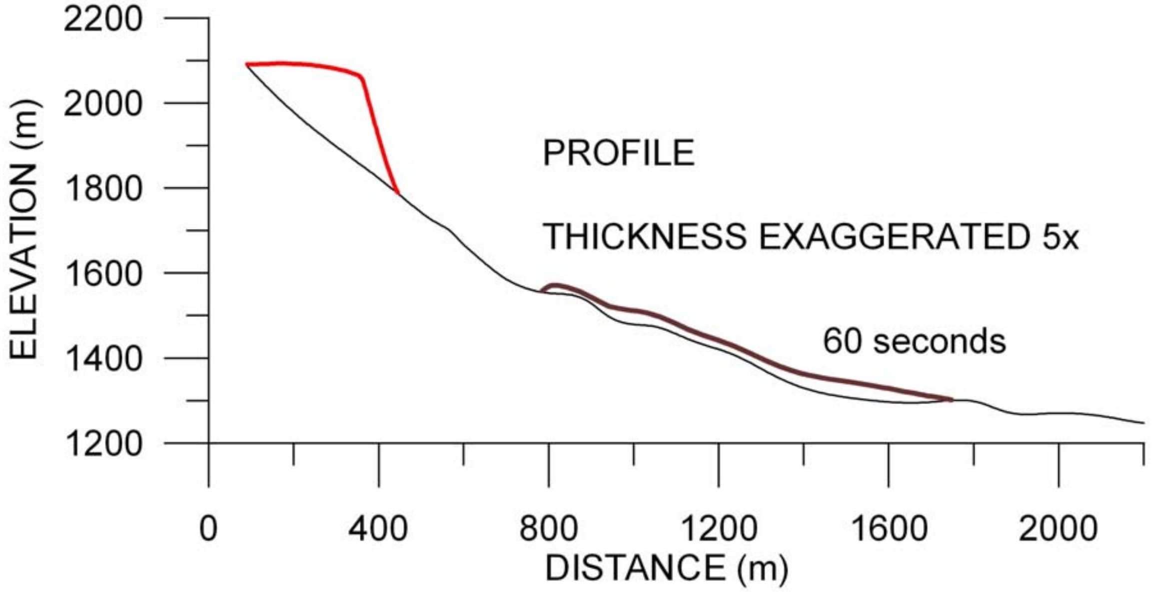
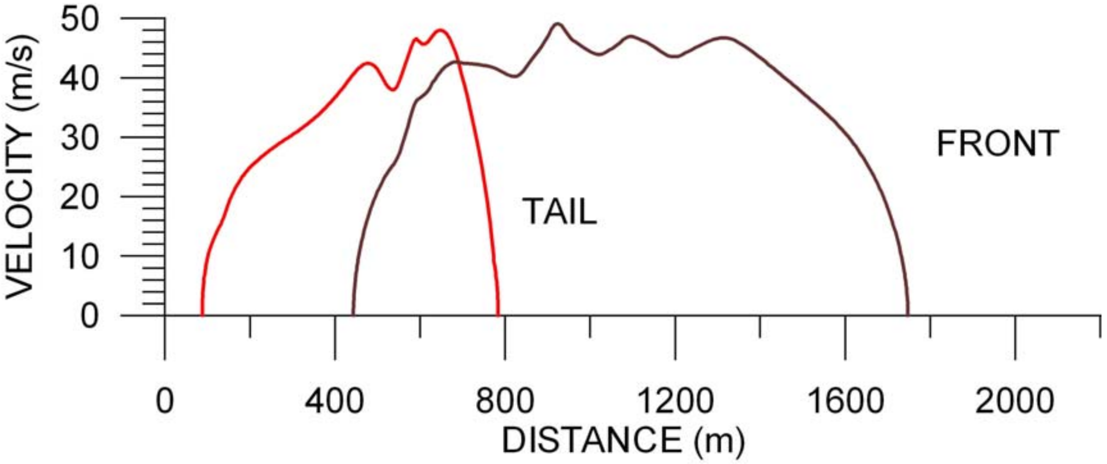
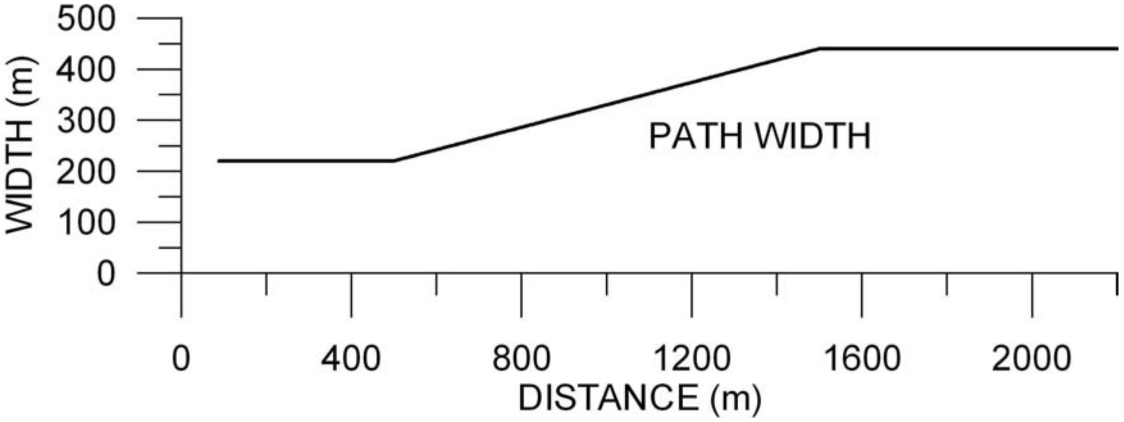
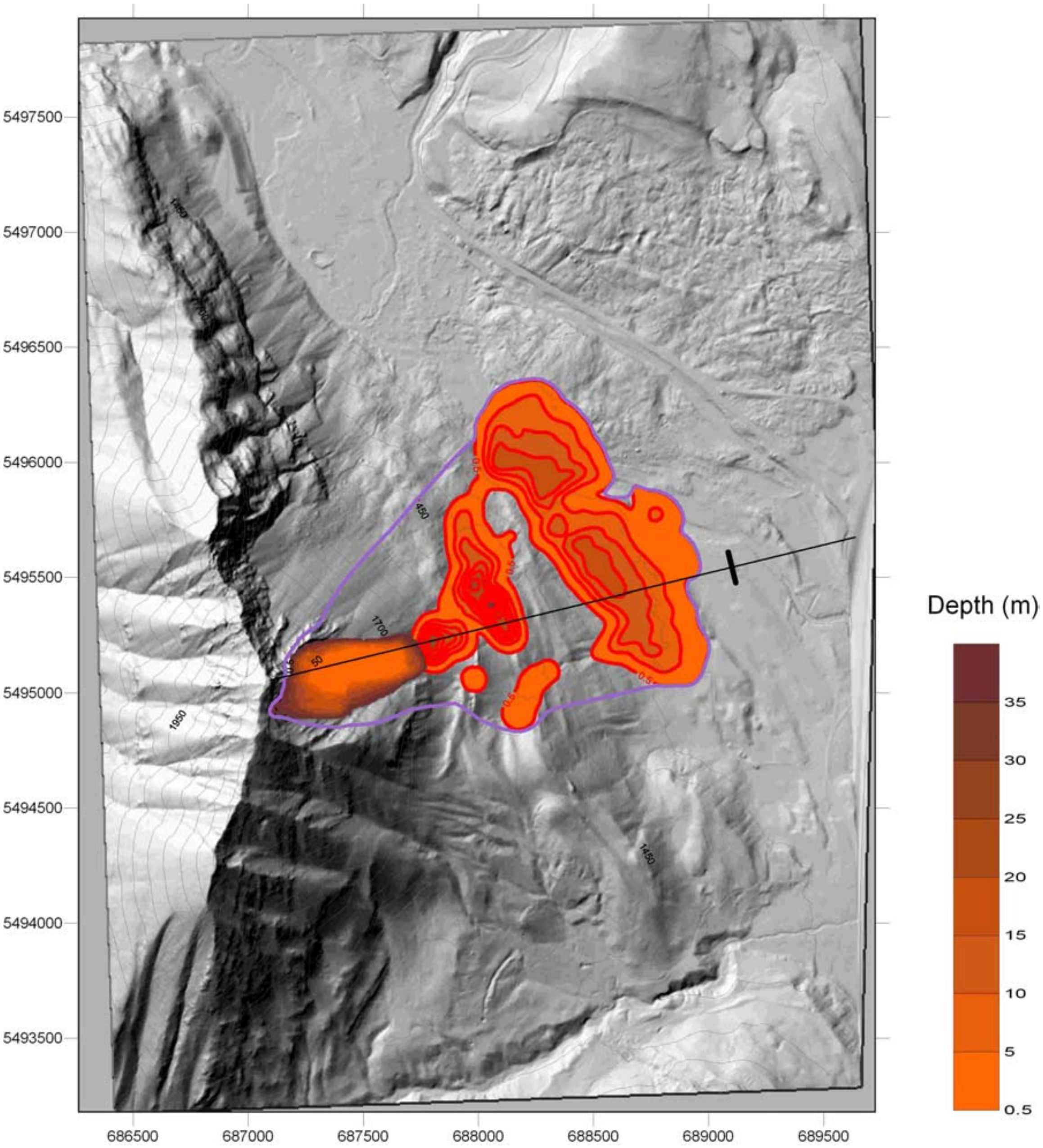






LSP-2, Lower South Peak, Total



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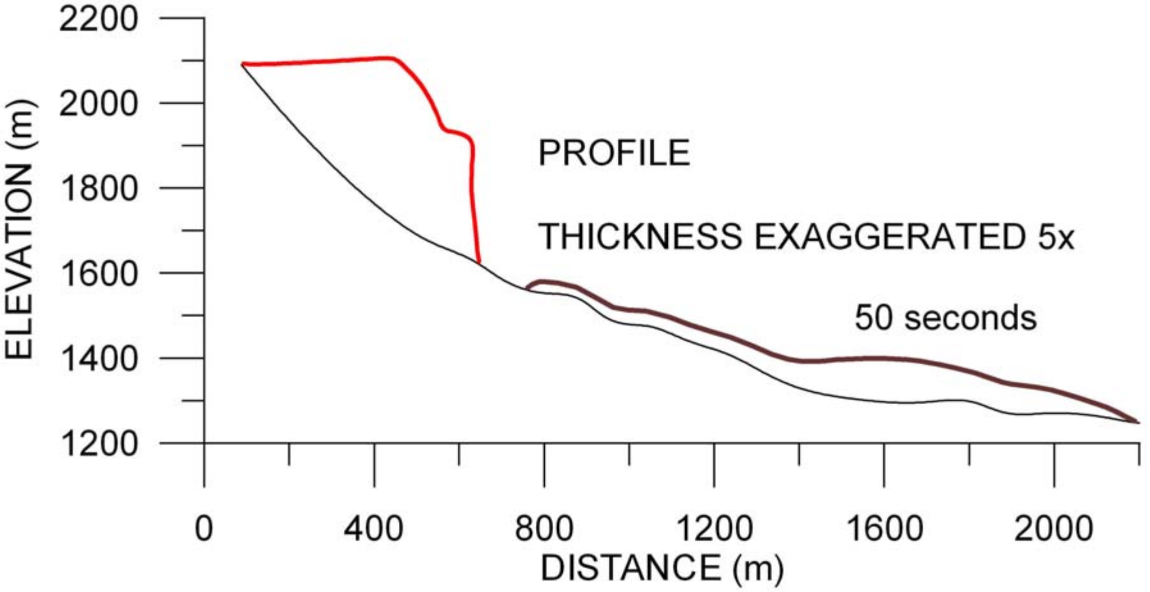
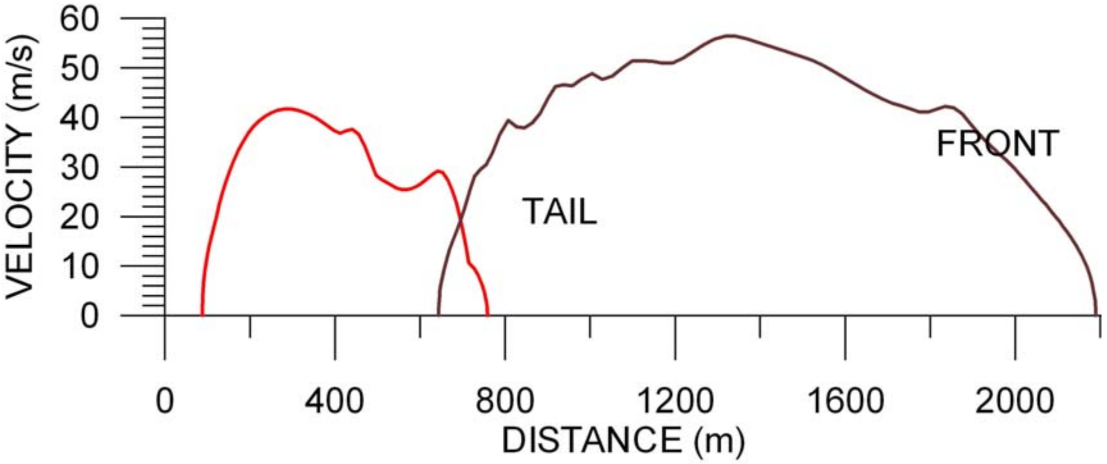
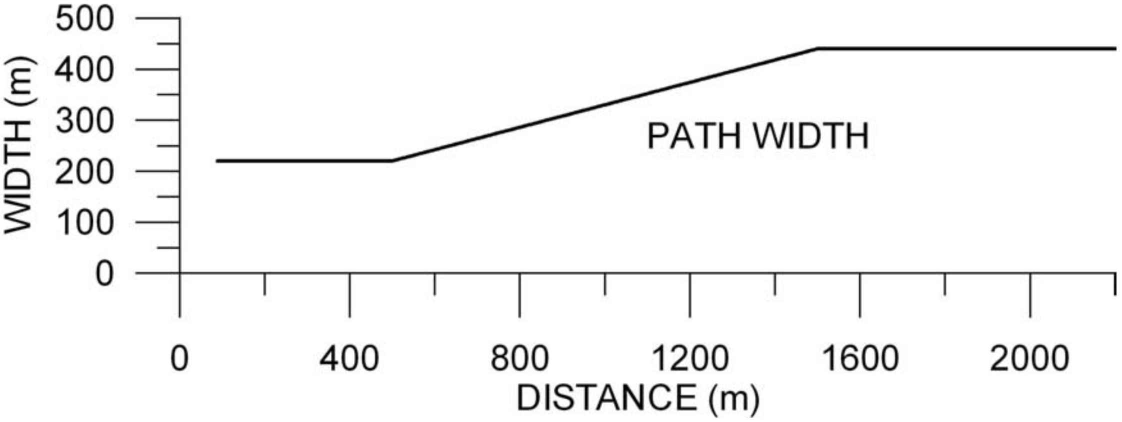
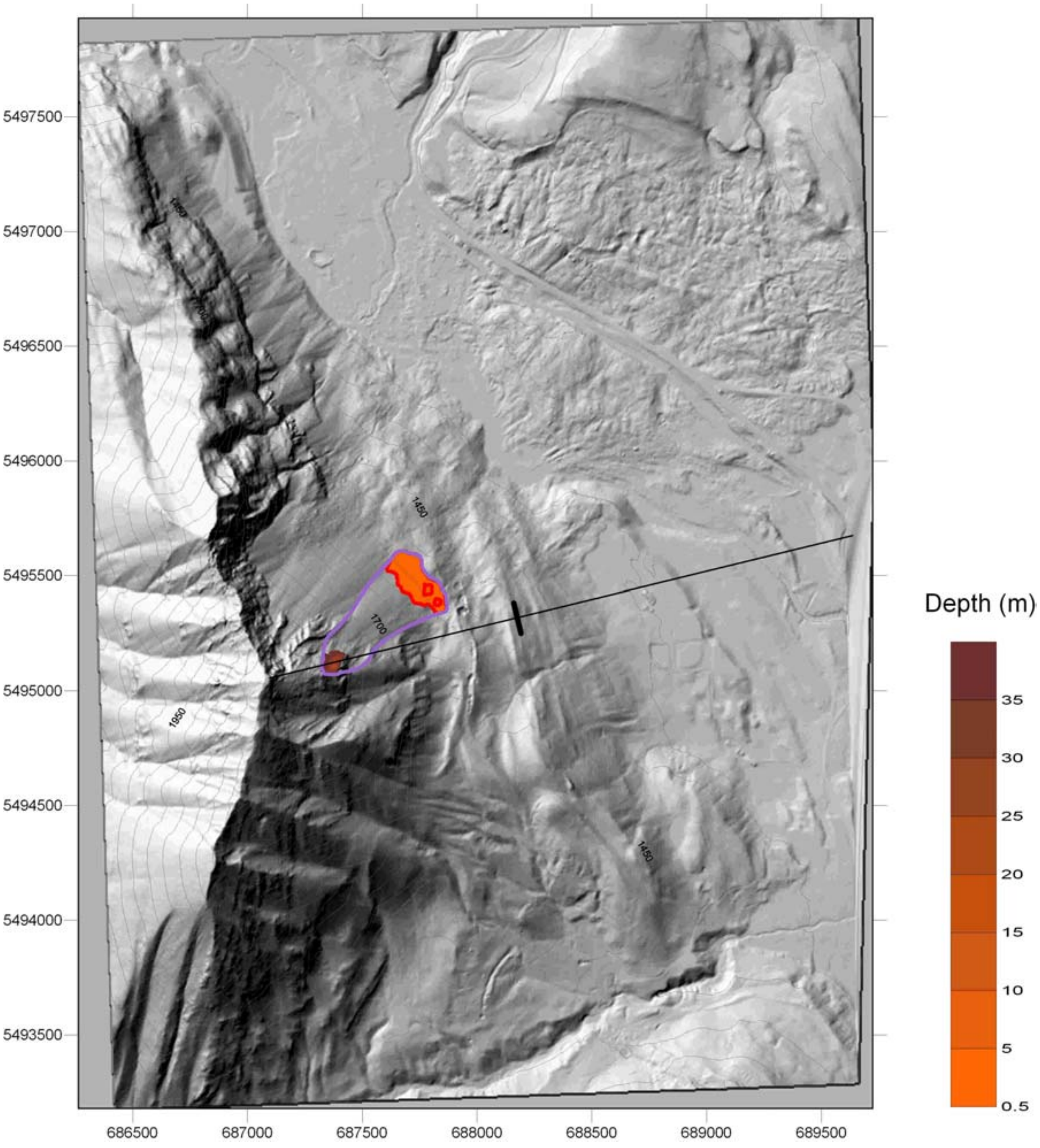






LSP-3, Lower South Peak, Slice 1



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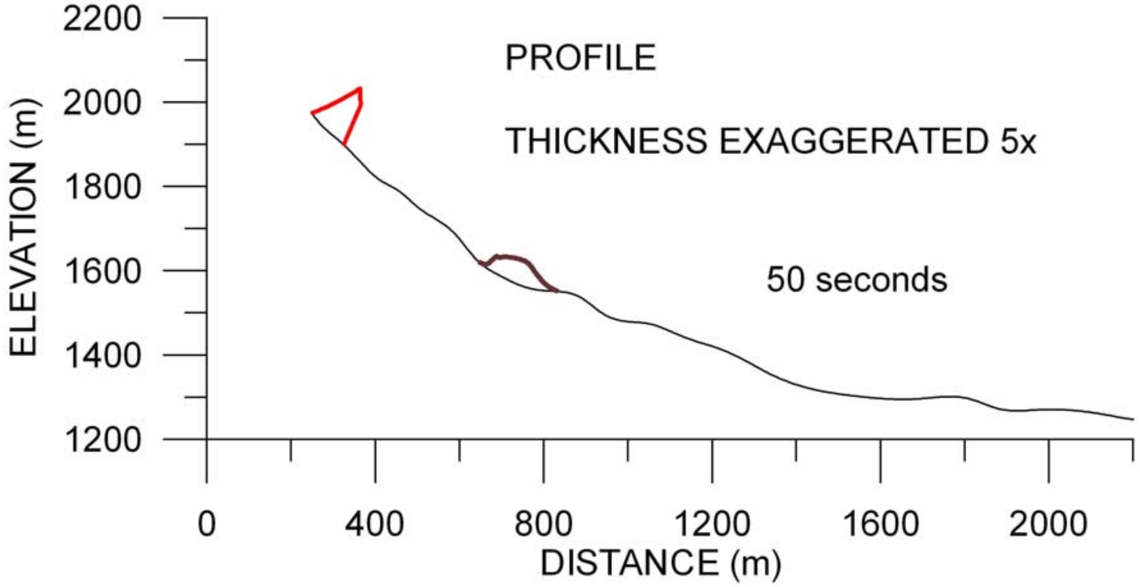
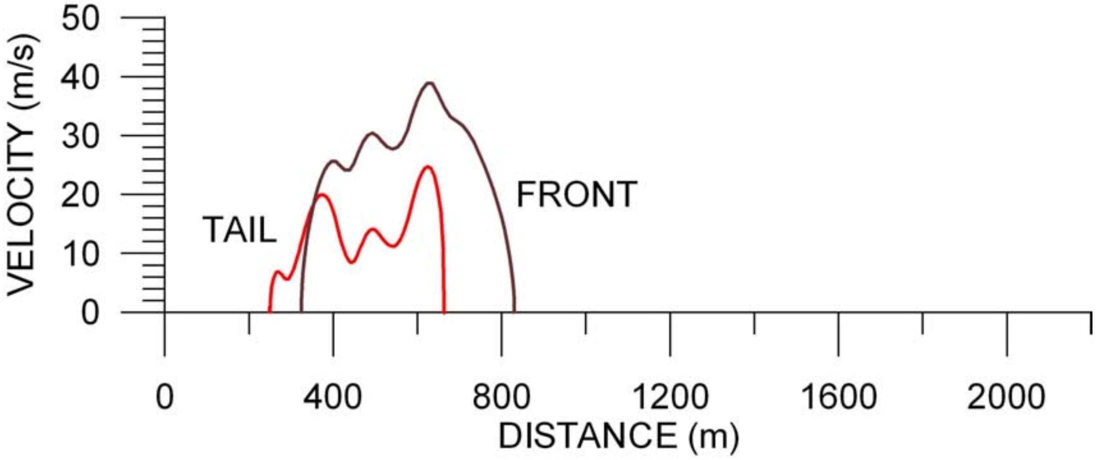
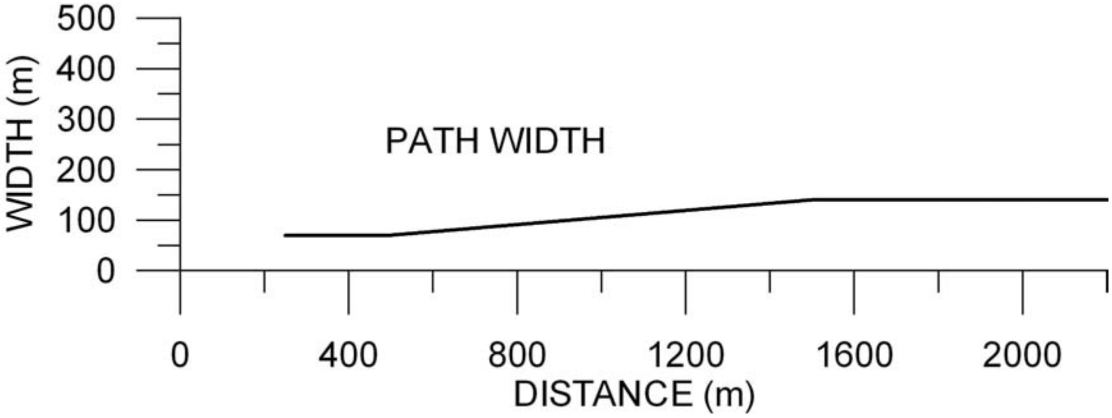
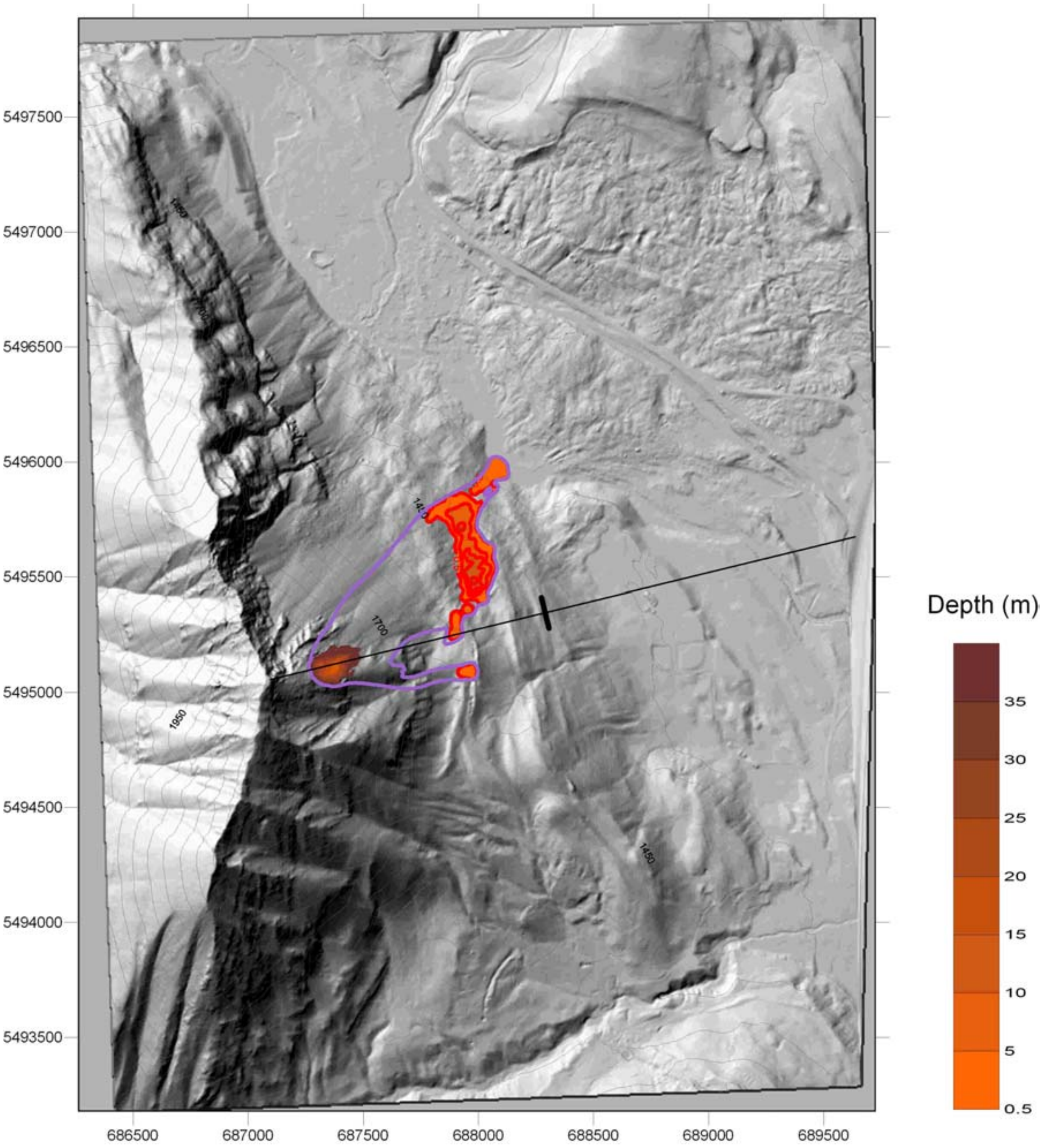






LSP-4, Lower South Peak, Slice 2



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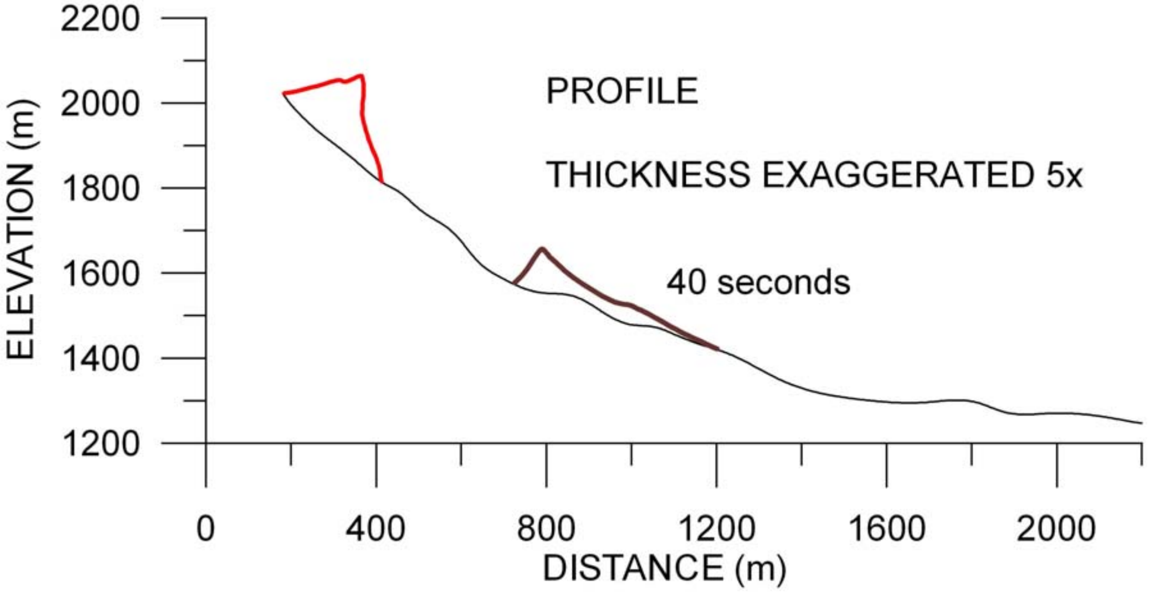
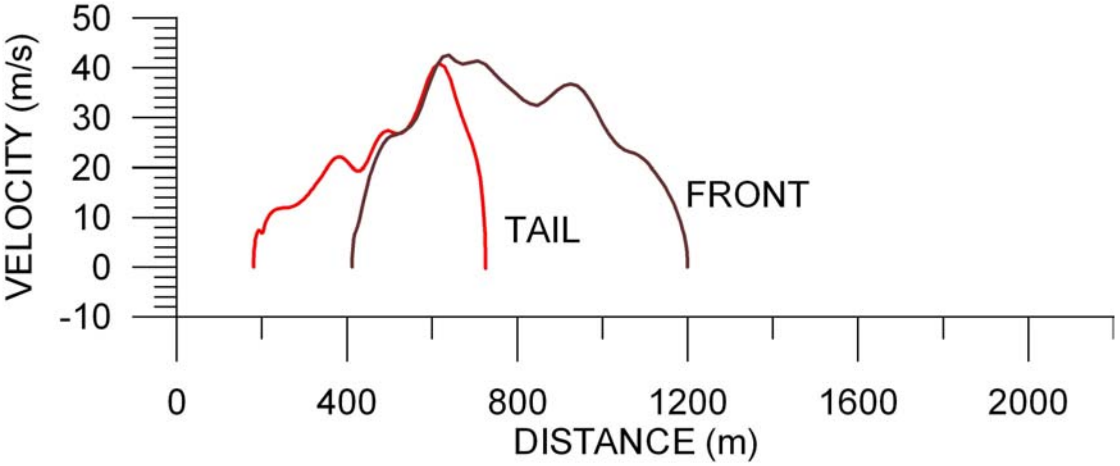
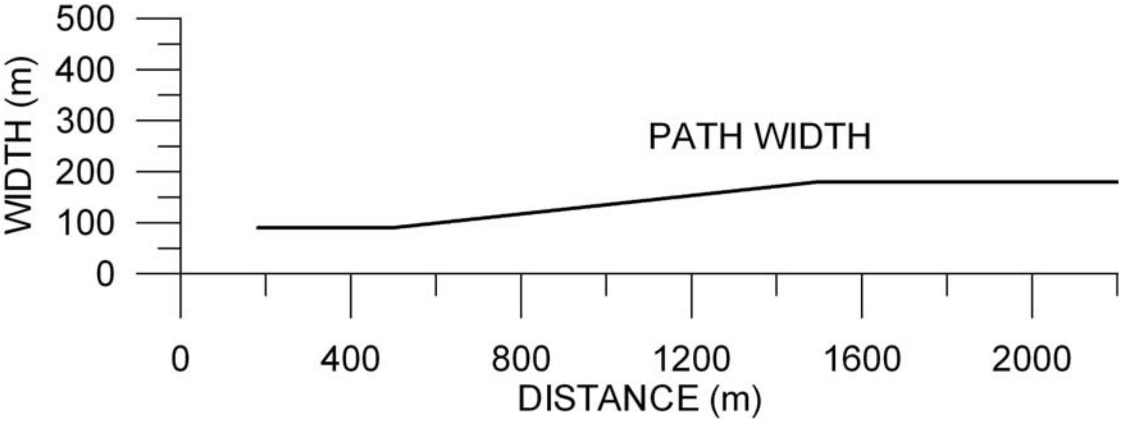
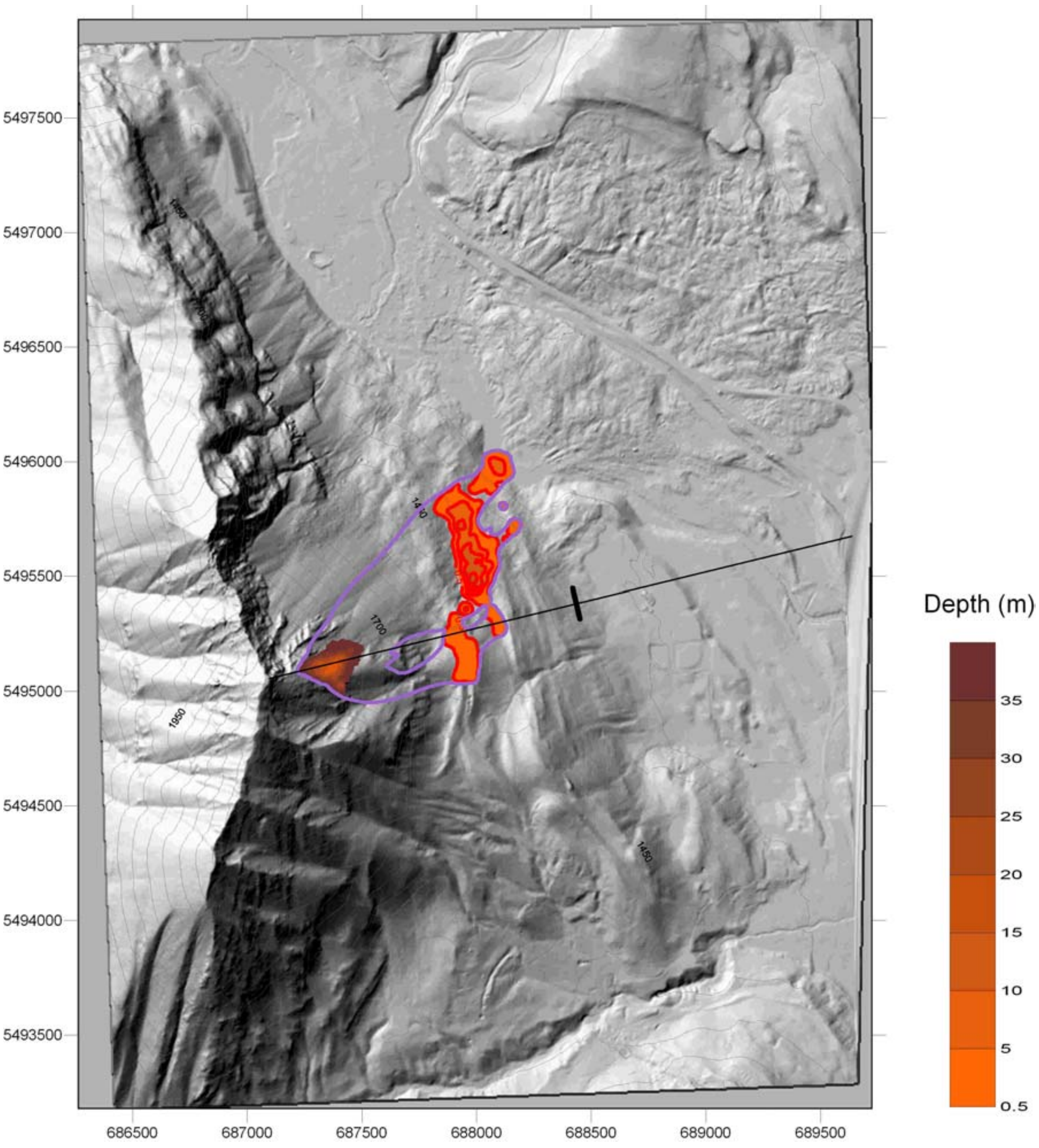


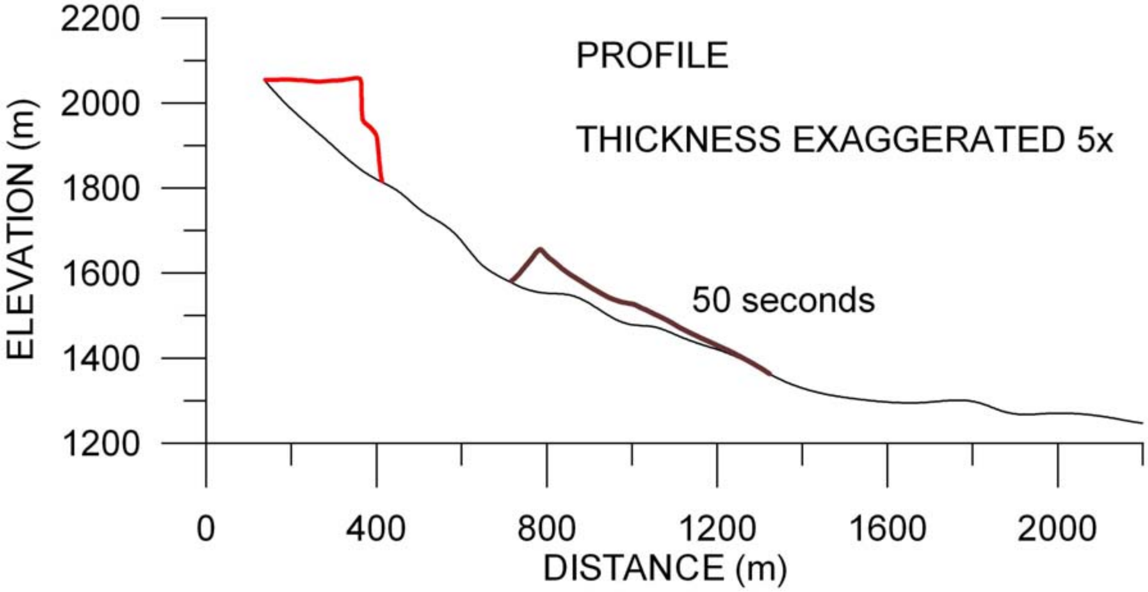


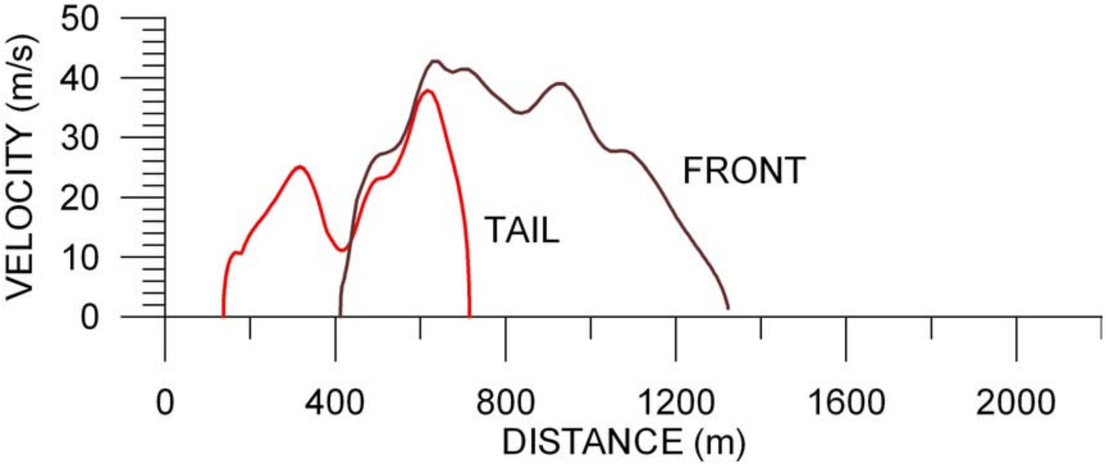


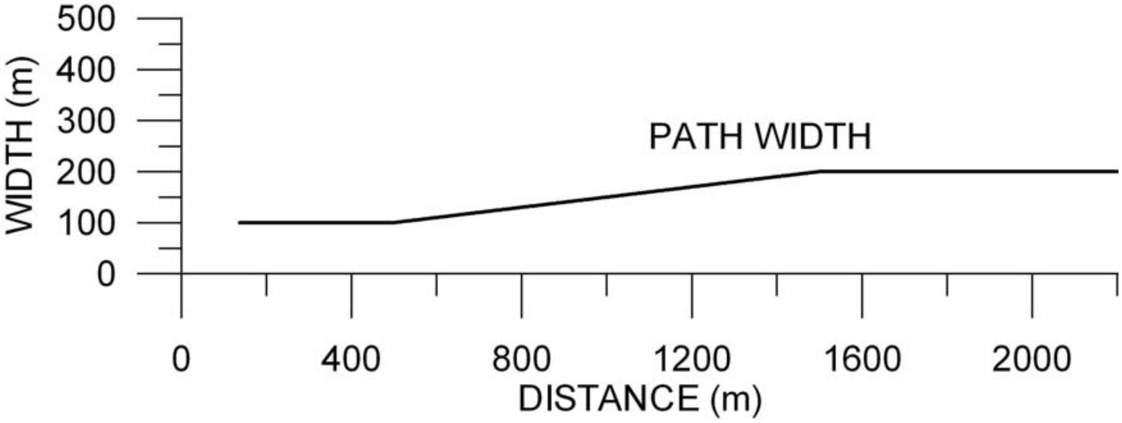
LSP-5, Lower South Peak, Slice 3



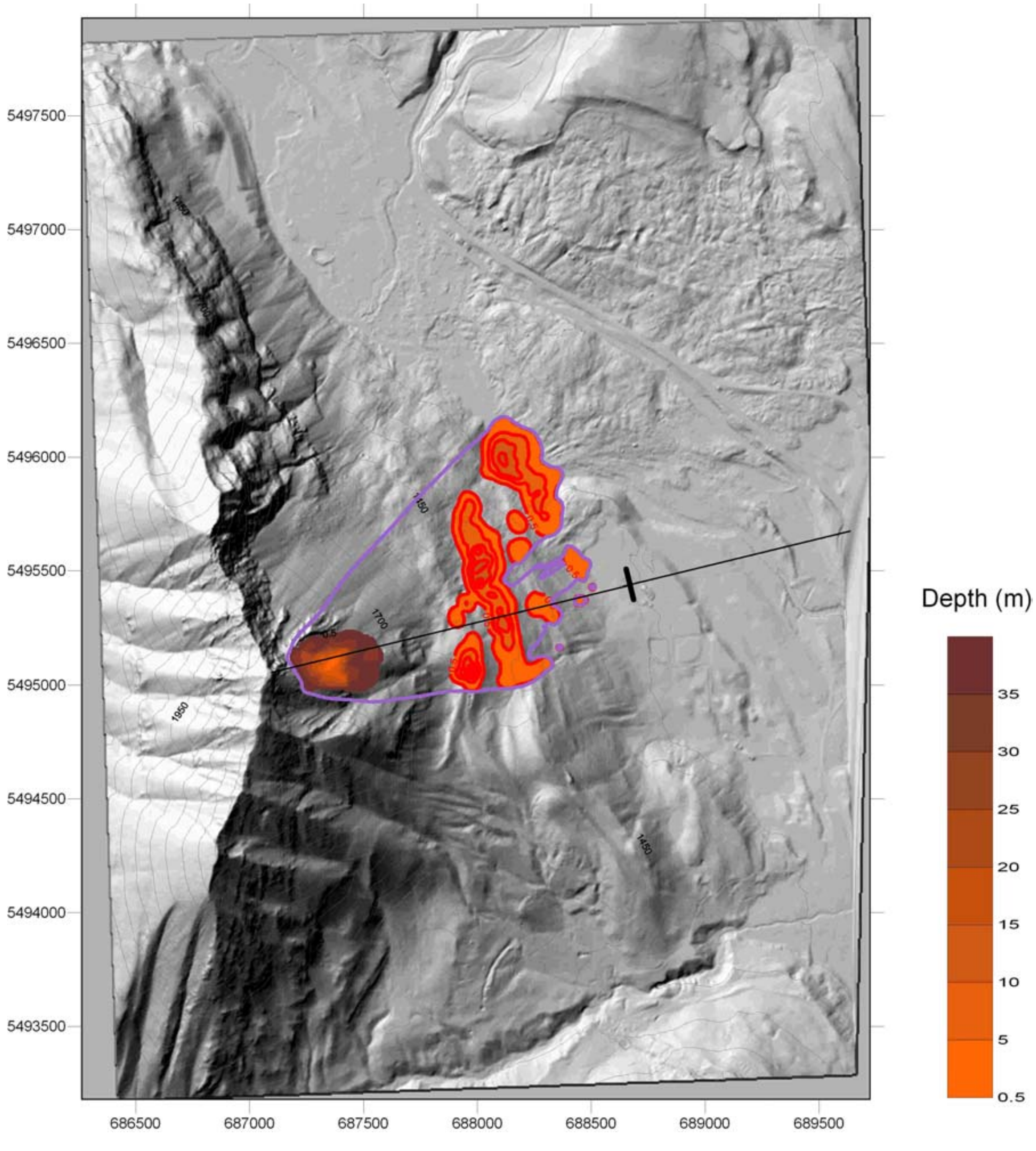
LSP-5, Lower South Peak, Slice 3







LSP-6, Lower South Peak, Slice 4



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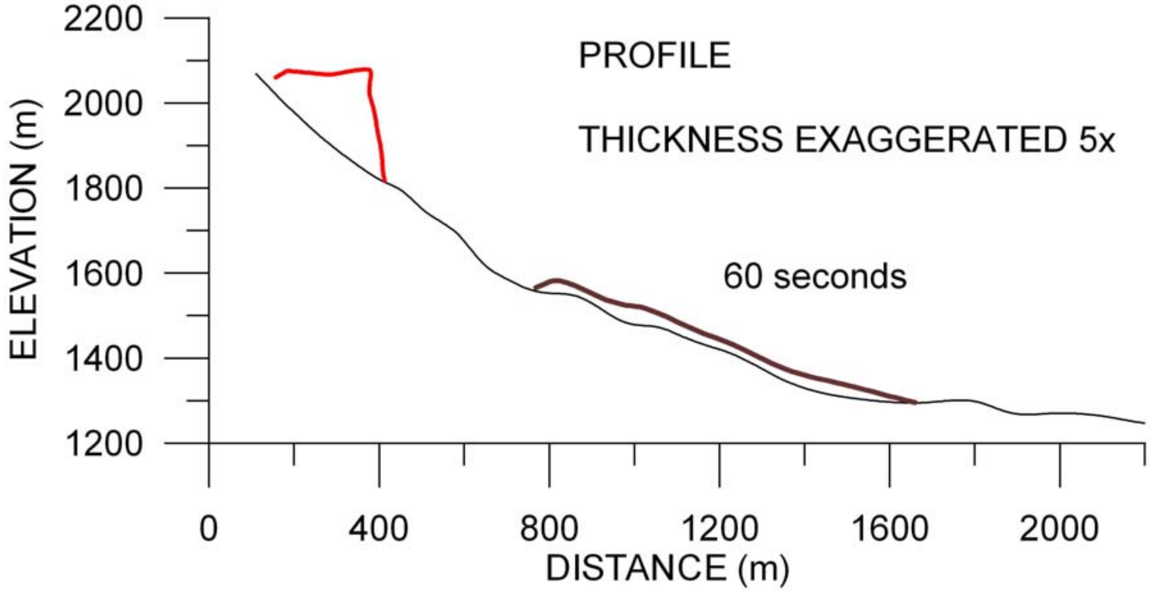
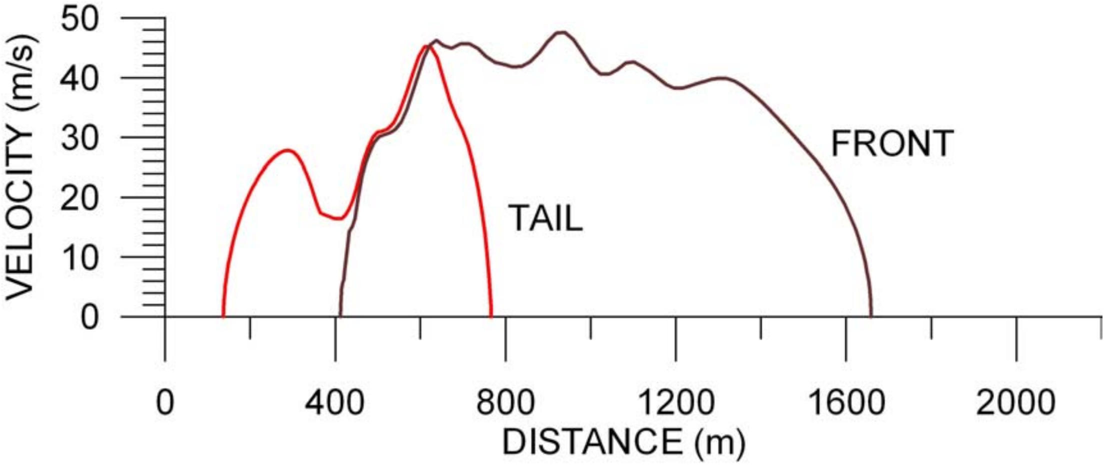
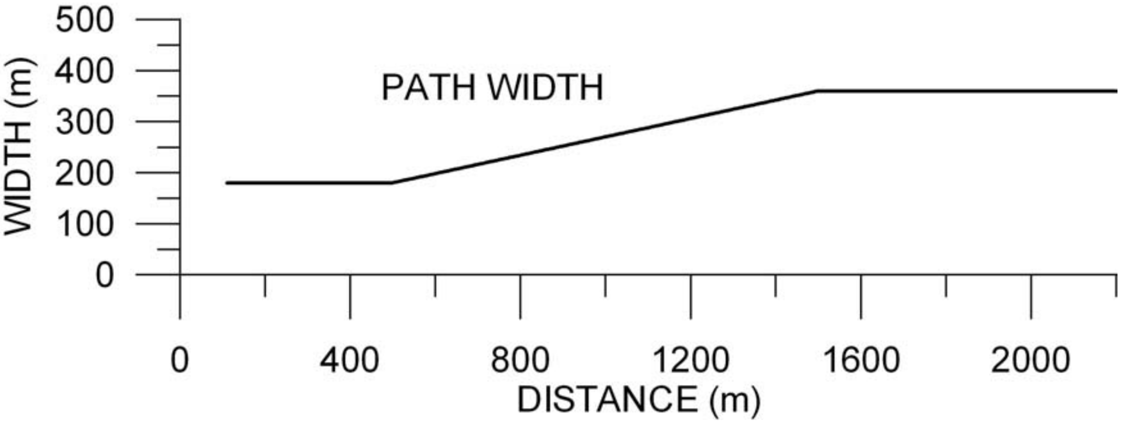
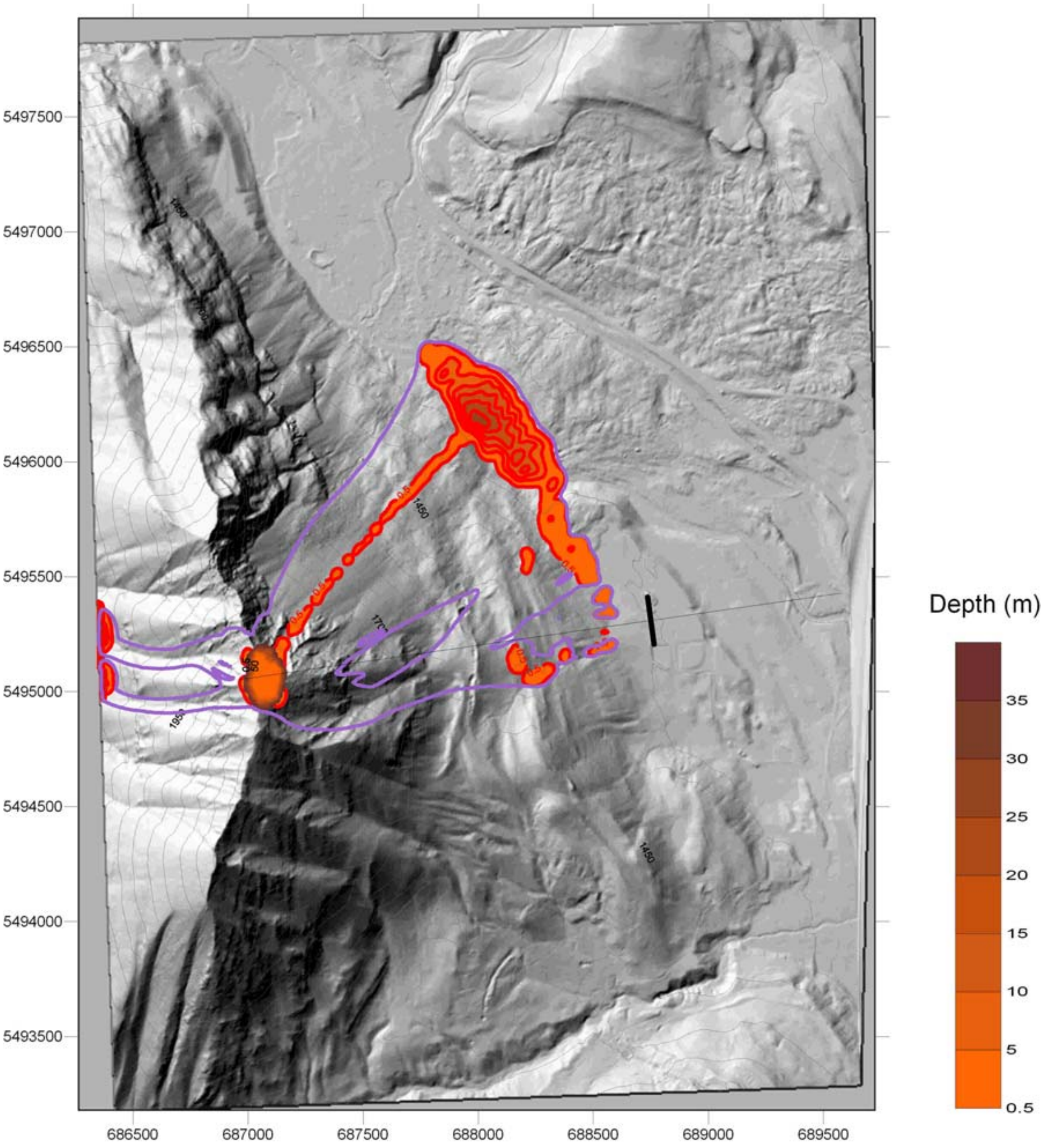


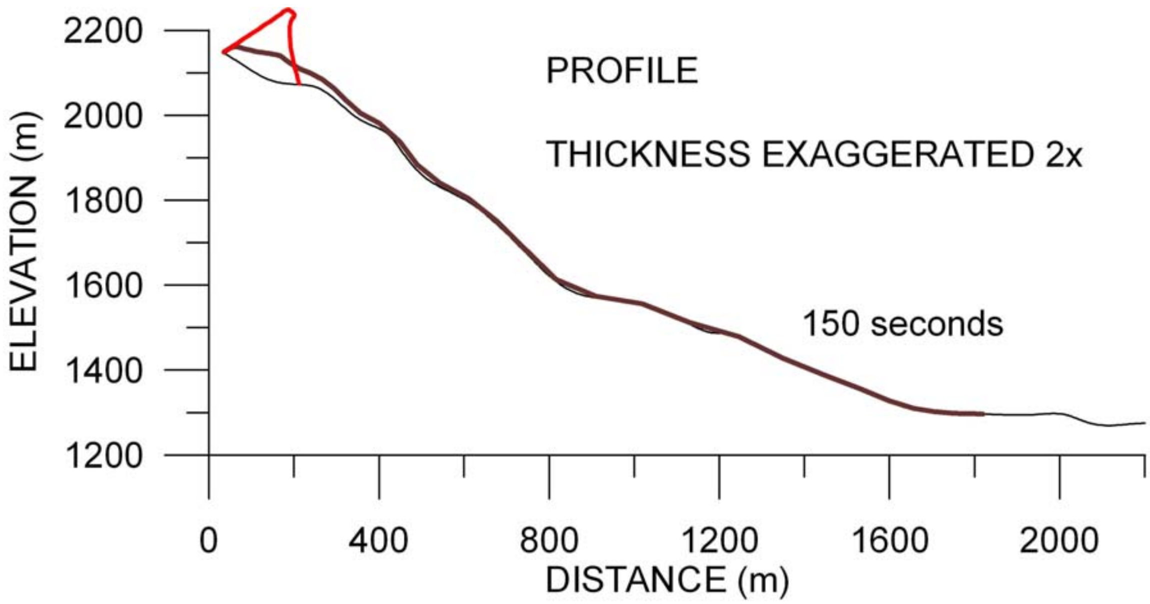


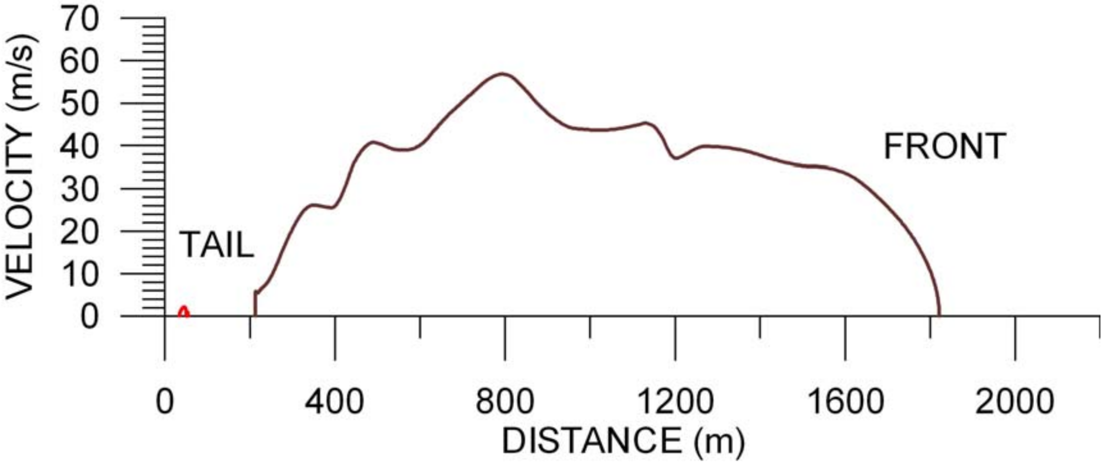


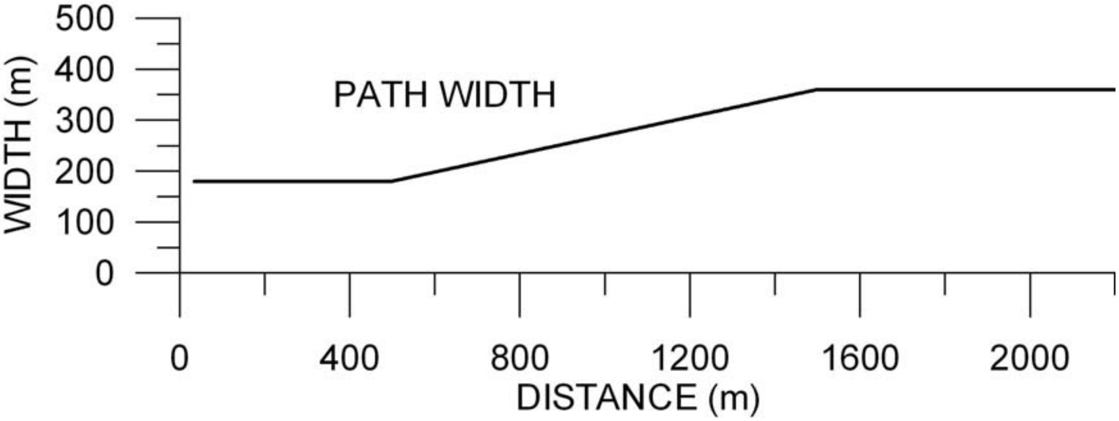
USP-1, Upper South Peak, Subsidence Zone



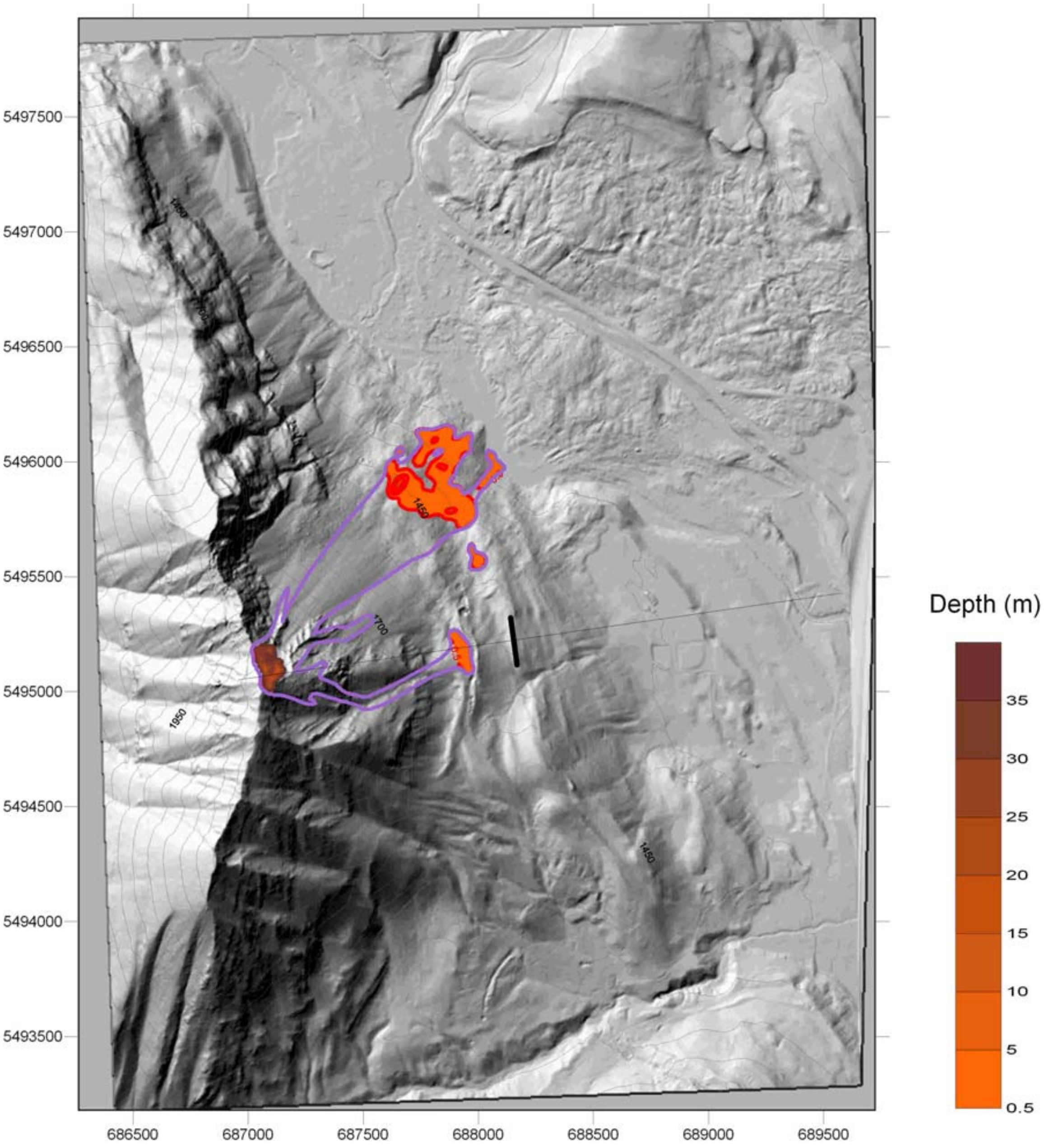
USP-1, Upper South Peak, Subsidence Zone



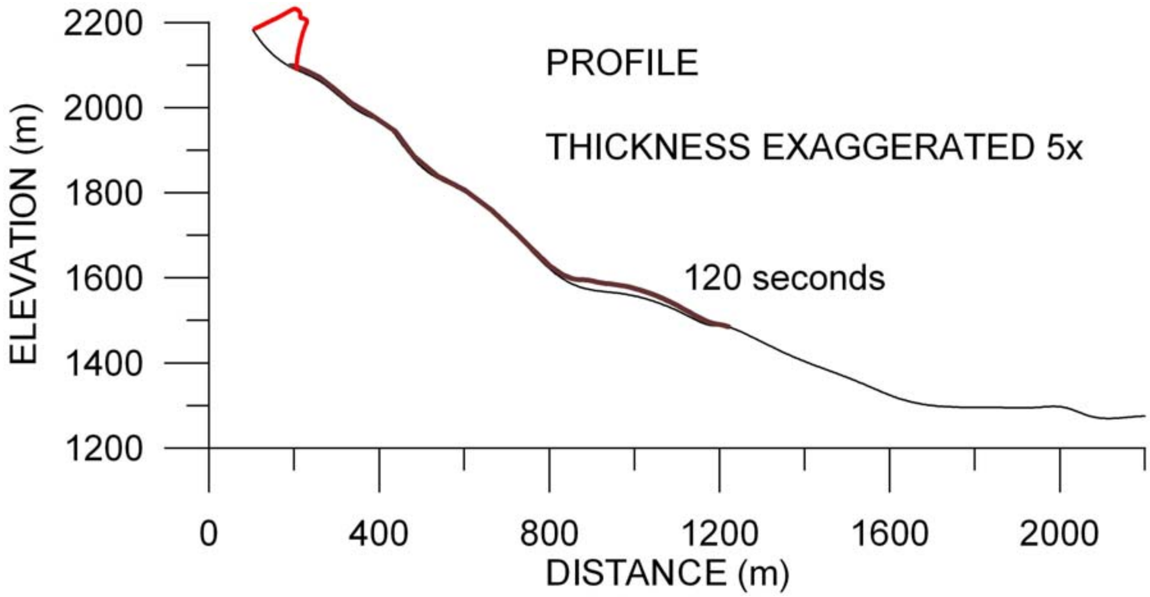


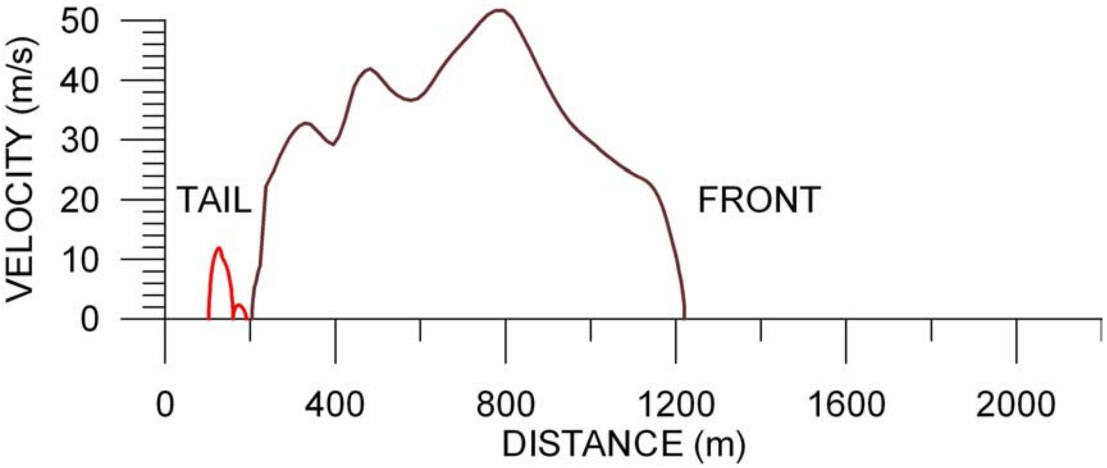


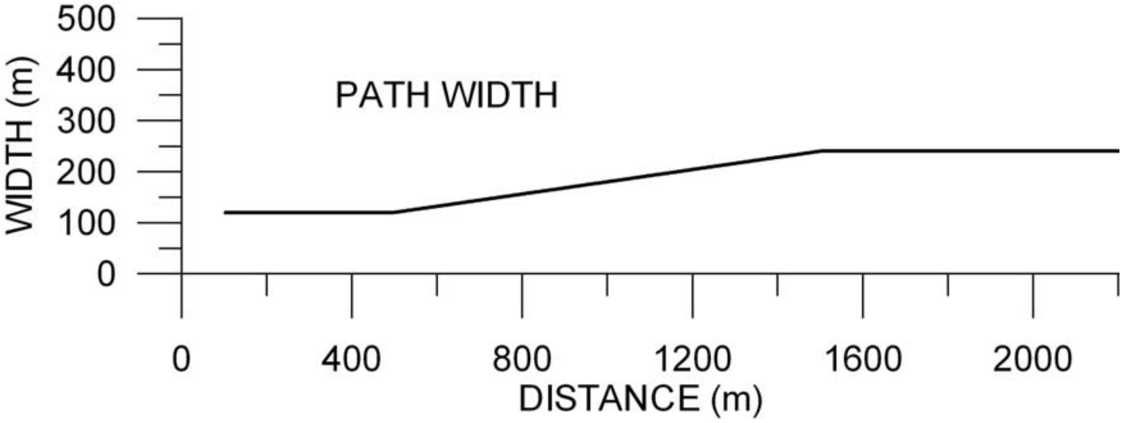
USP-2, Upper South Peak, Toppling Zone



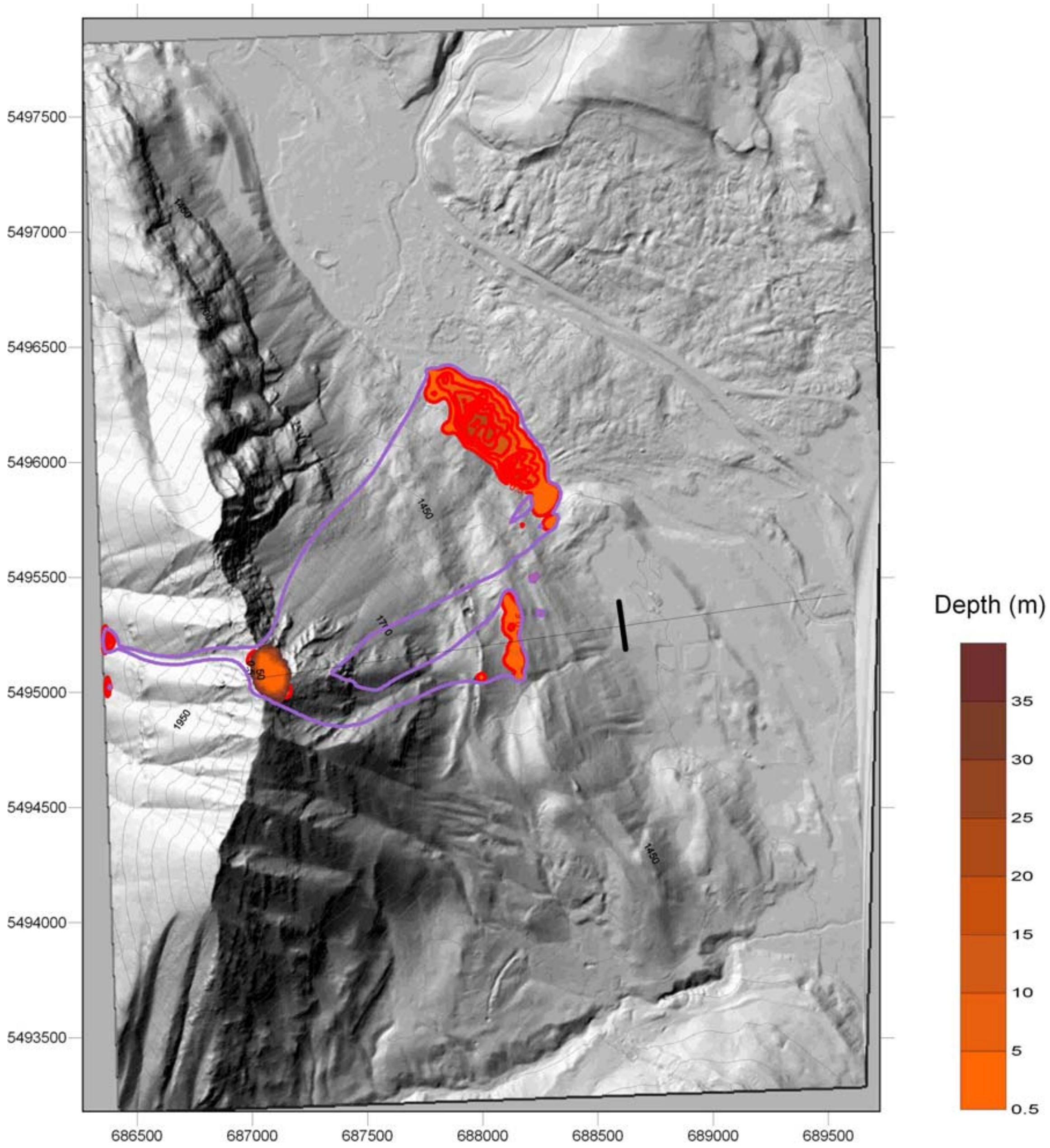
USP-2, Upper South Peak, Toppling Zone



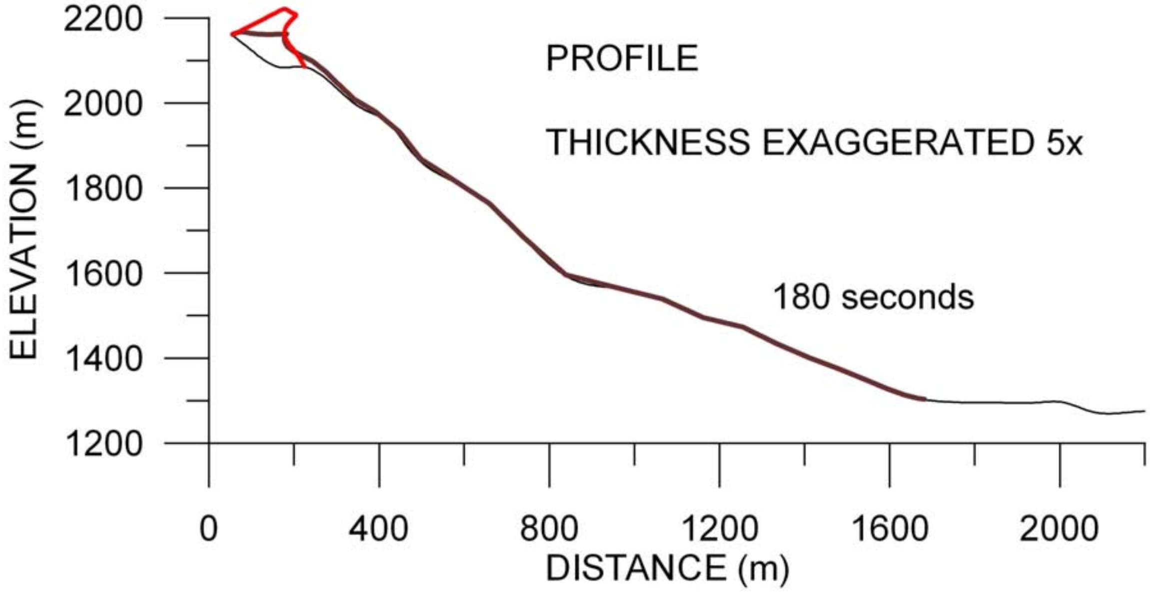


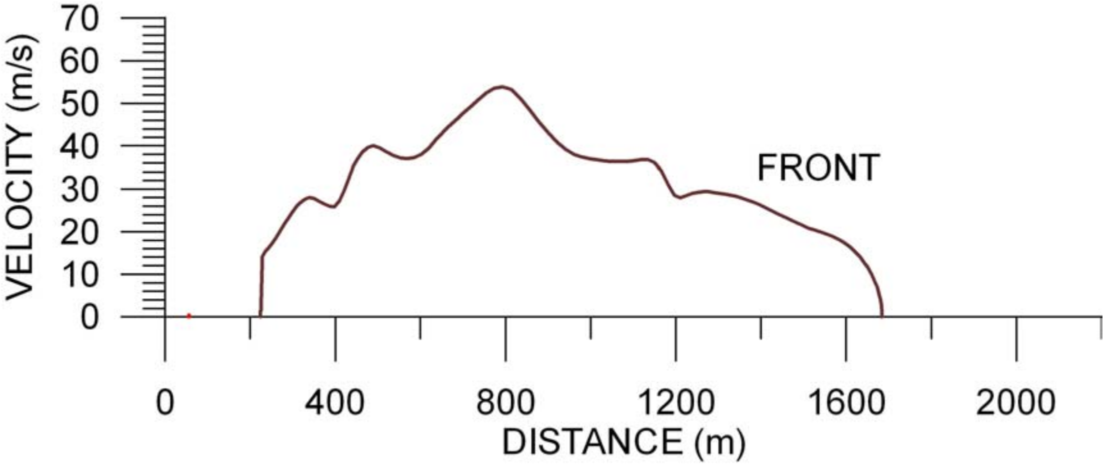


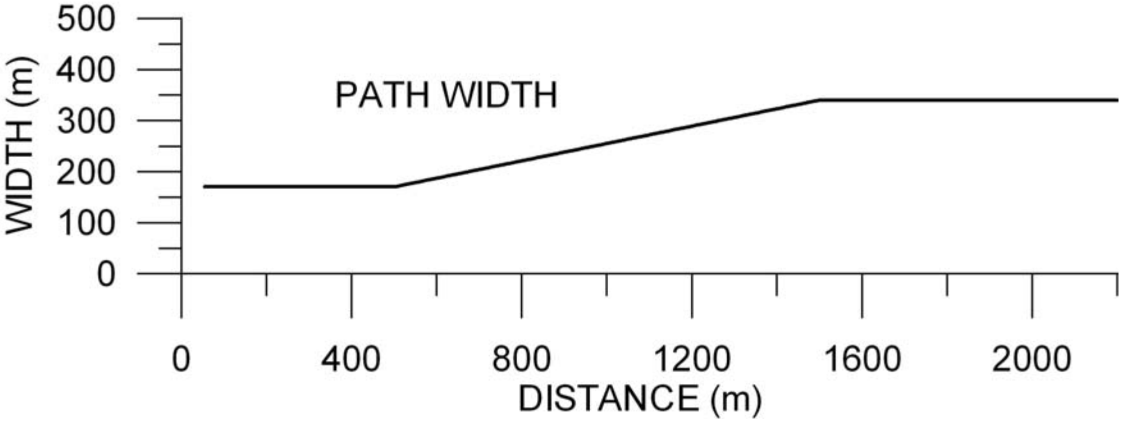
USP-3, Upper South Peak, Wedge Zone



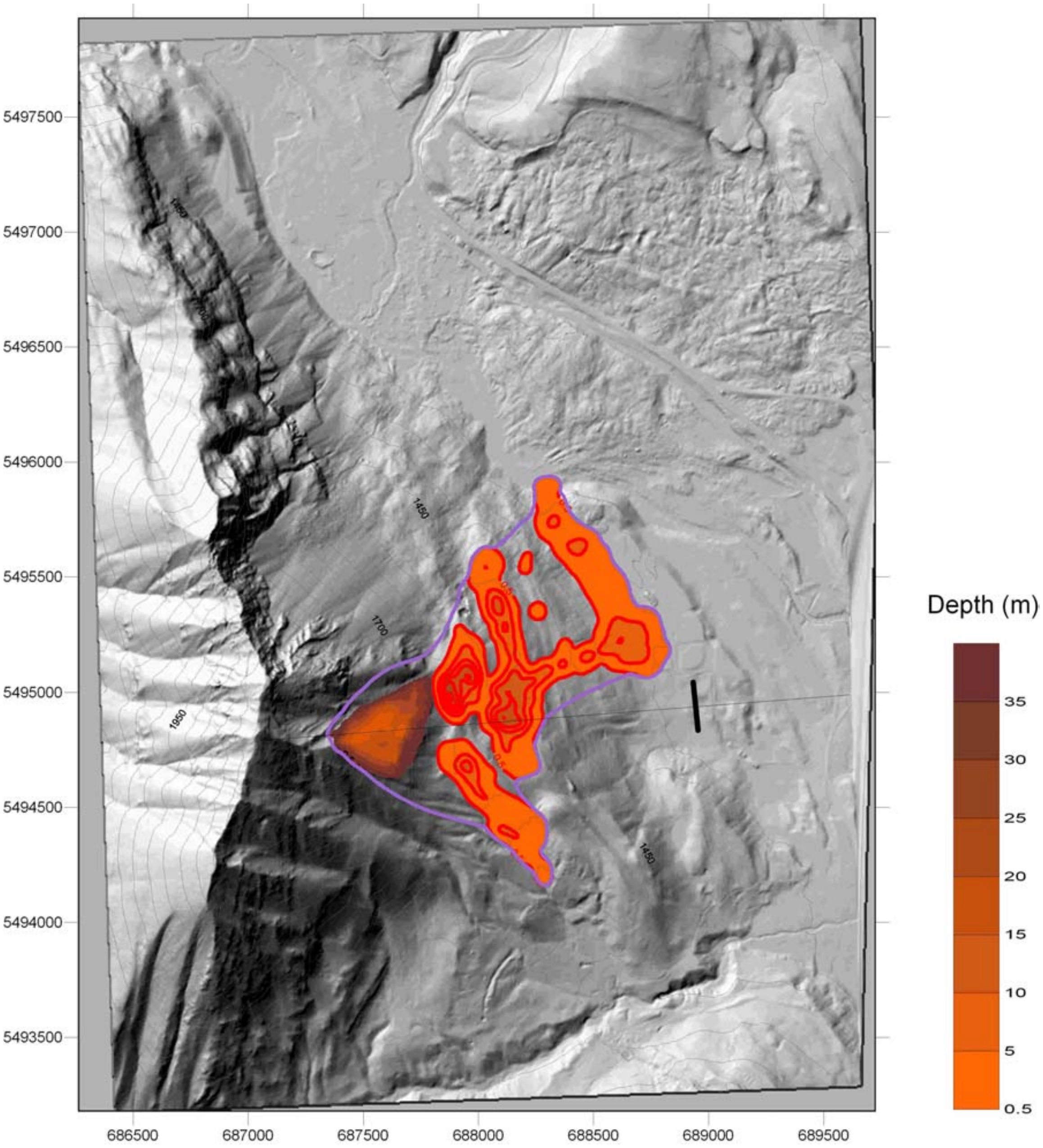
USP-3, Upper South Peak, Wedge Zone







3dP-1, Third Peak, DSGD



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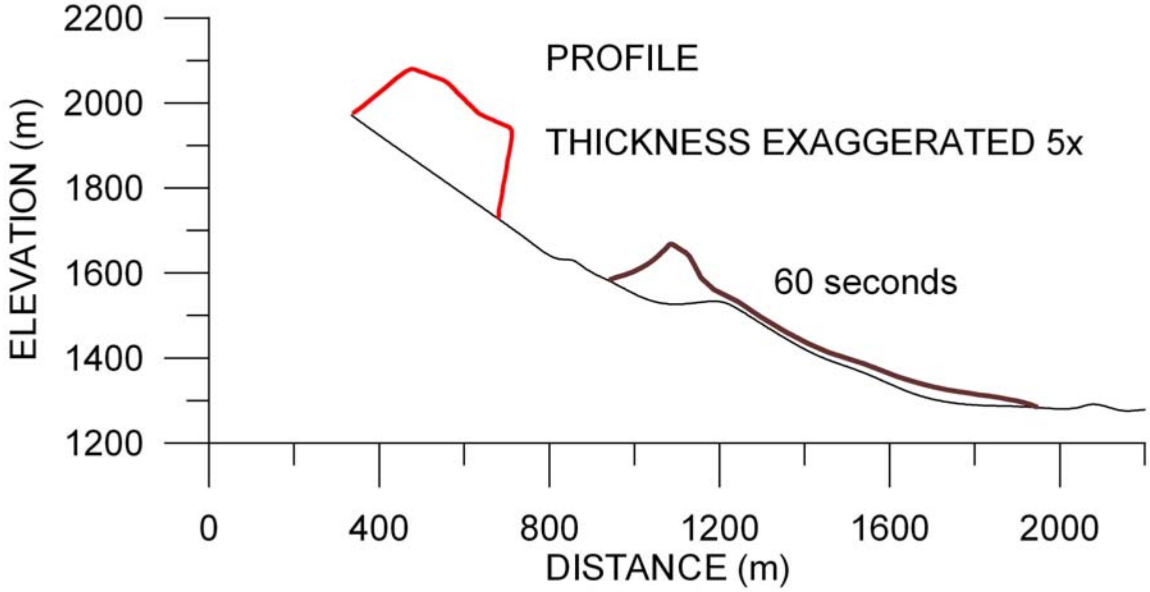
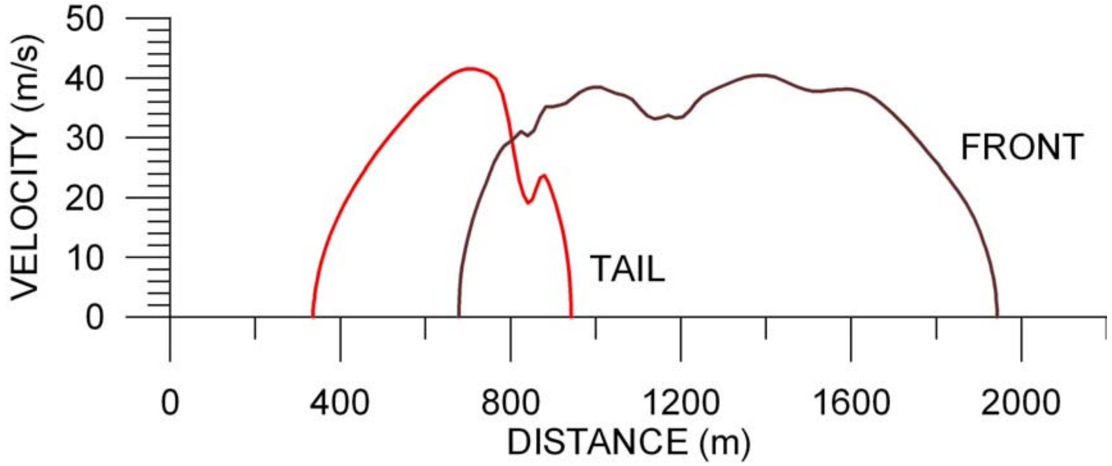
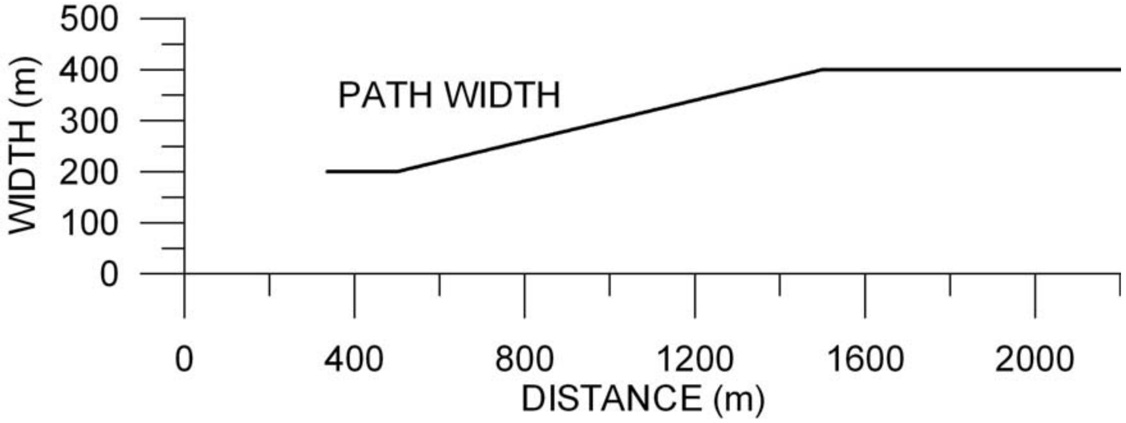
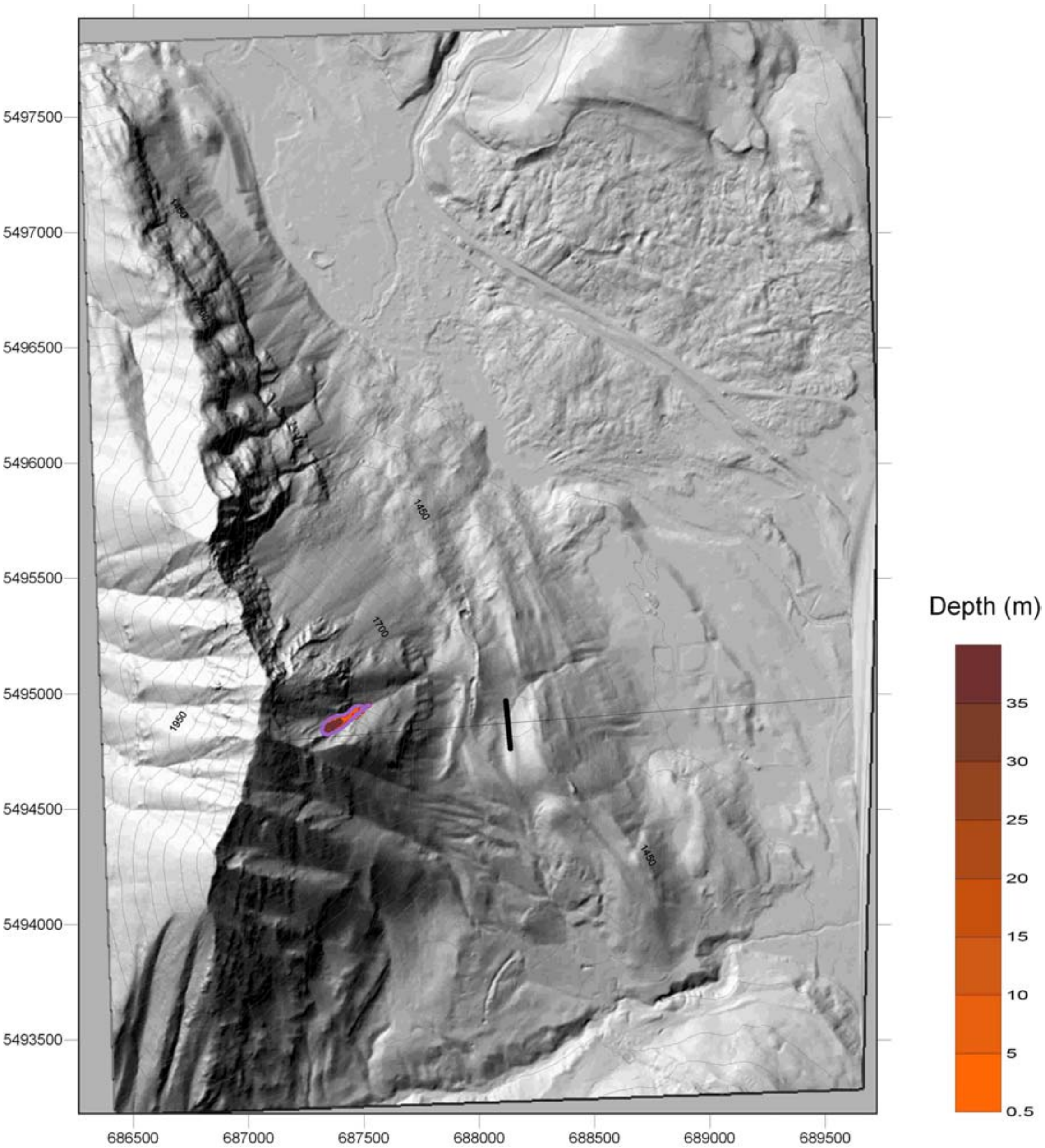






3dP-2, Third Peak, GPS Station



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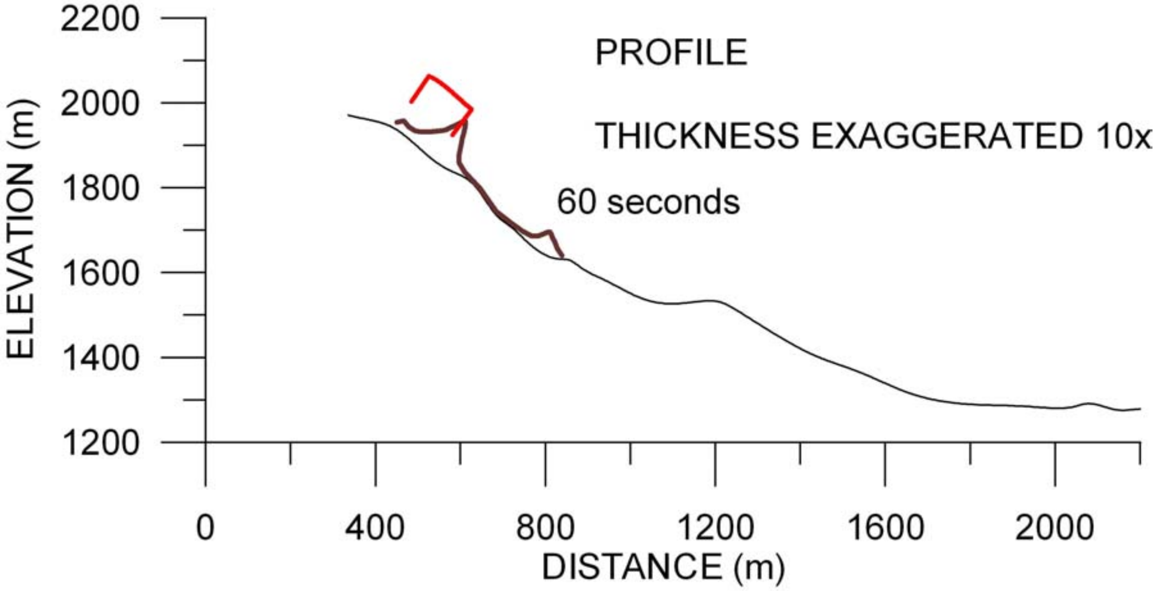
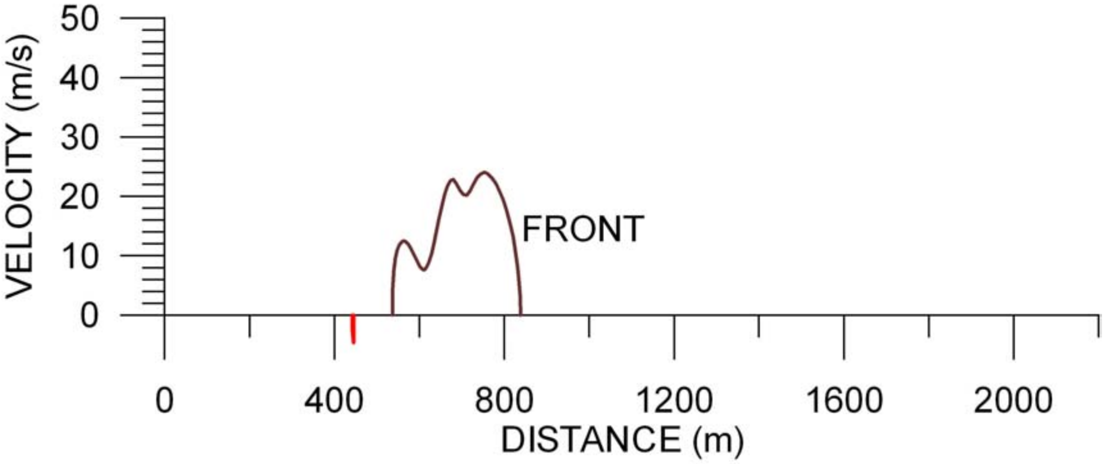
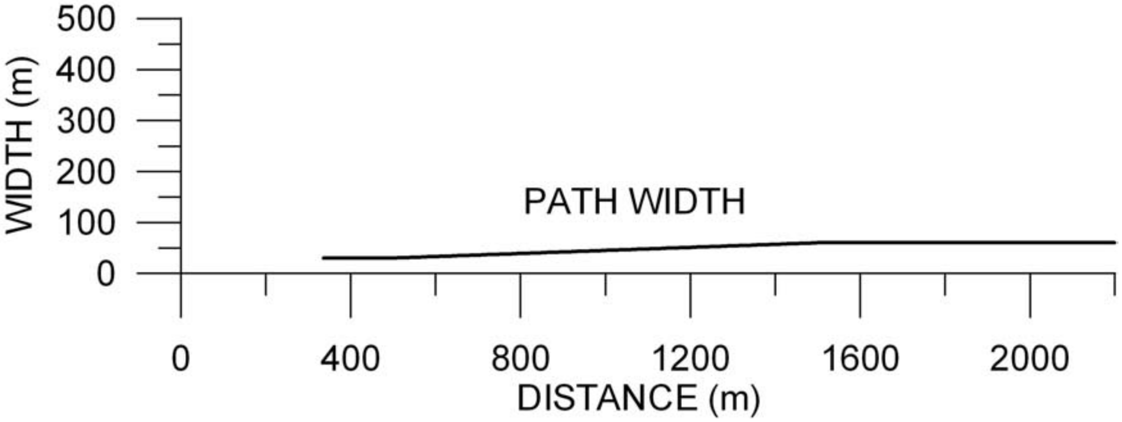
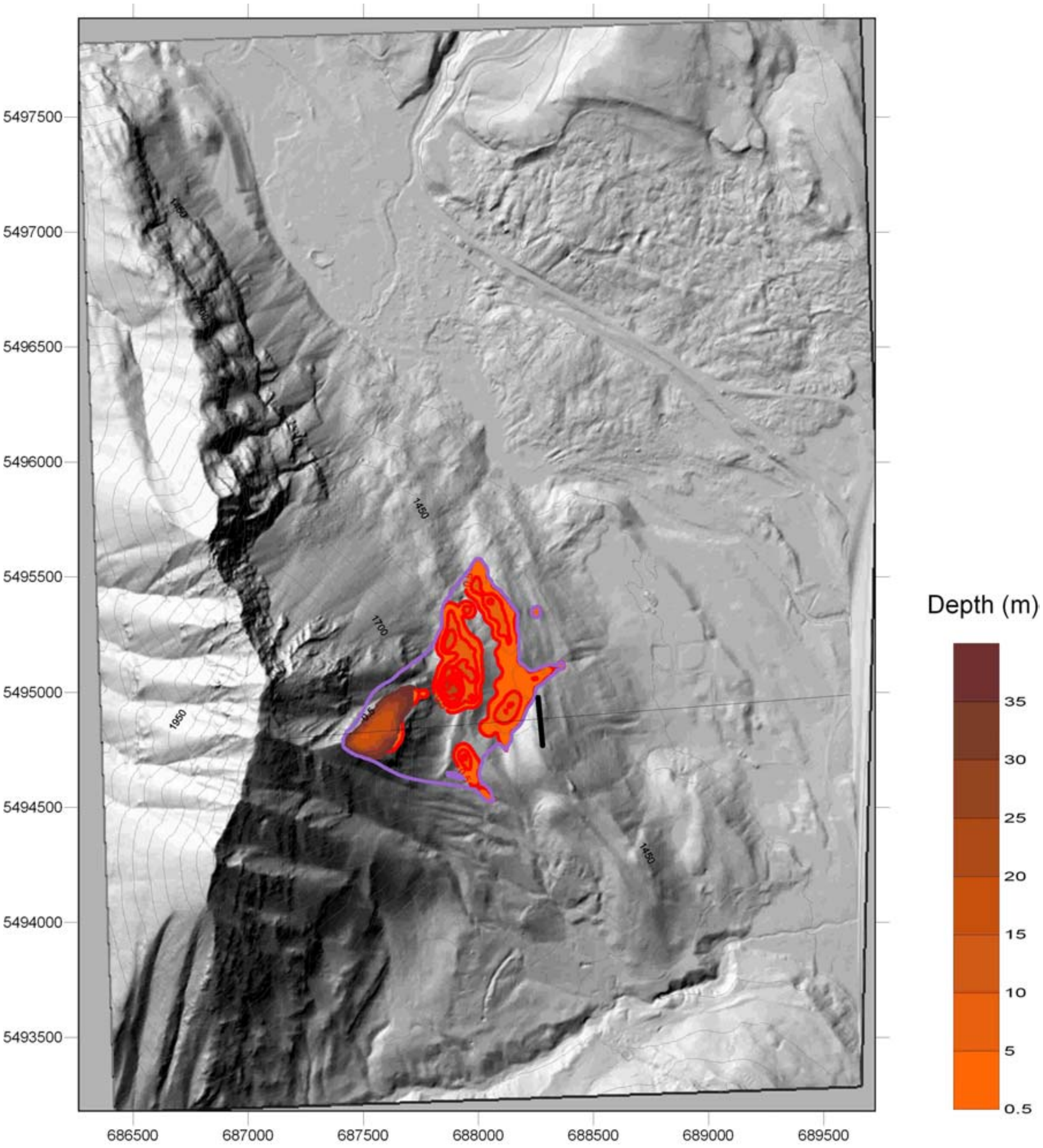






3dP-3, Third Peak, Sackung



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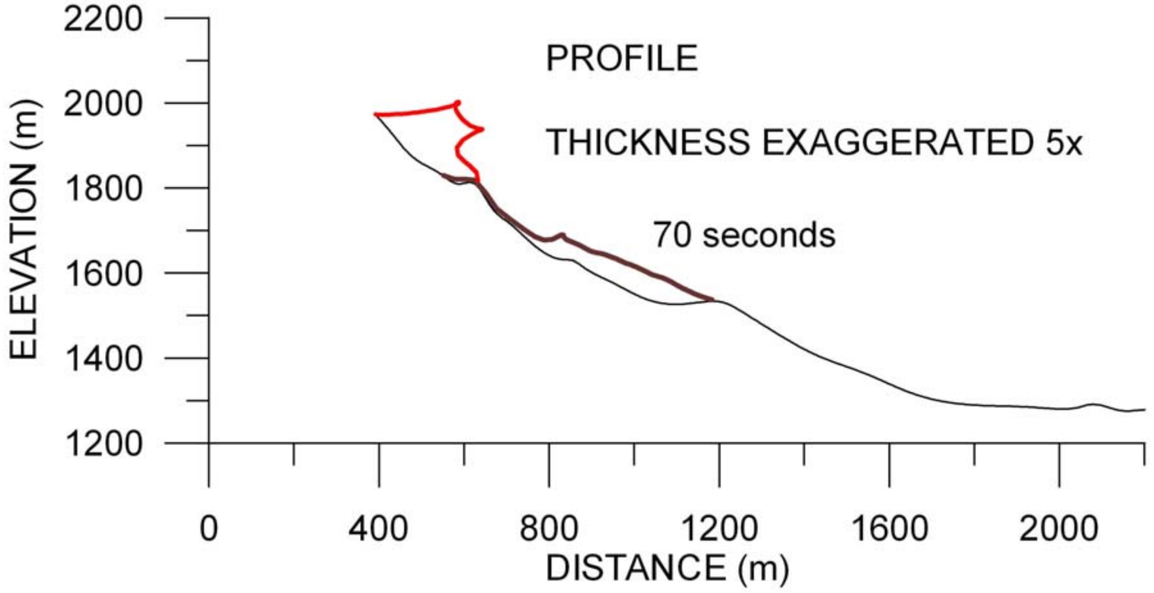

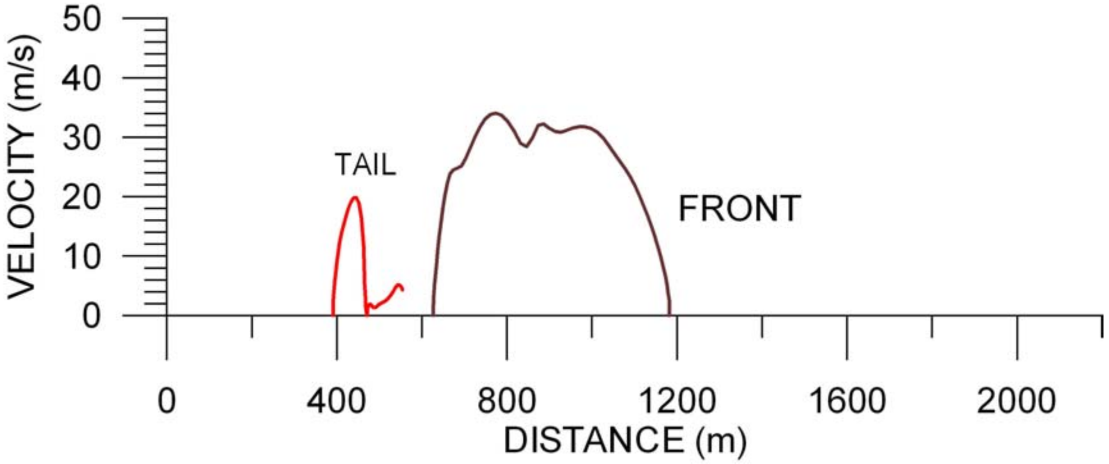

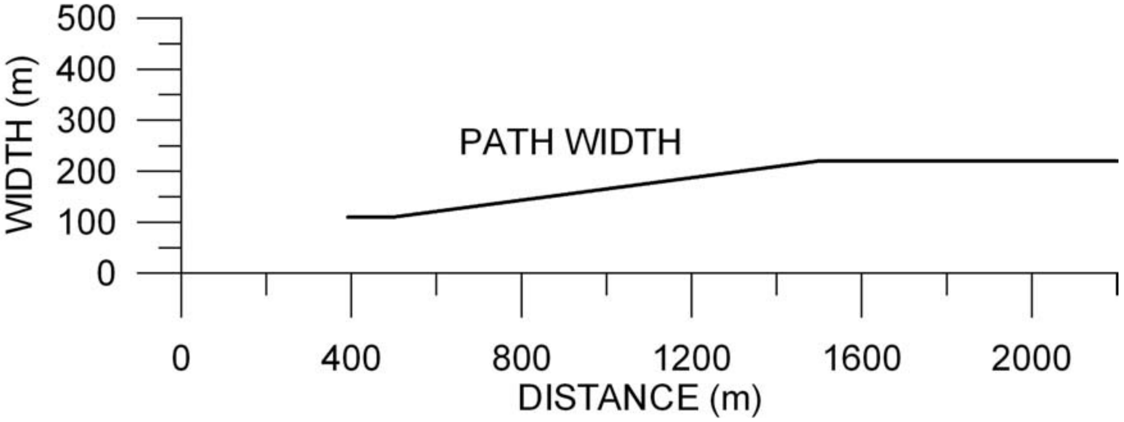

APPENDIX 2

Description of the models DAN-W and DAN3D

Hungr, O. _lb McDougall, S., 0. . 9, Two numerical models for landslide dynamic analysis. Computers and Geosciences, v. 35, no. 5, p. 978-992, doi: 10.1016/j.cageo.2007.12.003.