

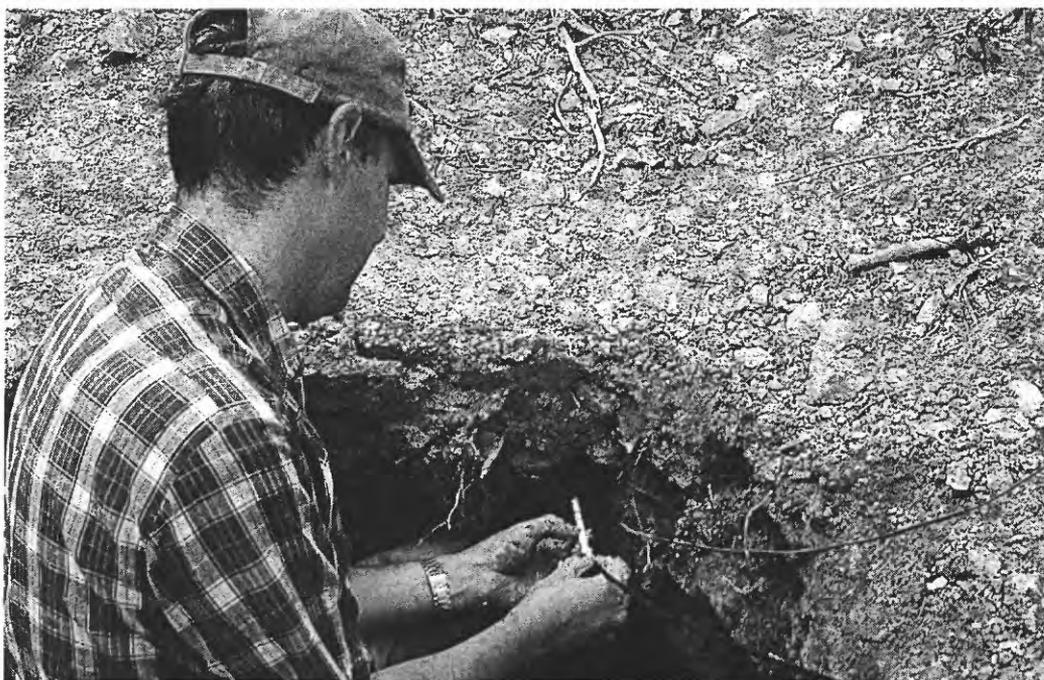
**U.S. Department of the Interior
U.S. Geological Survey**

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Brigham Young University**



**Preliminary interpretation of seasonal movement of the Slumgullion
landslide as determined from GPS observations, July 1998 - July 1999**

**by J.A. Coe, J.W. Godt, W.L. Ellis, W.Z. Savage, J. E. Savage, P.S. Powers, D.J.
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Installation of a soil temperature probe in the landslide. Data from the probe, as well as from other monitoring instruments, were used to interpret seasonal slide movement.

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Preliminary interpretation of seasonal movement of the Slumgullion landslide as determined from GPS observations, July 1998 - July 1999

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Abstract

Six sets of 19 GPS observations made between July 1998 and July 1999 show that the Slumgullion landslide in southwest Colorado moved throughout the year, but that daily velocities were highly variable on a seasonal basis. Seasonal variability in velocities is probably due to ground water levels that decrease when surface water is unavailable or cannot infiltrate frozen ground and increase when surface water from melting snow or rainfall infiltrates unfrozen ground. This hypothesis is supported by data showing seasonal changes in soil-water content and by a correspondence between velocity variability and air- and soil-temperature data from a meteorological station on the slide. In general, slide movement increased or decreased with rising or falling temperatures. Velocities of the middle and upper parts of the slide, which peaked between May and July, correlate with temperature especially well. Velocities of lower part of the slide, which peaked between March and May, correlate less well. This discrepancy in times of peak movement is probably due to the elevation difference between the lower and upper parts of the slide. Air temperatures at the lower part of the slide are probably 2-5 °C (5-9 °F) warmer than the upper part, which causes earlier spring melting of frozen ground and snow and a subsequent increase in velocities.

Annual movements and daily velocities were smallest at the head and toe of the landslide and largest in the central, narrowest part of the landslide. Movements and velocities deviated from this distribution in areas where they were affected by major structural elements within the slide. Movement occurred near the head of the slide on landslide deposits that were previously identified as inactive. Annual movements of the lower and middle parts of the slide were greater than any previously documented.

Introduction and Setting

The Slumgullion landslide is located about 5 km southwest of Lake City in the San Juan Mountains of southwestern Colorado (fig. 1). The landslide is about 6 km long and ranges in elevation from about 2750 to 3650 m. The active part of the landslide is about 3.5 km long and ranges in elevation from about 2950 to 3650 m.

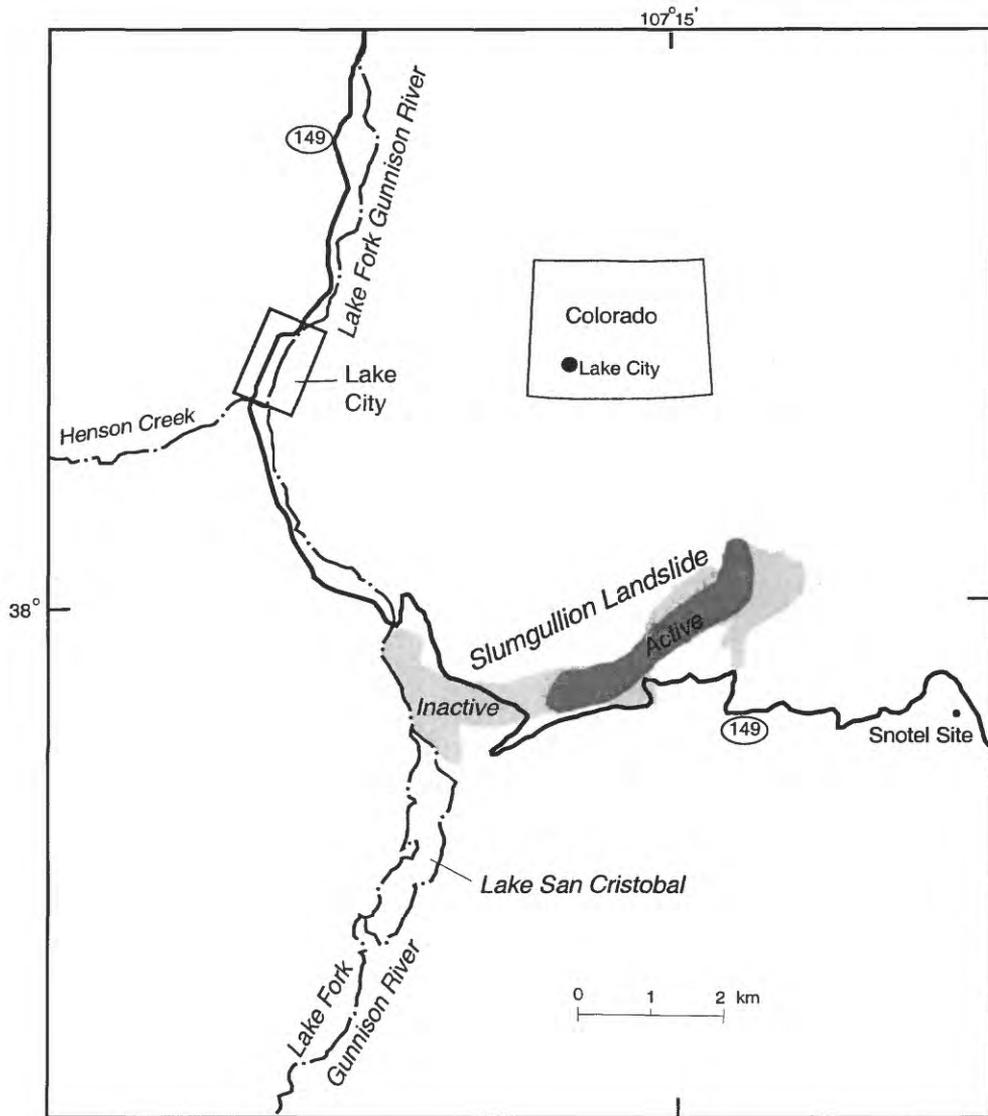


Figure 1. Location map showing the active and inactive parts of the Slumgullion landslide. Also see location of Snotel site.

The landslide is in the montane and subalpine ecological zones as defined by Löve (1970). Vegetation on the slide consists predominantly of deformed, open stands of Englemann spruce and aspen. Vegetation surrounding the slide consists of closed stands of conifers and aspen.

Meteorological data collected between October, 1993 and December, 1999 at a Snotel weather station (Western Regional Climate Center, U.S. Department of Agriculture unpublished data, 1999) located about 4 km southeast of the head of the slide at an elevation of 3520 m (fig. 1) reveal the following observations about precipitation and temperature conditions in the area. Annual precipitation totals ranged from 50-90 cm, about two-thirds of which came in the form of snow between October and June. Extreme temperatures ranged from -31°C (-23°F) on December 17, 1996 to 24°C (76°F) in July, 1995 and June and July, 1998. Average daily temperatures ranged from -27°C (-16°F) on December 17, 1996 to 15°C (59°F) on July 18, 1998.

The main scarp of the landslide occurs in Tertiary volcanic rocks of the Uncompahgre-San Juan caldera complex. Many of these rocks are highly altered by acid-sulfate hydrothermal alteration (Diehl and Schuster, 1996). The landslide is predominantly a yellow, sandy-silty-clay with scattered patches of bouldery debris. The lower portion of the slide contains large patches of reddish-brown and purple clay. The clay-rich landslide material has medium to high plasticity and high swelling potential (Chleborad and others, 1996).

Although the landslide has been observed and studied since the late 1800s. (e.g., Endlich, 1876; Atwood and Mather, 1932; Crandell and Varnes, 1961; Varnes and Savage, 1996), with the exception of limited observations by Savage and Fleming, (1996), little is known regarding the nature and magnitude of movements in response to seasonal variations and short-term meteorological changes, and nothing is known regarding the effect of surface and subsurface water on such movements. Previous studies (Crandell and Varnes, 1961; Powers and Chiarle, 1996; Smith, 1996; Baum and Fleming, 1996; Fleming and others, 1999) have documented annual rates of movement ranging from 0.5 m/yr at the head and toe of the slide, up to about 6 m/yr in the narrowest part of the slide (for example, see fig. 2). Several additional studies have documented movements over shorter periods of time. Jackson and others (1996) used GPS to measure daily velocities of up to 1 cm/day at 6 locations during a 4 day period in June, 1993. Savage and Fleming (1996) measured velocities over a 9 month period (April 1993 - January, 1994) at 3 locations on the landslide and documented an increase of movement in the spring, presumably with thawing of the landslide surface. They inferred that variations in velocity over the course of a year were in part due to hydrologic controls, but suggested that, because of the remarkable long-term record of relatively constant movement, the landslide might contain various internal mechanisms to counterbalance changing meteorologic and hydrologic conditions that act to decrease or increase the velocity of slide movement. For example, high ground-water pressures following a wet winter might be equilibrated through a network of springs, which would bleed off excess water and decrease ground-water pressures. Although some preliminary mapping of springs and sinks has been completed (Fleming and others, 1999), the overall hydrology of the landslide and its relation to movement and meteorology is unknown.

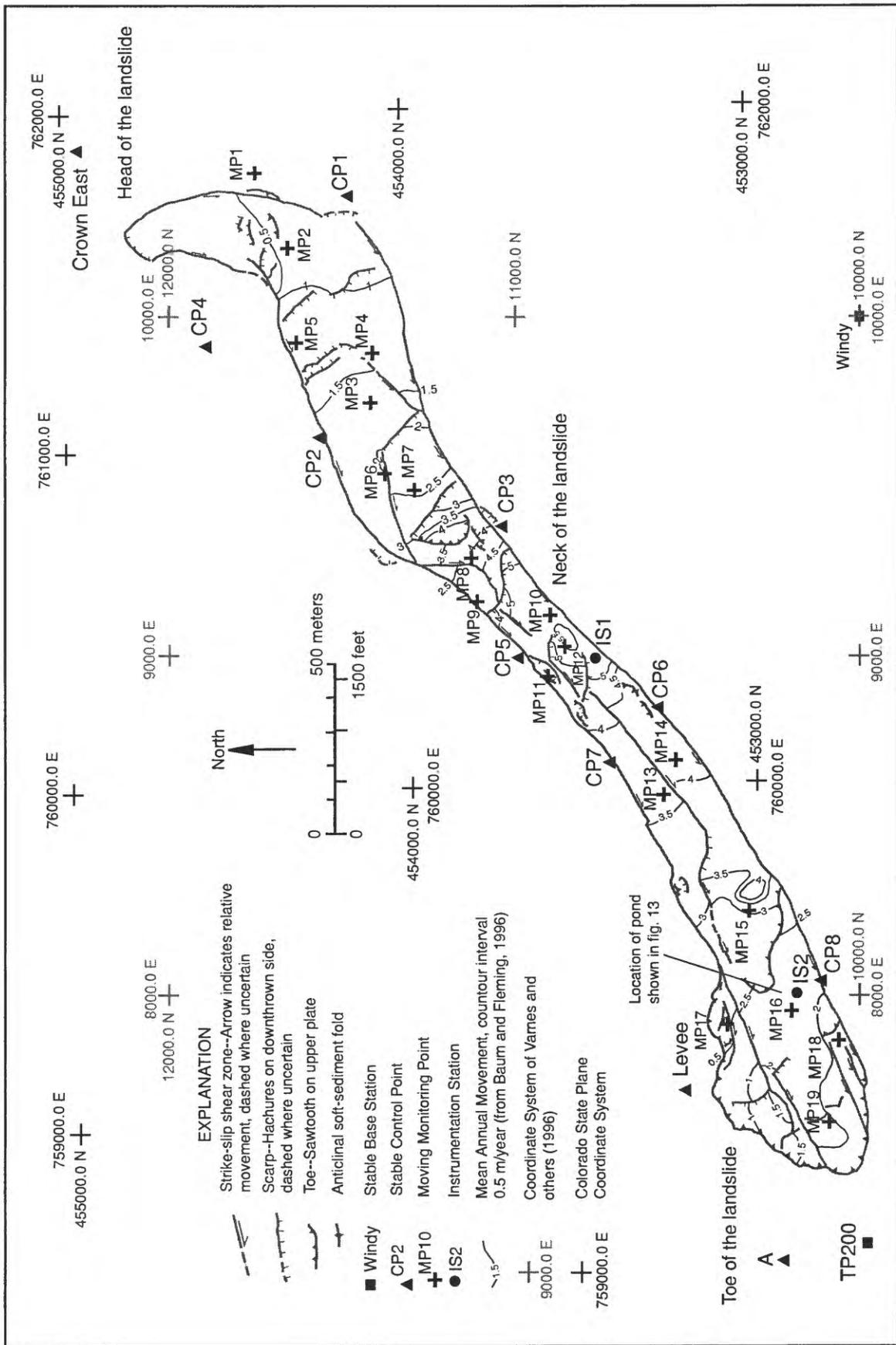


Figure 2. Active part of the Slumgullion landslide with structural elements, contours of mean annual movement, GPS base stations, control points, and monitoring points. See Coe and others (2000) for a description of base stations and control points. Modified from Baum and Fleming (1996).

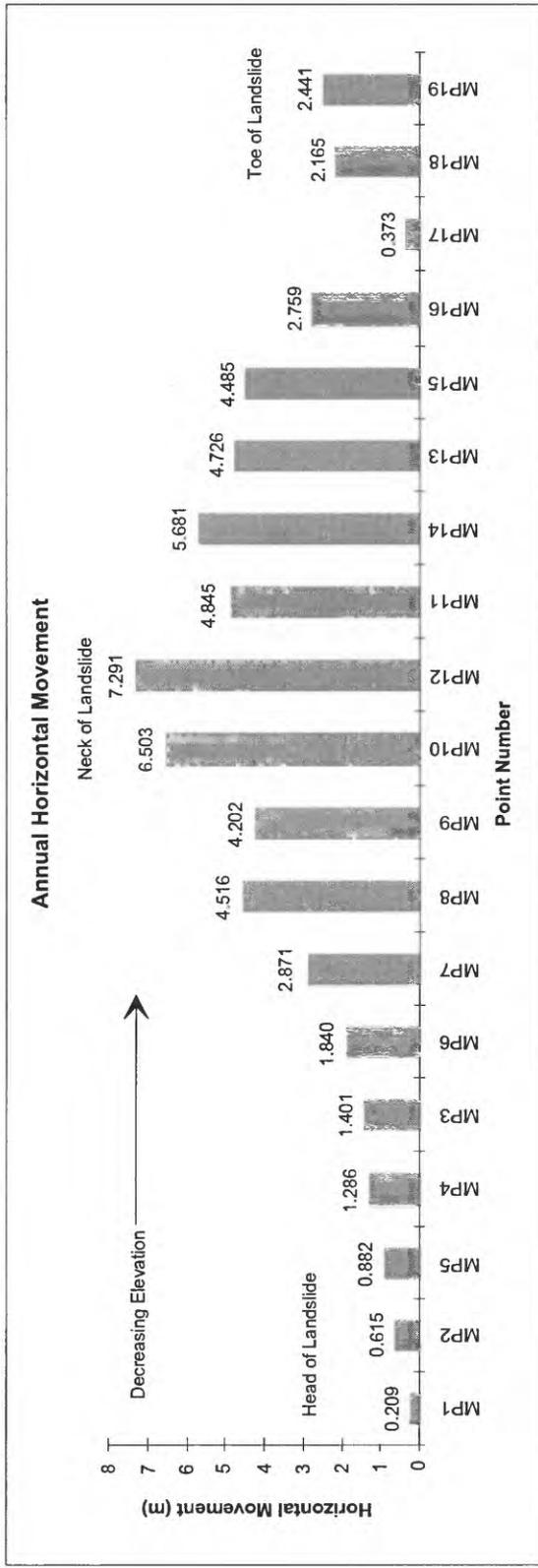
In 1998, Brigham Young University (BYU) and the USGS began work on a 3-year NASA-funded study of the Slumgullion landslide. The objectives of the study are to: 1) measure movement of the entire active part of the landslide on a seasonal basis using GPS, and an airborne, interferometric capable, Synthetic Aperture Radar and/or Scanning Microwave Altimeter remote sensing system; 2) attempt to correlate the measured movement with observed temperature, rainfall, snow depth, and ground- and surface-water levels and pressures, 3) evaluate the remote sensing systems for monitoring the movement of landslides by confirming a static velocity field surrounding the landslide and by comparing remotely sensed movement data to simultaneous measurements at GPS points and to previously measured deformation rates, and 4) develop a model for landslide deformation based on all of the combined data. BYU is responsible for designing, building, and operating the remote sensing system(s). Current (January, 2000) plans call for the acquisition of airborne remote sensing data beginning in the summer of 2000. The USGS is responsible for monitoring movement using GPS, as well as monitoring hydrologic and meteorologic fluctuations on the slide.

The purpose of this report is to present a preliminary interpretation of seasonal movement as determined from GPS observations between July 1998 and July 1999. The GPS observations, methods, and movement data are summarized in a separate report (Coe and others, 2000). We interpret seasonal movements in the context of selected hydrologic and meteorologic data. The entire set of hydrologic and meteorologic data will be published as a separate report. We also compare annual movements from 1998/1999 to previously measured annual movements. Below, we first review the movement data (from Coe and others, 2000), then briefly describe the meteorological conditions during the 1998/1999 monitoring year, and then follow with our interpretation.

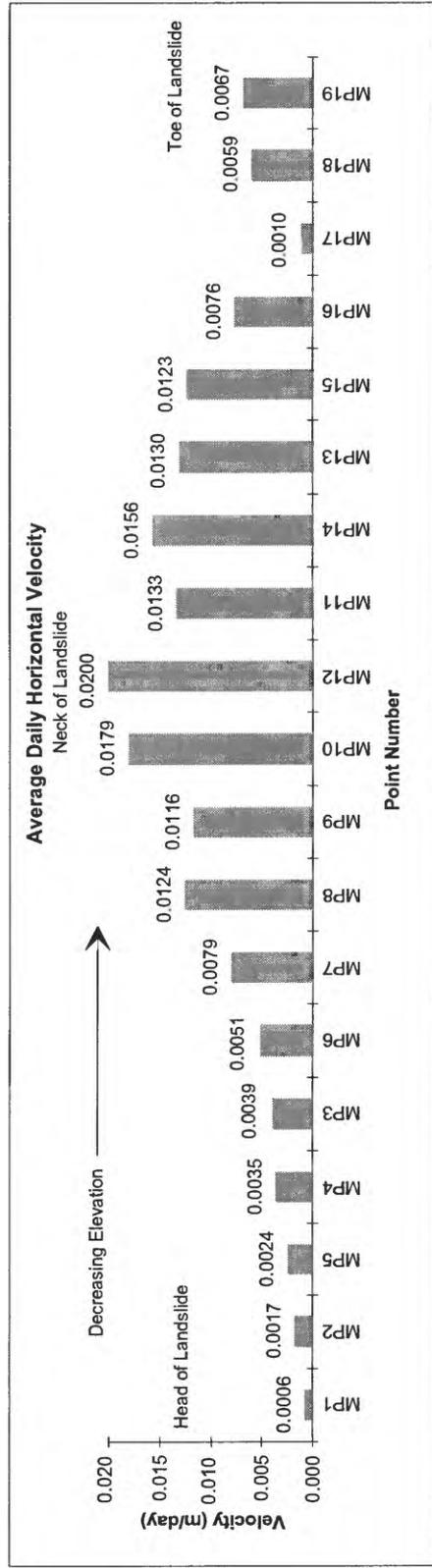
Landslide Movements Determined by GPS Observations

GPS observations were made at 19 monitoring points (MP1-MP19, fig. 2) on the active portion of the landslide. Observations were made during six, 2-day field campaigns. The dates of the six campaigns were as follows: July 28-29, 1998; October, 21-22, 1998; January 5-6, 1999; March 23-24, 1999; May 11-12, 1999; and July 27-28, 1999. All monitoring points moved between each set of observations. Total movement (combined horizontal and vertical movement) was largely dominated by the horizontal component. In a general sense, annual horizontal movements and average annual velocities are smallest near the head and toe of the landslide and increase to a peak at the central, narrowest part (neck) of the landslide (fig. 3 and fig. 4). Annual horizontal movements ranged from 0.15 m at MP1 to 7.3 m at MP12 (fig. 3a). Average daily horizontal velocities over the year-long monitoring period ranged from <0.001 m/day at MP1 to 0.020 m/day at MP12 (fig 3b). Annual vertical movements ranged from less than 0.01 m at MP1 to 1.29 m at MP10. All points, except MP16, moved downslope. MP16 moved upward (see discussion below).

Velocities of individual points varied considerably according to the season, with minimum values ranging from 10-66 percent of maximum values (fig 5). The largest differences occurred at points near the head of the slide (MP1, MP2, MP5) where the seasonal minimum velocities were 10-27 percent of the seasonal maximums.



a



b

Figure 3. Bar graph showing the distribution of a) annual horizontal movement and b) average daily horizontal velocities over the year-long monitoring period.

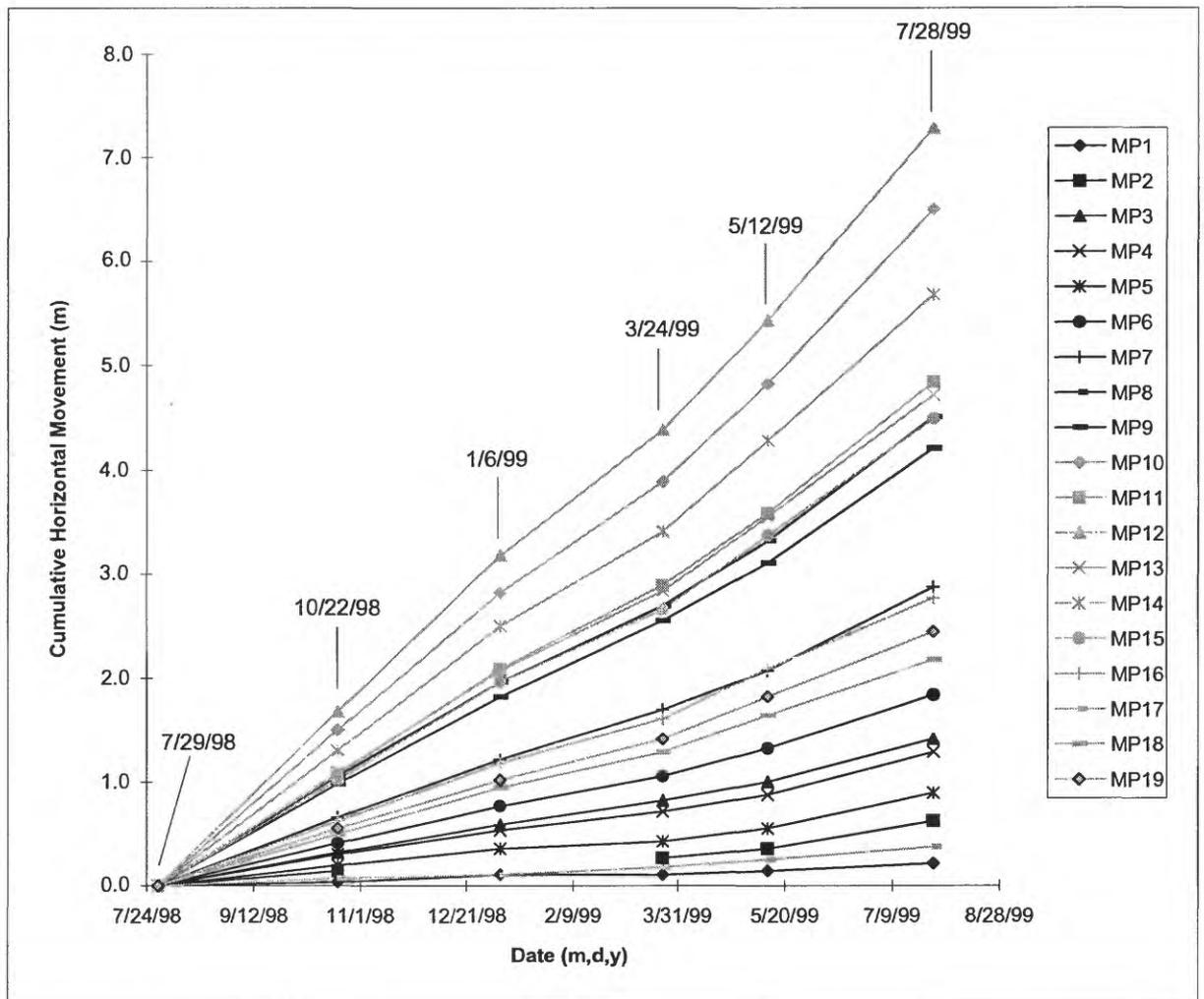


Figure 4. Diagram showing cumulative horizontal movement of monitoring points. Ending dates of GPS campaigns are shown.

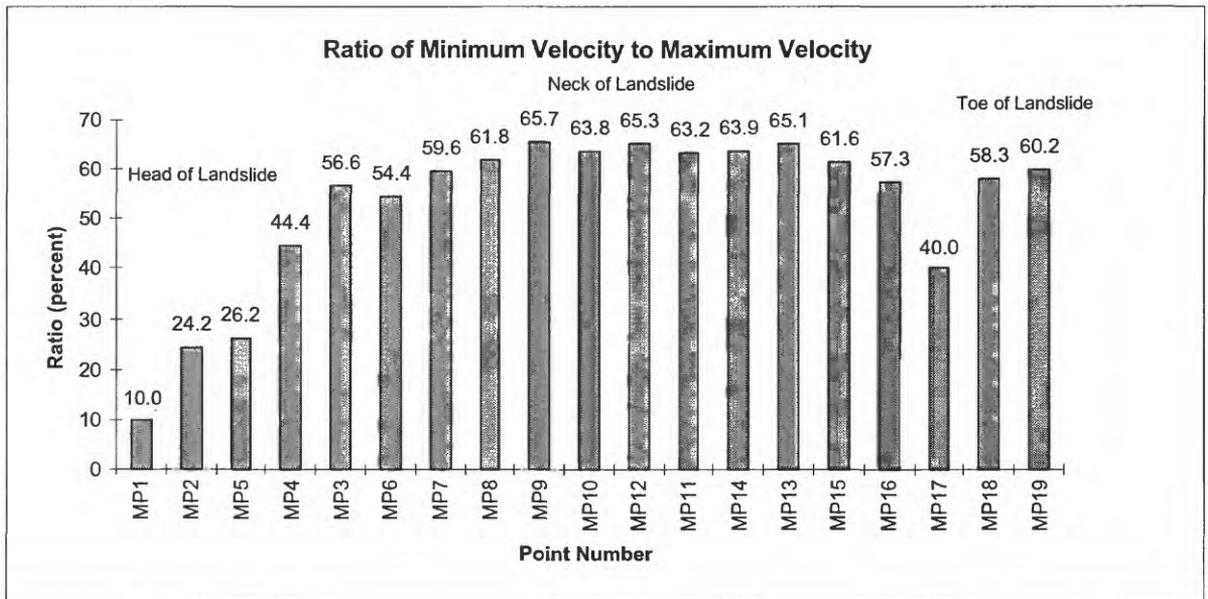


Figure 5. Bar graph showing the ratio of minimum velocity to maximum velocity at each monitoring point.

The smallest differences occurred at points in the neck of the slide (MP9, MP10, MP12, MP11, MP14, and MP13) where the seasonal minimums were 63-66 percent of the seasonal maximums.

Minimum and maximum velocities occurred at different times on different parts of the slide (fig. 6). At 15 of the 19 monitoring points (MP1-MP15), maximum velocities occurred between May 12 and July 28 (referred to as summer throughout the remainder of the report). At the remaining four points (MP16-MP19), located at the lowest elevations near the toe of the slide, maximum velocities occurred between March 24 and May 12 (referred to as spring throughout the remainder of the report). Minimum velocities at all points, except MP17 (briefly discussed below), occurred between January 6 and March 24. At MP17, the minimum velocity occurred between October 22 and January 6.

Meteorological Conditions During the 1998/99 Monitoring Year

Meteorological data collected since October, 1993 at the Slumgullion Pass Snotel station about 4 km southeast of the head of the landslide (fig. 1) show that the 1998 water year (October 1, 1997 to September 30, 1998) was average in terms of precipitation, but that the 1999 water year was the wettest on record during the 6 year period with about 89 cm (35 in.) of precipitation (fig. 7). Much of this anomalous precipitation occurred during the spring and summer. In the summer, the Slumgullion slide and the entire state of Colorado were subjected to a prolonged flow of monsoonal moisture that triggered numerous and widespread landslides and debris flows (see Colorado Geological Survey, 1999).

Air temperatures since Oct. 1993 show a distinct seasonal cycle with minimum temperatures occurring between mid-December and mid-January and maximums occurring between mid-June and mid-July (fig. 7). Between July 1998 and July 1999, the lowest temp (-24 °C, -12 °F) occurred on February 11 and the highest temperature (21° C, 70° F) occurred on June 28 (fig. 8). Measurable snowfall began in October, 1998 and lasted through May, 1999. Average daily temperatures dropped below freezing for the winter season on November 28, 1998 and rose above freezing for the first time in the spring on April 12, 1999.

Preliminary Interpretation

Probable causes for seasonal variability in velocity

Seasonal variations in velocity imply that slide movement is affected by seasonal changes within the landslide. Although one year of movement data is not entirely sufficient to link seasonal changes in movement to other seasonal changes (for example, meteorologic or hydrologic changes), all currently available data suggest that seasonal changes in movement are probably related to changing subsurface water levels that are controlled by the infiltration of surface water. The infiltration of surface water is a function of the availability

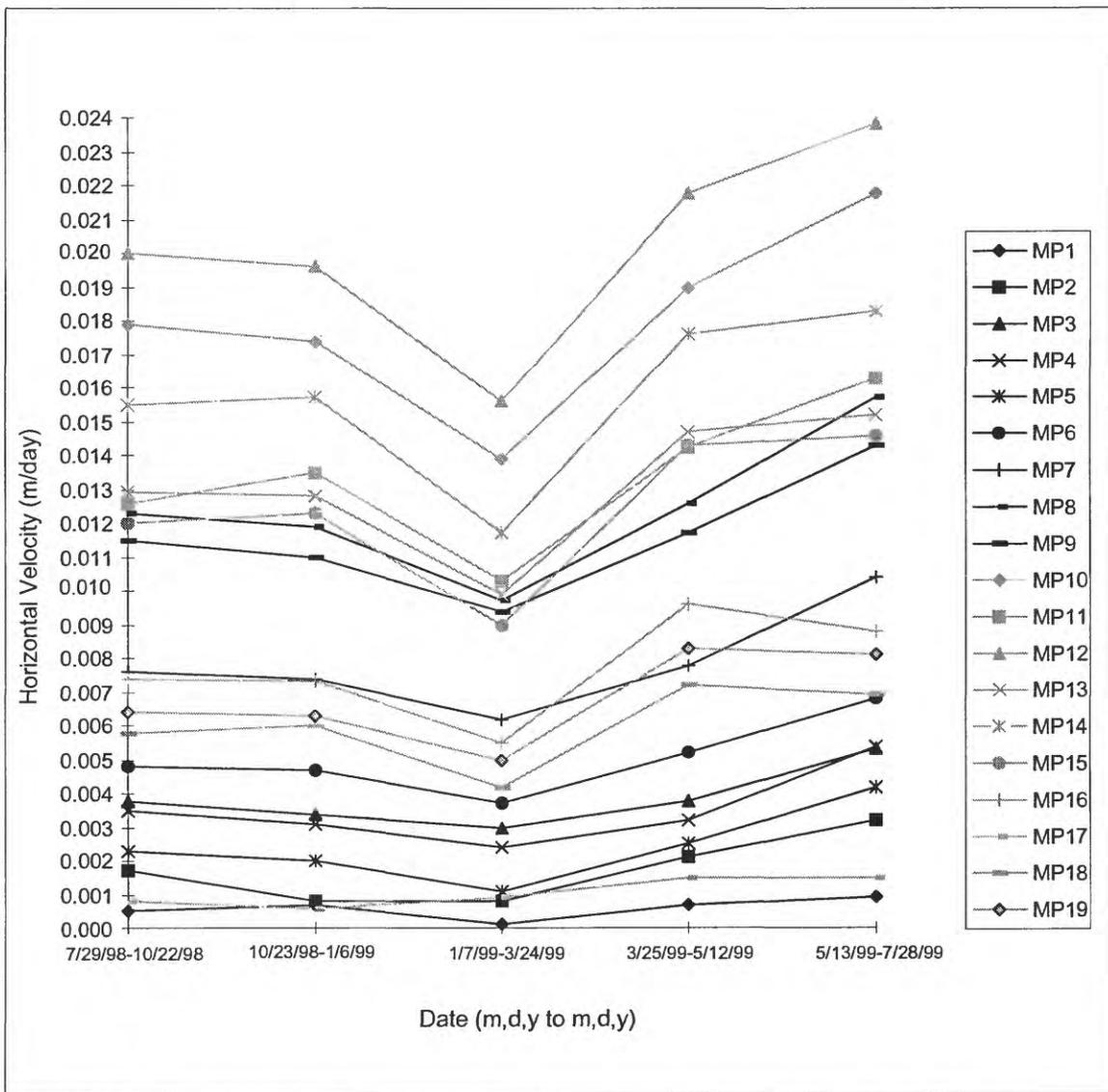


Figure 6. Diagram showing daily velocities of monitoring points. Dates shown are periods between GPS observations.

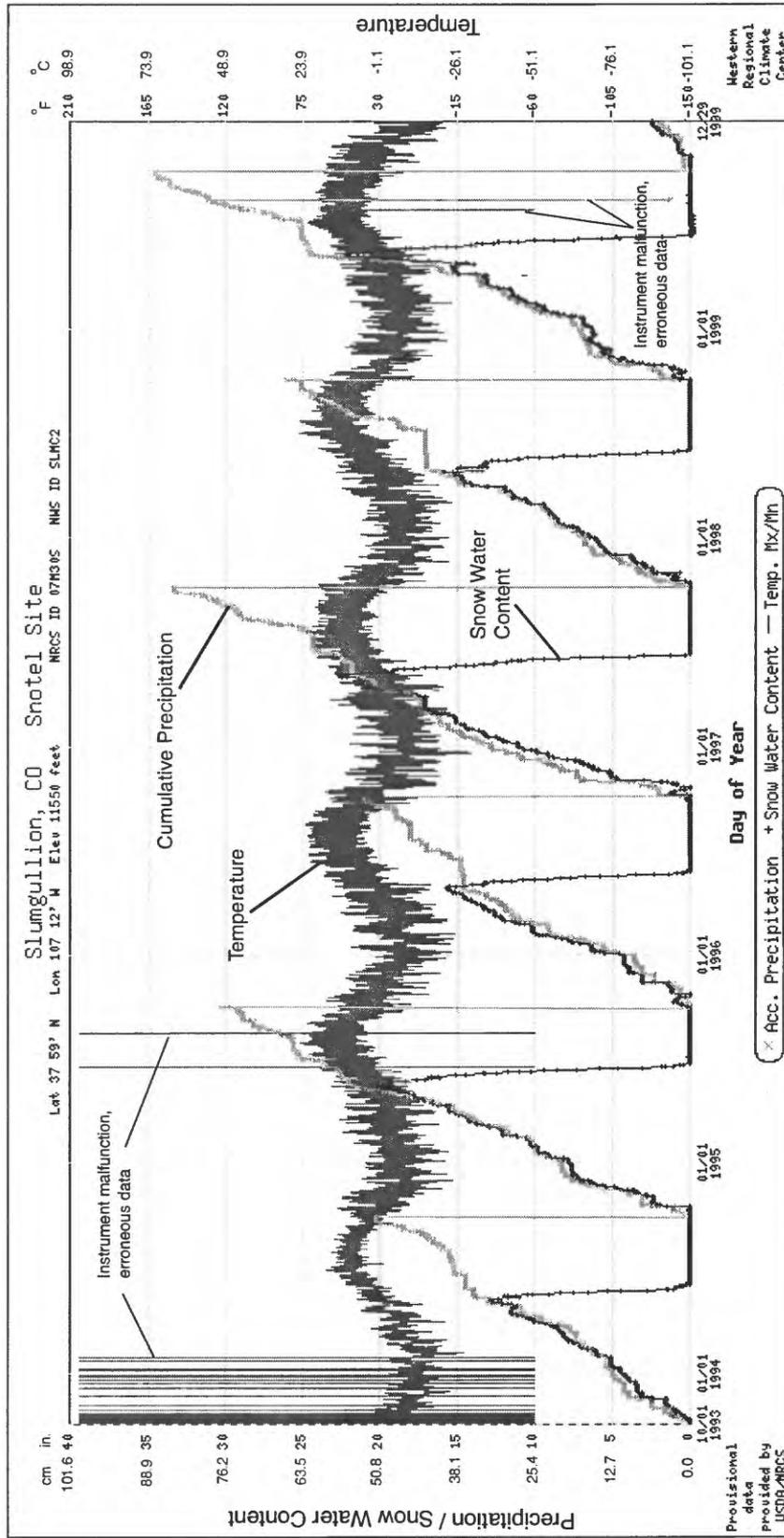


Figure 7. Precipitation, snow-water content, and air-temperature data from the Slumgullion Pass Snotel station for the period October 1, 1993 to December 29, 1999.

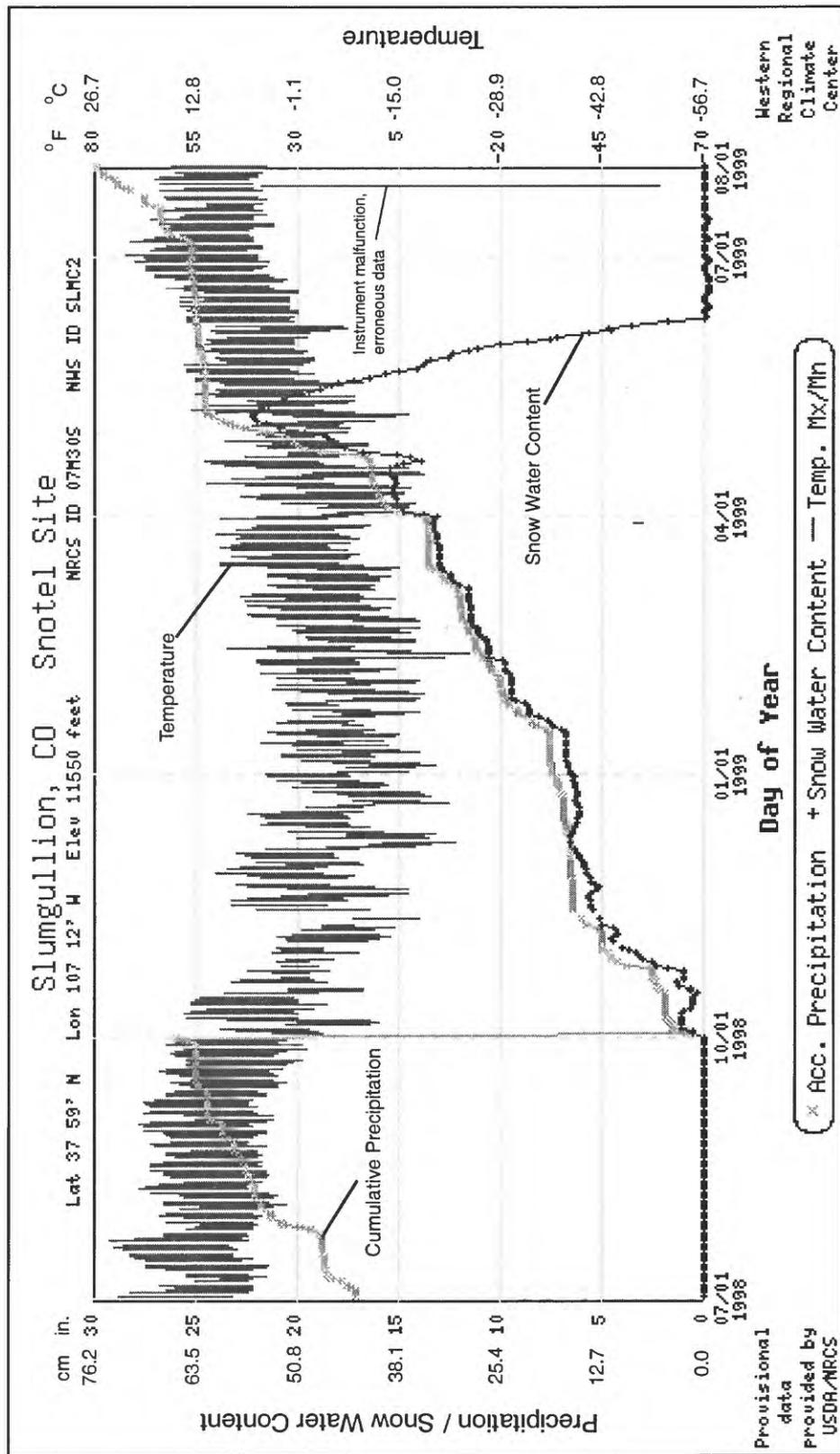


Figure 8. Precipitation, snow-water content, and air-temperature data from the Slumgullion Pass Snotel station for the period July 1, 1998 to August 1, 1999.

of water from snowmelt or rainfall and the nature of the slide material (frozen or unfrozen).

Frozen ground can dramatically decrease surface water infiltration by blocking soil pores with ice (Kane, 1980; Kane and Stein, 1983; Stähli and others, 1999). Water content of the soil is the primary factor that controls the degree to which freezing changes infiltration. Infiltration rates decrease with increasing water content. Previous work has shown that the soil-water content of the clay-rich, Slumgullion slide material is high (38-56 percent, Chleborad and others, 1996), suggesting that infiltration rates would be dramatically reduced by freezing.

Soil-water content and soil-temperature data collected during the 1998/1999 monitoring period at USGS Instrumentation Station 1 (IS1, fig. 2) indicate that the soil-water content at Slumgullion was high prior to, and following, freezing and that the surface-water infiltration was reduced during the winter months when the ground was frozen (figs. 9 and 10). Soil-water content data were collected using two different types of instruments, a Water Content Reflectometer (WCR in fig. 9) and two soil-moisture sensors (ST in fig. 9). The WCR determines volumetric water content based on the dielectric constant of the surrounding soil, which is sensitive to the soil-water content. The ST sensors are electronic resistant devices that are used to provide estimates of soil tension, which is related to the soil-water content (refer to figure 9 caption for further details). Because the operating principles of both types of instruments rely on the presence of liquid water, the meaning of the sensor's response with respect to water content in frozen ground is uncertain. For this reason we focus the following discussion on the soil-water content data that were obtained in non-frozen soil.

Soil water content data show that, with the exception of the winter months, slide material at a depth of 0.2 m had a volumetric water content that ranged from about 36-64 percent and was between 35-45 percent for most of the year (WCR, fig. 9). Soil moisture data from depths of 0.2 and 1 m show that, with the exception of the winter months, the slide material was saturated or nearly saturated (low soil tensions) for most of the year (ST, fig. 9). The response of the soil-moisture sensor at a depth of 0.2 m indicates a sudden and large apparent increase in soil tension in early December, 1998. This sensor response corresponds to ground freeze at 0.2 m depth as indicated by the soil temperature data (fig. 10). Likewise, the sudden and large decrease in soil tension shown by the 0.2 m sensor in late April, 1999, corresponds to the onset of ground thaw (see soil temperature plot in fig. 10). The soil-moisture sensor response during this period of ground freeze is not considered meaningful with respect to soil tension, or therefore, as an indicator of water content. The soil-moisture sensor at 1 m depth does not show the dramatic response attributed to freezing at the 0.2 m depth, and the soil-temperature data also indicated that the ground at the 1 m depth did not freeze (fig. 10). The soil-moisture sensor at 1 m depth does, however, show an increase in soil tension from about -5 kPa to about -30 kPa during the winter months, indicating a decrease in soil-moisture content at this depth when the ground above was frozen (fig. 9).

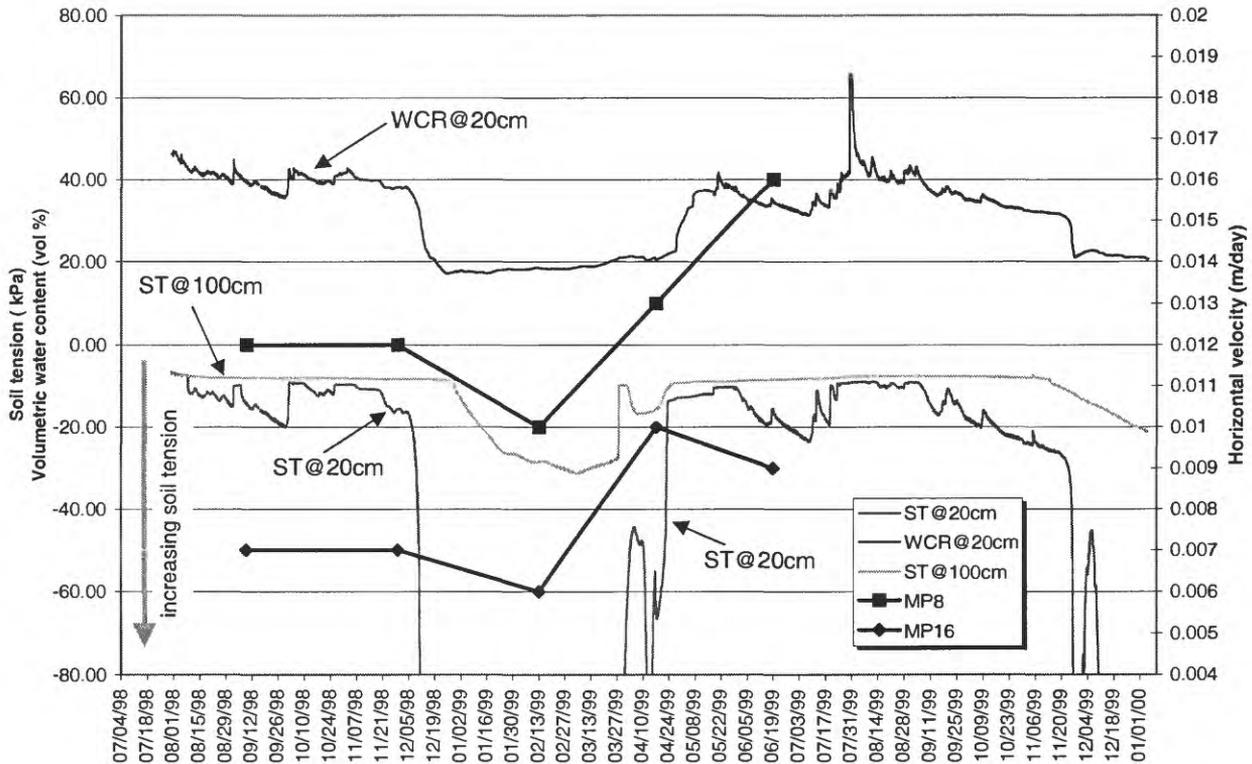


Figure 9. Volumetric soil-water content and soil tension at IS1 in relation to daily velocities of monitoring points MP8 and MP16 (see figure 2 for locations). Volumetric soil-water content (WCR) was measured at a depth of 0.2 m using a Campbell Scientific, Inc., Water Content Reflectometer (model CS615). The reflectometer uses time-domain measurement methods to determine the volumetric water content using an empirically derived calibration equation supplied by the manufacturer. Although Campbell Scientific suggests that the calibration equation is accurate within a few percent for a wide range of soil types and textures, a calibration curve has not yet been determined for the Slumgullion slide material. Therefore, the absolute values of volumetric water contents reported here should be considered estimates. Estimates of soil tension (ST) were obtained at depths of 0.2 and 1.0 m using Watermark model 200 soil moisture sensors manufactured by Irrometer Company, Inc. These sensors are electronic resistance devices whose output has been empirically calibrated to soil tension, also known as soil suction (see Eldredge and others, 1993). Saturated to near-saturated soil moisture conditions produce less negative soil tension values, whereas dryer soil moisture conditions result in more negative soil tension values. Guidelines from Irrometer suggest that saturated soils produce soil tension values ranging from 0 to -10 kPa, whereas dry soils are typically in the range of -100 to -200 kPa. Velocities of MP8 are representative of points MP1 – MP15 on the upper and middle parts of the slide (see fig. 6). Velocities of MP16 are representative of points MP16 – MP19 on the lower part of the slide. Velocities are plotted at the mid-points between GPS observations.

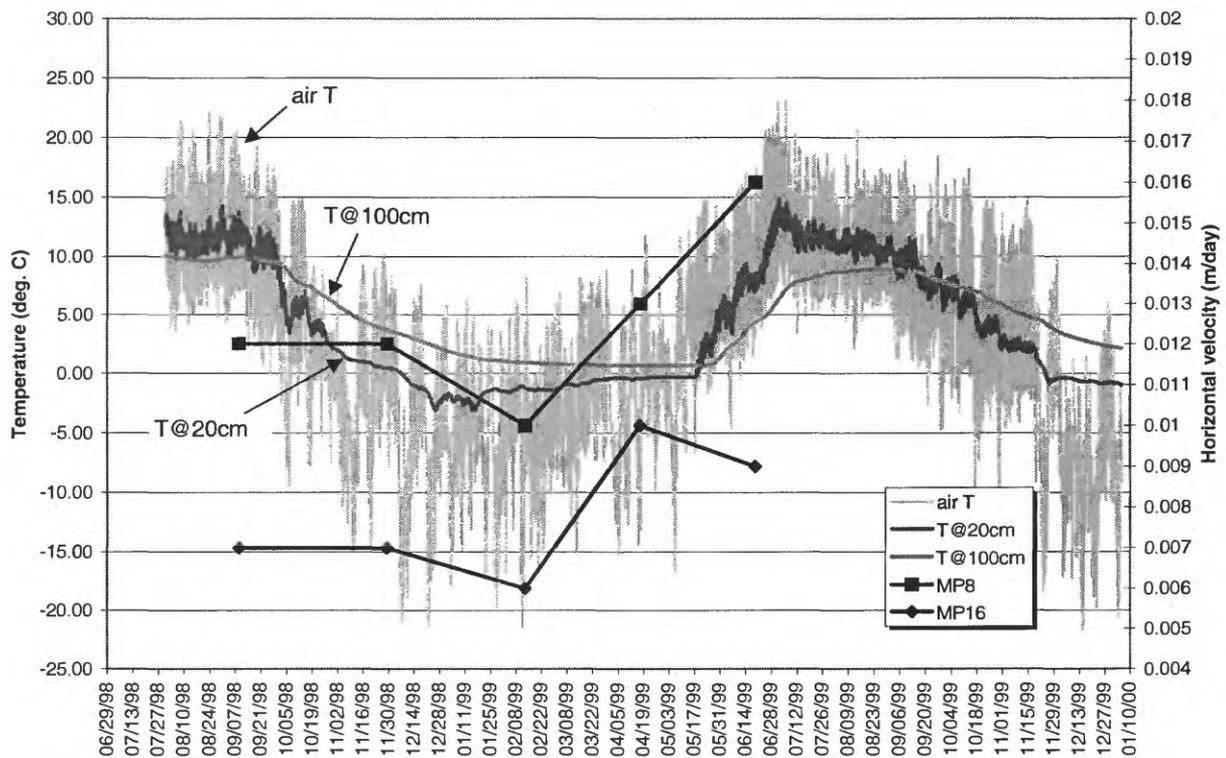


Figure 10. Air and soil temperatures measured at IS1 in relation to daily velocities of monitoring points MP8 and MP16 (see figure 2 for locations). All temperatures were measured with Campbell Scientific, Inc. temperature probes (model 107). The air-temperature probe (air T) was equipped with a solar radiation shield. Soil-temperature probes were installed at depths of 0.2 m (T@20 cm) and 1 m (T@100 cm). Velocities of MP8 are representative of points MP1 - MP15 on the upper and middle parts of the slide. Velocities of MP16 are representative of points MP16 - MP19 on the lower part of the slide. Velocities are plotted at the mid-points between GPS observations.

Relation between velocity variability, soil-water content, and temperature

There is a correspondence between variations in velocities of monitoring points and soil-water content, soil temperature, and air temperature data from IS1 (figs. 9 and 10). The strongest correspondence is to soil and air temperature. In general, slide movement increases or decreases with rising or falling temperatures (fig. 10). The correspondence is probably due to the control that air temperature has on the freezing and thawing of ground and snow, which in turn controls the influx of surface water, and ultimately the ground-water level within the slide. Rising or falling ground-water levels would tend to respectively decrease or increase the effective normal stress at the basal surface of the slide. According to the effective stress law (Terzaghi, 1943), a reduction in effective normal stress requires a corresponding reduction in resisting shear stress along the base of the slide. The velocity of the slide, therefore, would increase or decrease as ground-water level rises or falls.

The correspondence of velocity and temperature is especially strong for points MP1-MP15 (represented by MP8 in figs. 9 and 10) located above 3040 m on the upper and middle parts of the slide. There is less of a correspondence at points MP16-MP19 (represented by MP16 in figs. 9 and 10) located below an elevation of 3040 m on the lower part of the slide. The 3040 m elevation coincides approximately with the location of a large pond that may have been created when the toe of the active slide emerged from, and overrode old landslide deposits (see Parise and Guzzi, 1992; Fleming and others, 1999; and discussion below). Velocities of points on the upper and middle parts of the slide peak in the summer, whereas velocities of points on the lower part of the slide peak in the spring. Similar observations have been reported for the Aspen Grove landslide in Utah (Baum and others, 1993).

The difference in velocity peaks is probably caused by warmer temperatures at the toe of the slide than at the middle and upper parts. There is a 500 m difference in elevation between the lowest and highest parts of the slide. Adiabatic temperature lapse rates (9.8 °C and 5 °C per thousand meters of elevation for dry and wet air, respectively, from Barry, 1992) suggest that air temperatures for the lowest part of the slide are 2.5 to 4.9 °C (4.5 to 8.8 °F) warmer than those at the upper part of the slide. This difference in temperature would cause ground on the lower part of the slide to remain unfrozen for longer periods of time than that at higher elevations. Additionally, snow would melt faster on the lower part of the slide as compared to the upper part. Furthermore, observations of snow depth made during winter GPS surveys indicate that less snow falls on the lower part of the slide than on the upper and middle parts. Less snow and more rapid snowmelt suggest that the period of spring surface-water infiltration would be earlier and shorter on the lower part of the slide than on the upper and middle parts. The difference in the amount of snowfall and the rate of snowmelt on the upper and lower parts of the slide is readily visible in spring months (for example, see fig. 11). Thawing and melting of frozen ground and snow on the lower part of the slide in the spring probably raises the ground-water level within the slide which increases the slide velocity. In the summer, when ground-water levels and velocities are decreasing on the lower part of the slide, they are peaking on the upper and middle parts of the slide when snowmelt there is at a maximum.

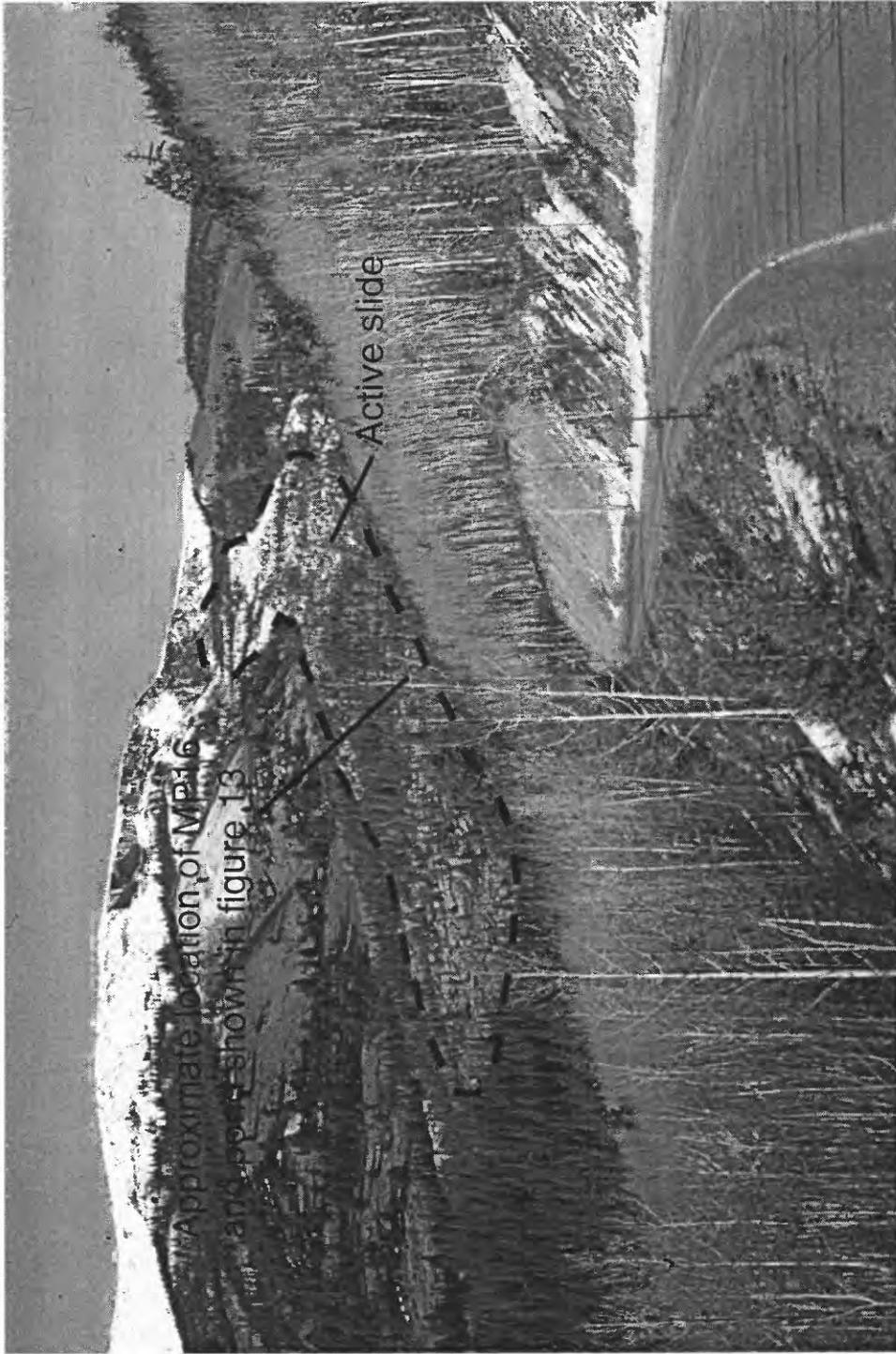


Figure 11. Springtime distribution of snow on the active part of the Slumgullion landslide. View is to the northeast. Photo taken May 10, 1999.

Inconsistent velocity response to seasonal changes

The upper part of the slide reacts more dramatically to seasonal changes than the middle and lower parts. Maximum velocities of points on the upper part of the slide are up to 10 times greater than minimum velocities, whereas for most of the lower and middle parts of the slide, maximum velocities are about 1.6 times greater than minimum velocities. The dramatic change along the upper part of the slide could be due to several factors. First, because of the high elevation (3400-3650 m) of the head of the slide, prolonged periods of frozen ground could dramatically decrease ground-water levels for long periods of time. Second, as mentioned above, more snow falls on the upper and middle parts of the slide than on the lower part. The melting of this snow in the spring and summer would provide a larger influx of surface water than that received by the lower part of the slide.

Relation between landslide structures and velocities

Velocities vary gradually along the length of the landslide, with the smallest velocities occurring at points near the head and toe, and largest velocities occurring in the neck. This overall distribution resembles a normal distribution and is consistent with patterns established by earlier photogrammetric studies (Powers and Chiarle, 1996; Smith, 1996). The velocity distribution appears to be largely a function of the hour-glass shaped lateral boundaries of the slide (Fleming and others, 1996; also observed at the Aspen Grove landslide in Utah by Baum and others, 1993). Locally however, velocities deviate from the approximately normal distribution according to the location of major structural elements. This is especially evident at points located in pull-apart basins and on opposite sides of southwest-northeast trending strike-slip faults (see fig. 2). Velocities of points MP11 and MP17, for example, are anomalously low when compared to surrounding points (fig. 4). MP11 is located in a pull-apart basin along the north flank where the northern boundary of the slide widens (described by Baum and Fleming, 1996; and Fleming and others, 1999) and MP17 is located on the northwest moving side (appendix A, MP17) of a strike-slip fault along the north flank of the toe. Velocities of MP13 and MP14, which are about 150 m apart (fig. 2), but on opposite sides of a large strike-slip fault, are significantly different, with MP14 on the southern side moving about 20% faster than MP13 on the northern side (first observed by Fleming and others, 1999).

Movement of MP1

Movement of MP1 was somewhat unexpected because the point is located on an old landslide flank ridge on a part of the slide that was previously mapped as inactive (figs. 1, 2, and fig. 12). The average horizontal velocity of the point was 0.0006 m/day for an annual horizontal movement of 0.21 m toward the southwest (downslope, see Coe and others, 2000, appendix, MP1). The point was installed in an attempt to verify that the old landslide deposits were indeed inactive. Movement of the point suggests that at least some of the old deposits in the vicinity of the head of the slide are active. The movement also suggests that control points (used to register remote sensing imagery to a local coordinate system,



Figure 12. Monitoring point MP1 in relation to the previously established boundary of the active slide. Boundary from Baum and Fleming, 1996. View is to the southwest. See Highway 149 in the distance for scale.

see Coe and others, 2000), which are often located on old flank ridges around the periphery of the active slide, should be resurveyed to verify that no movement is occurring.

Movement of MP16

Point MP16, located on pond sediments just southwest of a pond on the lower part of the slide (fig. 13), is moving upslope (see Coe and others, 2000, appendix, MP16). All other monitoring points are moving downslope. The point increased 0.18 m in elevation between July 1998 and 1999. Previous studies (Parise and Guzzi, 1992; Fleming and others, 1999) have suggested that the location of the pond is controlled by a depression at the basal surface of the slide which was created when the toe of the active slide emerged and overrode old landslide deposits. By emerging from, and overriding existing deposits, debris in the active slide was backtilted, forming a closed depression that pools water. These studies also suggested that the pond location remains fixed over time while landslide debris is transported into the pond, receives a coating of pond sediments, and is then transported out of the pond. The upward movement of MP16 and a backtilted trail of pond sediments southwest of the pond (fig. 13) supports this hypothesis.

Comparison of velocities to previously measured velocities

A comparison of velocities measured in this study to velocities reported in previous studies reveals that annual horizontal velocities of 12 of the 19 monitoring points are greater than any previously documented for the same locations (fig. 14). Velocities from this study are higher at points downslope from MP6 (see fig. 2), but lower at points MP2-MP6, on the upper part of the slide. Although several exceptions to this observation exist (fig. 14), most notably at MP17 where velocities in this study are all lower than those previously documented, the overall pattern is consistent and convincing.

The reasons for these velocity disparities are unclear, although several possibilities seem plausible. First, at least some of the differences are due to inherent differences in measurement techniques. Annual velocities in previous studies were determined by averaging movement measured from photo identifiable features in aerial photographs taken in 1985 and 1990. Movement in this study was measured over the course of a single year. Movement during one or more years between 1985 and 1990 may have been very similar to 1998/99 measurements but would have been muted by averaging with slower movements from other years. A second explanation for the disparities may be that annual velocity (when measured during a single year) is moderately variable in time and that velocities on different parts of the slide vary somewhat episodically. In this scenario, the lower and middle parts of the slide moved faster in 1998/99 than between 1985 and 1990, and the upper part moved slower in 1998/99 than between 1985 and 1990. Continued monitoring during this study should help to clarify variability in annual movement.

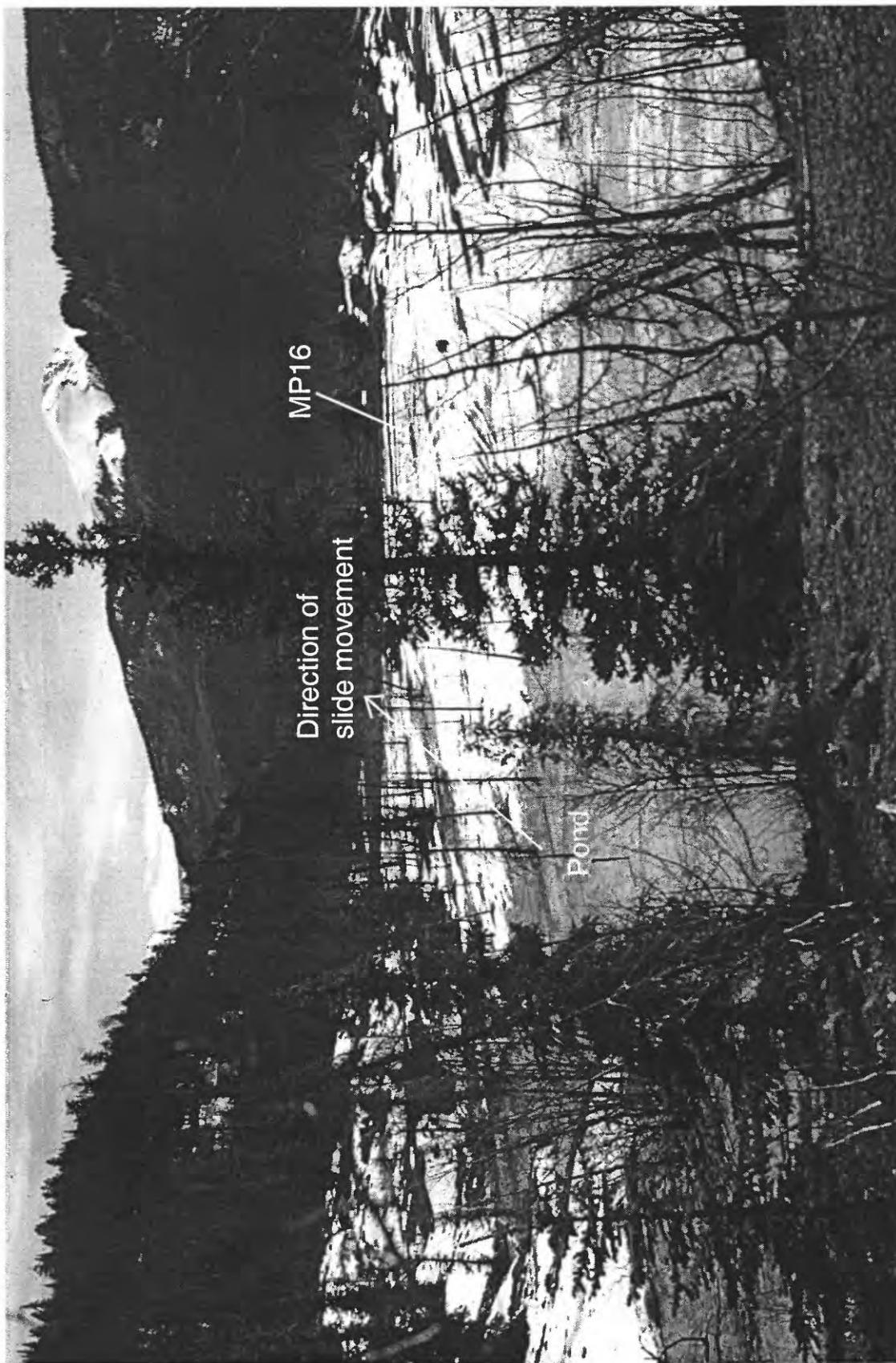


Figure 13. Monitoring point MP16. Backtilted pond sediments surround MP16.

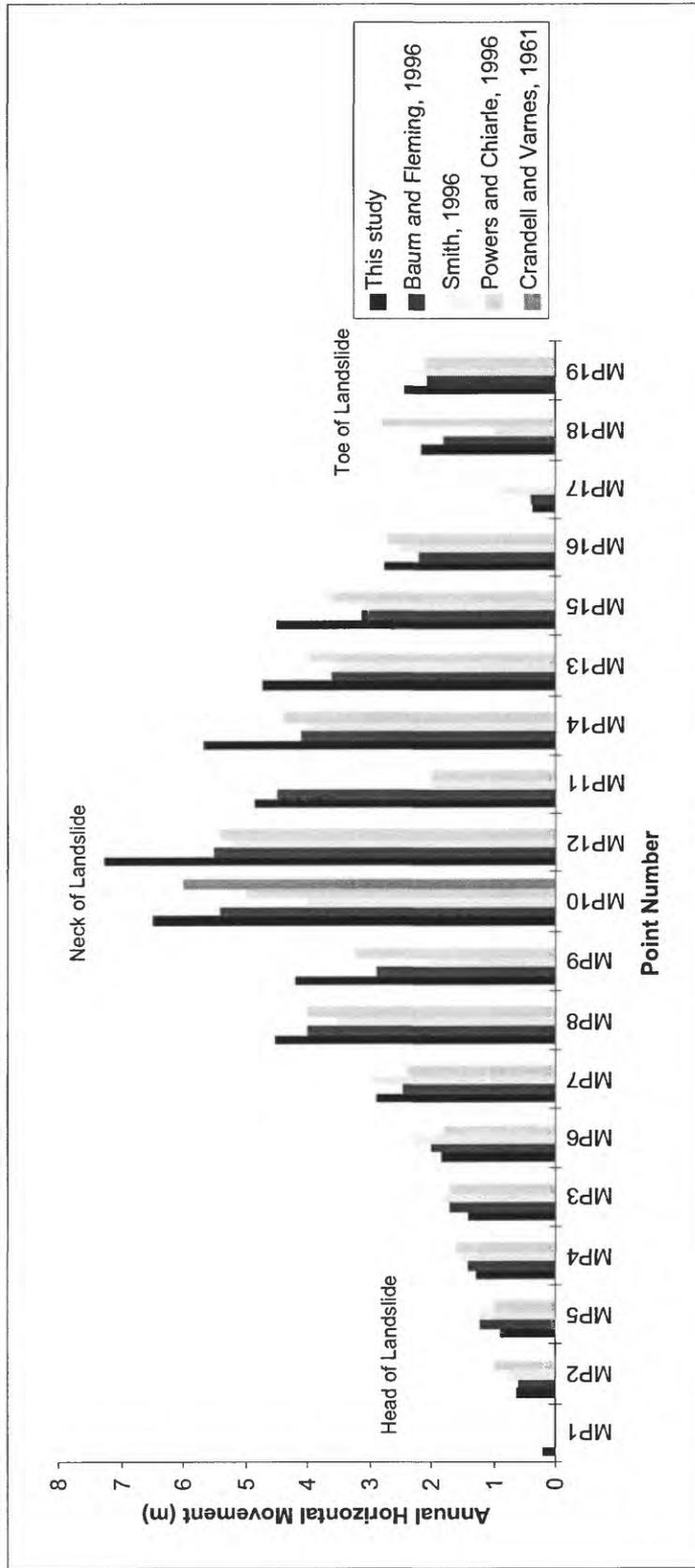


Figure 14. Bar graph showing annual horizontal movement of individual points compared to previous measurements.

Conclusions

We suggest that seasonal variability in daily landslide velocities during the 1998/1999 monitoring period was probably caused by changing ground-water levels that were primarily controlled by the infiltration of surface water, which in turn was controlled by the availability of water and the state of the slide material (frozen or unfrozen). Soil temperature and soil-water content data from the middle part of the slide indicate that frozen ground between December, 1998 and May, 1999 reduced the infiltration of surface water into the landslide, probably causing a period of minimum velocities (January-March). Spring snowmelt and/or rainfall accompanied by surface-water infiltration into the landslide were probably responsible for velocity maximums between March and May on the lower portion of the slide and between May and July on the middle and upper portions of the slide.

In general, annual and seasonal velocities are greatest at the neck of the landslide and gradually decrease both upslope and downslope with the lowest velocities occurring at the head and toe of the slide. Locally, landslide structures cause velocities to vary from this distribution. Some of the movement documented near the head of the slide occurred on landslide deposits previously thought to be inactive.

A comparison of annual movements measured in 1998/1999 to those measured between 1985 and 1990 revealed that movement was greater in 1998/1999 on the lower and middle parts of the slide, but less in 1998/1999 on the upper part of the slide. Continued monitoring should help to further clarify annual and seasonal variability in movement.

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