The Cathedral Cliffs Landslide, Park County, Wyoming

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INTRODUCTION

In May of 1995, a complex landslide occurred on the steep northwest-facing slopes below Cathedral Cliffs, in the Clarks Fork Valley of northwestern Wyoming. The slide had a maximum length of 550 m, a maximum width of 300 m, a relief of 190 m, and occurred in an area which was burned by the 1988 Yellowstone fires. The mechanics of slope failure and movement were diverse, ranging from slumping of intact blocks to earthflow. Bedrock stratigraphy of the slope suggests significant structural control on the landslide. Sedimentological evidence, in cores from a shallow lake below the slide, and geomorphological evidence show that the 1995 slide occurred at a site of earlier sliding. Personal accounts indicate that the slide occurred during the middle of the night and lasted several hours. It took weeks to settle and is still not completely stabilized. The purpose of this study is to describe and map the 1995 Cathedral Cliffs Landslide, study its kinematics, determine its major causes, and establish a perspective on mass-wasting events in the slope's history.

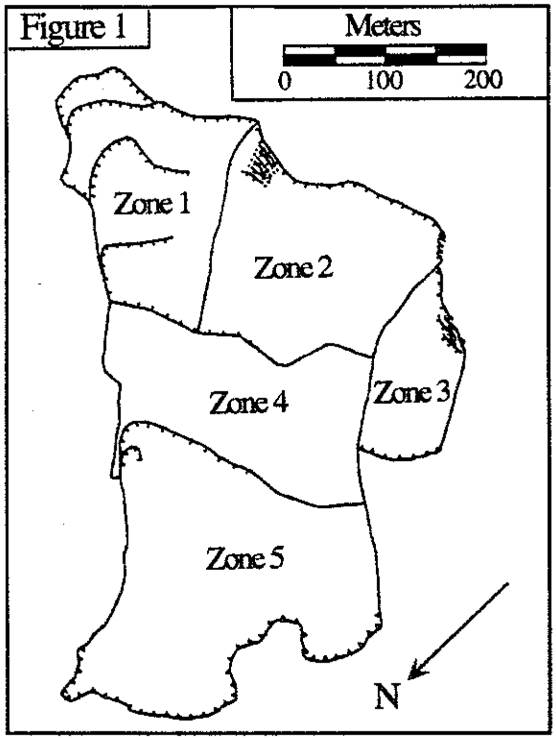
METHODS

The field area was surveyed with a tape measure, inclinometer, a Brunton compass, and a barometric altimeter. A base map was created from this survey, upon which I mapped the various geomorphic features. A core was extracted from Swamp Lake below the slope using a sediment corer and many strong backs. The core was split, measured and described in the field, and then wrapped in tin-foil for transportation back to the lab. There it was kept in cold storage before sampling for radiocarbon dating.

BEDROCK GEOLOGY

The slide occurred in bedrock consisting of two nearly flat-lying limestone units interbedded with shales. From the base to the top these layers are: Wolsey Shale, Meagher Limestone, Park Shale, and Pilgrim Limestone. Colluvium covers the lower part of the slope obscuring most of the bedrock below the Pilgrim Limestone. There are only a few small outcrops and benches of Meagher Limestone. The Pilgrim Limestone, however, outcrops as a continuous cliff up to 10 meters high. The only place along the cliffs where the Pilgrim Limestone is significantly fractured and slumped is directly above the landslide area.

Figure 1



DESCRIPTION

The landslide occurred mostly in the colluvium, but locally affected the shale bedrock. The slumped blocks of Pilgrim Limestone do not appear to have moved during the 1995 slide, and they appear to have limited the uphill extent of the slide. The landslide can be divided into five zones based on geomorphic features and type of failure: the first three are in the head of the slide; the fourth is the neck; and the fifth is the lower neck and toe (see figure 1).

Zone 1: This zone has four well-defined, steep scarps (each 2-5 m high), corresponding with slumped blocks of intact turf and standing trees. There are interesting relationships between compressional folds and tensional cracks in the slumped turf blocks.

Zone 2: This section has one well-defined head scarp (up to 8 m high), with a more broken up terrain below. This terrain consists of many small scarps (up to 1 m high) with thin strips of turf in-between, resulting in a "striped" appearance. There are also some debris flows, giving Zone 2 a more fluid appearance than Zone 1. There is a large, previously-slumped Pilgrim Limestone block above here that controls the position of the head scarp. There are only a few

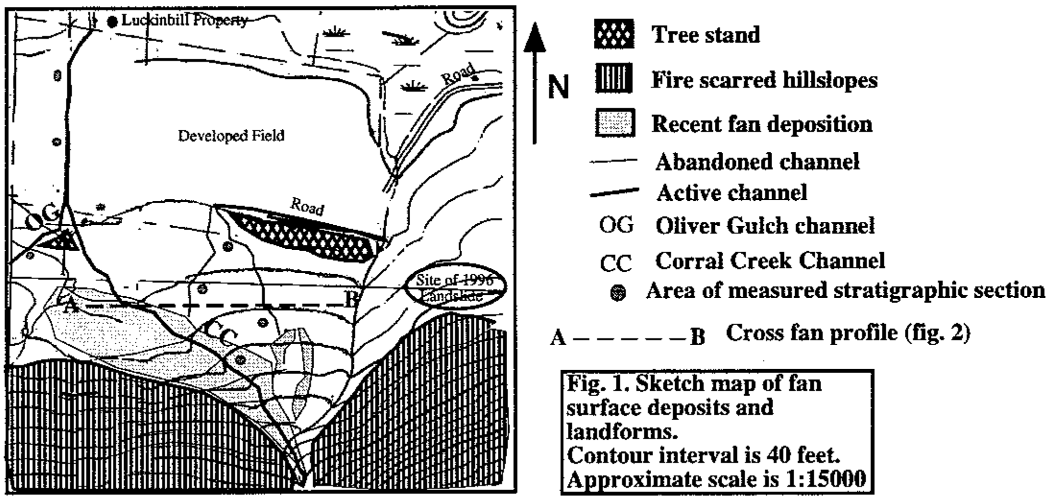


Fig. 1. Sketch map of fan surface deposits and landforms. Contour interval is 40 feet. Approximate scale is 1:15000

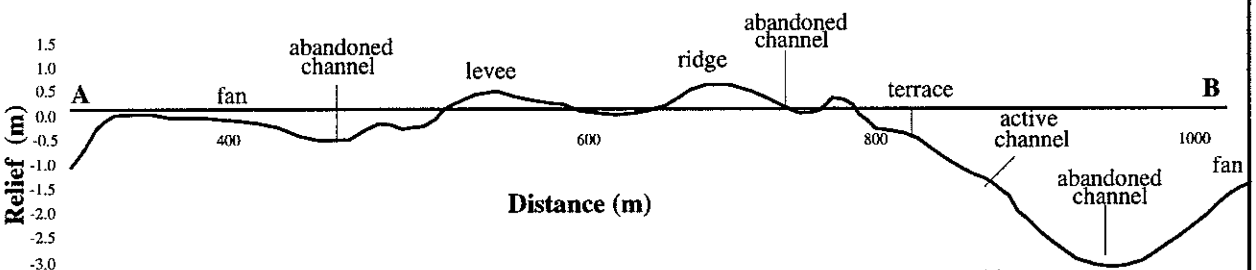


Fig 2. Section of cross fan profile (300-1120 m). Vertical exaggeration: 30x.

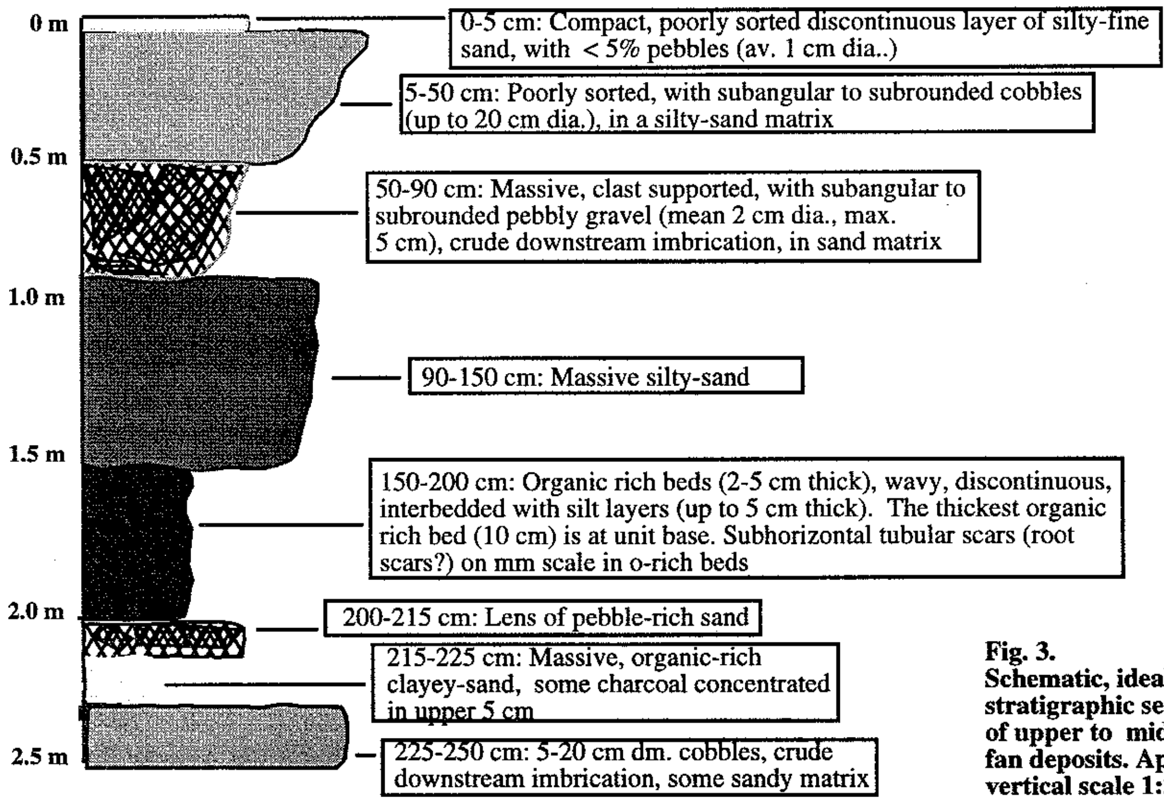


Fig. 3. Schematic, idealized stratigraphic section of upper to middle fan deposits. Approx. vertical scale 1:25

trees still standing in this section.

Zone 3: This zone contains cracks and small scarps (up to 2 m high) at the head, as well as small pressure ridges (up to 0.3 m high) near the toe, but the toe never moved significantly downhill. Like Zone 2, there are previously slumped blocks of Pilgrim Limestone which control the position of the head scarp and act as slope stabilizers. However, in this zone they are broken into 1 m size boulders and piled together, as opposed to one large block in Zone 2. Some of these moved with the landslide but most remained in place. Nearly all the trees here are still standing although some are tilted uphill.

Zone 4: An uphill facing scarp (1-3 m high) marks the uphill boundary of a large mass of turf and trees that stayed relatively intact, despite considerable downslope displacement. This block of earth has a low surface slope and is extremely deformed, with such features as depressions, knolls, folds, tilted trees, fallen trees, cracks, horst and graben structures, faults, and sag ponds. There have been both lateral compression and extension here. The lower boundary of the middle section corresponds with the ledge of Meagher Limestone. This ledge appears to have stopped the middle section from sliding further. In general, the east side of Zone 4 is more intact than the west side. This corresponds with the transition from distinct scarp on the east side to a gradual change in slope on the west.

Zone 5: A large scarp (3-15 m high) separates the intact earth block (Zone 4) from a fluid debris flow (Zone 5). There are almost no trees standing in this zone and turf only appears in small clumps on the lower portion. There are two main toes: the larger more fluid one on the east, and the smaller one with more intact blocks of turf on the west. Between the two toes are two peculiar groupings of dead trees. Both are roughly piled with all trees in a similar orientation (pointing west-southwest, at a 0 - 30 degree angle to the ground). The prominent drainage runs down the east side of Zone 5, dispersing into many smaller streams at the bottom, saturating a large portion of the toe. This lower section is characterized by trees which were pushed over by the advancing toe, illustrating the general direction of advance of the toe.

PRESSURE RIDGES AND FRACTURES AS INDICATORS OF FAILURE SEQUENCE

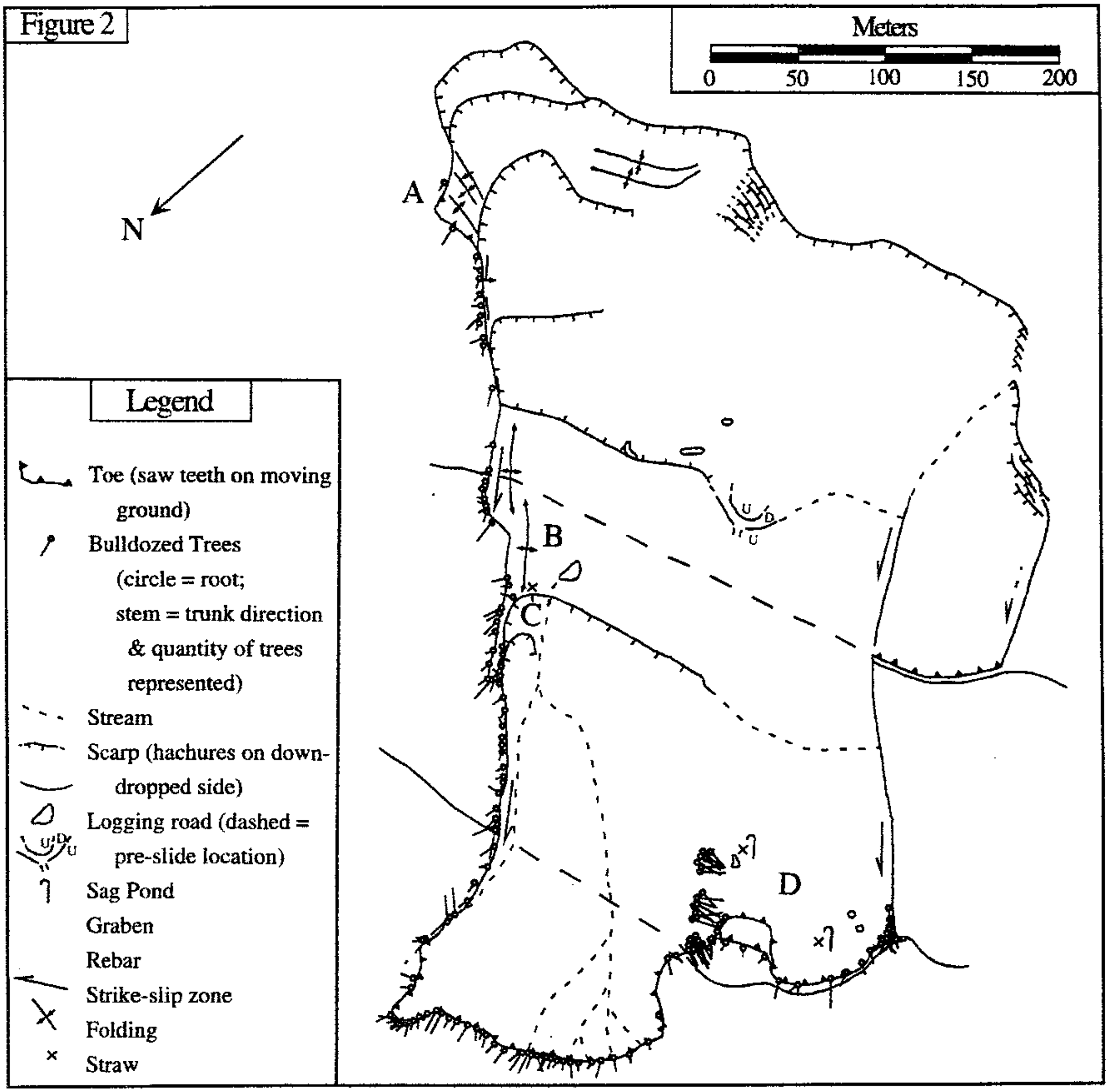
The east flanks of Zone 1 and Zone 4 contain both pressure ridges and tension cracks suggesting a two-stage sequence of events: lateral compression followed by extension (see "A" & "B" in figure 2). In both Zone 1 and Zone 4, the pressure ridges are 2 - 4 m high folds that accommodate a lateral component of movement towards the east flank. In Zone 4, they can are en echelon folds with axes roughly parallel to the east flank of the slide. Trees are generally normal to the ground surface and create a rough fan shape over the fold. The cracks exist in many orientations and positions in this area. The most striking are the ones on or next to the limbs that parallel the crest of the fold. There are also small scarps facing slightly more downhill than the folds and located approximately 5 m away. These cracks and scarps represent extension near a compressional feature. There are also cracks at the crests of the folds which accommodate extension, but in this case accommodate local extension of the outer layer being folded. In Zone 1, the east flank of the landslide was constrained by a levee created by a past landslide. The folds occurred on a mass of turf that was pushed over a low point in the levee and into a depression (see "A" in figure 2). The toe of this small mass of turf bulldozed over trees. The uphill side of this mass of turf is cut by a significant scarp and slump block, showing a secondary phase of deformation. Below this scarp there is another fold, with its axis oriented parallel to the east flank. This structure represents a component of lateral pressure to the northeast because this flank is constrained by the old levee. The folds and bulldozed trees are compressional features while the scarp is tensional.

Because there are folds regionally bounded by cracks and scarps, movement in this part of the slab must have been a multistage event, where compression pushed sediment laterally and caused the folds, which then was followed by an extensional failure leaving the cracks and scarps below. This interpretation means that the scarp between Zones 4 and 5 was active after Zone 4 slid onto the Meagher ledge. This does not necessarily mean that Zone 4 slid onto the ledge and then the whole of Zone 5 subsequently failed. There is not enough evidence to conclude that. In fact it is nearly impossible to do more than speculate about the chain of events in the landslide's development. Despite this, it is true that there was localized compression and then extension in Zone 4.

SLIDE DISPLACEMENT

The landslide crossed the paths of two of logging roads, displacing them down the slope. The lower road was just barely covered by the west toe in Zone 5, but the east toe completely destroyed the road. The road was not found in this very fluidized section. The upper road lies just downslope of Zone 3 which never slid, but zone 4 cuts through it, leaving a large mass of trees and turf where the road once was. We could not find any portion of Zone 4 that could accommodate a road. There were too many trees. Therefore it must be downslope, somewhere beyond the end of the turf block, somewhere in Zone 5. Because this zone is so fluid a road is hard to find. However, we noticed that straw bales and rebar had been used on other sections of the road to control erosion. We found straw and numerous tree stumps on the east flank, about 60 m below the intact road, at the edge of Zone 4, and both straw and rebar along the west flank, about 150 m below the intact road, far into Zone 5 (see "C" & "D" in figure 2). This disparity in displacement is related to the difference of cohesion between the east and west flanks of Zone 4. The east flank experienced compression and is very intact, whereas the west flank is more broken up. Perhaps more of the west side of the turf block slid down the scarp into Zone 5 and thus added a great deal of distance to the overall displacement of the road.

Figure 2

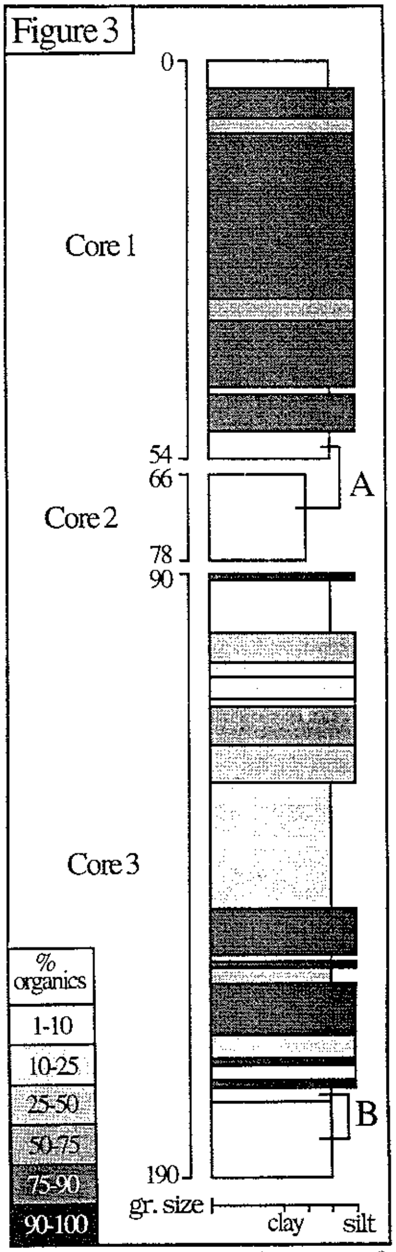


SLOPE HISTORY

The entire Cathedral Cliffs slope is characterized by geomorphic features related to landslides. Besides the mantle of colluvium, which consists dominantly of shaley material with dispersed sand to boulder sized limestone clasts, there are old levees, scarps, toes, and rotationally-slumped Pilgrim Limestone blocks. The presence of a well-vegetated bulging toe immediately downslope from the 1995 landslide suggests an earlier slide at the same site. The slope's susceptibility to mass-wasting is emphasized by another landslide, though smaller and steeper, which occurred in 1996 at the western end of the Cathedral Cliffs.

In order to examine the history of past landslides at the site of the 1995 slide, we took a sediment core from Swamp Lake at the base of the slope directly below the landslide site. The two meter core from the swamp was dominated by dark organic-rich silts, punctuated by infrequent organic-deficient layers of fine clastic sediment a few cm to 10 or more cm thick. The youngest of these organic-deficient layers is at the core top and appears to represent material eroded from the 1995 slide debris. On the assumption that similar organic-deficient layers lower in the core also represent mass-wasting events on the slope above the swamp, the core provides a record of Holocene landslides.

The core revealed two other thick organic-deficient layers of fine clastic sediment, one at 50-78 cm depth, and the other at the bottom of the core, 179-190 cm depth (see "A" & "B" in figure 3). The upper clastic layer is interpreted as deposition of fines after a landslide on the Cathedral Cliffs took place. The lower fine clastic layer may also represent a mass-wasting event but could be fine sediment deposited as outwash from a retreating glacier up valley. By radiocarbon dating the organic rich sediment directly above a fine clastic sediment layer, we can determine a minimum age of the upper layer (i.e., a mass-wasting event). The two layers, upper and lower, had minimum ages of 1,830 +/- 85 years BP (GX-22525) and 7,490 +/- 200 years BP (GX-22652), respectively. Because there is limestone in the immediate environment, possible hardwater effects must be considered when interpreting radiocarbon ages. The lower layer was primarily terrestrial material that had fallen into the lake and therefore was not subject to hardwater effects. Thus the lower date should be reliable. The upper layer consisted of an intact mass of roots, suggesting that they grew in situ, at the base of a lake. This would suggest the hardwater effect could easily be a factor, and so the date may be too old. In conclusion, core shows that there were at least two and no more than three large mass-wasting events in the last ~7500 years.



CAUSES

Glacial oversteepening of valley walls of weak Cambrian rocks is the cause for repeated landslides over the entire Cathedral Cliffs area. The portion of the Cathedral Cliffs, which slid in 1995, is likely prone to sliding because of the channeling of runoff. With a channel encised in hard rock cliffs, the stream does not migrate much and thus saturates this area. The slumped blocks of Pilgrim Limestone are evidence for this susceptibility to repeated sliding. The 1988 fire may have played an important role, as the east flank of the landslide coincides with the boundary of burned and unburned trees. The death of trees and the decrease in evapotranspiration over the landslide area may have raised the water table and decreased the slope's shear strength. Road construction across the site during salvage logging after the fire may have further destabilized the slope. The immediate trigger for the 1995 event was a combination of intense rainfall and spring snow melt.

CONCLUSION

It is not surprising to have repeated landslides on an oversteepened postglacial slope consisting of shales and limestones. However, this landslide was significant in the slope's history as there has been only one or two other landslides of this magnitude recorded since deglaciation. Structure played a very important role. The resistant Pilgrim Limestone blocks redirected the head scarp to weaker areas in the slope, and the Meagher Limestone provided slope stability to keep Zone 4 from sliding further. The geomorphic features provide evidence as to the sequence of some events on the slide, but the whole story cannot be inferred. The displacement of the logging road is a useful tool in determining the distance the slide moved, but because of the diverse nature of the slide mechanics, it is not representative of the slide displacement as a whole.

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TOURMALINE IN SOUTHWESTERN MAINE

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