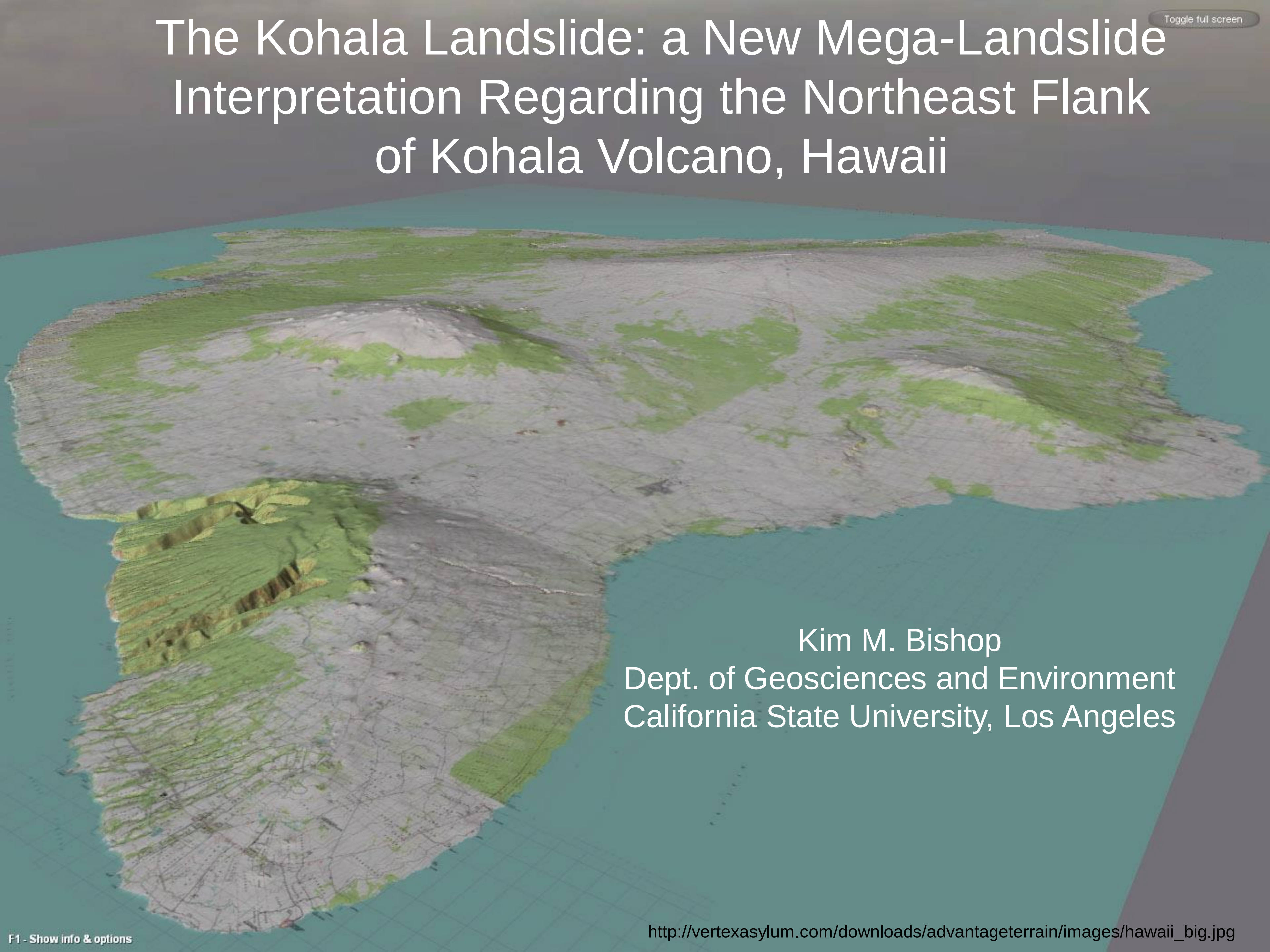
The Kohala Landslide: a New Mega-Landslide Interpretation Regarding the Northeast Flank of Kohala Volcano, Hawaii



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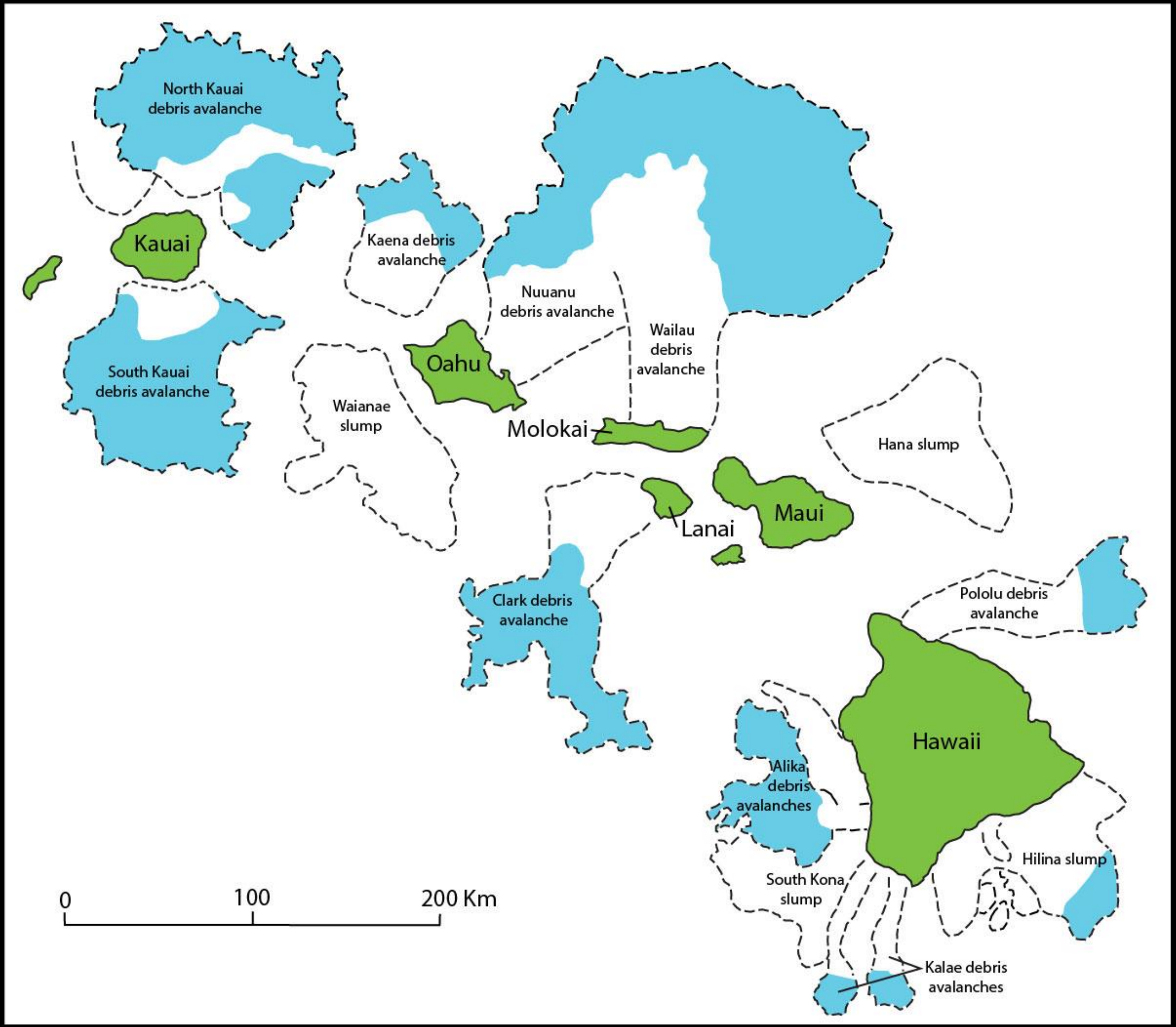
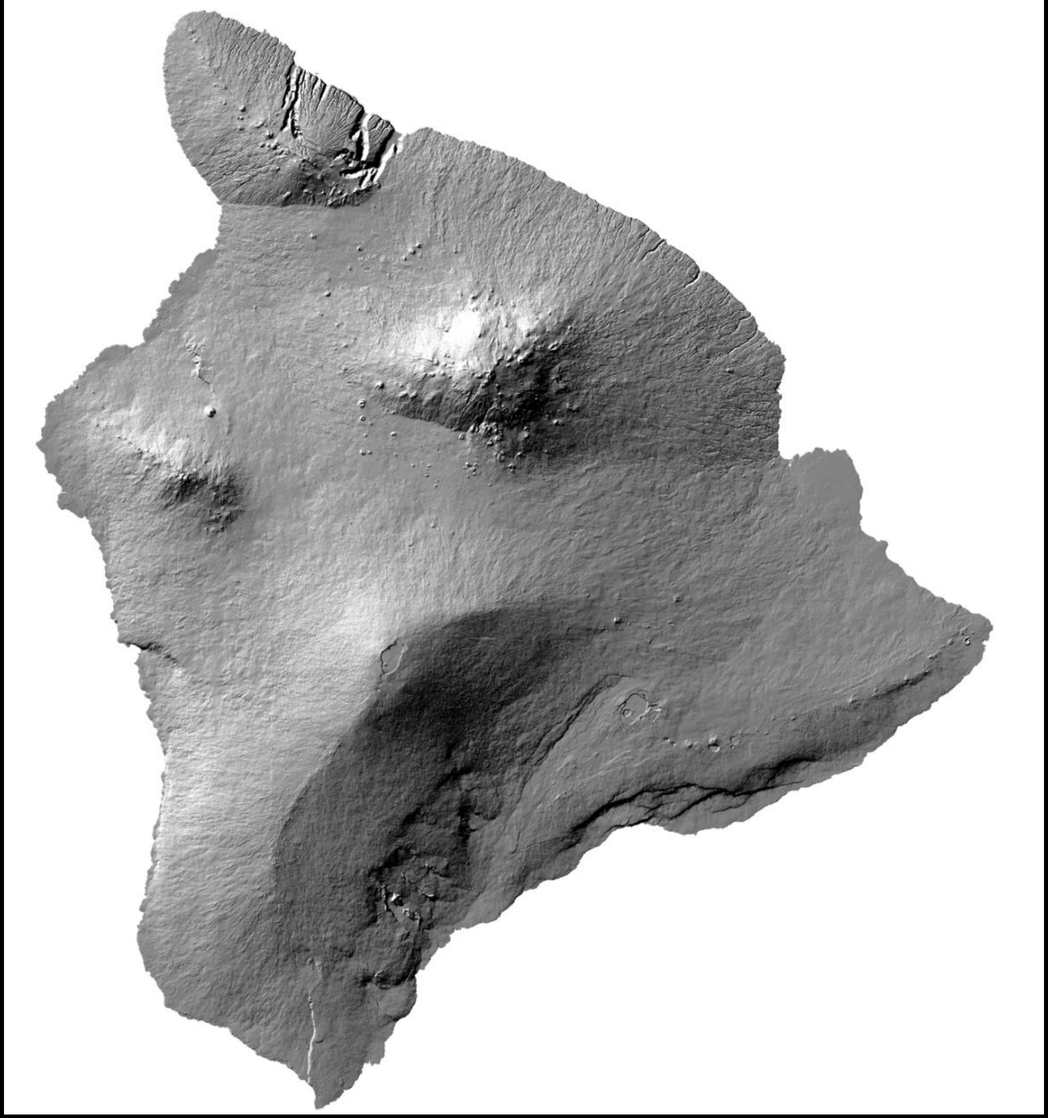


Mega-landslide map of the Hawaiian Islands as interpreted by Moore et al. (1989). Notice that many landslides are classified as debris avalanches that have long run-outs and were emplaced catastrophically, Others are classified as slumps that move slowly over hundreds to thousands of years and do not have long run-out.

Modified from Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., and Torresan, M.E., 1989, Prodiguous submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v. 94, no. B12, p. 17465-17484.



The topic of this presentation is the northeast flank of Kohala volcano, the northernmost volcano on the Big Island of Hawaii. This slope contains anomalous features for the island including deeply incised valleys and a 20 km long, 2 km wide re-entrant. The coast at the re-entrant has cliffs up to 450 m high, another anomalous feature.

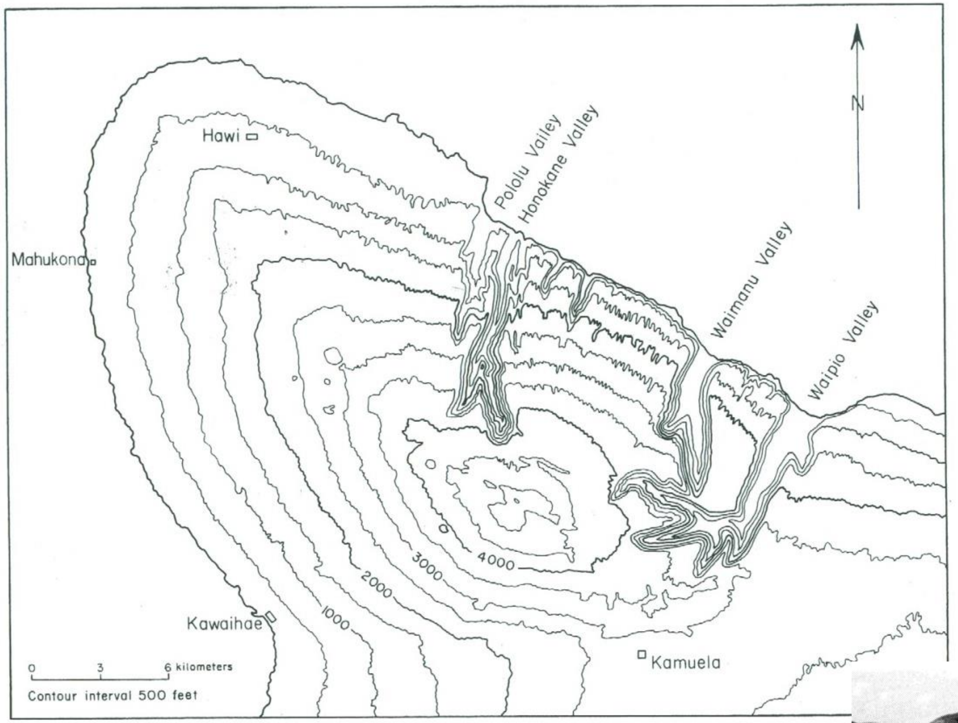
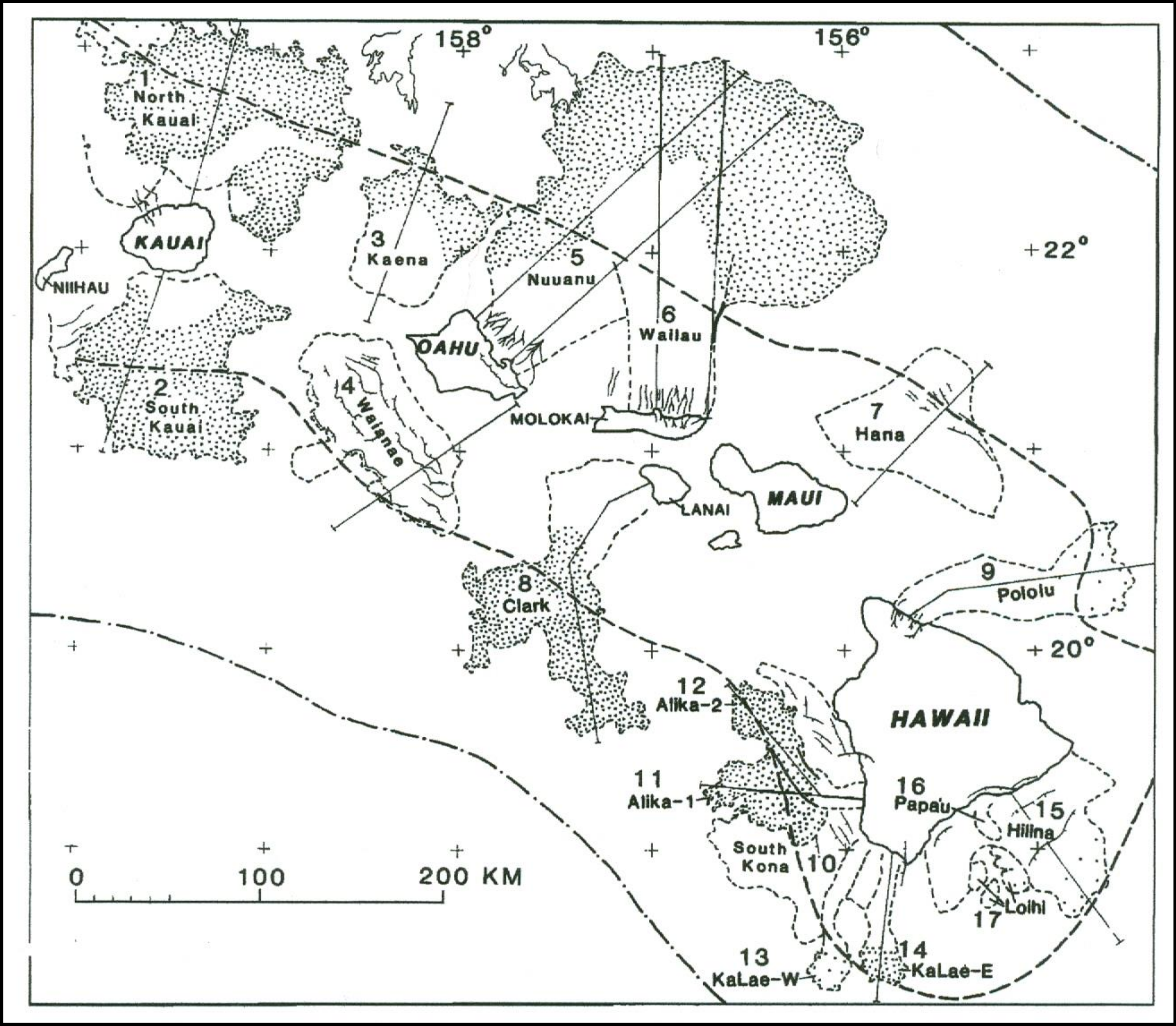


Figure 19.8. Map of Kohala Mountain, showing the huge valleys cut into the windward (northeastern) slope, and the s
dissection of the leeward slope.

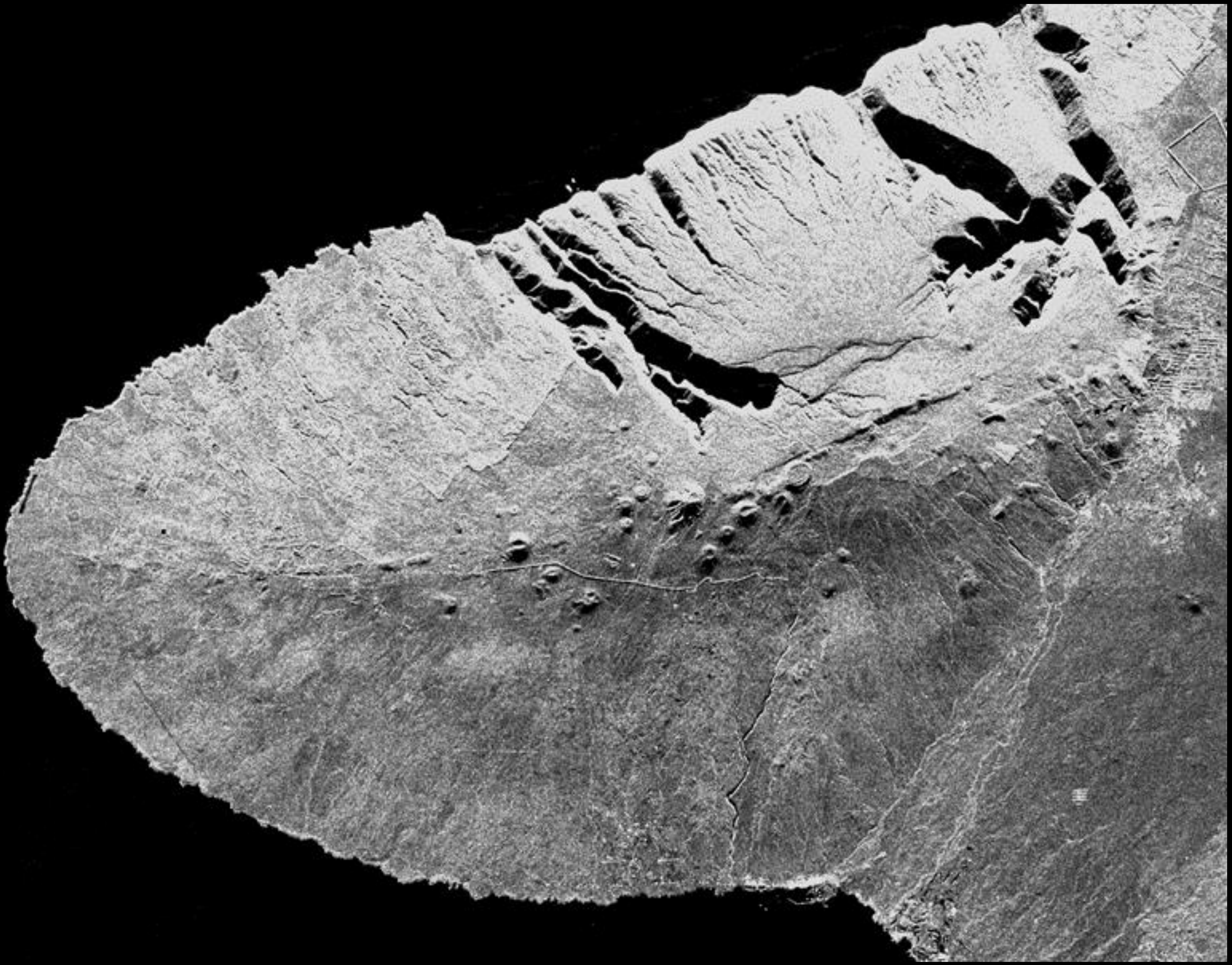
The photo below shows the high cliffs along the re-entrant.

From: Macdonald, G.A., Abbott, A.T., and Peterson, F.L., 1983, Volcanoes in the Sea, The Geology of Hawaii, 2nd ed., University of Hawaii Press, Honolulu, HI, 517 p.



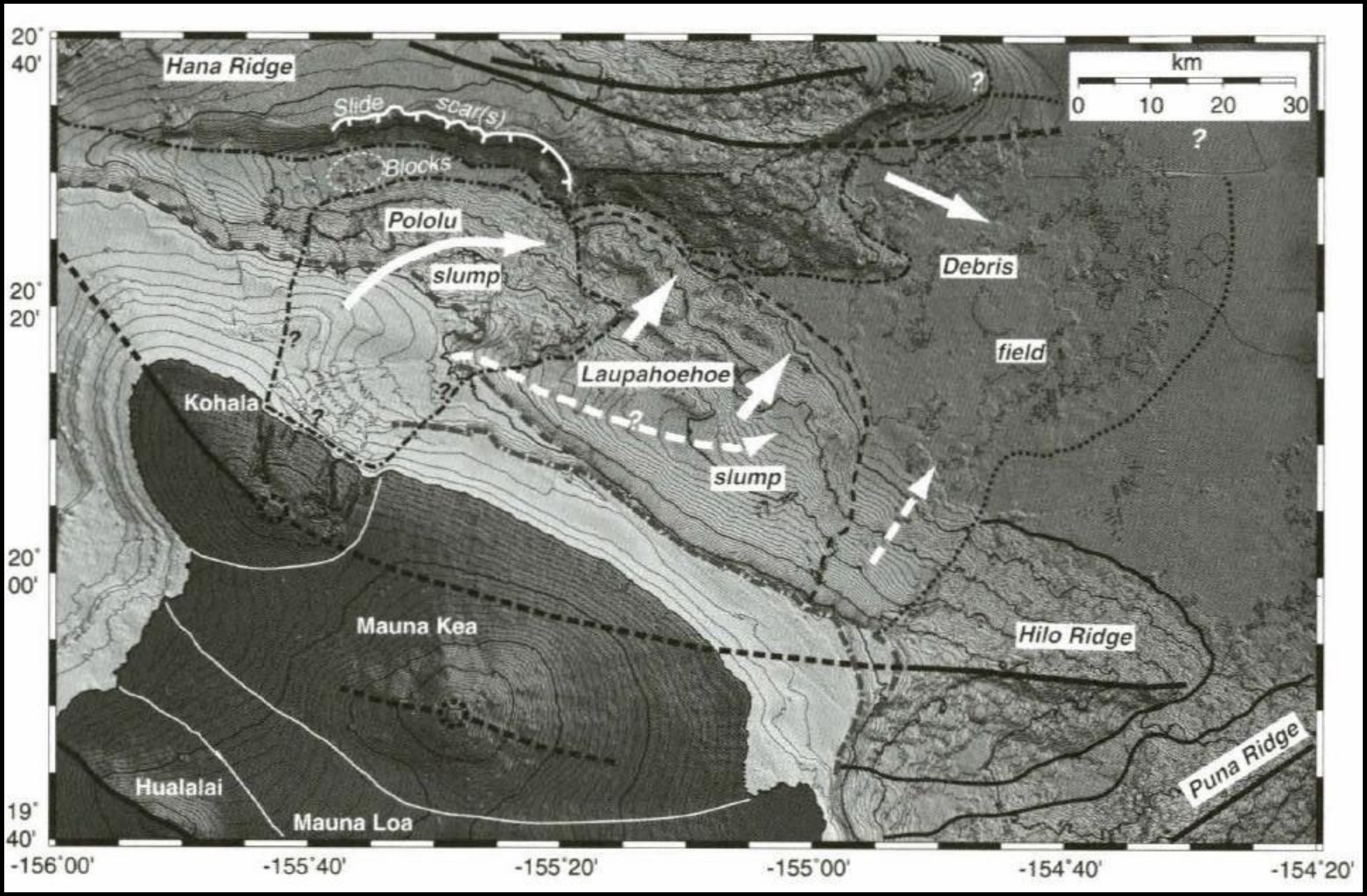
Landslide interpretation of Moore et al., 1989. Notice the Pololu landslide. The interpretation of the authors is that the head of the landslide is near the summit of Kohala volcano and that Pololu and Waipio valleys form the lateral boundaries on the north and south sides of the subaerial part of the landslide. The landslide was classified as a debris avalanche.

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., and Torresan, M.E., 1989, Prodiguous submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v. 94, no. B12, p. 17465-17484.



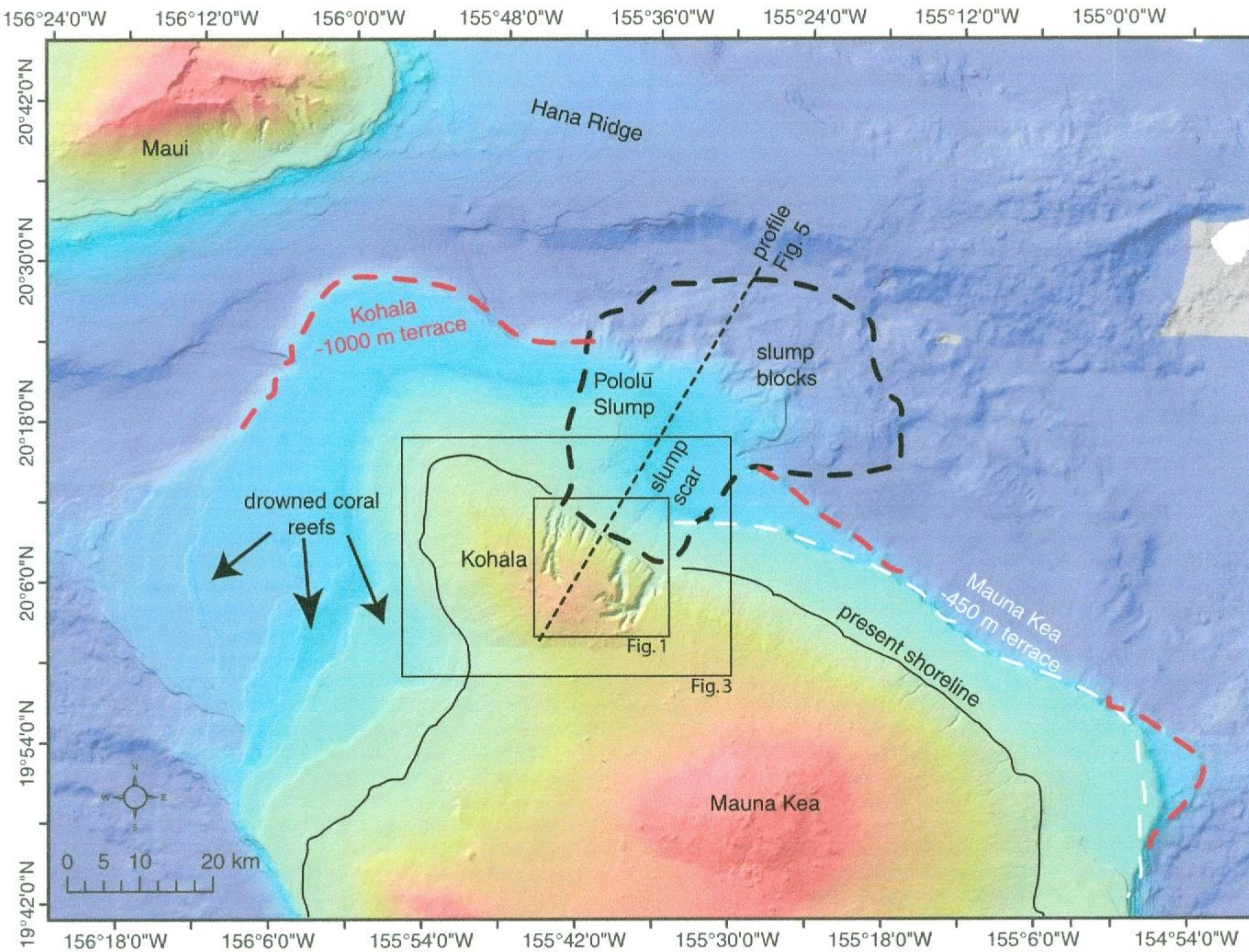
Moore et al. (1989) propose that the faults near the summit of the volcano are the result of extension at the head of the landslide.

From USGS: Spaceborne Imaging Radar-C



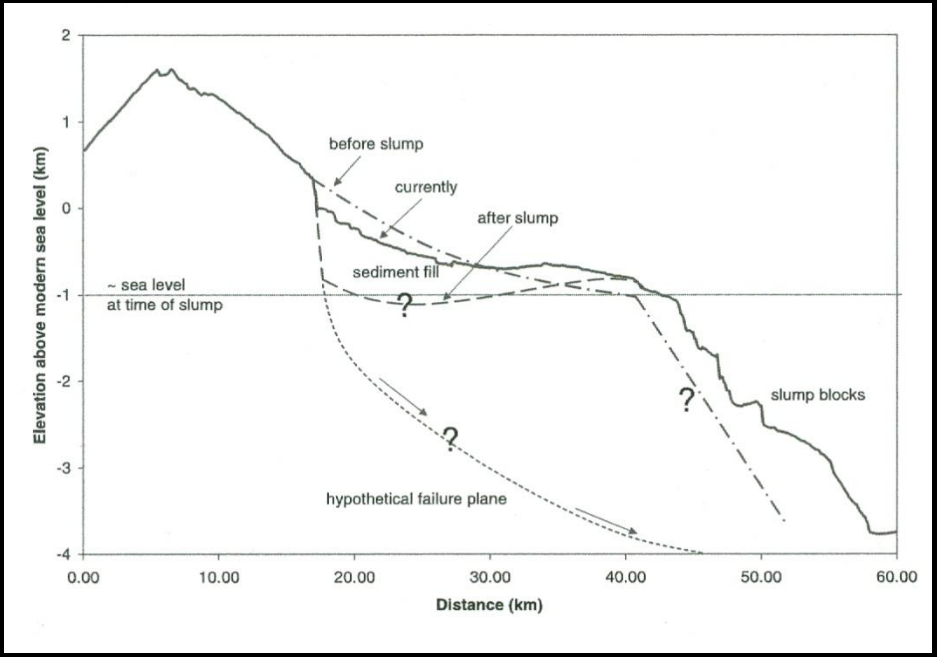
A reinterpretation of the Pololu landslide by Smith et al. (2002) that shows the landslide as a much smaller feature than the earlier interpretation. The authors also reclassified the landslide as a slump. Notice that the authors suggest the head of the landslide is at the coastal cliffs. They reject the notion that the landslide extends below the subaerial part of Kohala volcano.

Smith, J.R., Satake, Kenji, Moran, J.E., and Lipman, P.W., 2002, Submarine landslides and volcanic features on Kohala and Mauna Kea volcanoes and the Hana Ridge, Hawaii, in Takahashi, Eiichi, Lipman, P.W., Garcia, M.O., Naka, Jiro, and Aramaki, Shigeo, eds., Hawaiian volcanoes deep underwater perspectives: Washington D.C., American Geophysical Union, Geophysical Monograph 128, p. 11-28.



Landslide interpretation by Lamb et al. (2007). Notice that the authors accept most of the interpretation of Smith et al. (2002). A main difference is that Lamb et al. definitively place the head of the landslide at the coastal cliffs. They, too, reject the notion that the landslide involves the subaerial part of Kohala volcano. The cross-section for the dashed line is presented in the next figure.

Lamb, J.R., Howard, A.D., Dietrich, W.F., and Perron, J.T., 2007, Formation of amphitheatre-headed valleys by waterfall erosion after large-scale slumping on Hawaii: Geological Society of America Bulletin, v. 119, nol7/8, p. 805-822.



Lamb, et al., 2007

Note the interpretation for the head of the landslide at the coastal cliffs. Also note the interpretation that the subaerial part of the volcano above the cliffs is not involved in the landslide.

Macdonald, et. al., 1983

View North across Waipio Valley showing coastal cliffs interpreted as the headwall of a large landslide.

Notice the seaward displacement of contours between Waipio and Pololu Valleys. The best example is the 2000 foot contour.

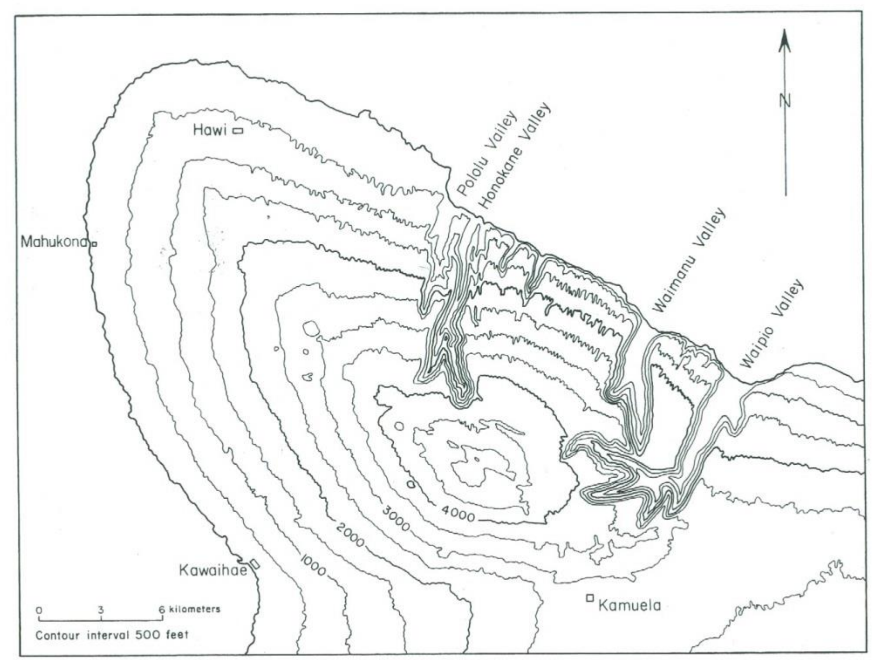


Figure 19.8. Map of Kohala Mountain, showing the huge valleys cut into the windward (northeastern) slope, and the small degree of dissection of the leeward slope.

Macdonald, et. al., 1983

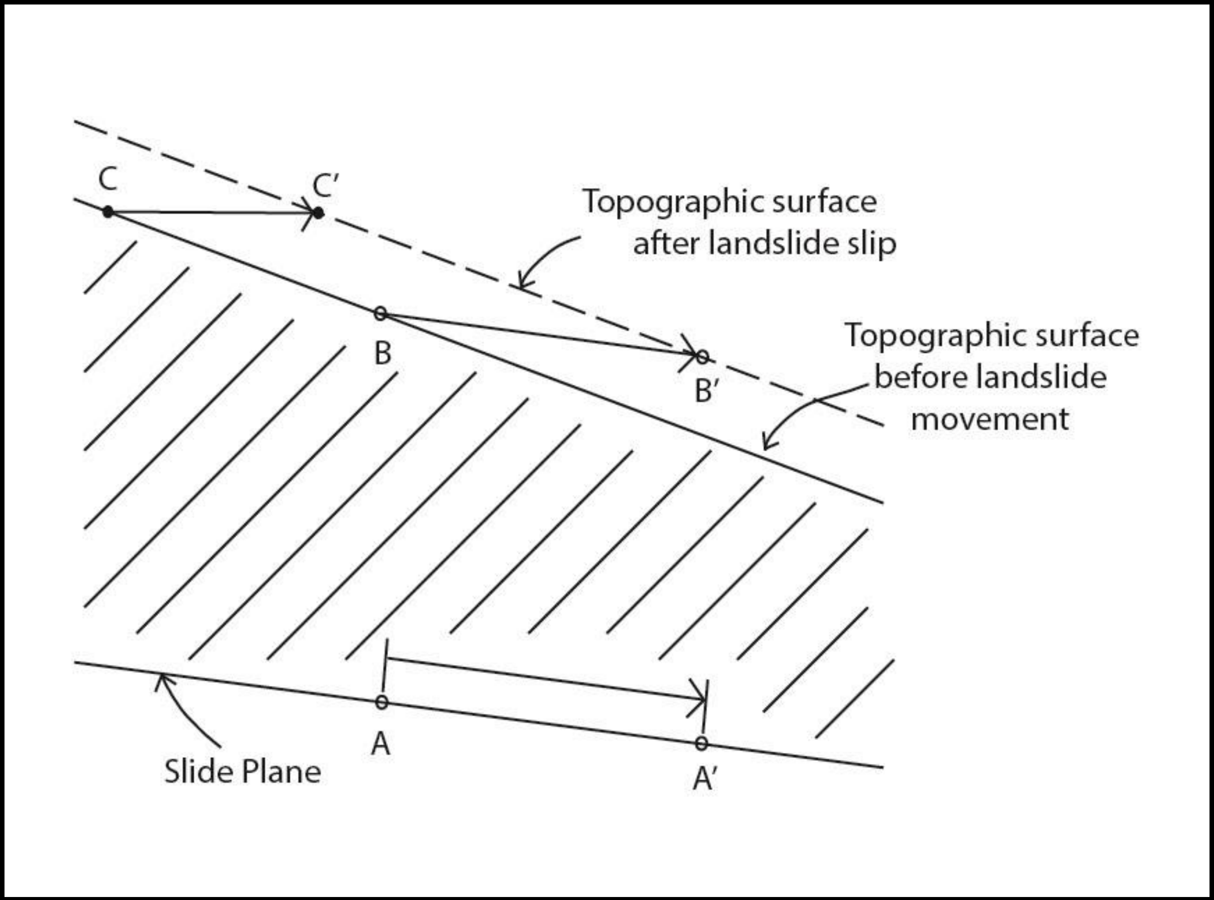
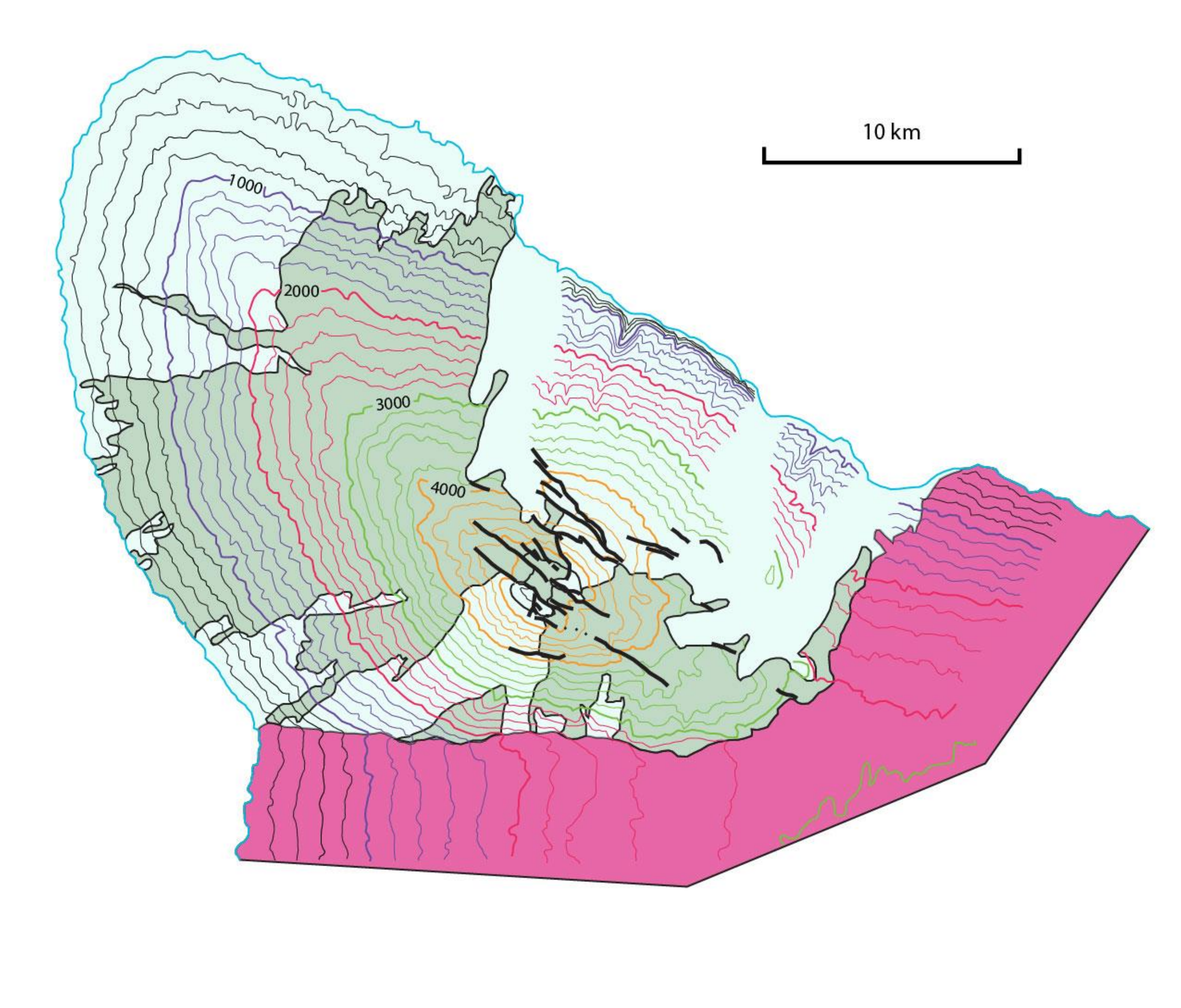


Diagram providing an explanation for the seaward displacement of contour lines see in previous figure. The contours have moved outward because the slope is underlain by landslide surface along which there has been displacement and the slip surface is less steep than the topographic slope.

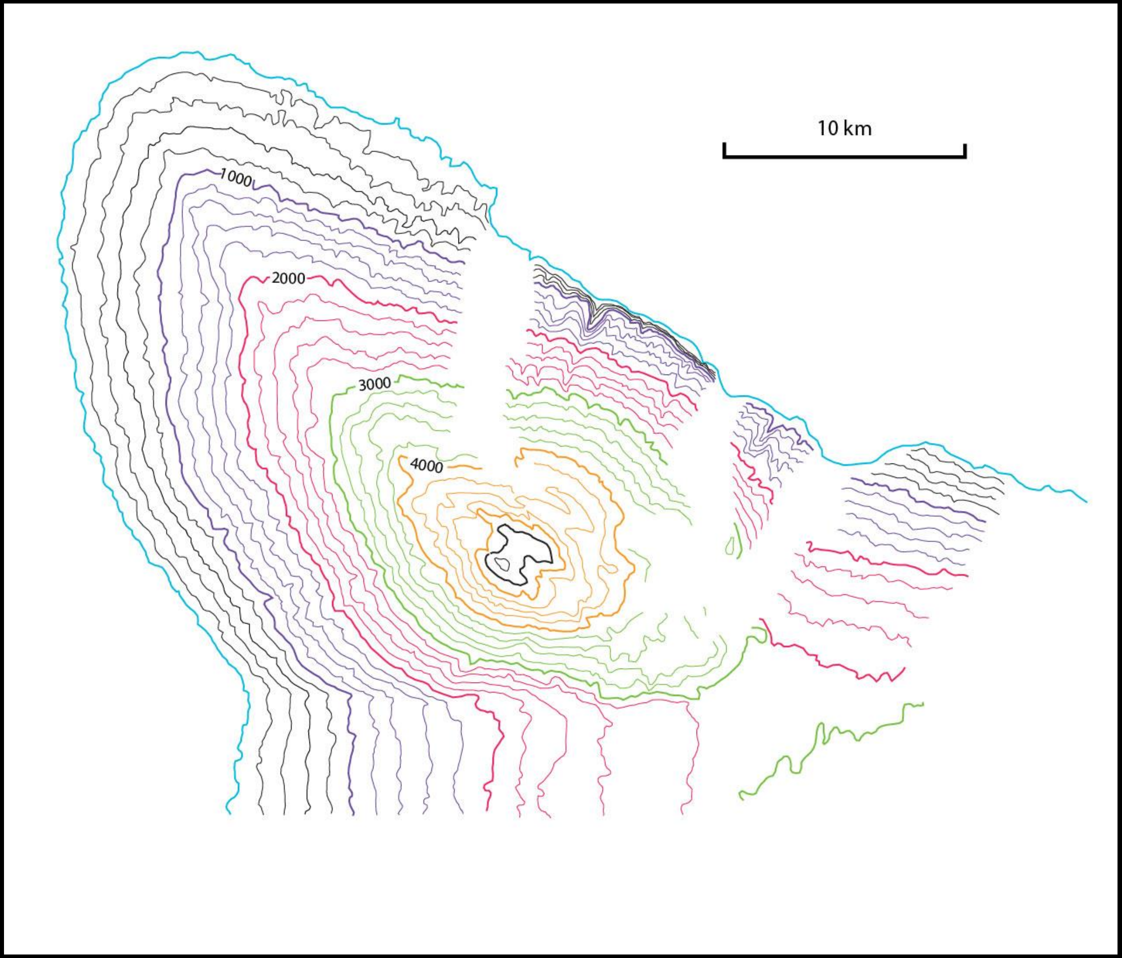
Geologic map of Kohala volcano

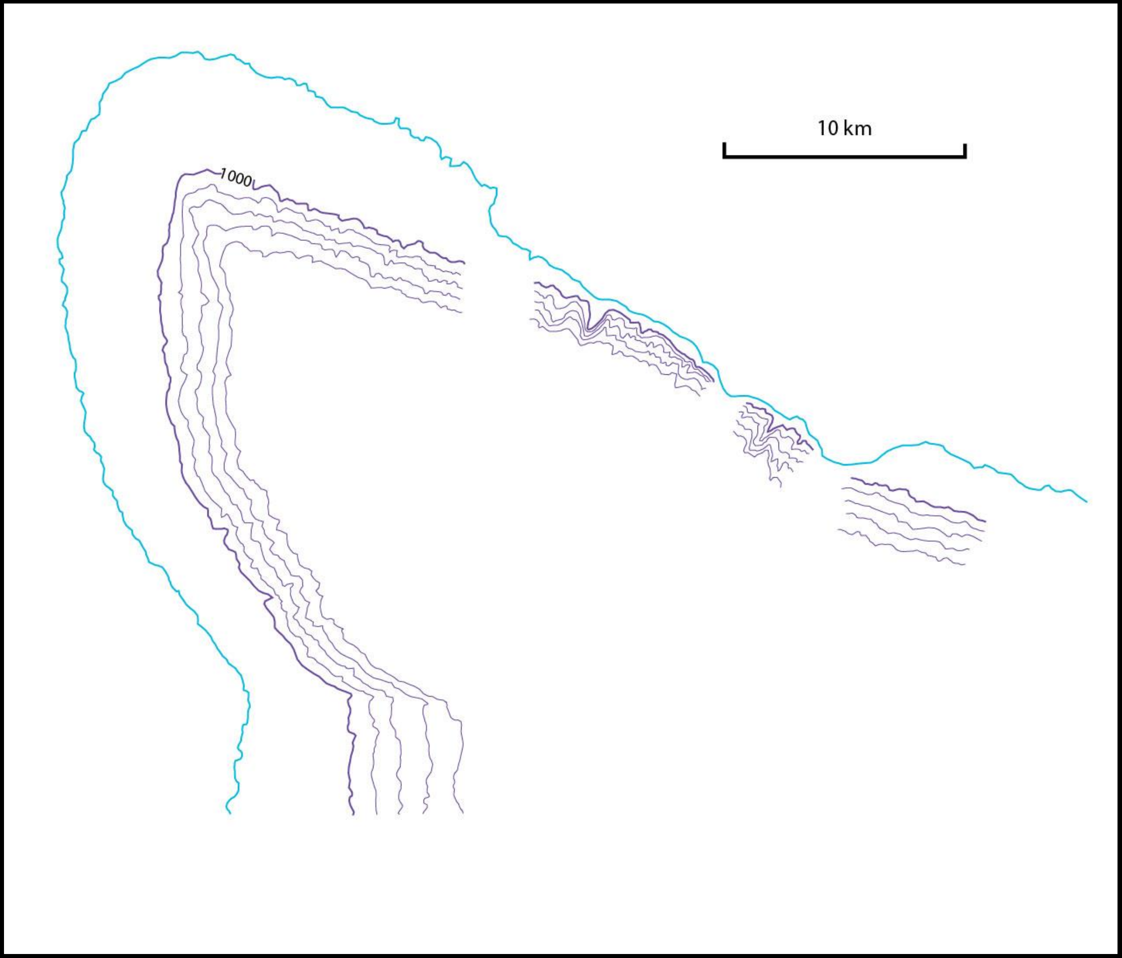
Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M., 2007, Geologic Map of the State of Hawai'i: U.S., Geological Survey Open-File Report 2007-1089.



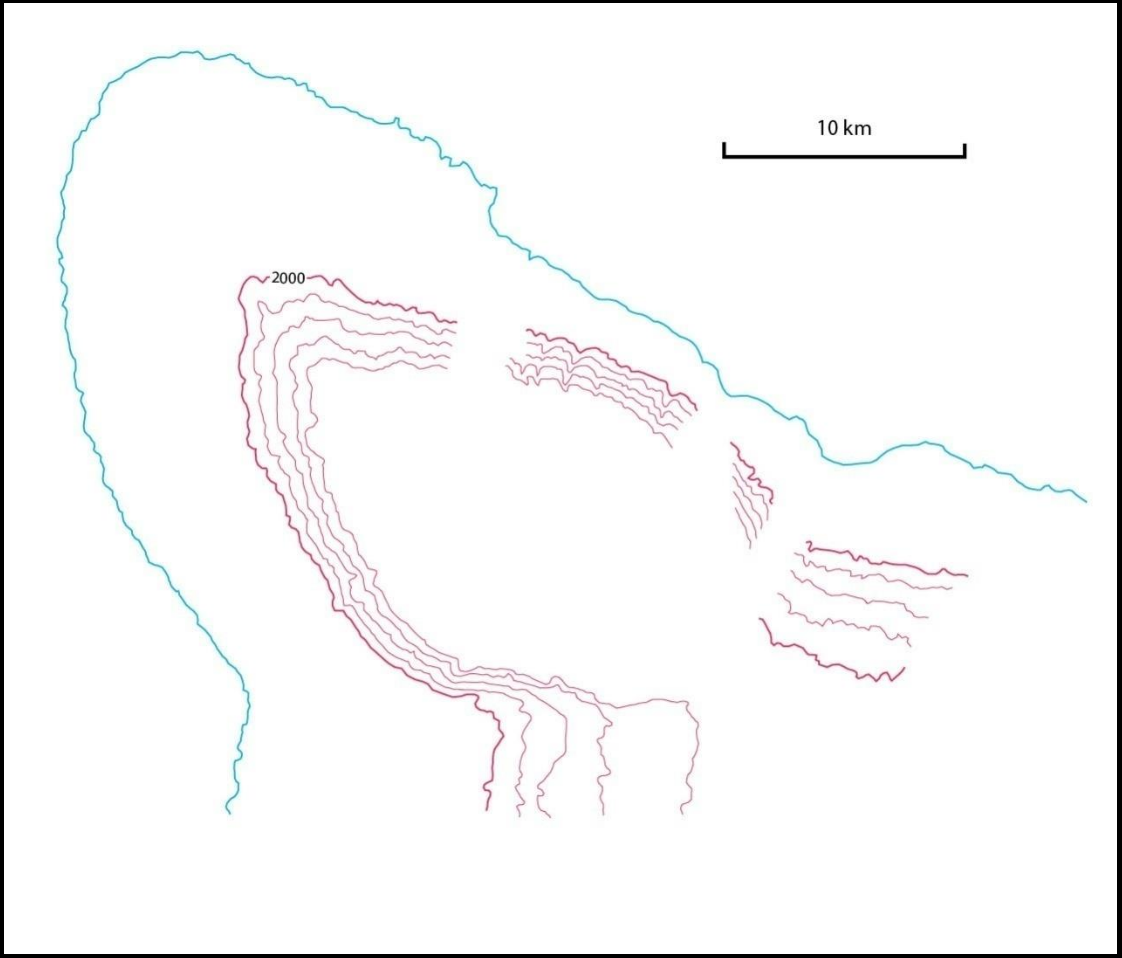
Redrawn map of previous figure. Contours within the large valleys have been omitted for clarity.

Is the slope underlain by a landslide?

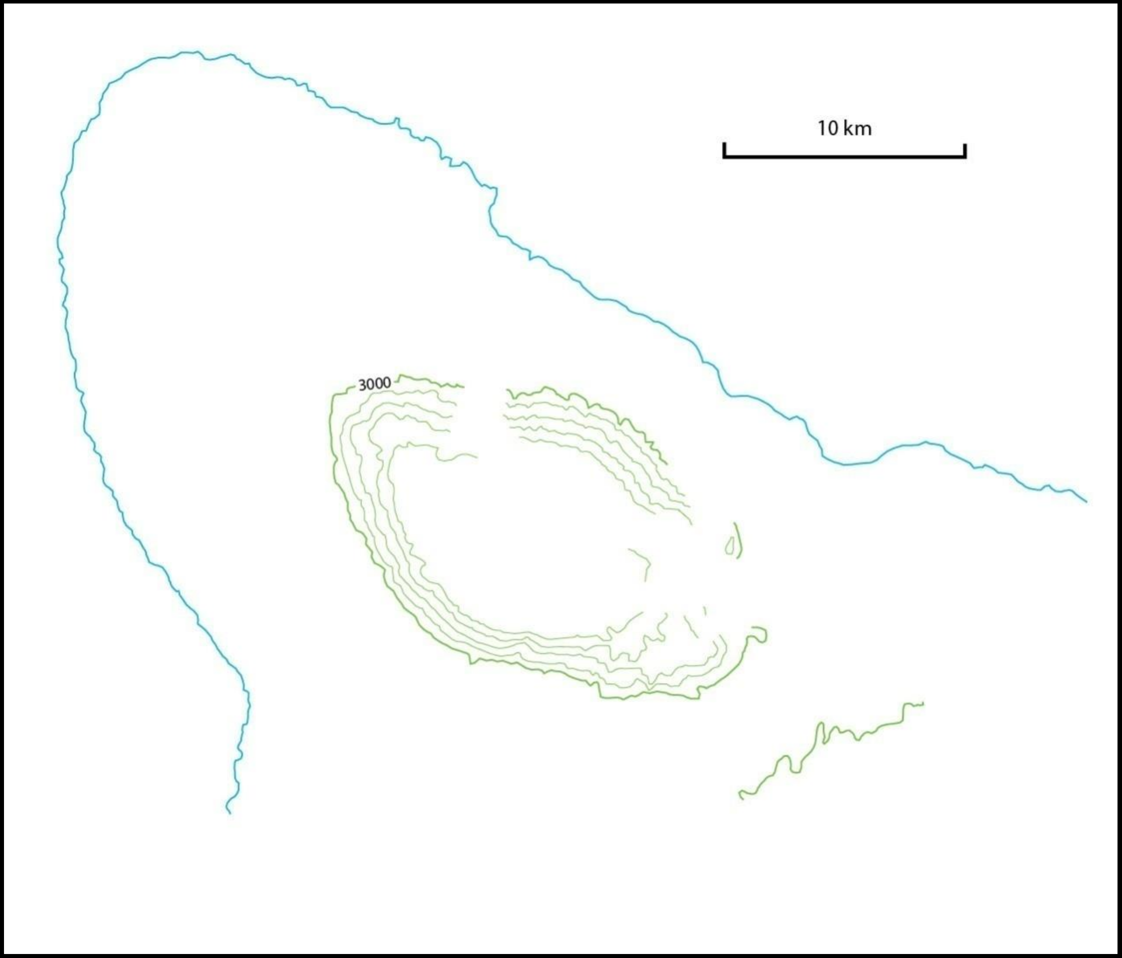




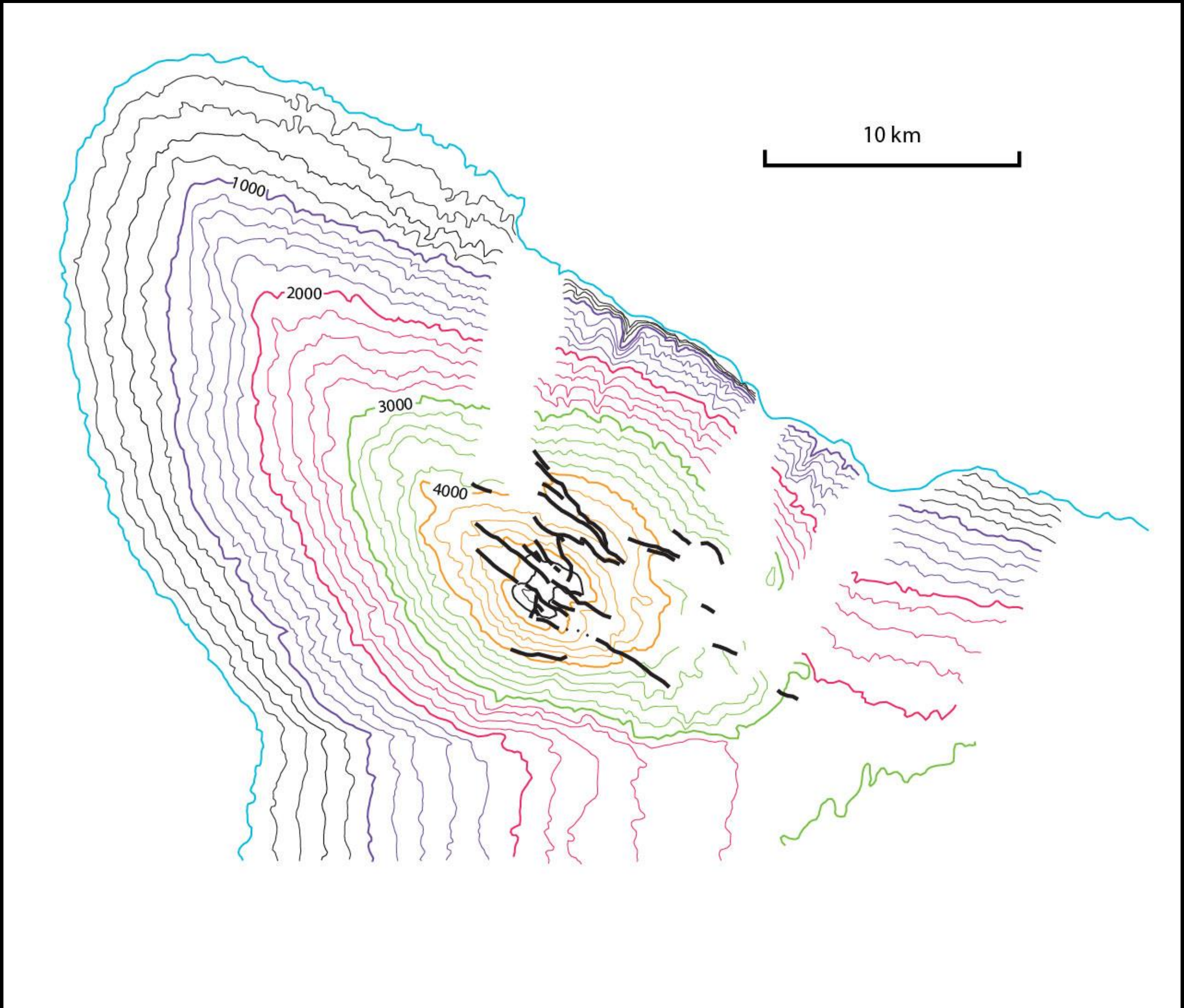
Notice the seaward offset of the 1000 – 1800 foot contours.



Notice the seaward offset of the 2000 – 2800 foot contours.

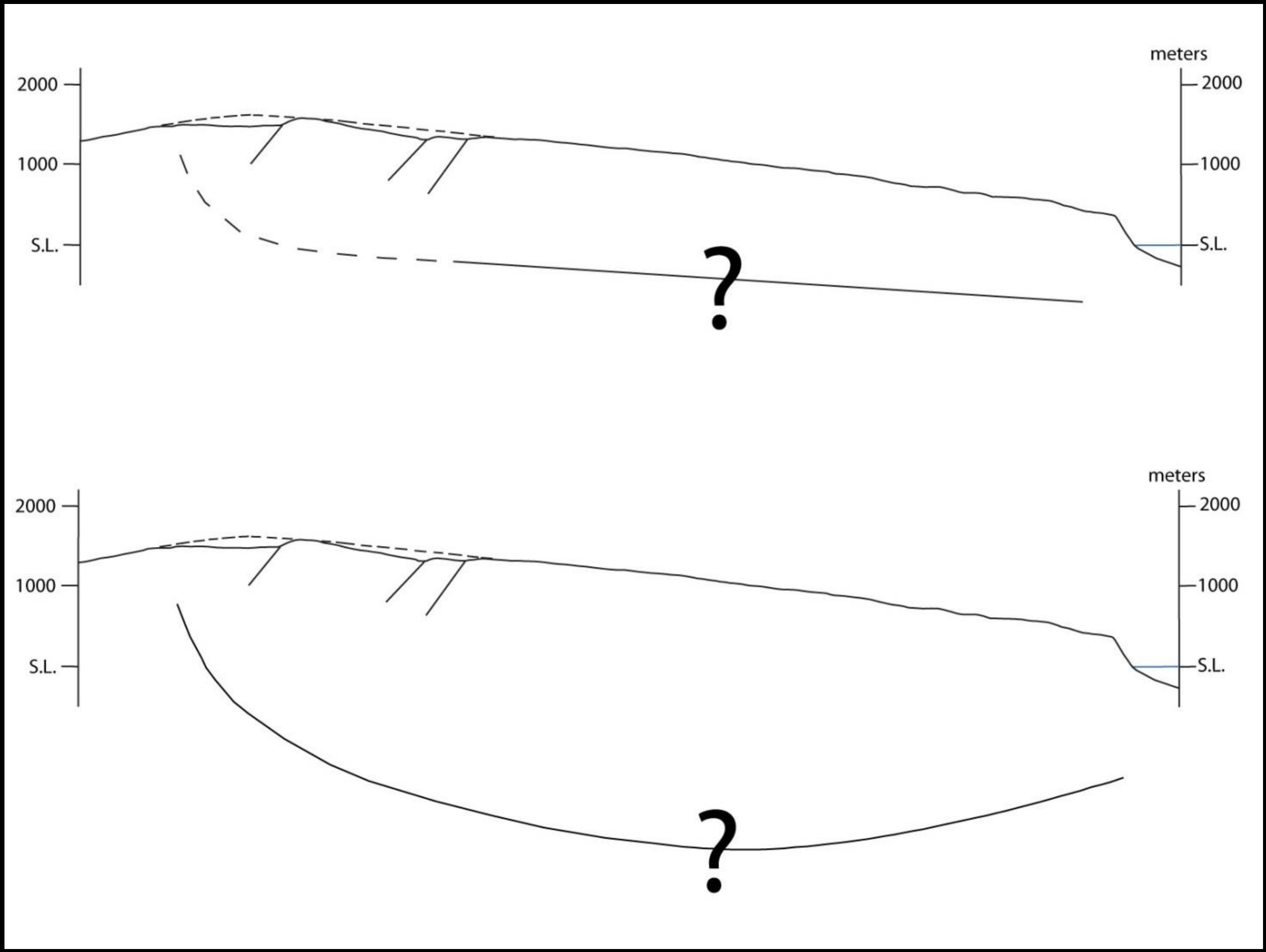


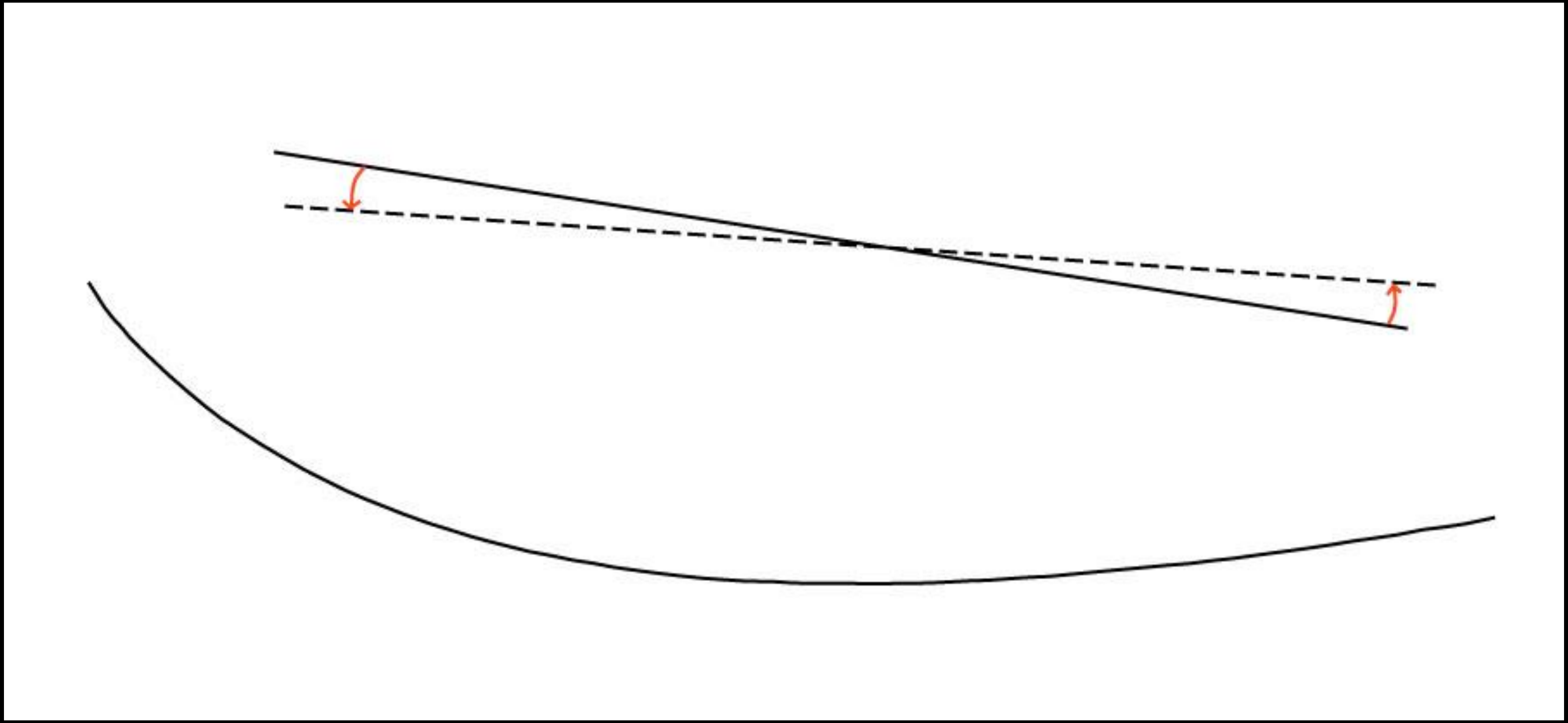
Notice the seaward offset of the 3000 – 3800 foot contours.



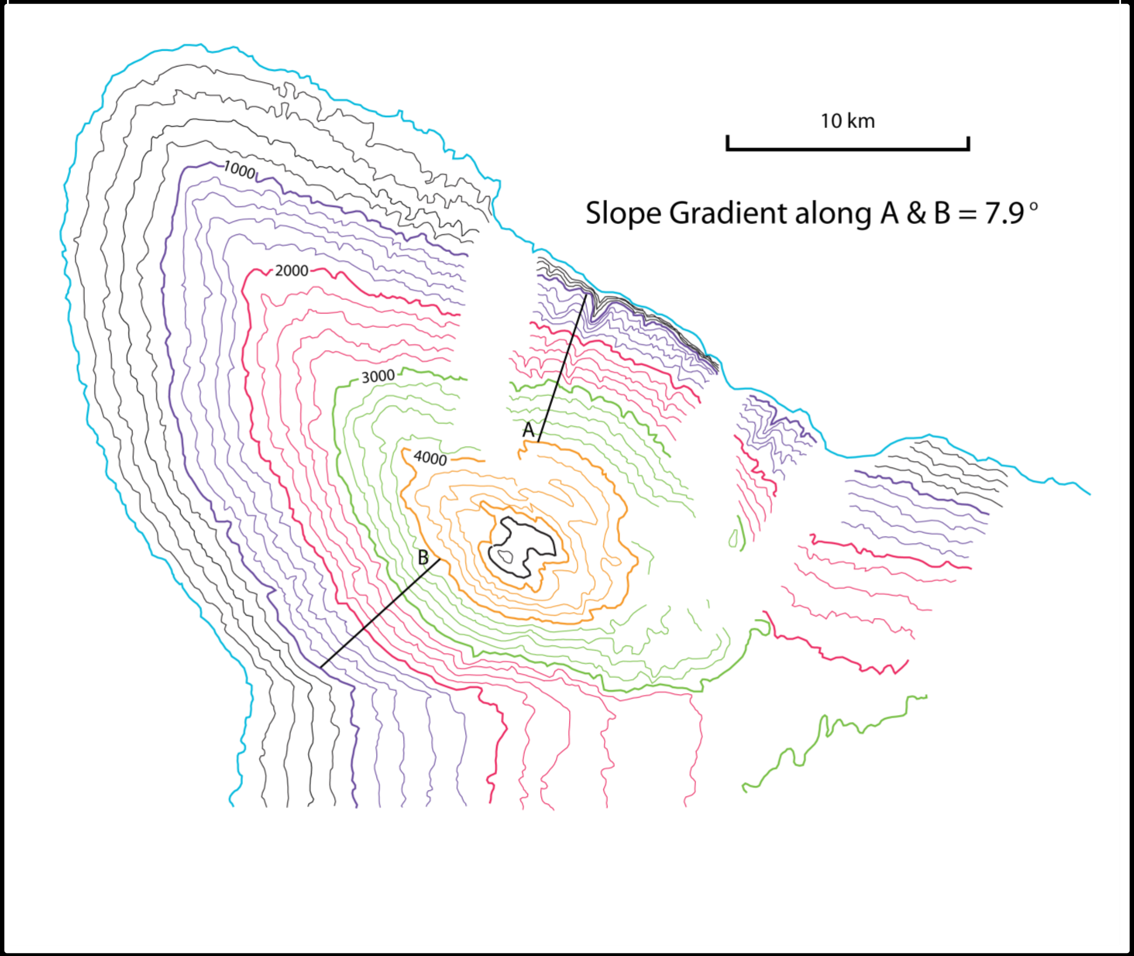
Seaward offset of the contours between Pololu and Waipio Valleys supports the contention of Moore et al. (1989) that the subaerial slope of Kohala volcano is underlain by a landslide and that the faults resulted from extension at the head of the landslide.

Is the slide surface below the subaerial slope planar or curved?

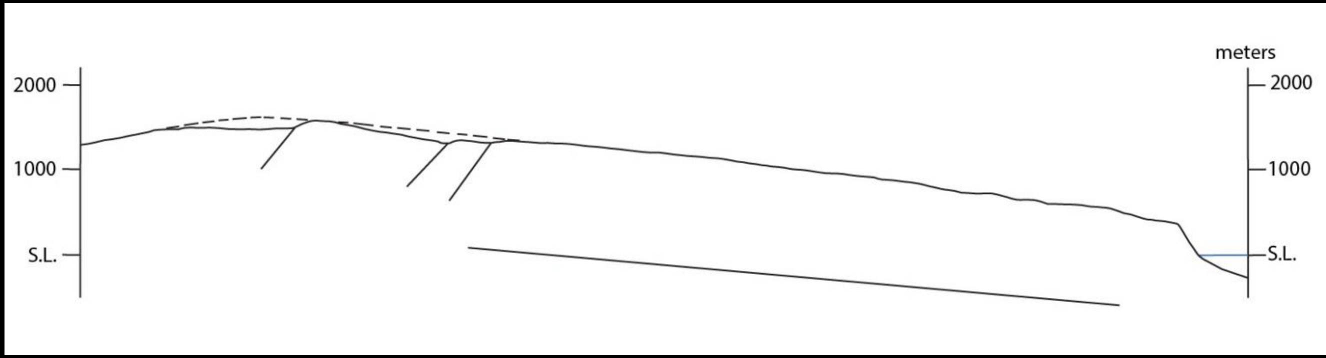




If the surface is curved the slope should be rotated to a lesser gradient by slide displacement.



The slope gradient on the opposite side of the volcano is the same as on the landslide side leading to the conclusion that the slide surface is planar (below the middle and lower part of the slope downslope from the head).



Conclusions, so far, from slope contour analysis

1. Contour offsets indicate the slope contains a landslide
2. Outward step of landslide contours indicates the slide surface is less steep than the topographic slope.
3. The slope gradient indicates a planar slide surface and, thus, the landslide is translational.

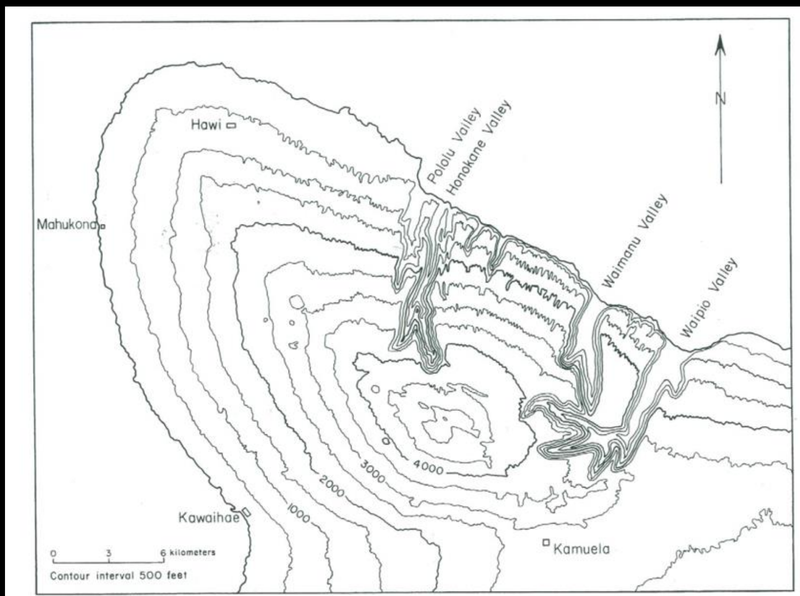
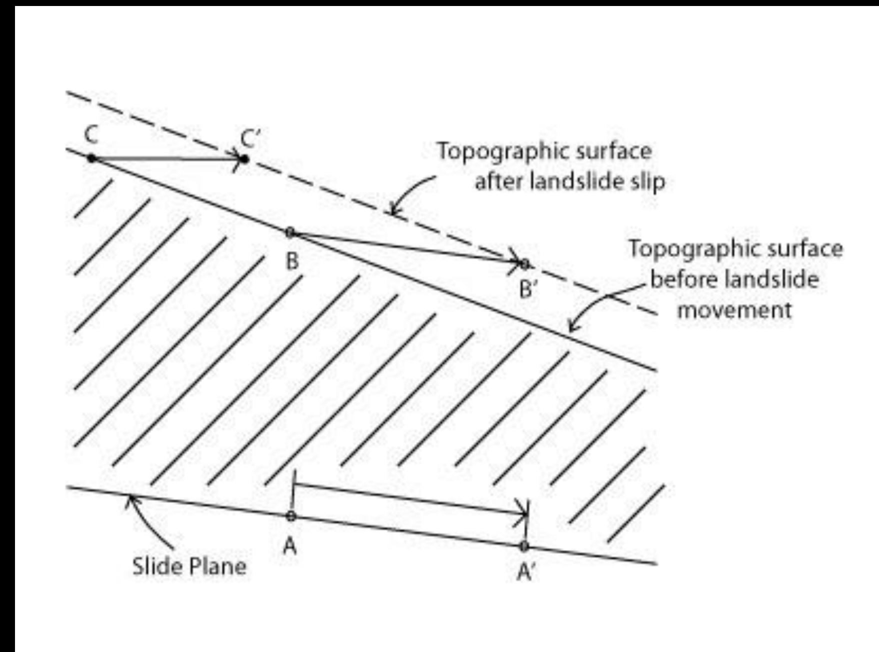
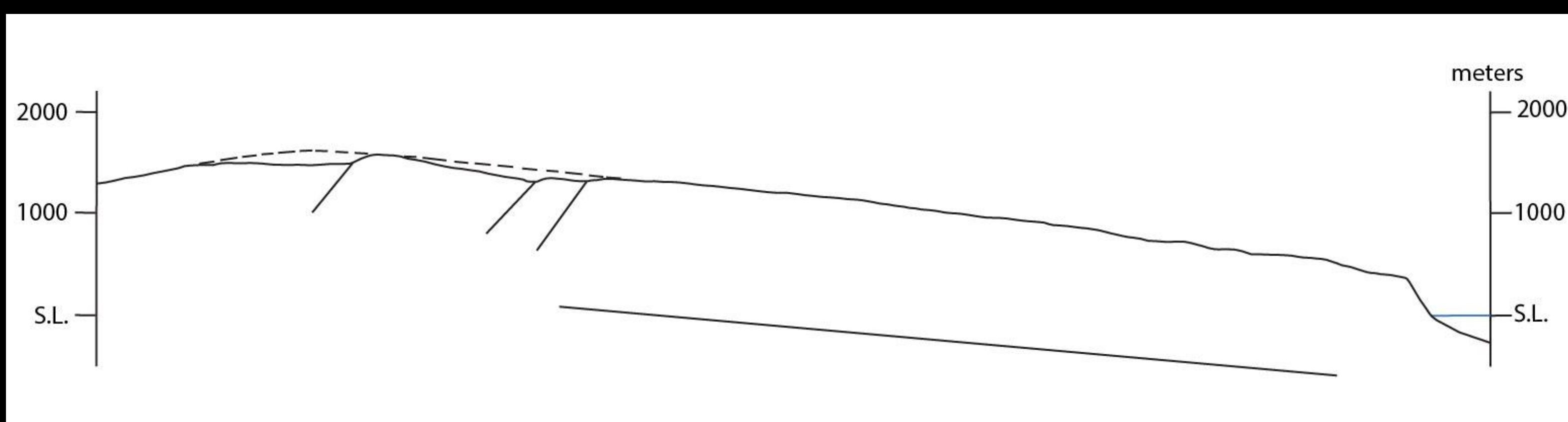
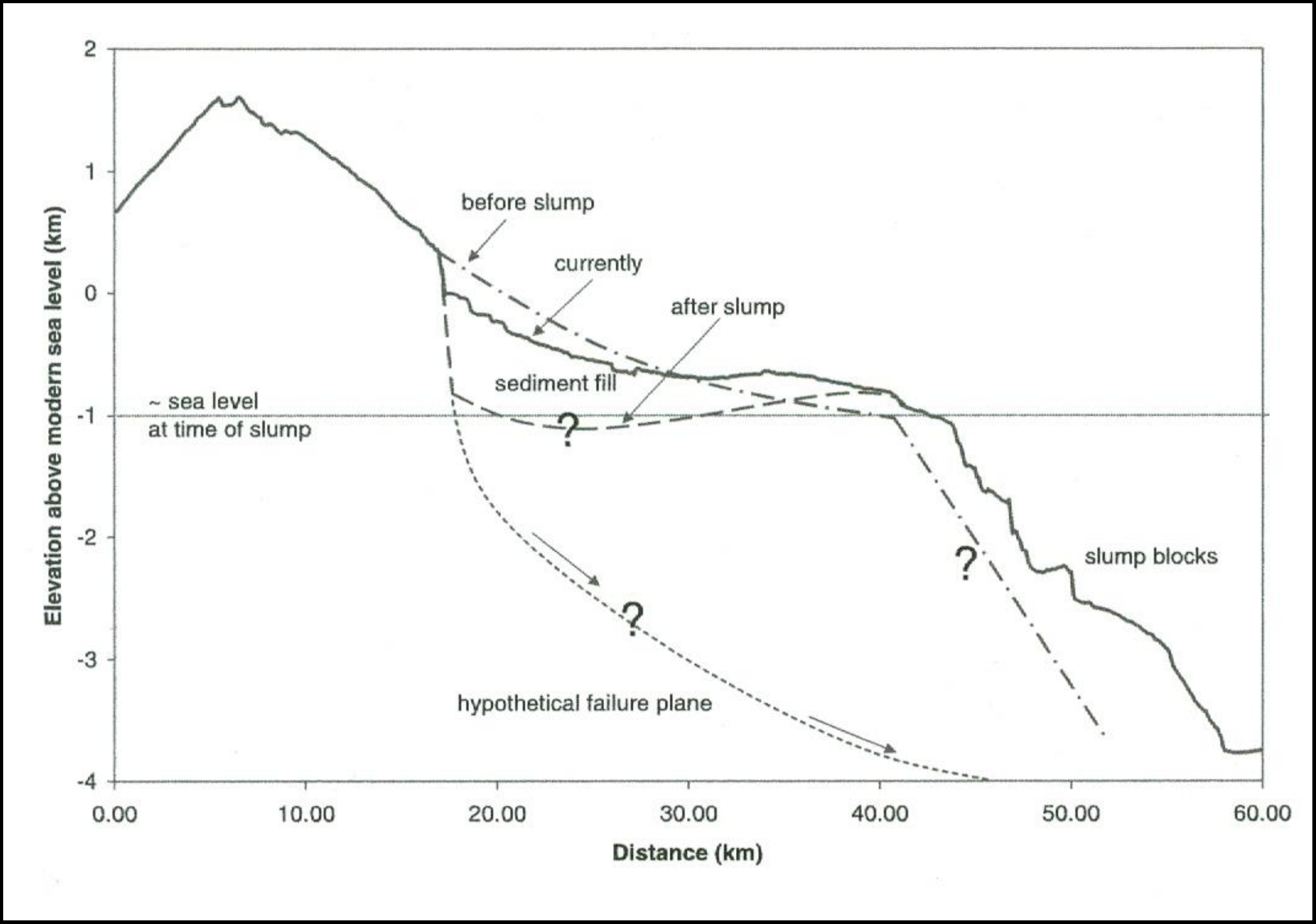


Figure 19.8. Map of Kohala Mountain, showing the huge valleys cut into the windward (northeastern) slope, and the small degree of dissection of the leeward slope.

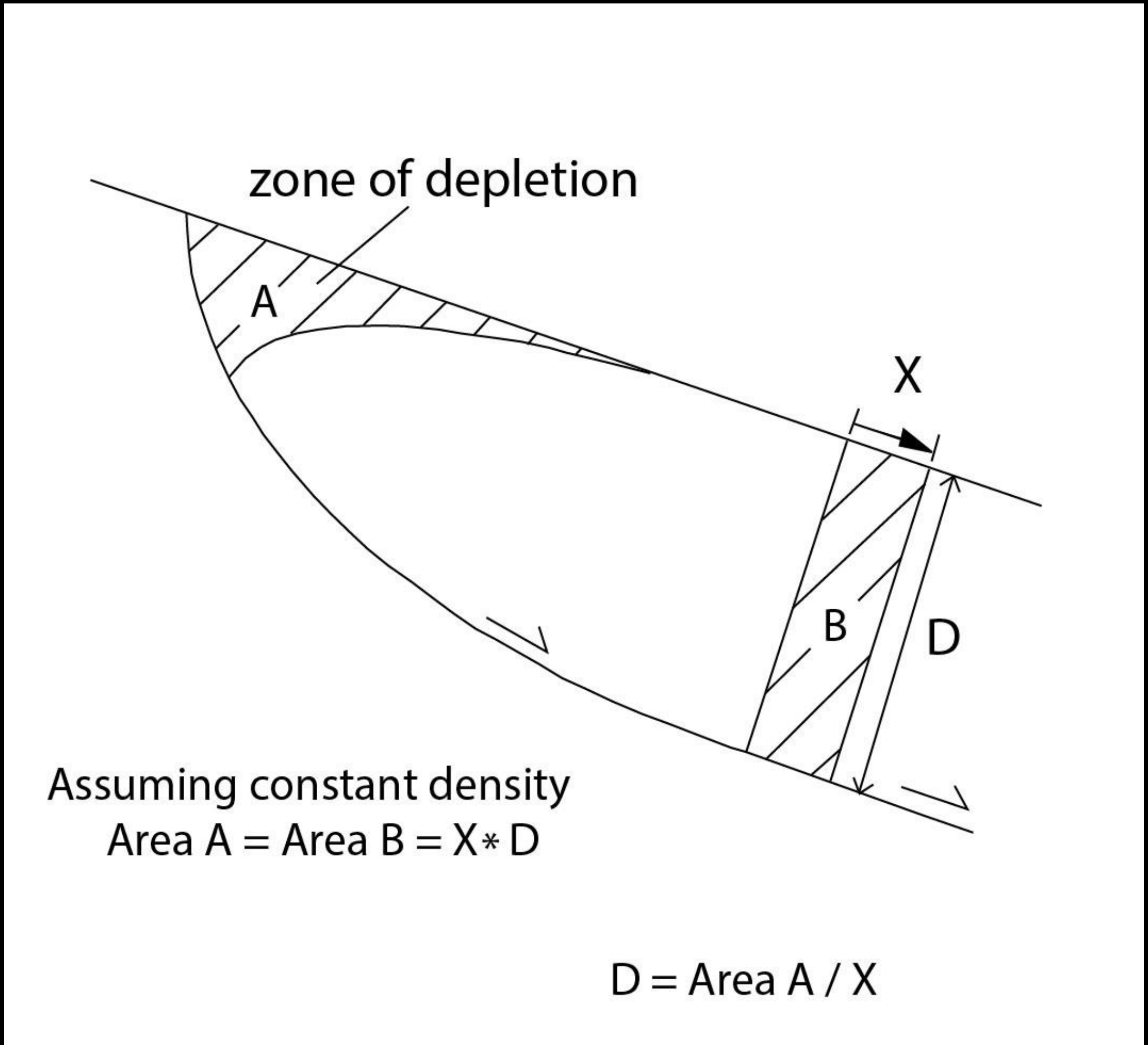




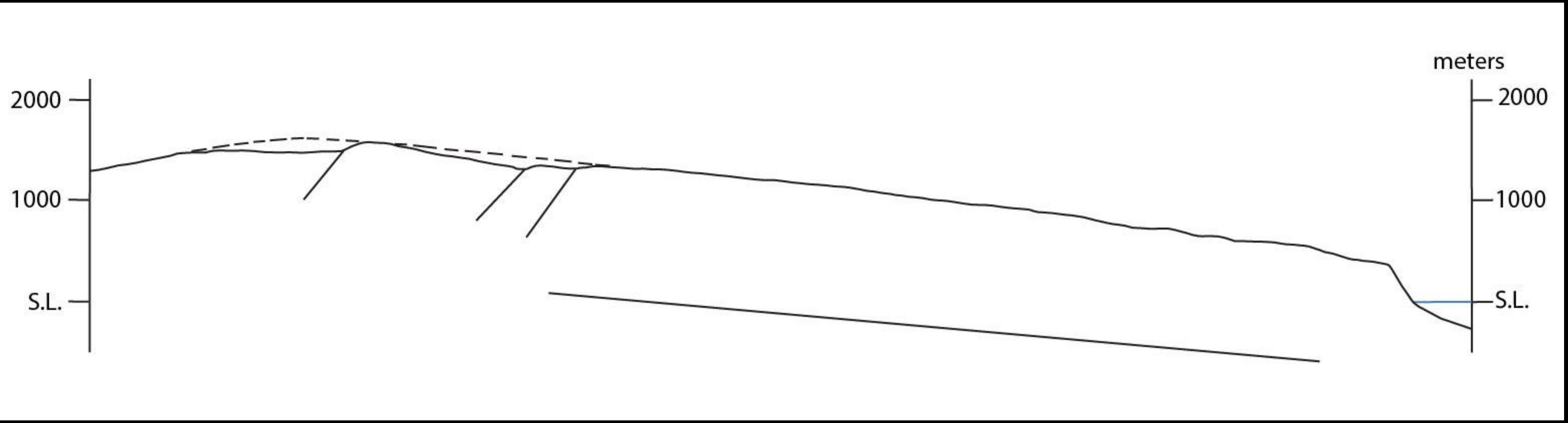


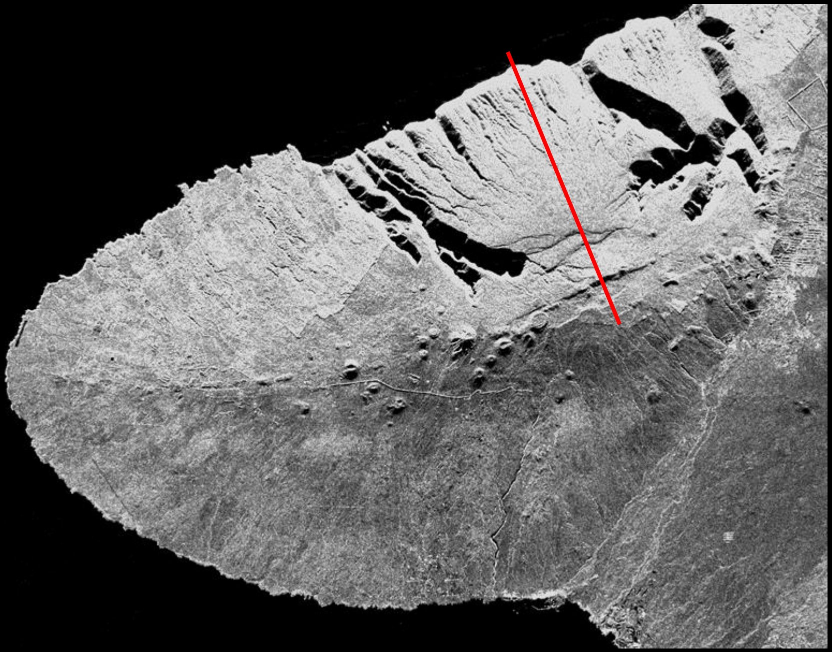
Lamb, et al., 2007

Question: how does the landslide below the subaerial slope relate to the Pololu slump as interpreted by Smith et al. (2002) and Lamb et al. (2007)?

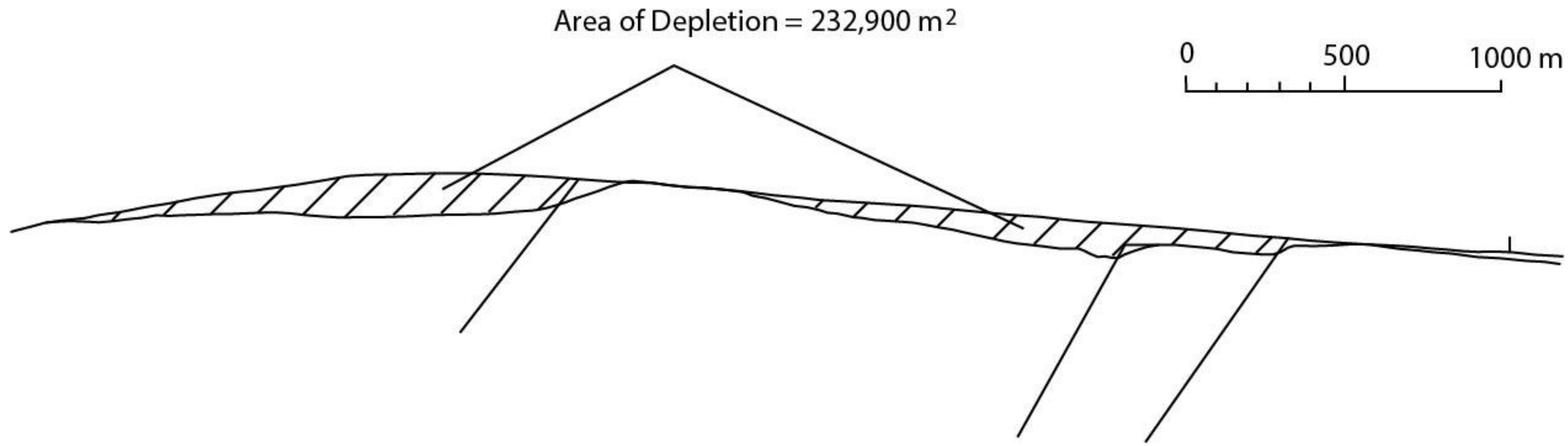


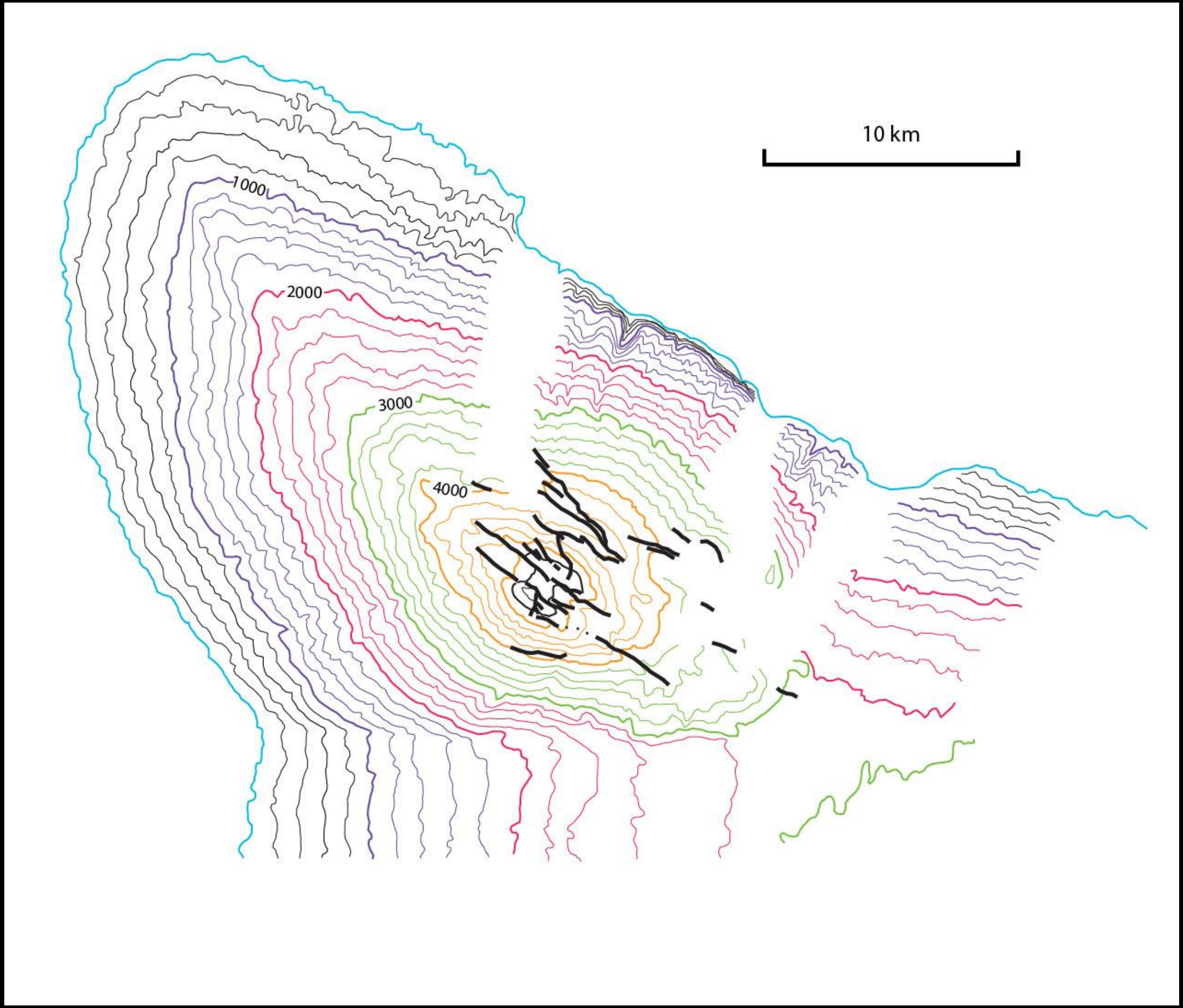
To help answer that question, it would be useful to estimate the depth of the landslide slip surface for the landslide below the subaerial slope. An estimate can be made using the concept shown in the above figure. If the zone of depletion is measured for a cross-section and the displacement (X) of the landslide can be determined, then the depth (D) can be calculated.



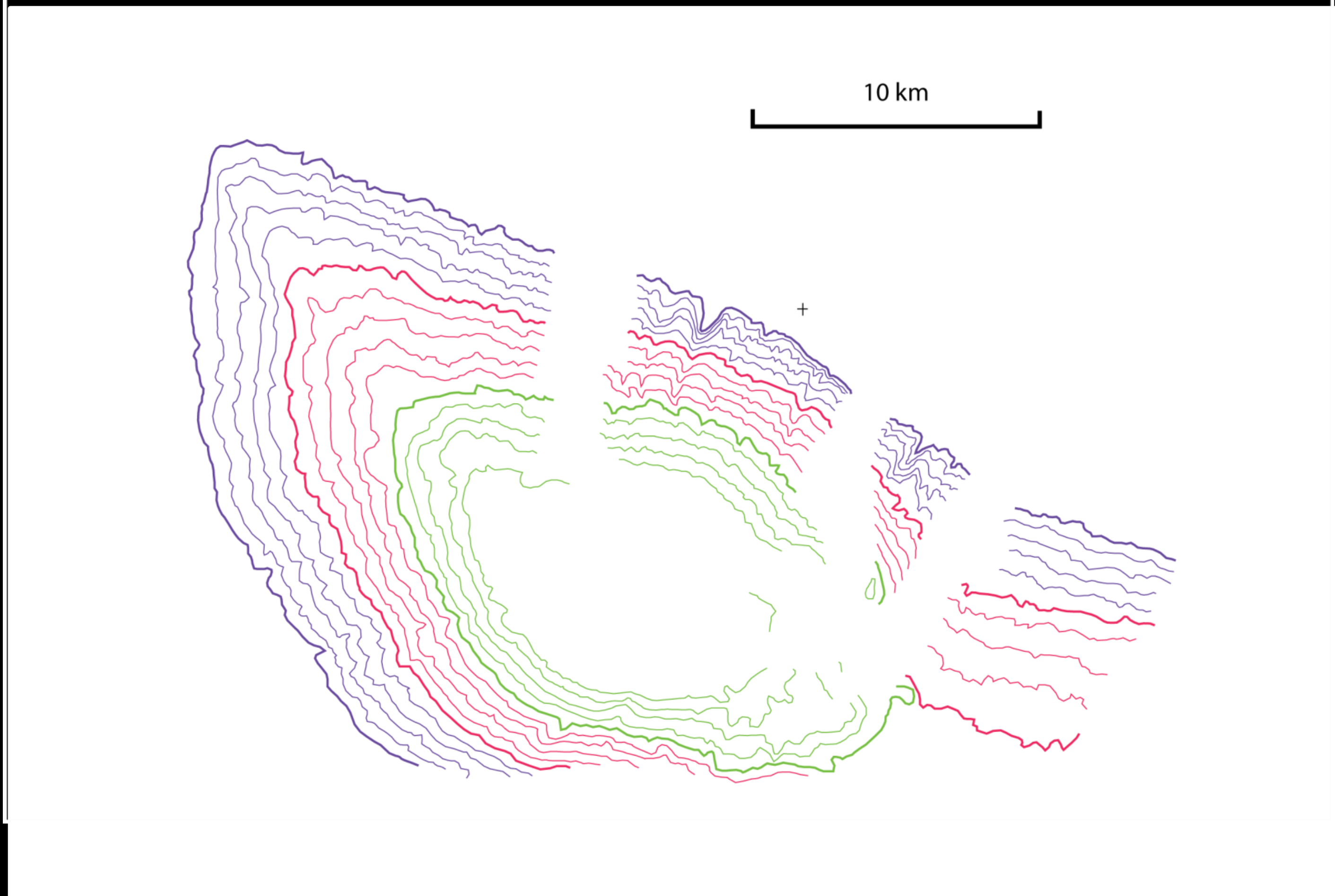


The cross-section above shows a reconstruction of the volcano's surface at the summit area before the landslide movement. From this the area of depletion can be measured.

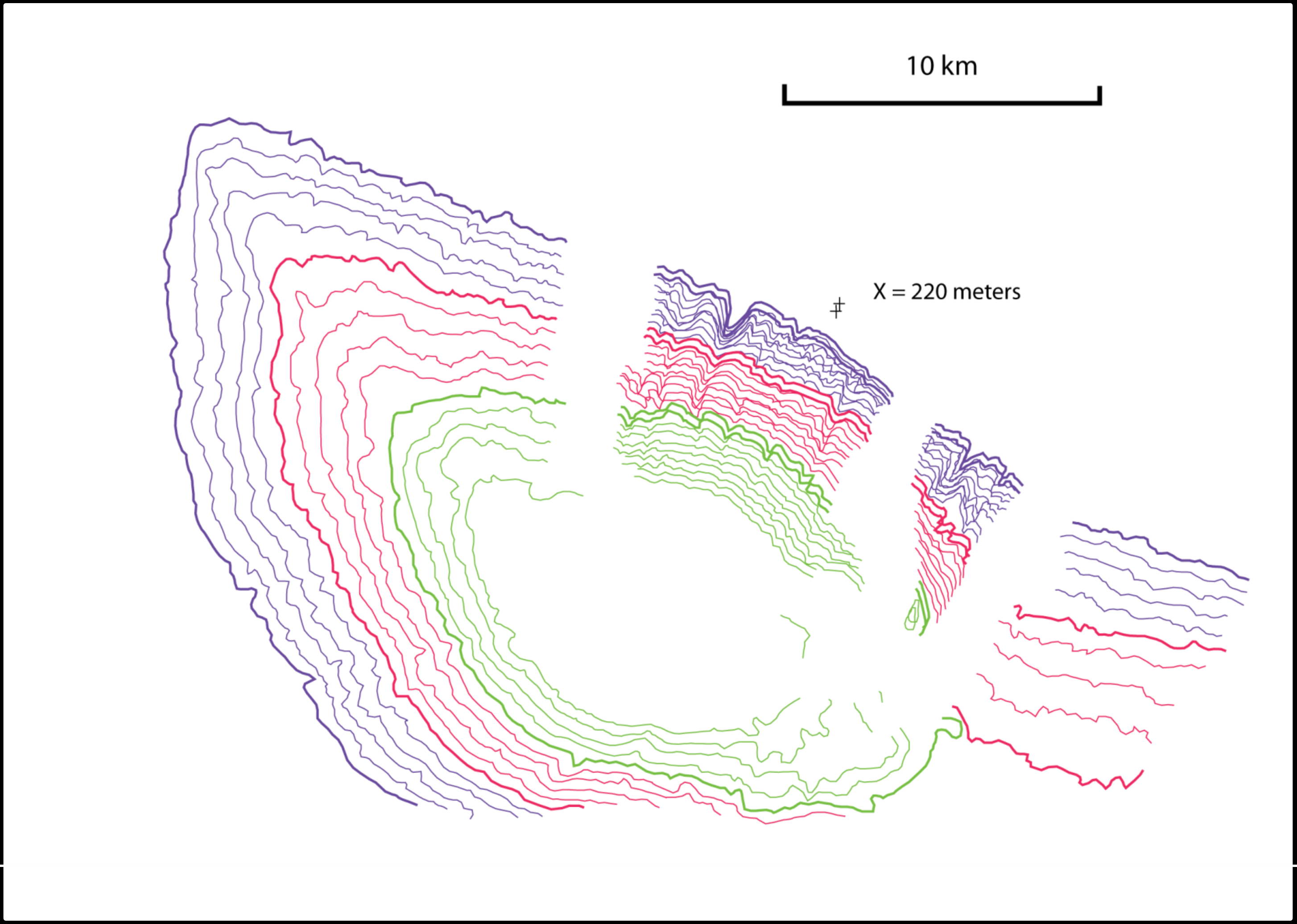

Area of Depletion = 232,900 m2
0
500
1000 m



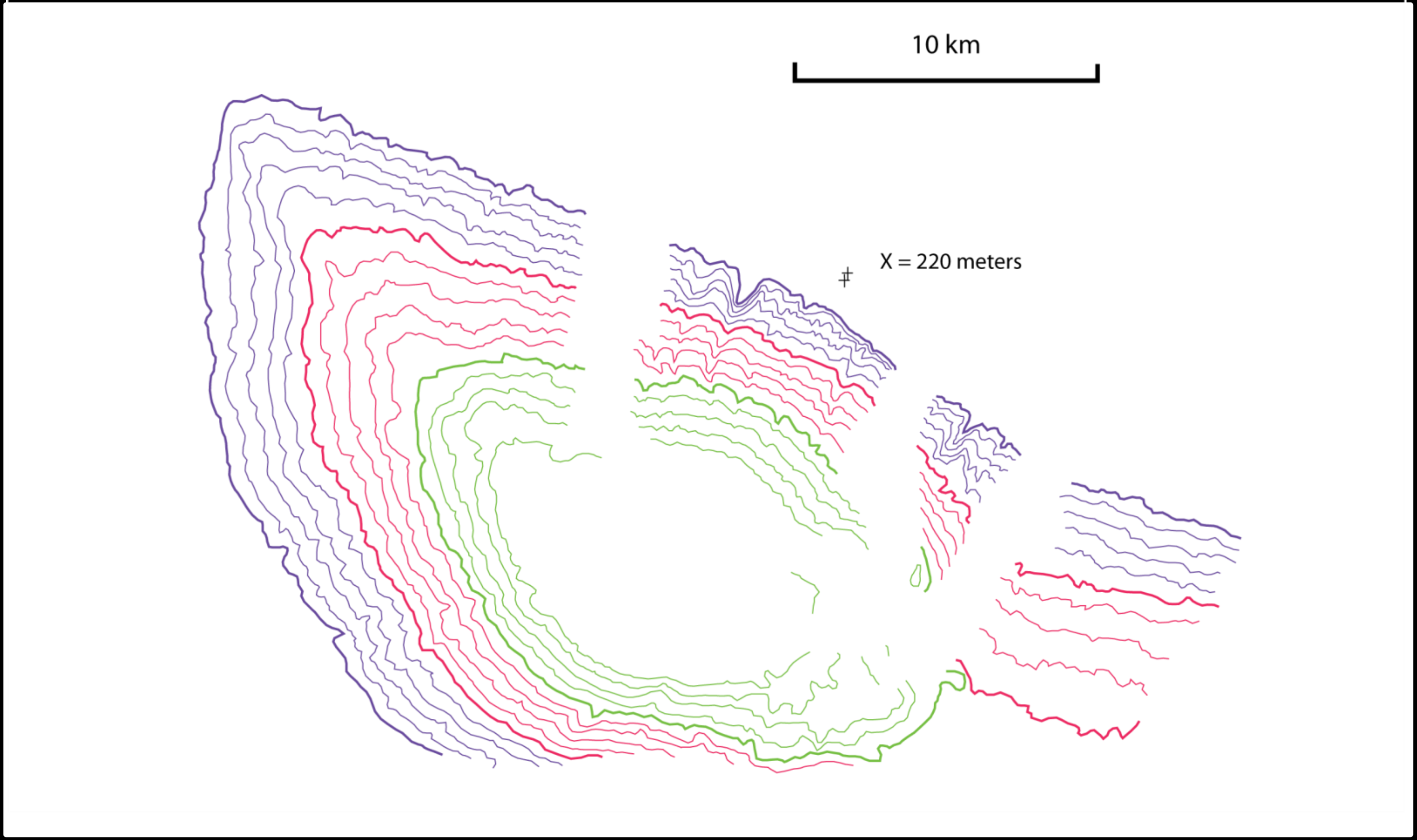
One method for determining the displacement is to use the amount of offset of the contours by landsliding.



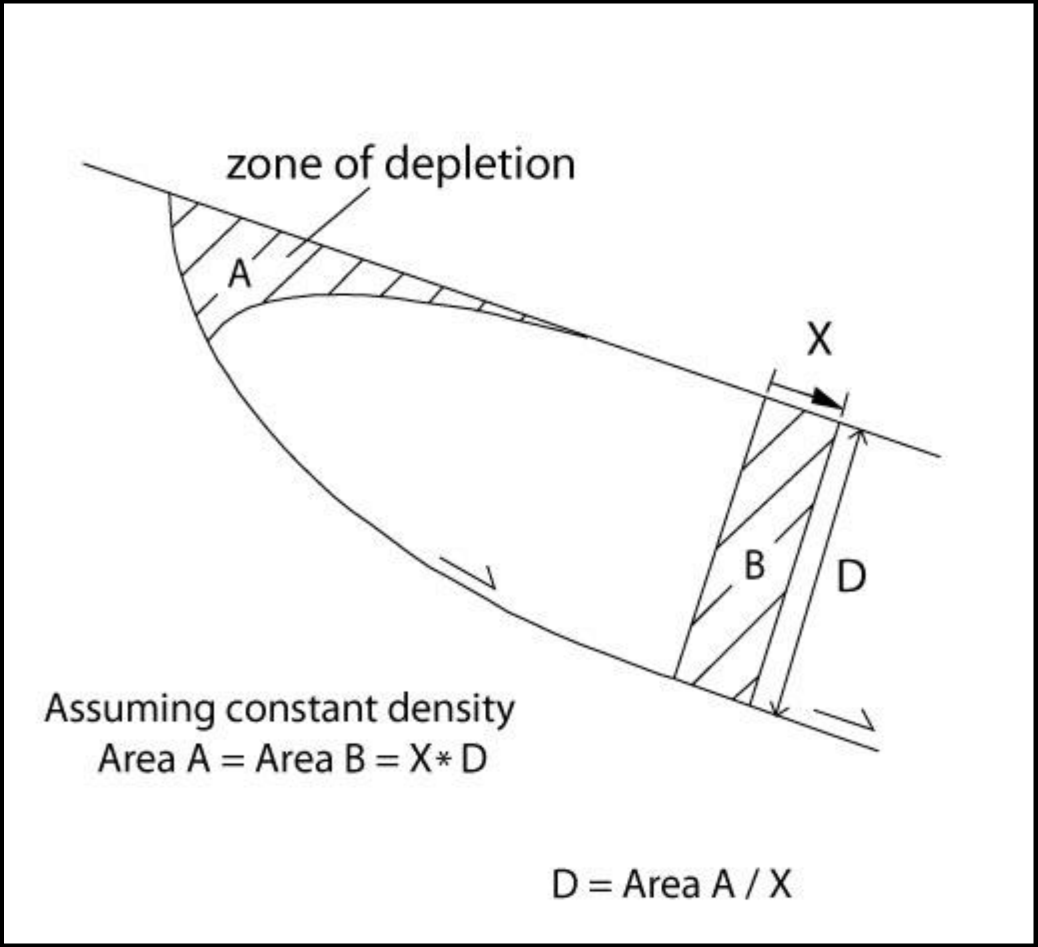
This diagram shows the contours used for estimating displacement. The contours will be moved to an "eye balled" best fit. Notice the reference marker shown just northeast of the contours.



This diagram shows the contours both before and after moving into alignment with the non-landslide contours. Notice the amount of movement needed for alignment as indicated by the change in position of the reference point is 220 meters. This represents an estimate, then, of the displacement magnitude of the landslide.



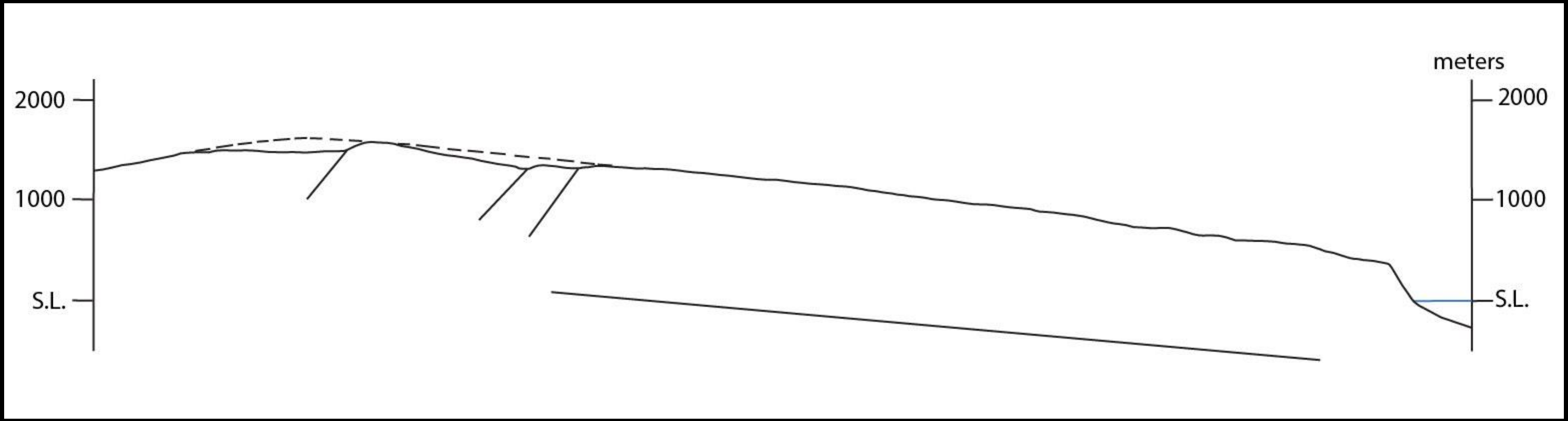
This diagram shows the re-aligned contours, only. Realize that the displacement determined represents only the horizontal component of landslide displacement and does not include any vertical component. However, the slide plane is indicated to be less steep than the topographic slope and the topographic slope is only 7.9 degrees, therefore the slide plane is nearly flat-lying and any vertical component is minor.

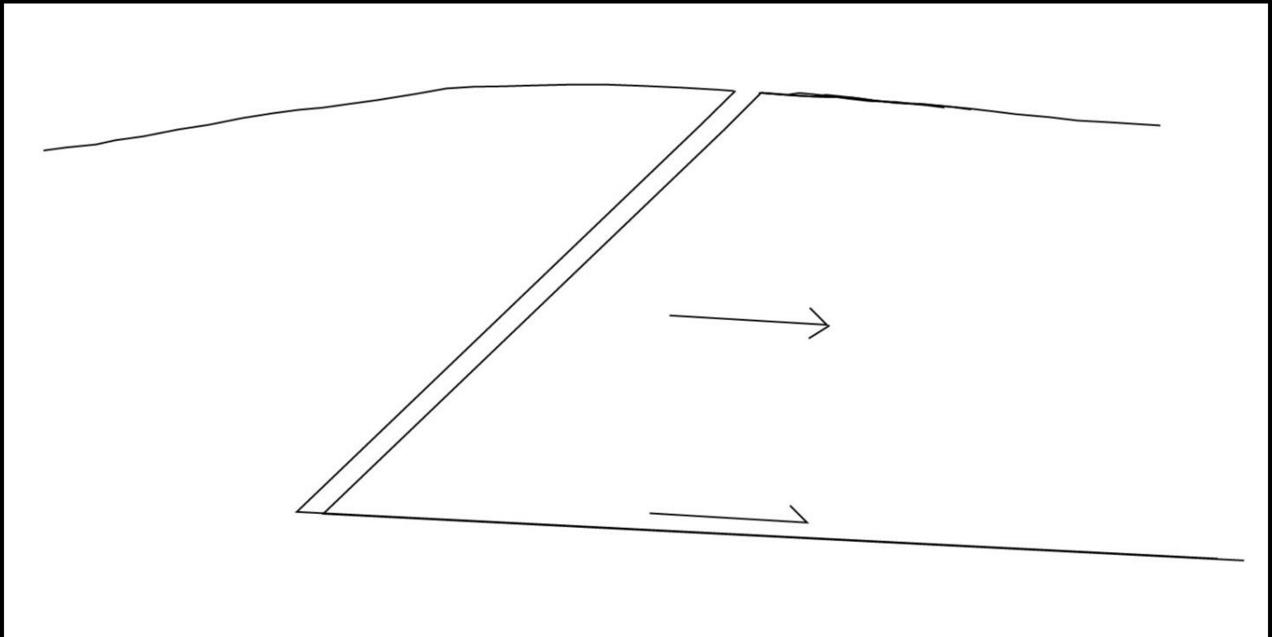


$$232{,}900\ m^2 / 220\ m = 1060\ m$$

<u>D = 1060 m</u>

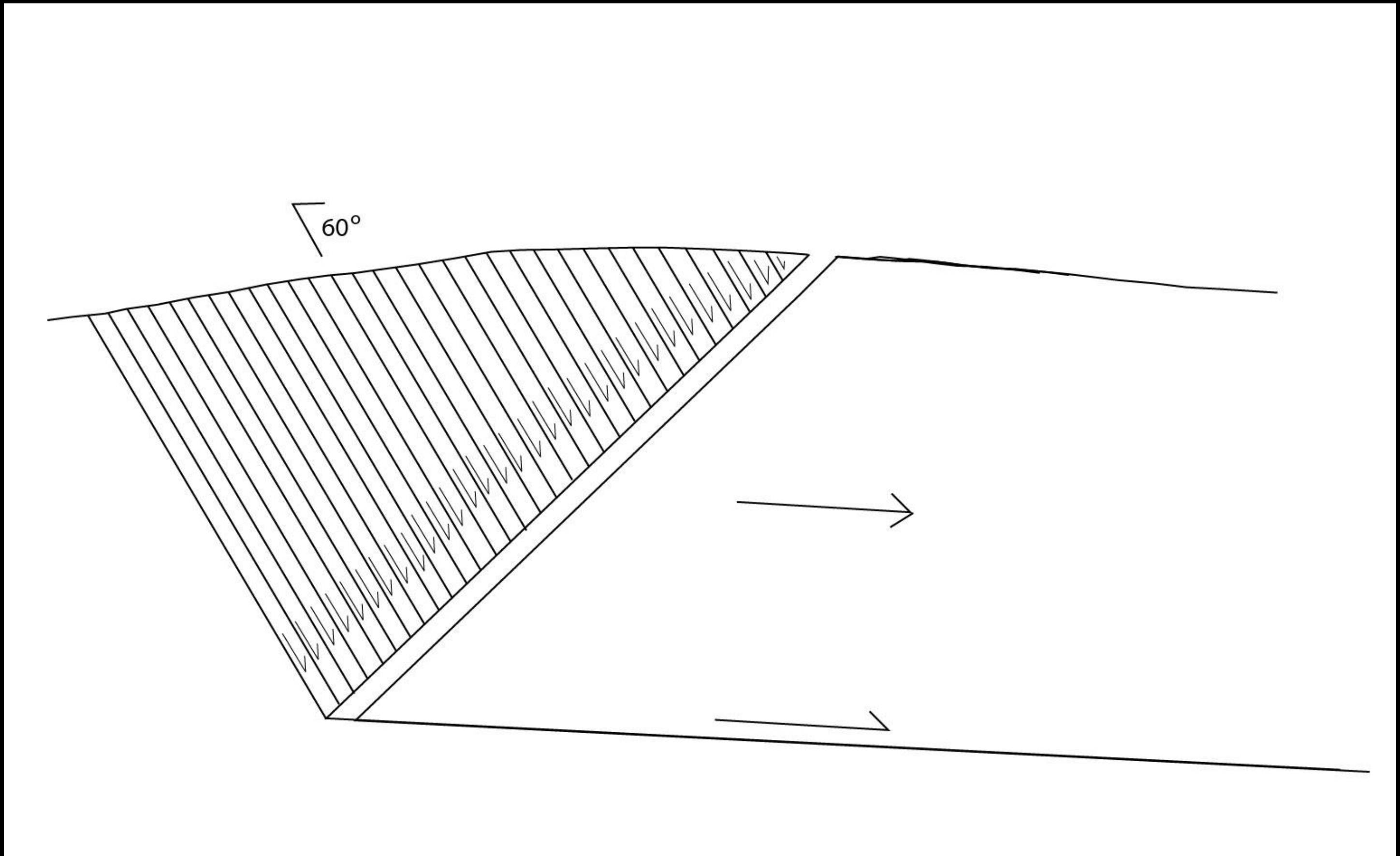
From the area of depletion and displacement parameters, the depth is calculated to be 1060 m, approximately 1 km.



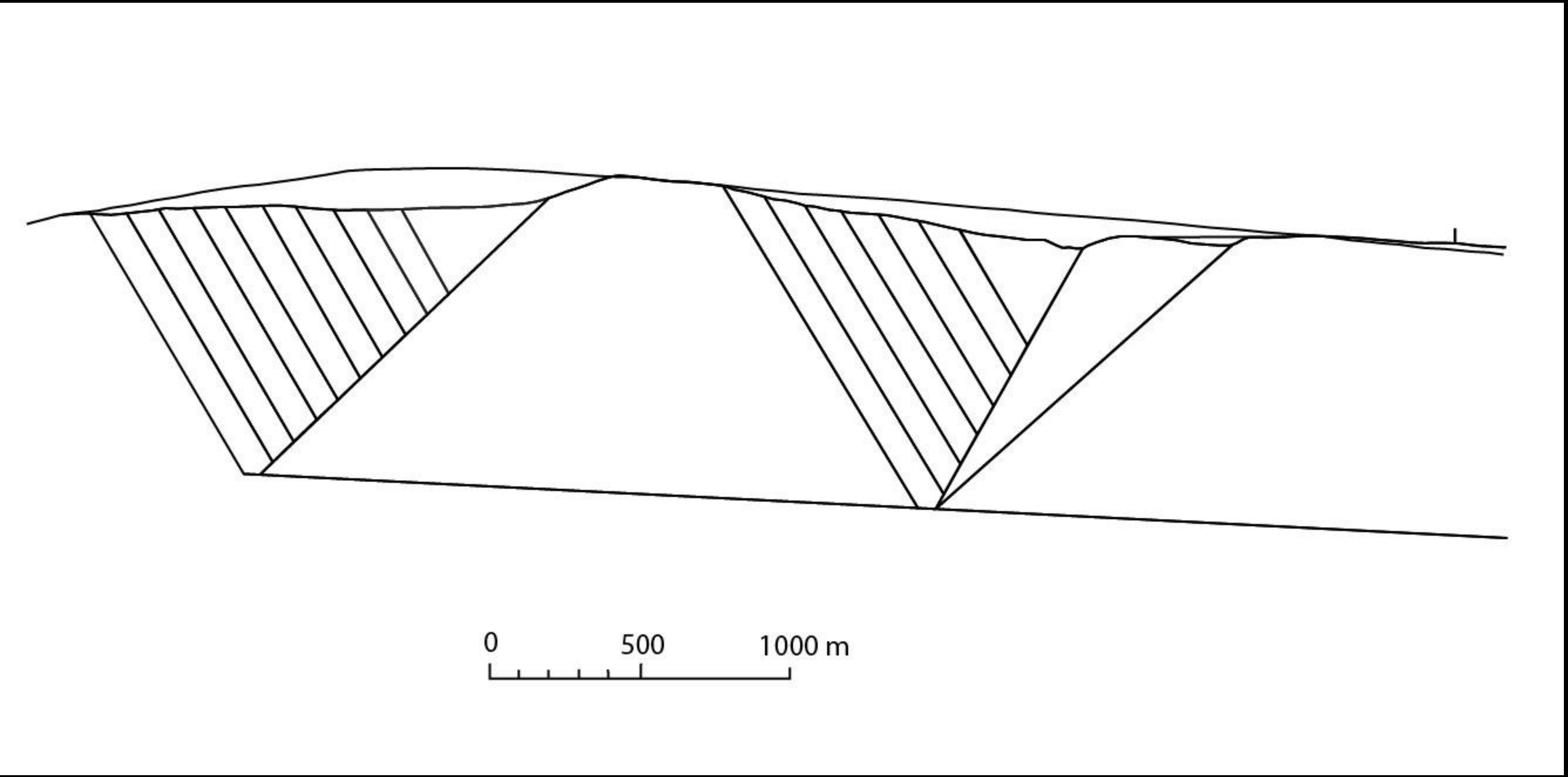


Is there another way to estimate the landslide displacement? The answer is yes. We can retro-deform the landslide and determine how much retro-displacement is required to achieve the retro-deformation. First, note that there are 3 large faults that accommodate graben formation in the extensional area at the head of the slide. The concept that will be used is to assume that the footwall of each slide displaces downslope, which would create a void if the hanging wall block was sufficiently strong to allow the void to exist.

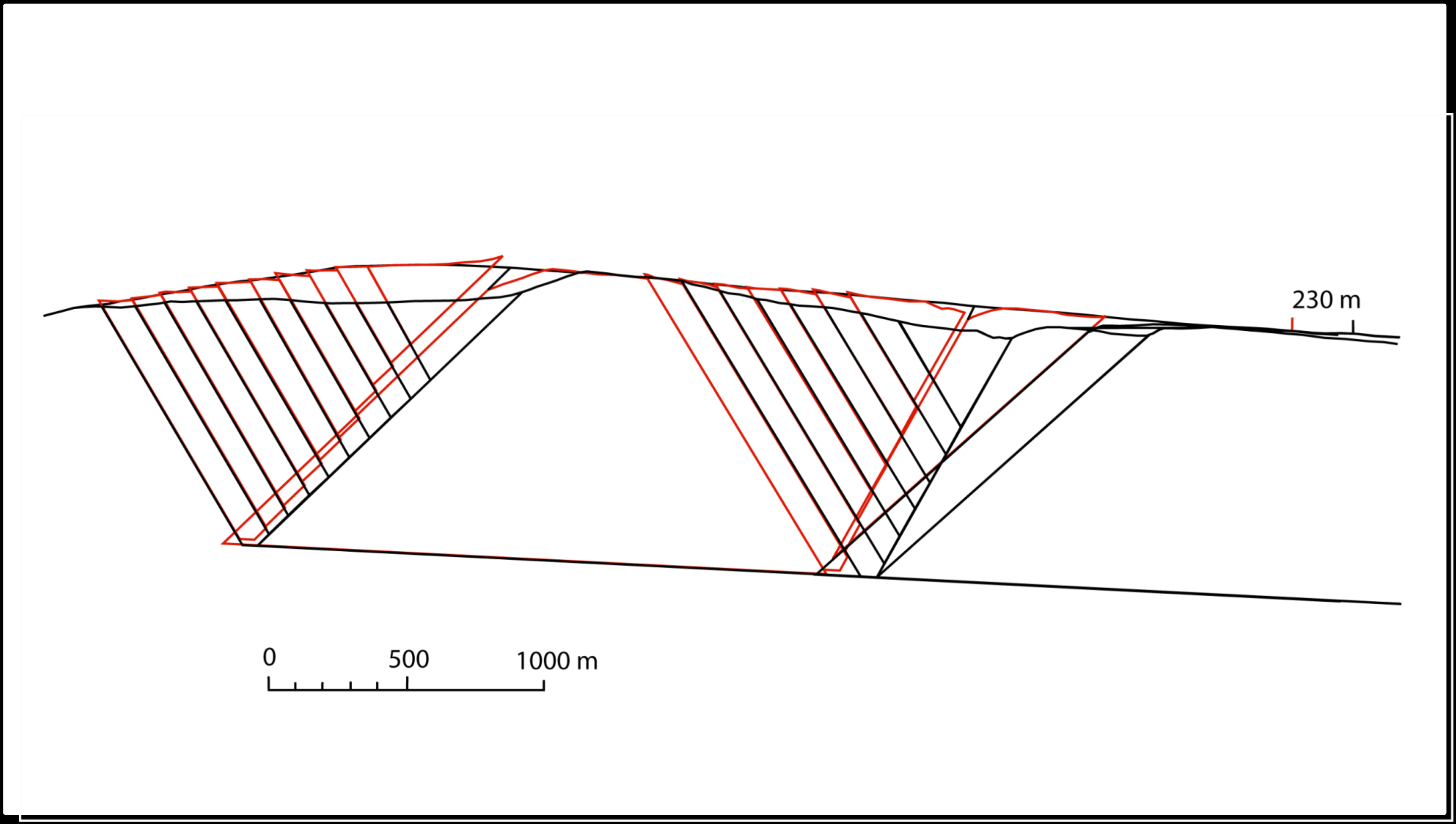
60º Distributed Shear Model



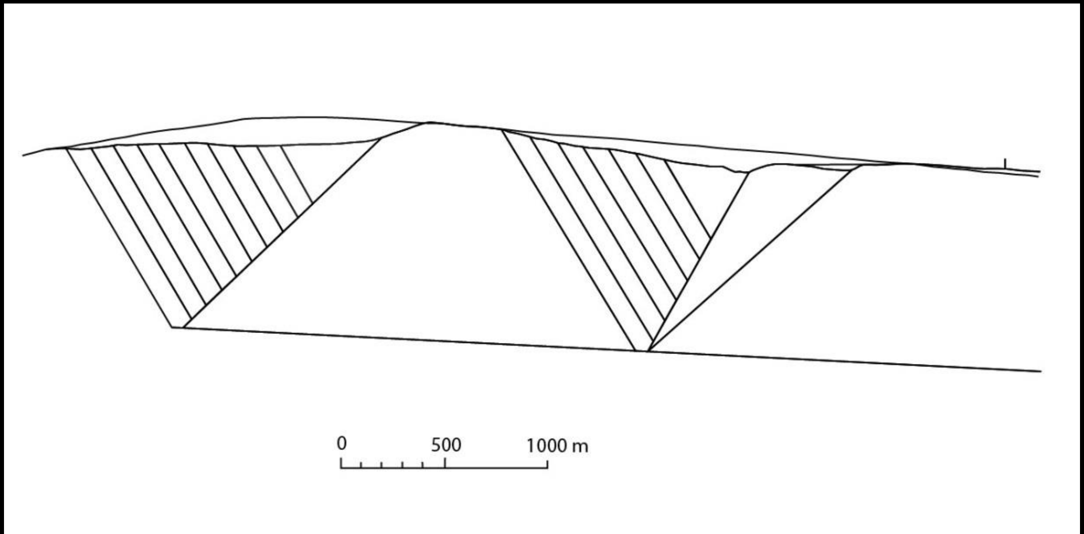
However, the hanging wall block is not sufficiently strong, so the rock material deforms to fill in the void, thereby creating the surficial graben. A question that arises is: how does the hanging wall material deform. One model is that deformation occurs by distributed shear along slip planes dipping 60 degrees as shown above. This model follows after Mohr-Coulomb mechanics.



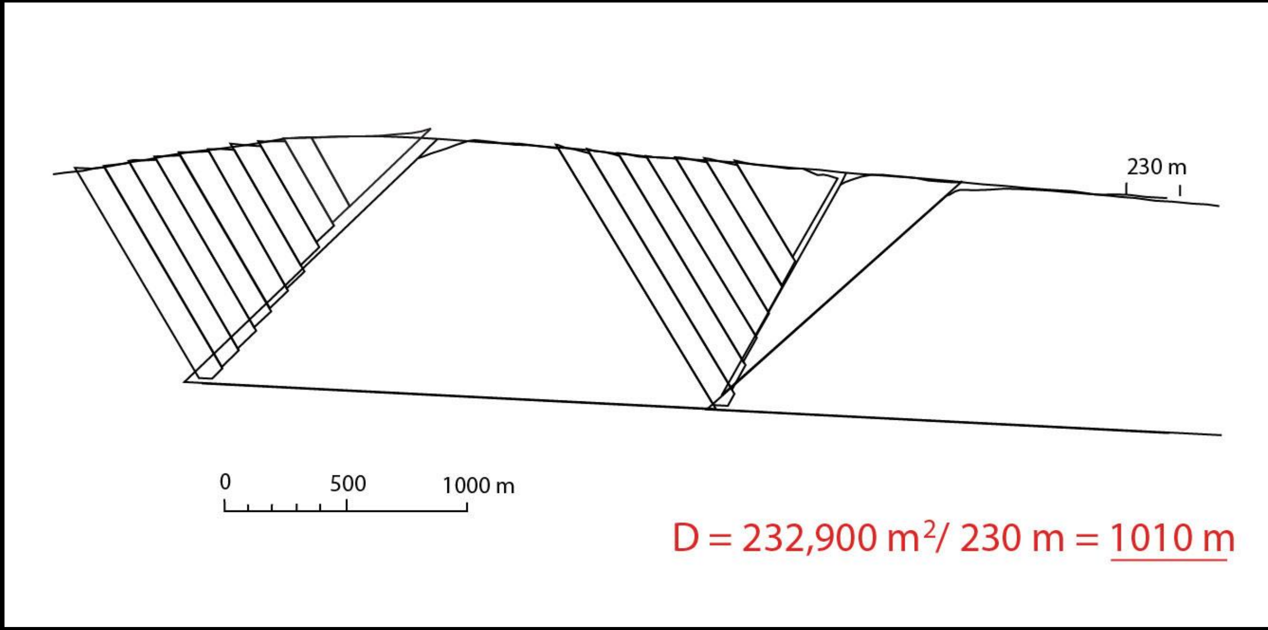
To model the 60 degree distributed slip planes to retro-deform the slide, the landslide material is divided into a series of rigid blocks shown above. The blocks will be “un-slipped” to reconstruct the configuration before landslide movement. After retrodeformation, the amount of movement of the reference point shown on the surface at the right will be measured, which will indicate that amount of displacement of the landslide.



The figure above shows in red the retro-deformed (pre-landslide) configuration and the black shows the present (post-landslide) configuration. The amount of movement of the reference point in creating the retro-deformation is 230 m.

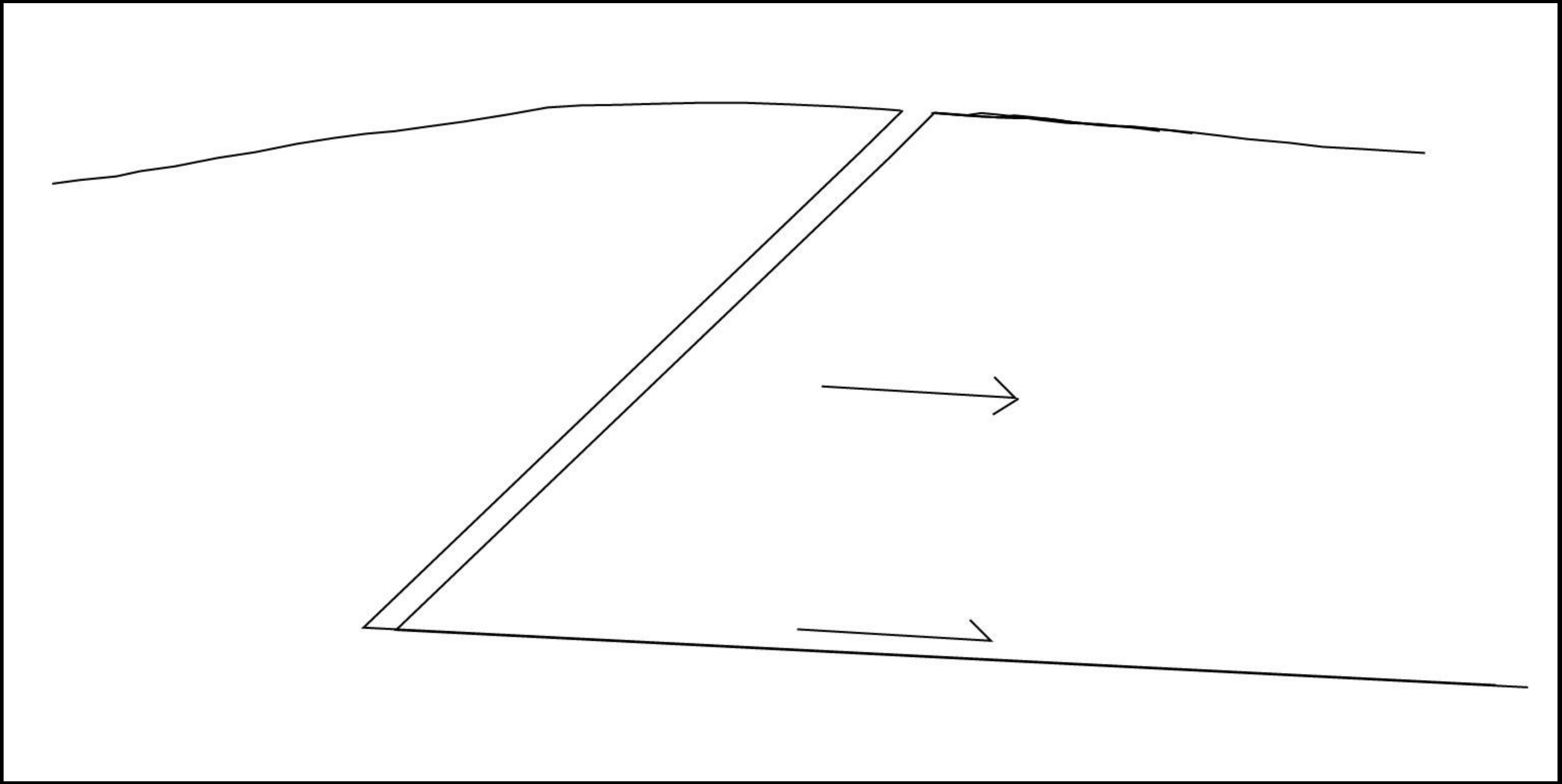


Post-landslide configuration with pre-landslide topographic surface shown.



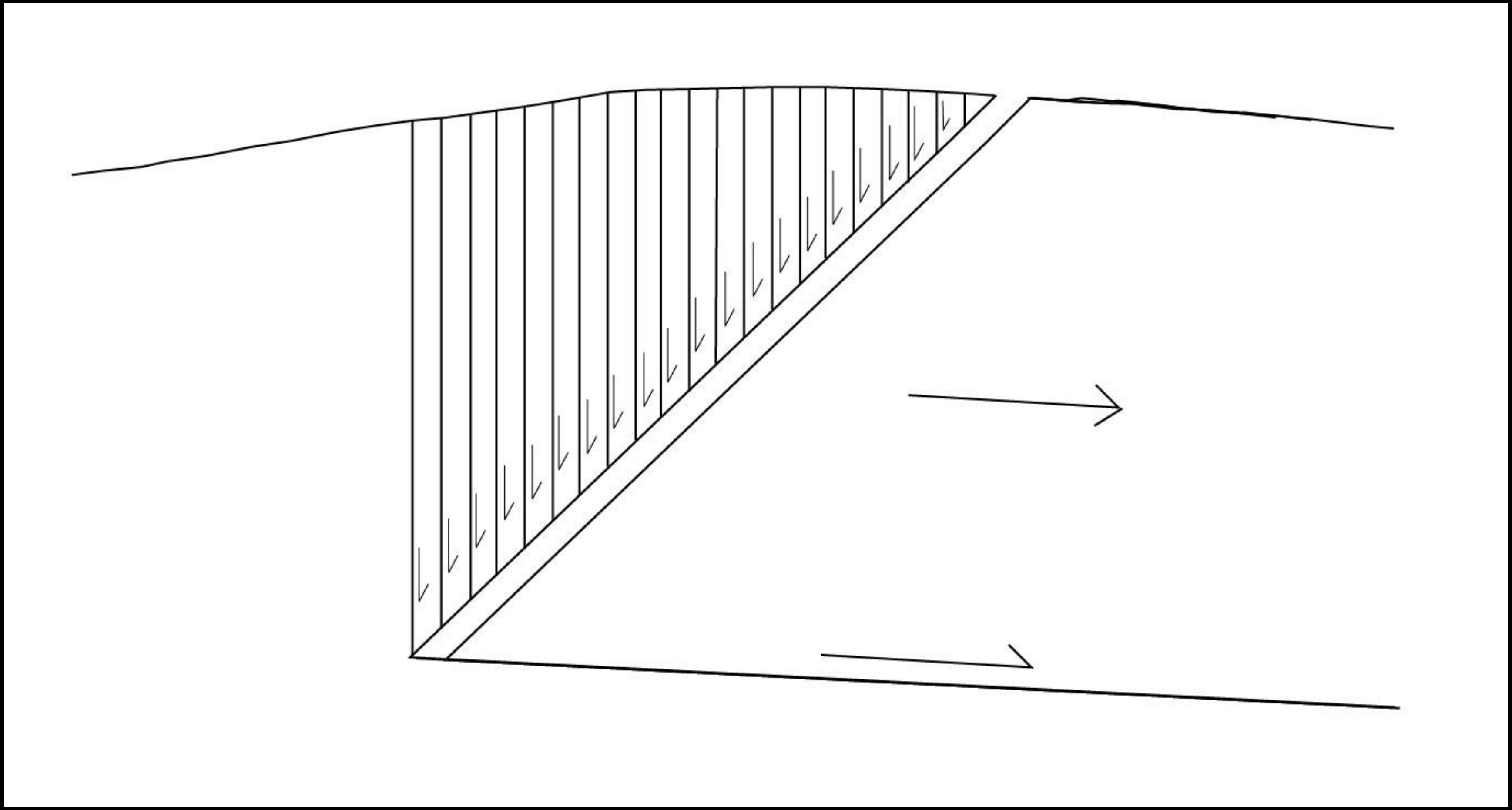
Retro-deformed landslide configuration.

Displacement indicated from retro-deformation is 230 m. Calculated depth of the landslide is 1010 m, or approximately 1 km. Note that the retro-deformation with the assumed model of rigid blocks is not a perfect reconstruction. Gaps and overlap are present .

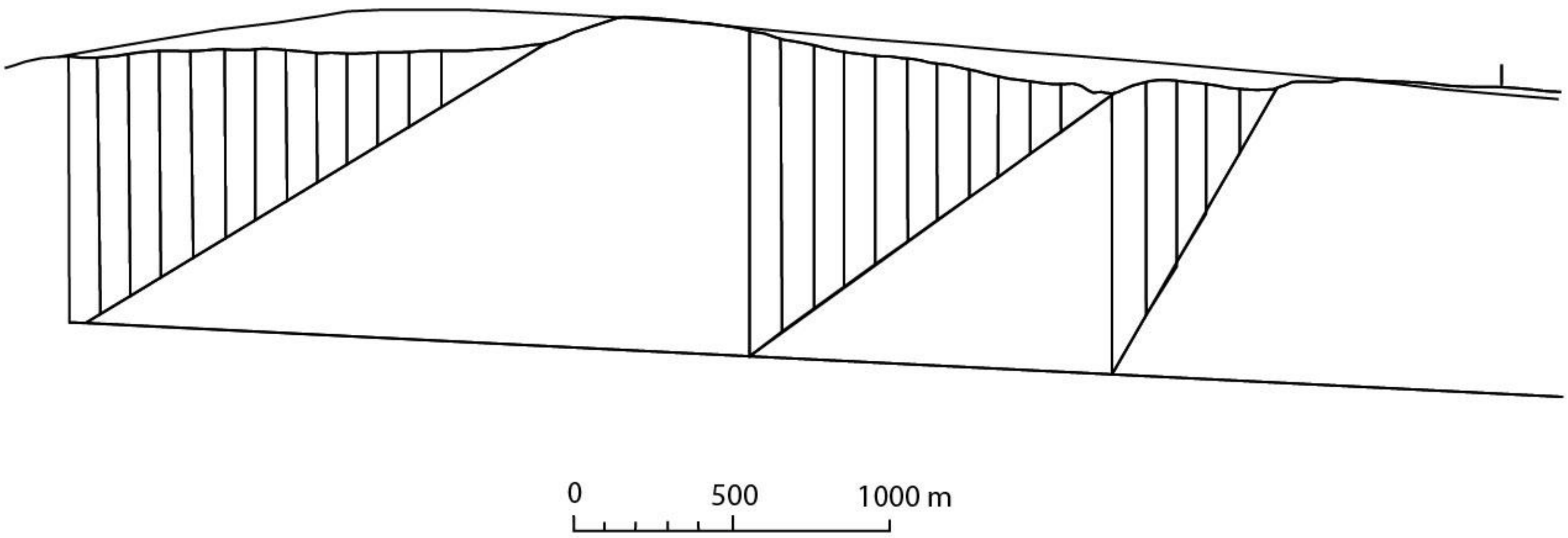


Although the 60 degree distributed shear model seems reasonable, the question can be asked whether or not there are any other reasonable distributed shear models for hanging wall deformation.

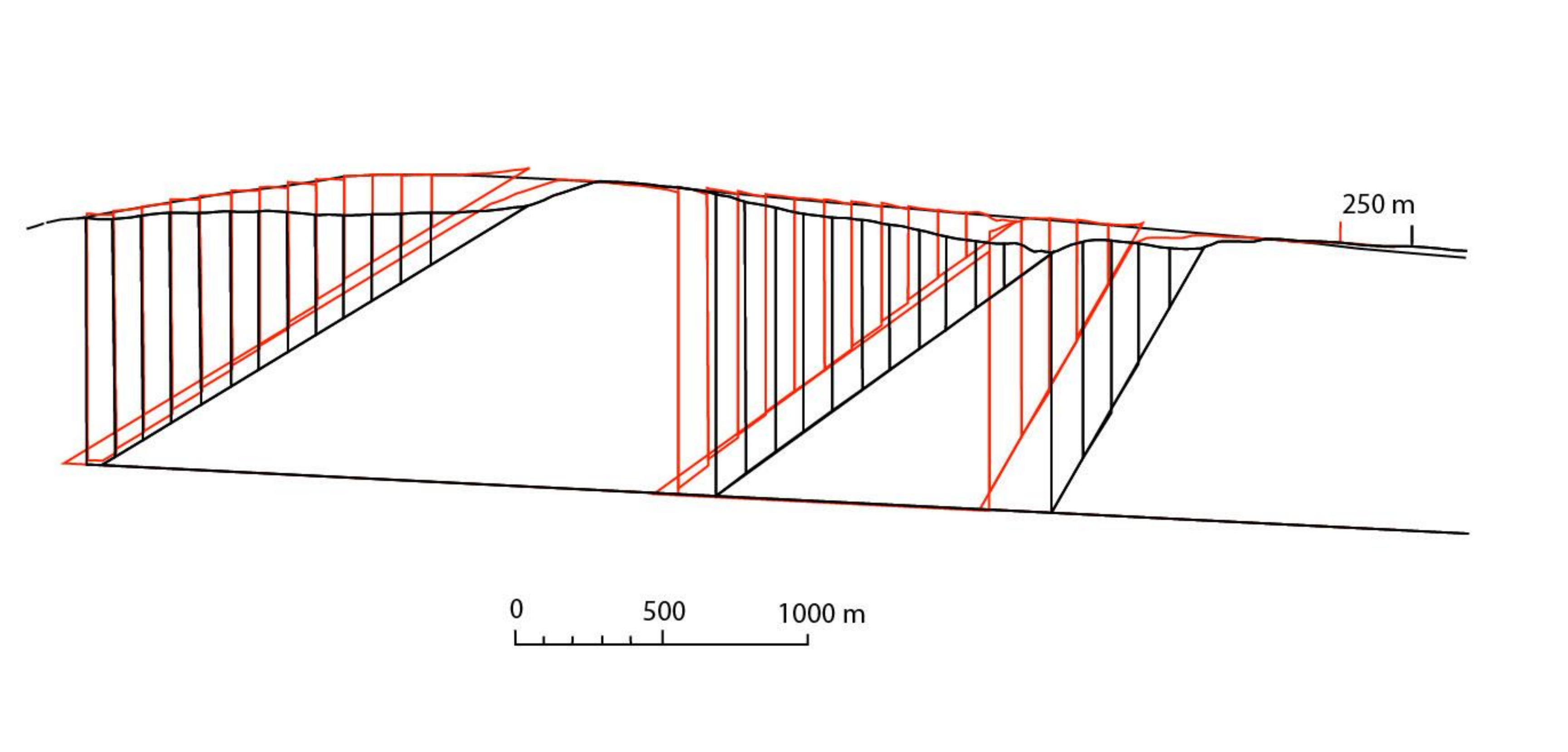
Vertical Distributed Shear Model



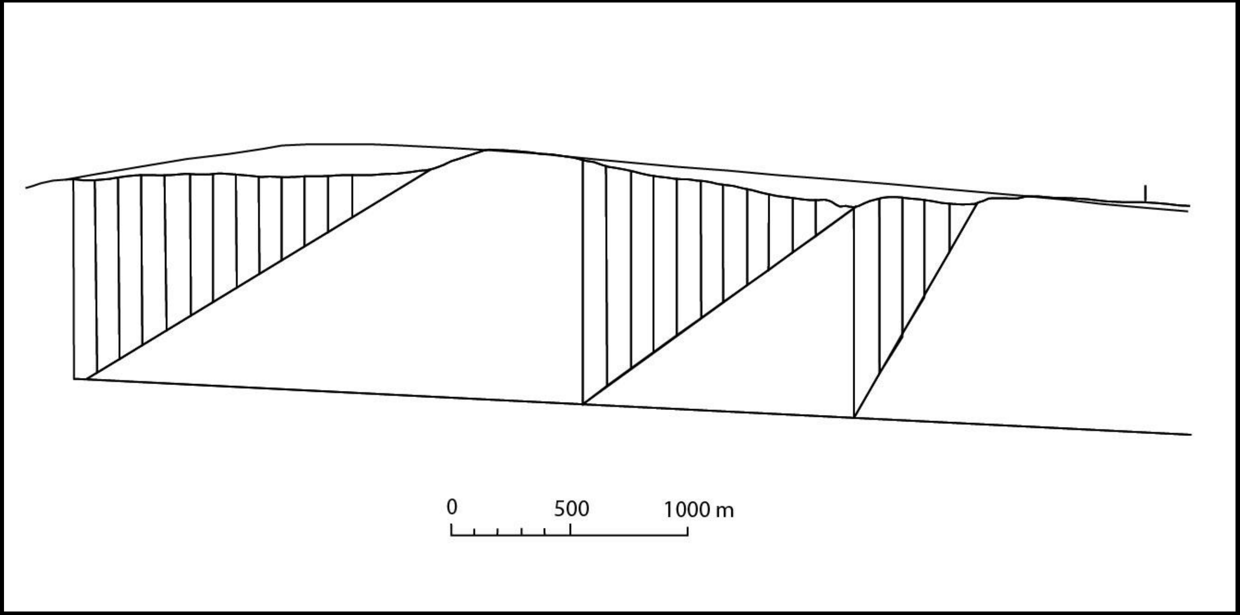
Another model that seems feasible is a vertical distributed shear model, where distributed shear along vertical shear planes could accommodate the closure of the gap created by displacement of the footwall block.



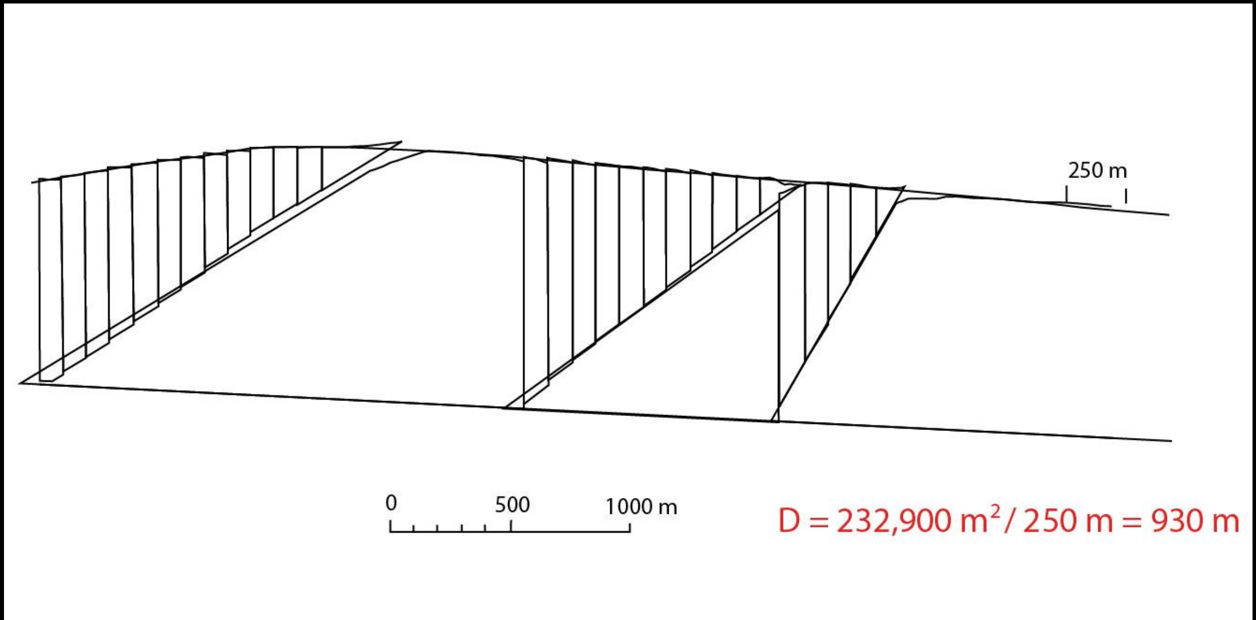
In order to approximately determine the landslide displacement for the vertical distributed shear model, the landslide head area is divided into the above discrete rigid blocks. Similar to the previous model, the blocks will be "un-slipped" to fill in the area of depletion and the amount of movement of the reference point will be determined.



As in the previous retrodeformation, the red lines indicate the retro-deformed landslide position and the black lines the present (post-landslide) postion. The amount of displacement for this model is 250 m.



Post-landslide configuration with pre-landslide topographic surface shown.



Retro-deformed landslide configuration.

Displacement indicated from retro-deformation is 250 m. Calculated depth of the landslide is 930 m, or approximately 1 km. Note that the retro-deformation with the assumed model of rigid blocks is, again, not a perfect reconstruction. Gaps and overlap are present .

Slide Plane Depth Determinations

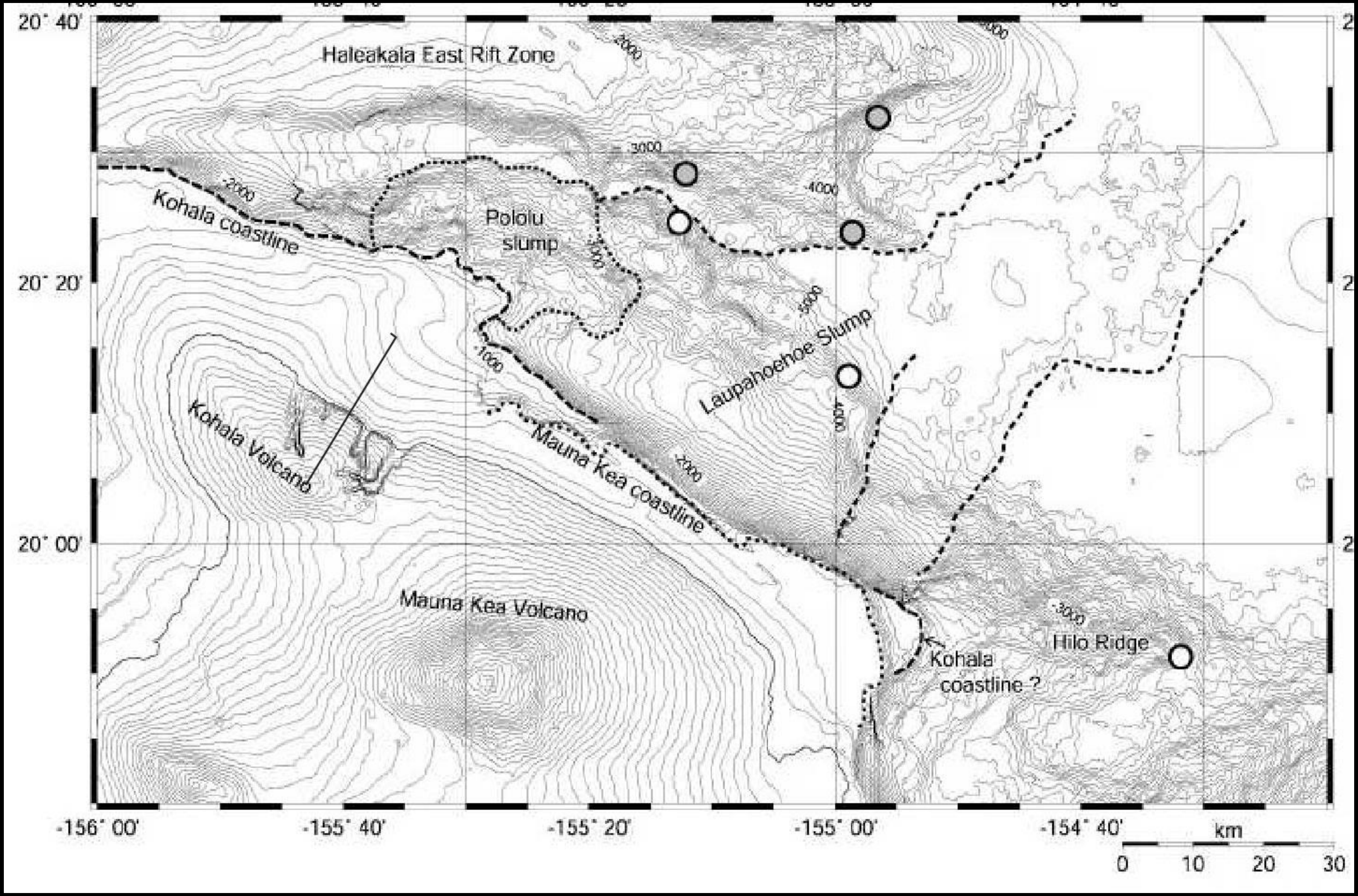
	Displacement	Calculated Depth
Contour Offset	220 m	1060 m
60º Distributed Shear	230 m	1010 m
Vertical Distributed Shear	250 m	930 m

The above figures show the amount of displacement determined from the 3 methods described in this presentation. Also shown are the calculated landslide slip plane depths corresponding to each of the displacements. All 3 methods give an approximate depth of 1 km for the slide plane.

None of the methods give an exactly accurate measurement for the depth. The two distributed shear models have the greatest uncertainty. Both of these models are reasonably permissible, but neither are known to be the correct model and neither is perfect.

However, all 3 models give the same rough estimate for the depth of the slide plane. In previous work with retro-deformation of landslides to determine displacement and from that depth of the slide plane, that the displacement determined is relatively insensitive to the method of shear deformation assumed. If the retro-deformation reasonably well fits the pre-landslide configuration without large areas of overlap or void space, the amount of displacement will be similar regardless of style of internal deformation assumed.

The evidence from the 3 displacement analyses indicate an approximate depth of 1 km for the slide plane just downslope from the area of the grabens at the head. Because of the consistency of the result across the 3 methods, there is confidence that roughly 1 km is the correct value.

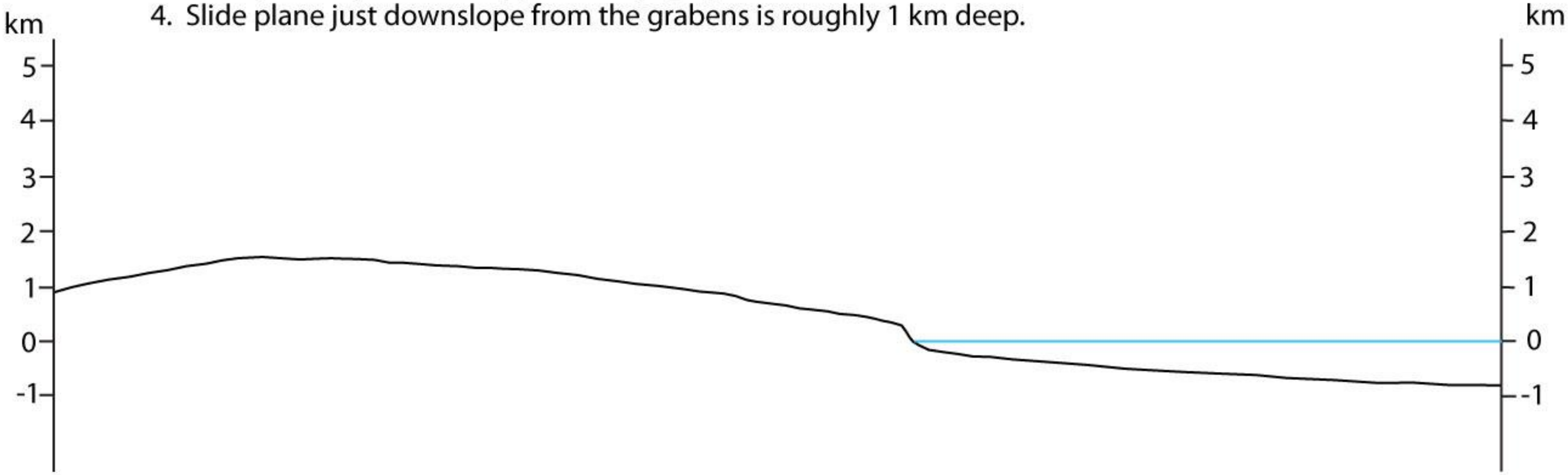


Using the approximate depth of 1 km for the landslide depth near the head of the landslide along with the constraints shown earlier, we can look at the "big picture" for the landslide. To do this, we'll look at a cross-section across the slope as shown on the figure above.

Map from: http://pubs.usgs.gov/ds/2006/171/data/cruise-reports/2001/html/27.htm

Conclusions from Contour Analysis

1. Slope contains a landslide
2. Slide surface is planar
3. Slide plane dips less steeply than topographic surface
4. Slide plane just downslope from the grabens is roughly 1 km deep.



Conclusions from Contour Analysis

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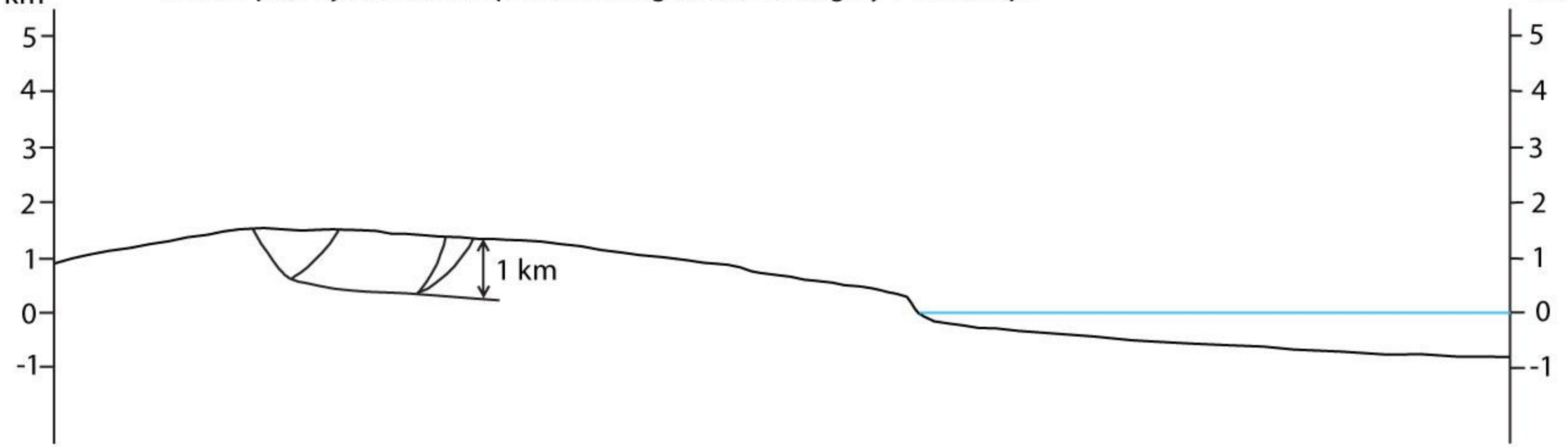
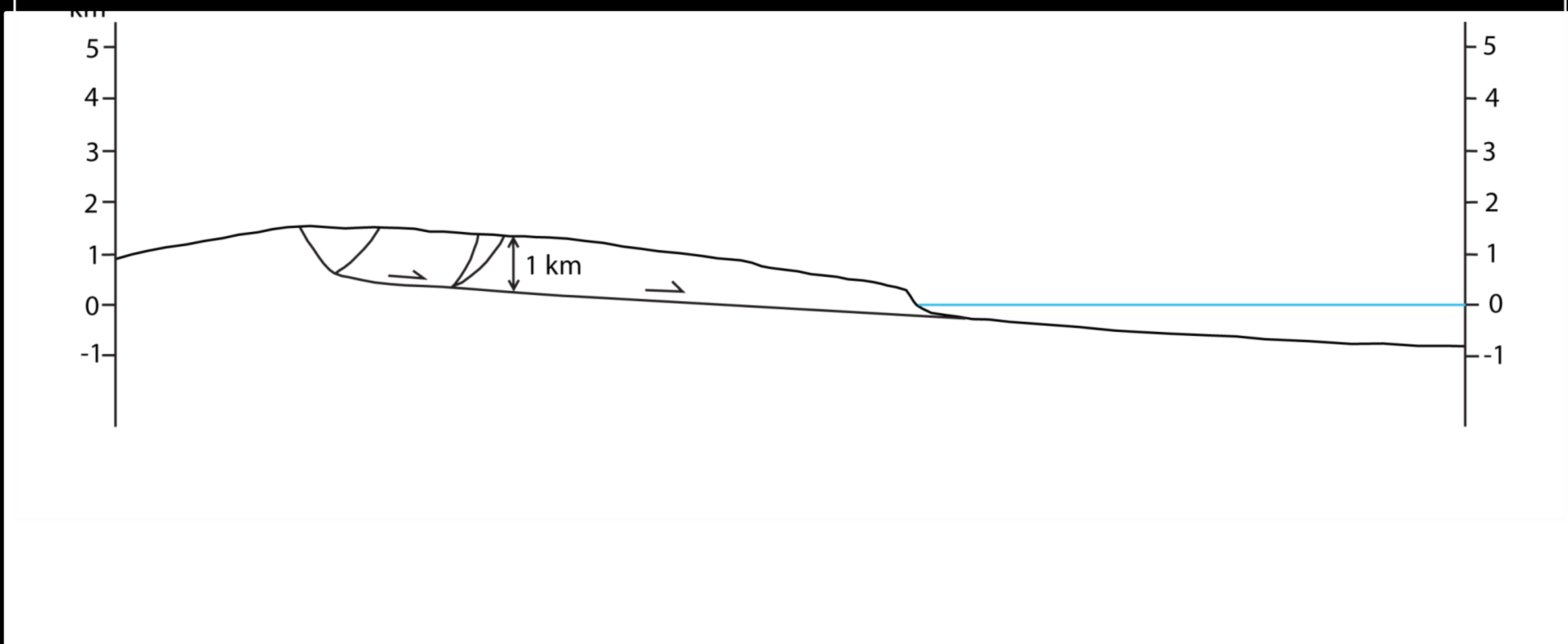
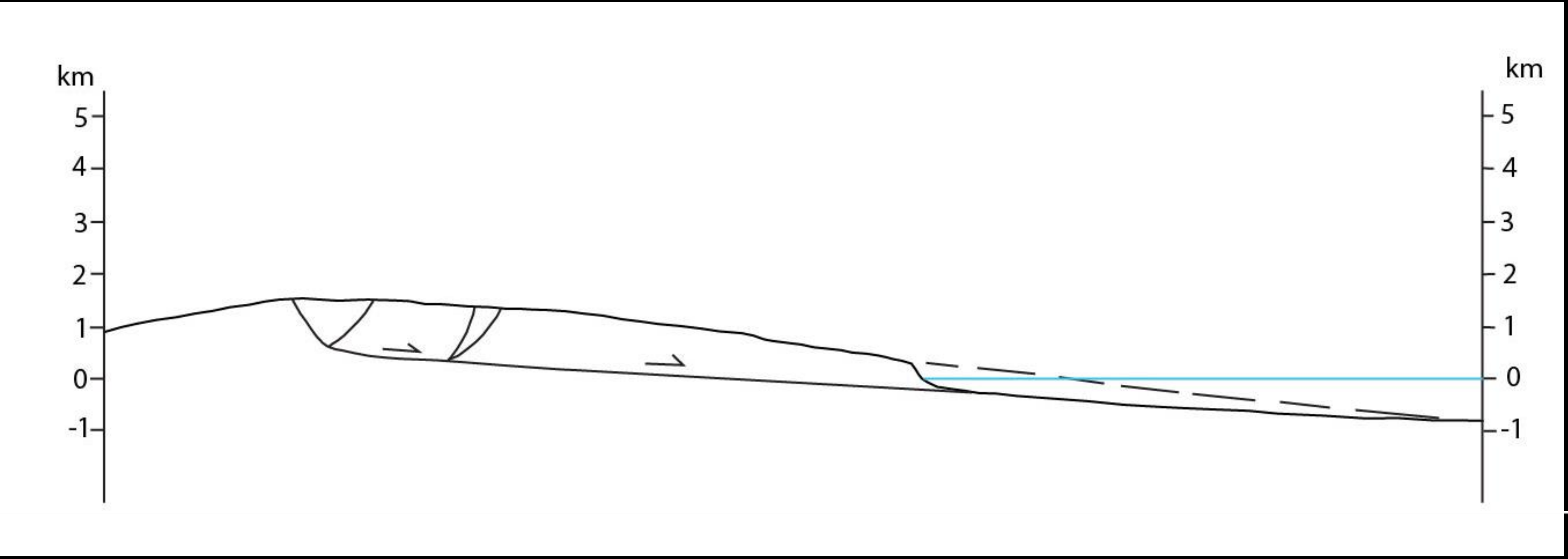
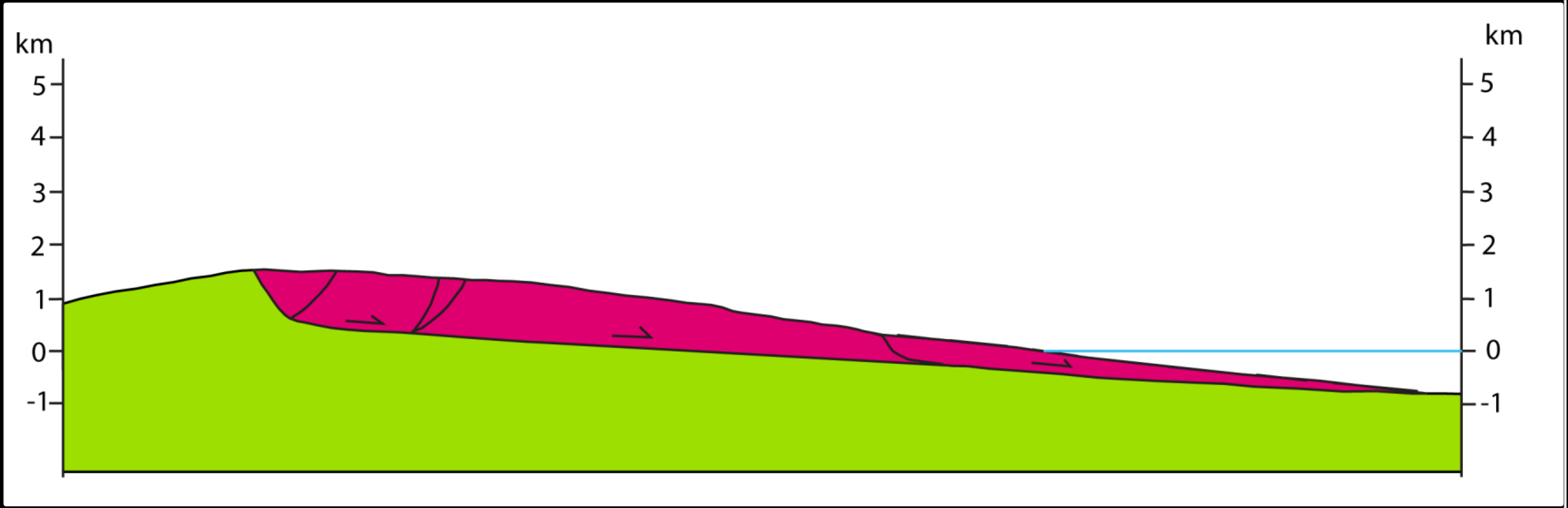


Starting with the final conclusion, the landslide has the configuration shown above near it’s head.

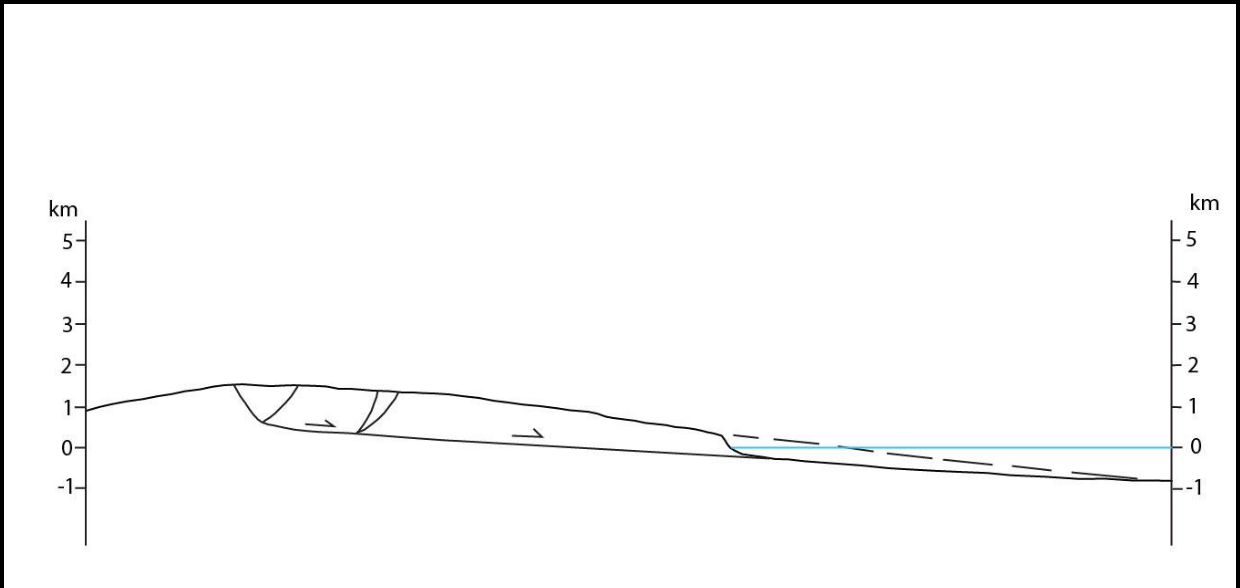


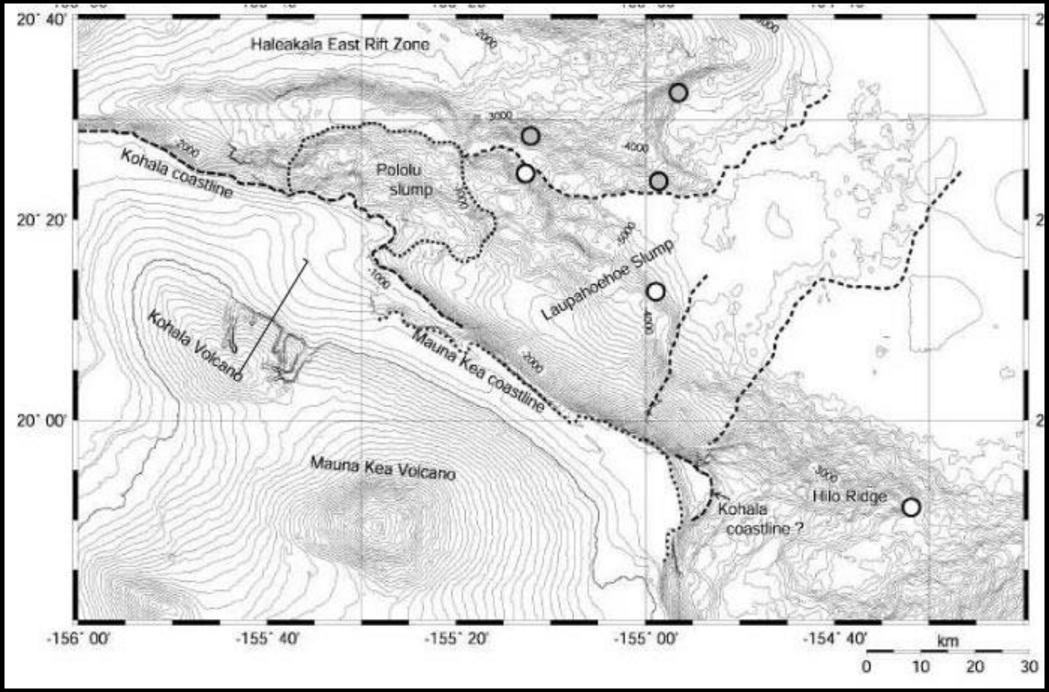
Utilizing the other 3 constraints, the most logical geometry for the landslide slide surface is as shown above. Although not required, the slide surface that neatly fits all of the conclusions based on topographic analysis and also seems logical is that the slide plane daylights at the base of the coastal cliffs. A remarkable aspect of this interpretation is that the slide plane has the same gradient as the seafloor descending from the sea cliff area. This leads to another logical interpretation.





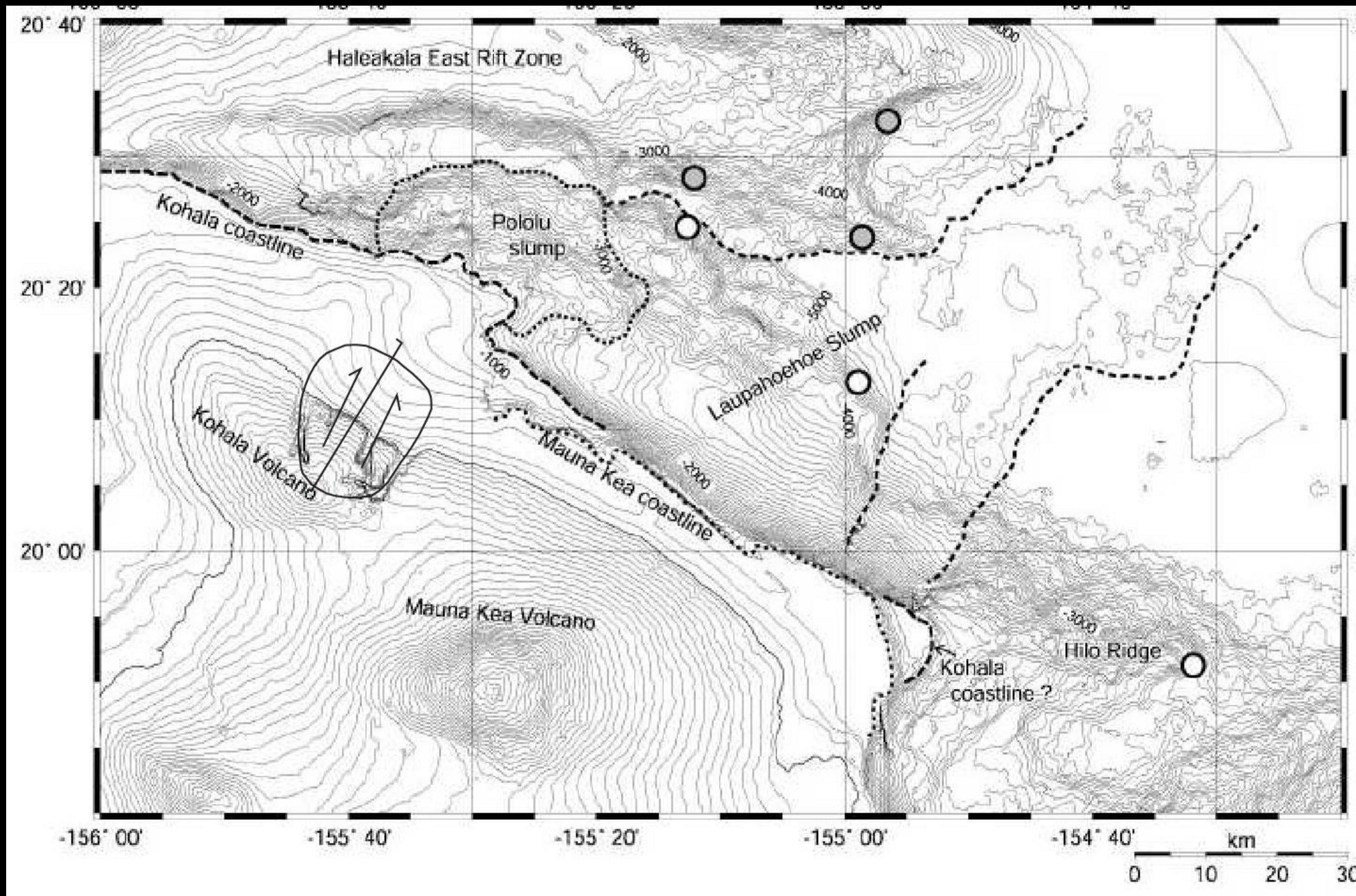
It is inferred that the landslide was initially larger than at present and that the lower part was mobilized at some point as a debris avalanche. Removal of this material resulted in the creation of the sea cliffs.





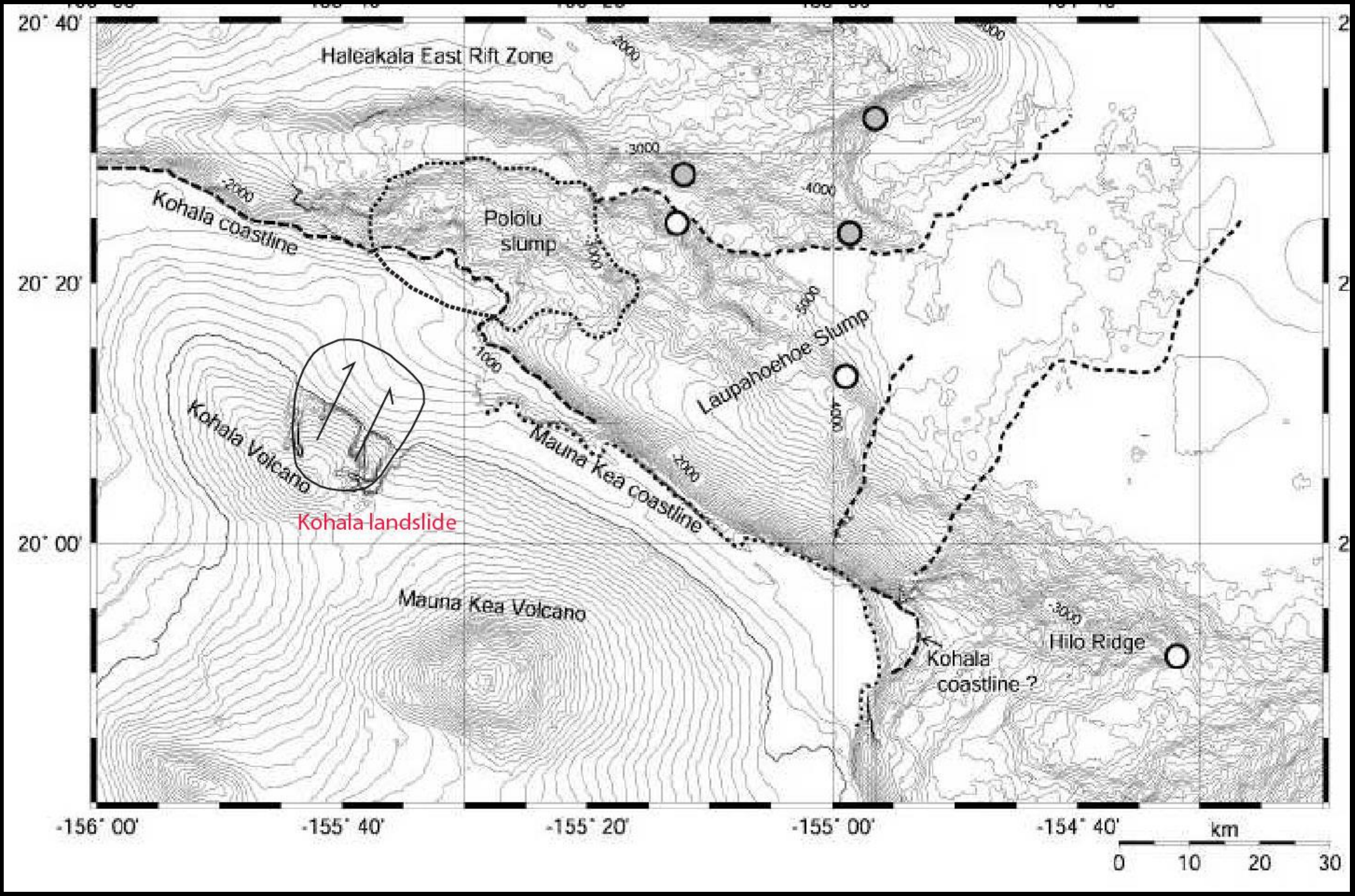
Projecting the existing topographic slope seaward beyond the cliffs allows for determination of the landslide's toe. This toe can be placed on the cross-section. Using this placement and recognizing that the lateral boundaries of the landslide correspond to the location of Pololu and Waipio Valleys allows for a reconstruction of the landslides limits.

Map from: http://pubs.usgs.gov/ds/2006/171/data/cruise-reports/2001/html/27.htm



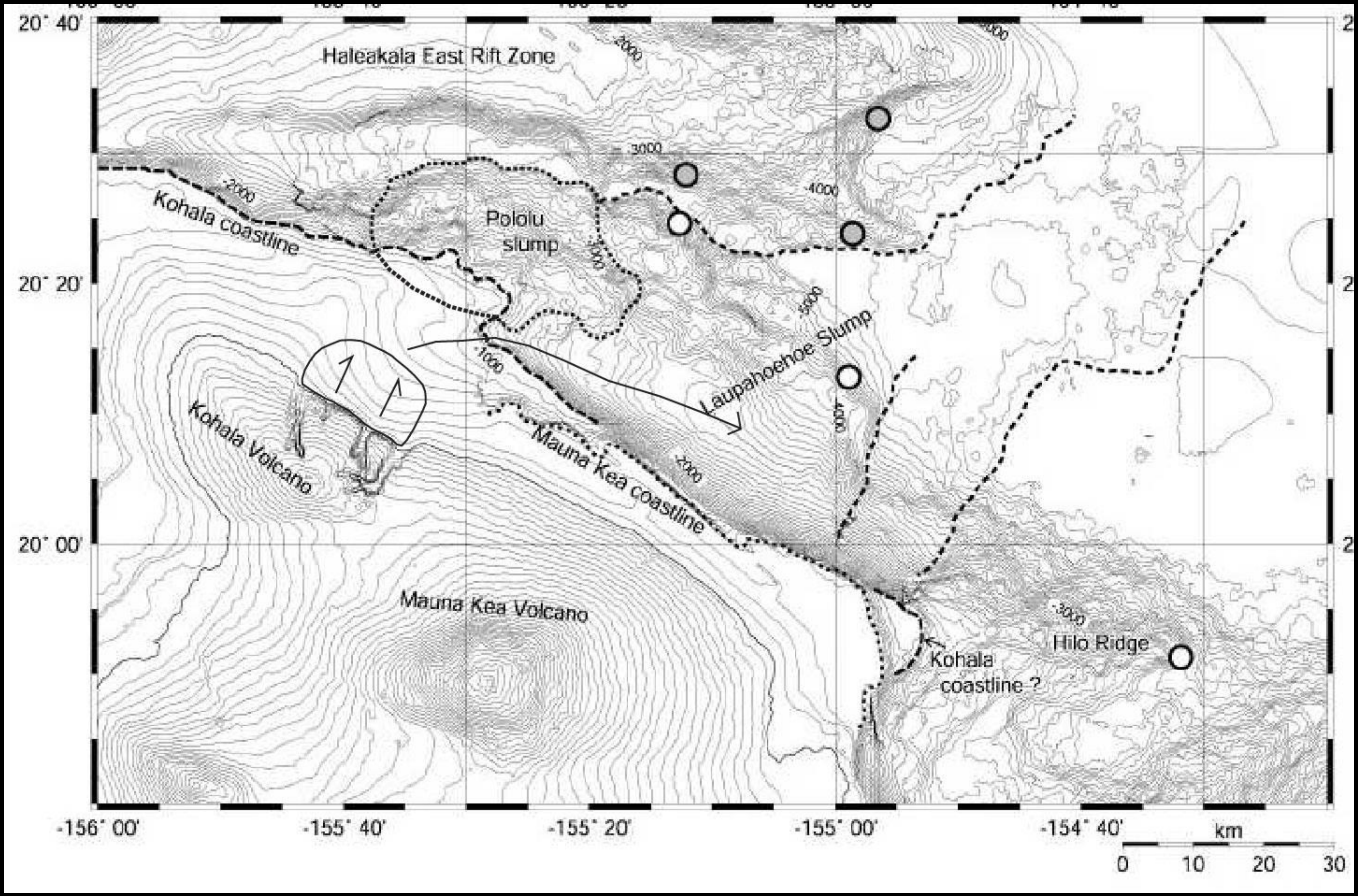
Shown above is the reconstruction for the landslides limit. An important conclusion is that the landslide is separate from the Pololu landslide.

Map from: http://pubs.usgs.gov/ds/2006/171/data/cruise-reports/2001/html/27.htm



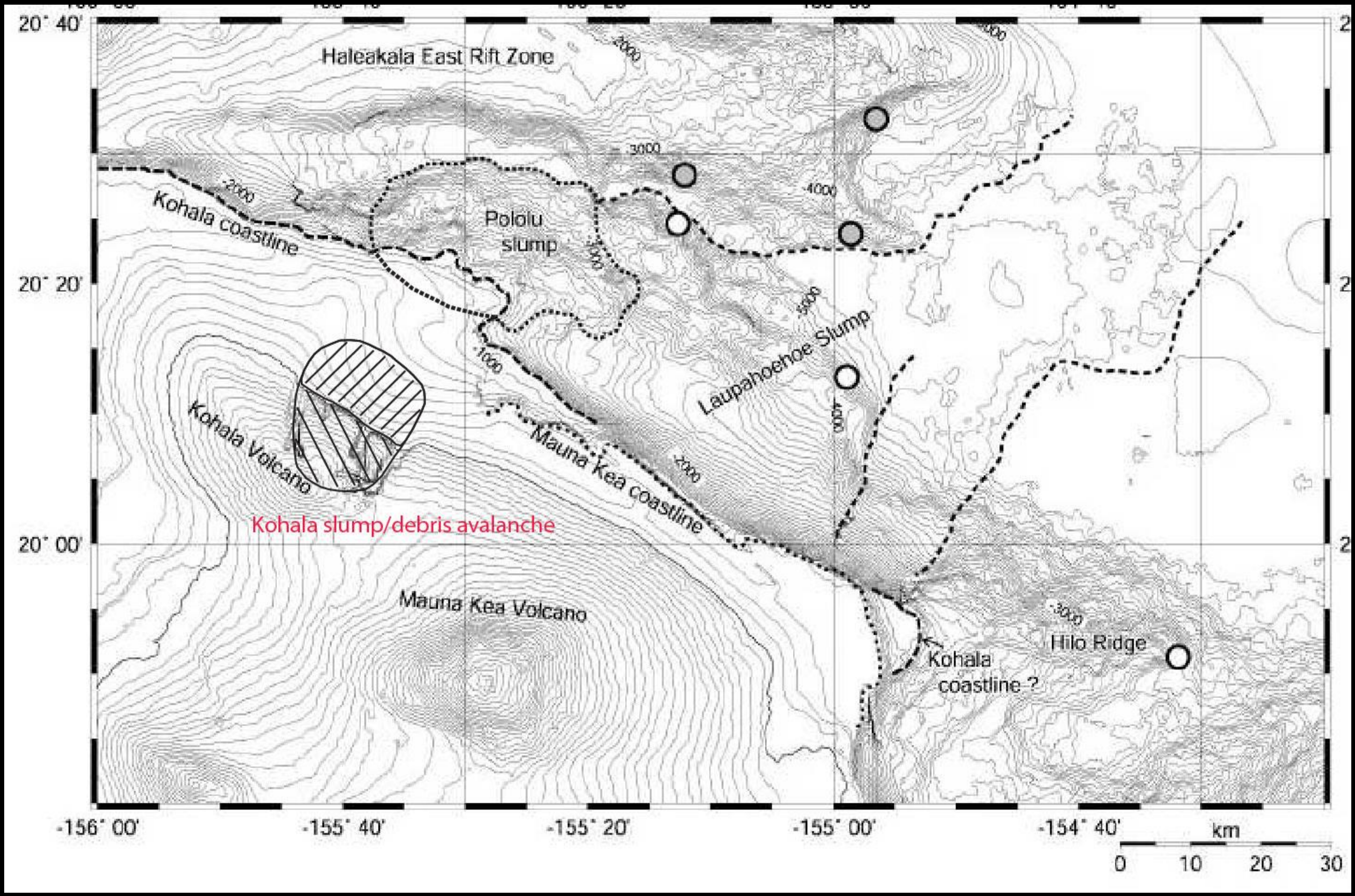
The proposed name for this landslide, then, is the Kohala landslide.

Map from: http://pubs.usgs.gov/ds/2006/171/data/cruise-reports/2001/html/27.htm



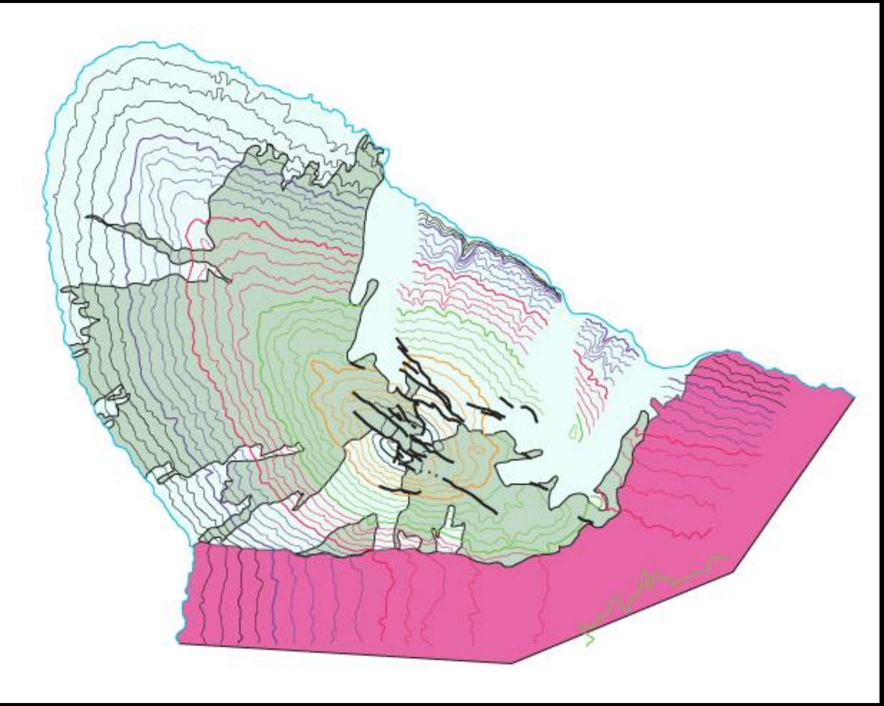
Again, the lower part of the landslide is proposed to have mobilized as a debris avalanche, which traveled far off-shore.

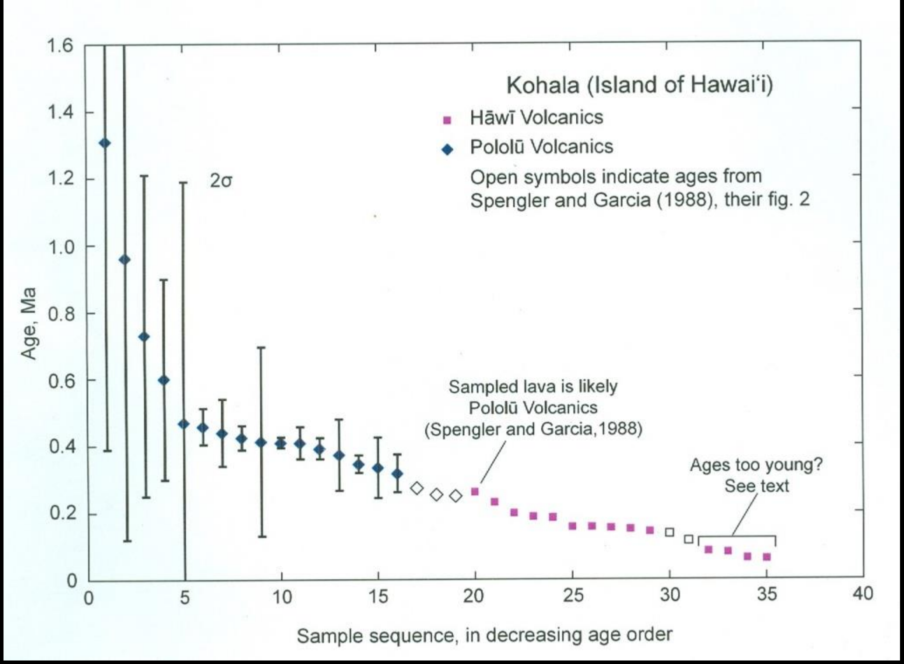
Map from: http://pubs.usgs.gov/ds/2006/171/data/cruise-reports/2001/html/27.htm



The landslide is, thus, a composite landslide and classified specifically as a slump/debris avalanche.

Map from: http://pubs.usgs.gov/ds/2006/171/data/cruise-reports/2001/html/27.htm

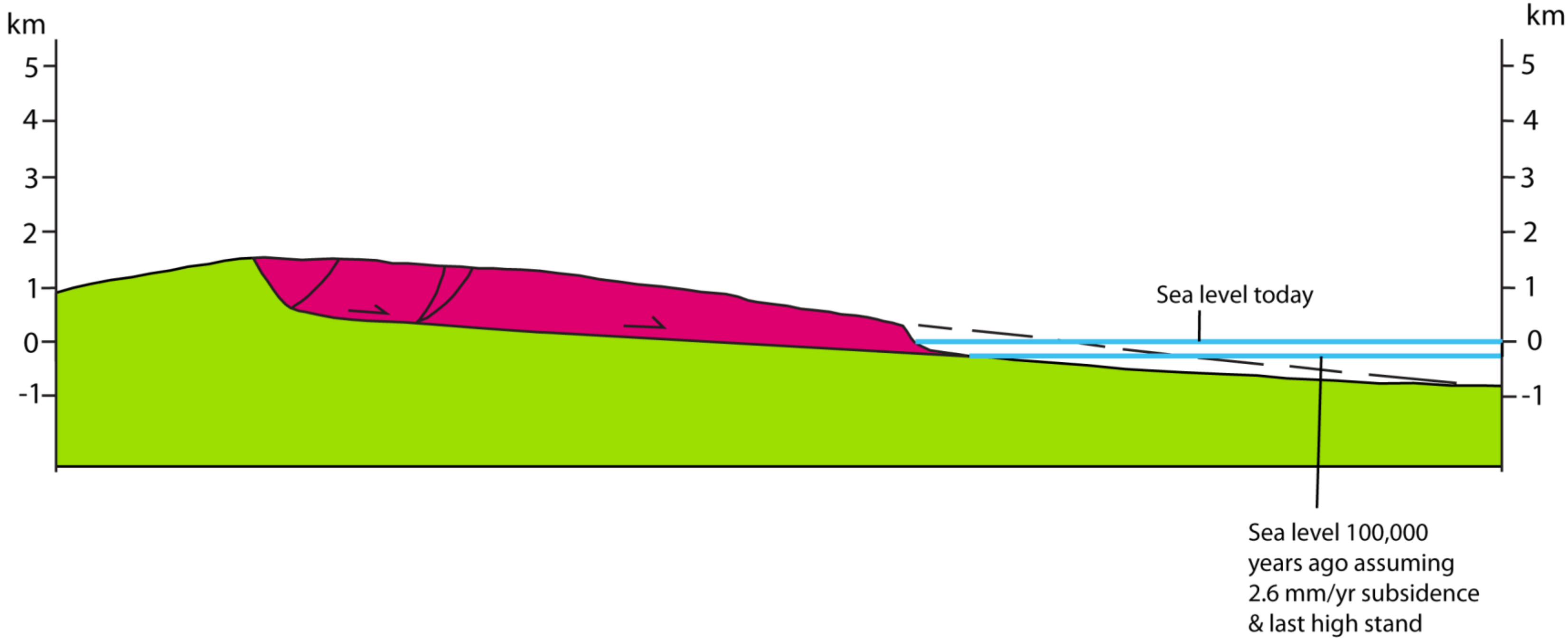




The age of the landslide is not well-constrained, but some constraints are placed on it by the age of the Hawi flows seen in green-gray color on the left. The youngest known Hawi volcanics are approximately 120,000 years old (Sherrod et al., 2007). Because the faults at the head of the landslide cut the Hawi volcanics, it is inferred that the most recent movement of the landslide occurred no less than approximately 120,000 years ago.

Furthermore, a flow of Hawi-age volcanics occurs in Pololu Valley. Assuming the valleys were eroded as a result of the landsliding, then the occurrence of the Pololu Valley flow is more evidence that movement ended by about 120,000 years ago.

Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M., 2007, Geologic Map of the State of Hawai'i: U.S., Geological Survey Open-File Report 2007-1089.



A question that can be asked is why did the lower part of the landslide mobilize as a debris avalanche and the upper part remained as a slump. One possibility is that pore-water pressure in the lower part was sufficient to lower the effective friction. The pore water pressure could have resulted from the lower part of the landslide being at and below sea level.

In evaluating this possibility, a factor that needs to be considered is the elevation of sea level at the time of landslide movement. Assuming the landslide moved 120,000 to 100,000 years ago, then global sea level may have been close to the present given that this time period is approximately the time of the last interglacial. However, local sea level would have been different because the island of Hawaii is subsiding. Assuming subsidence at the rate of 2.6 mm/yr, then sea level would have been roughly 260 m lower at the time of landsliding. If correct, then pore water pressures as a cause for mobilization of the landslide's lower part seems possible.

Kohala Slump/Debris Avalanche