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May 1999 view looking southwest down the landslide from GPS monitoring point MP5.

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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. The upper part of the slide reacted more dramatically to seasonal changes than the middle and lower parts. Maximum velocities were up to 10 times greater than minimum velocities on the upper part of the slide and 1.8 to 1.6 times greater on the middle and lower parts of the slide. Maximum velocities occurred between March and May on the lower part of the slide, and between May and July on the middle and upper parts of the slide. Minimum velocities occurred between January and March for 18 of the 19 monitoring points.

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. Annual combined horizontal and vertical movement ranged from 0.15 m at the head of the slide to 7.3 m in the neck. Daily velocities ranged from <0.001 m/day to 0.024 m/day.

Introduction

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

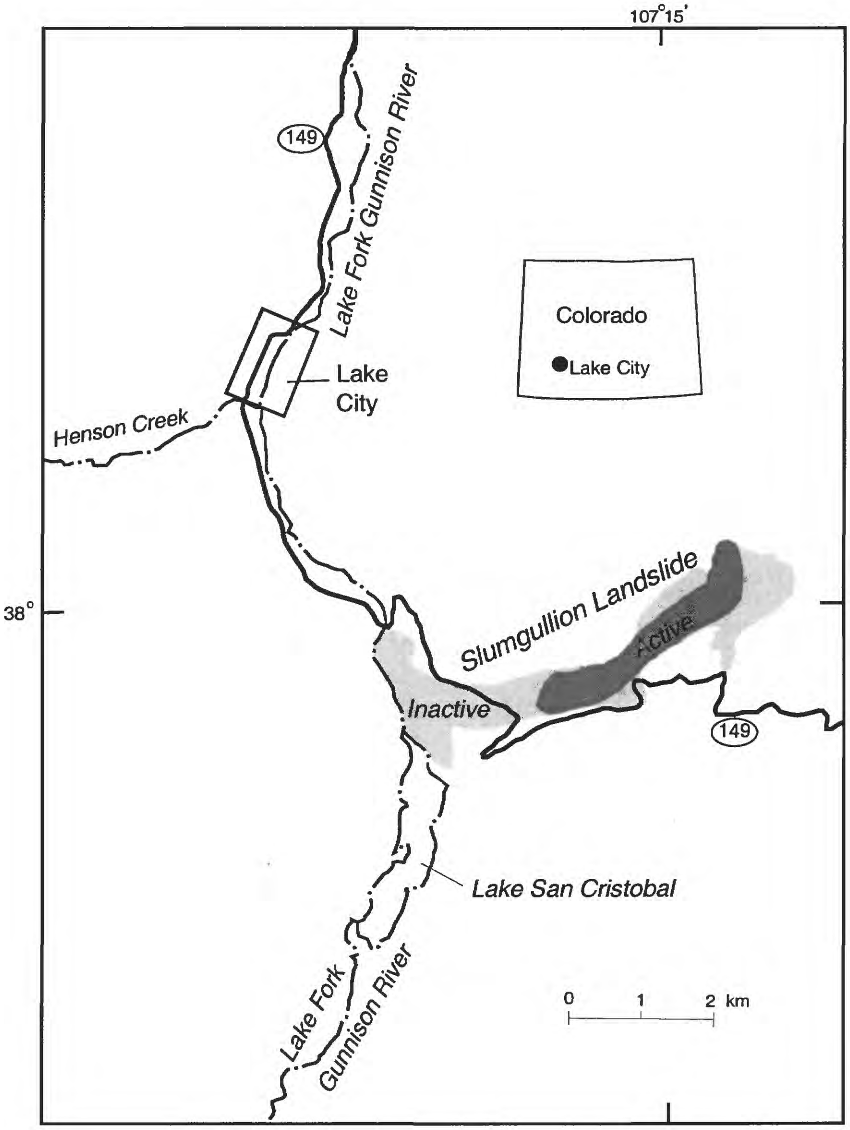


Figure 1. Location map showing the active and inactive parts of the Slumgullion landslide.

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 1) present 6 sets of GPS observations made between July 1998 and July 1999 and 2) describe the annual and seasonal landslide movement indicated by the observations. A preliminary interpretation of the landslide movement is given in a separate report (Coe and others, 2000).

Methods

Installation and distribution of control points, monitoring points, and corner reflectors

In July, 1998, 11 control points and 19 monitoring points were installed around and on the active landslide, respectively (fig. 2). Control points were evenly distributed in stable areas around the periphery of the slide. Control points were commonly installed on old landslide flank ridges just outside the boundaries of the active slide. The purpose of control points is to provide a stable reference frame in which to register remote sensing imagery to a local coordinate system. The 19 monitoring points were evenly distributed on the active slide, but also strategically placed in relation to the main structural components of the slide (fig.2) and with a clear view to the sky. The purpose of monitoring points is to monitor seasonal movement of various structural components using GPS and to provide ground-truth to compare with movements measured by remote sensing.

At each control and monitoring point location, a 1.5-cm-diameter, 60-cm-long rebar rod was hammered into the ground and an aluminum cap was attached to the end at the ground surface. A dimple and the point name were stamped on each cap. The dimple was the location measured by GPS. At each point, a corner reflector was installed about 1.5 m above the dimple (fig. 3). The outside corner of each reflector was aligned so that it was plumb above the dimple and the distance from the dimple to the corner was measured and recorded. The function of corner reflectors is to make points visible to the airborne remote sensing system by reflecting the microwave signal directly back to the airborne sensor, creating a spike in the digital data and a bright pixel in imagery.

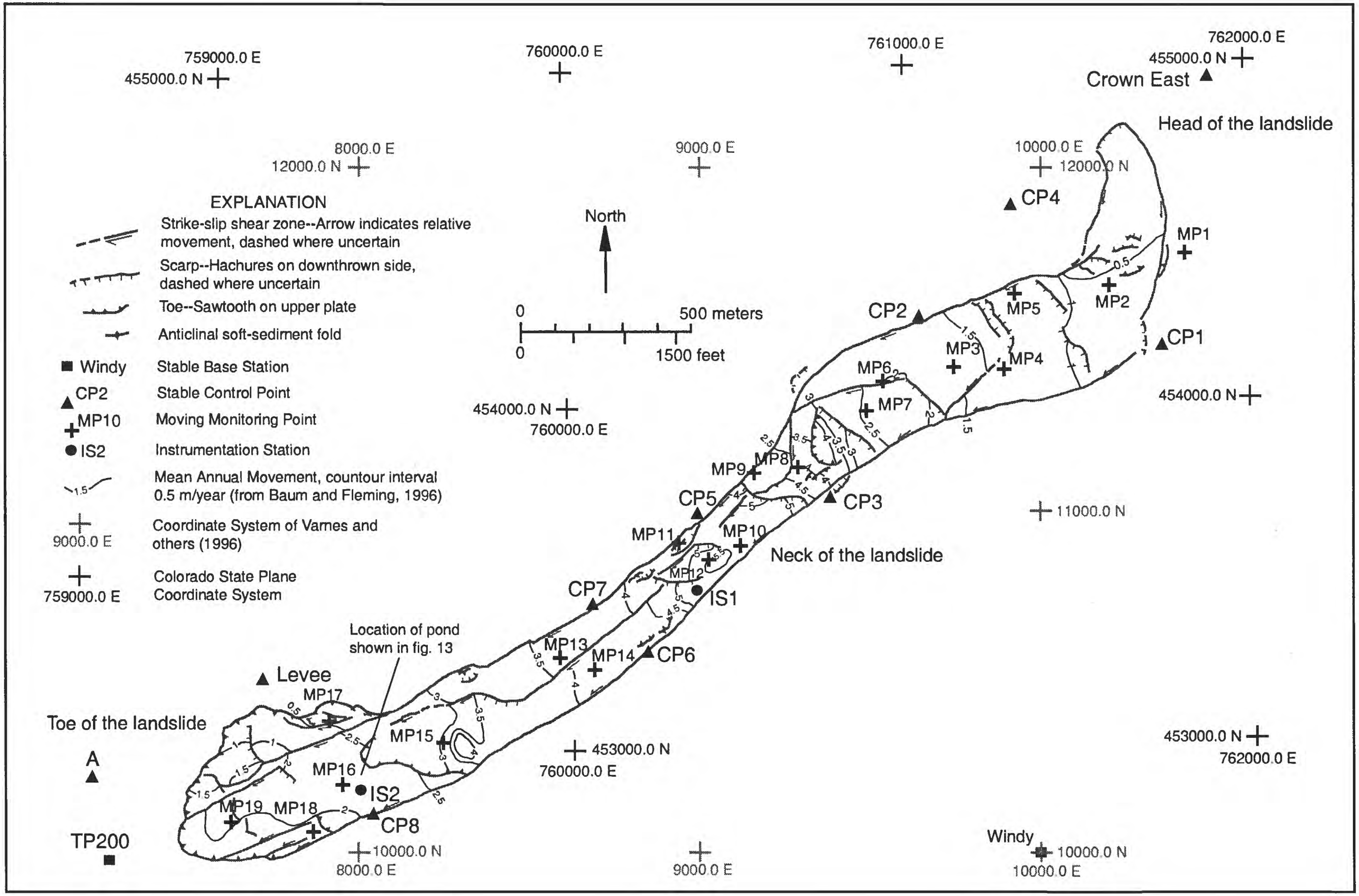


Figure 2. Active part of the Slumgullion landslide with structural elements, contours of mean annual movement, GPS base stations, control points, and monitoring points. See Coe and others (2000) for a description of base stations and control points. Modified from Baum and Fleming (1996).

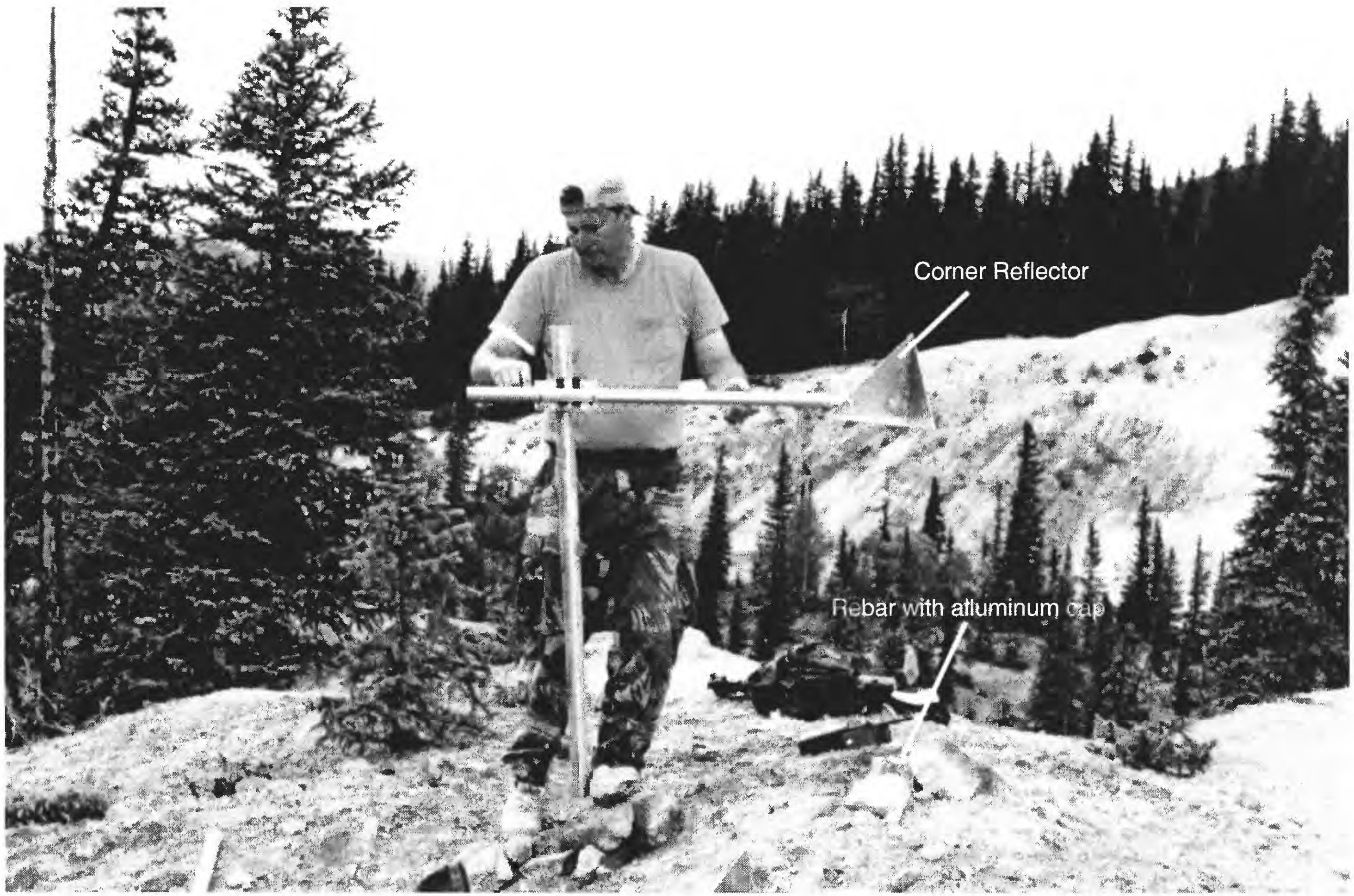


Figure 3. Installation of a corner reflector above monitoring point MP6. Photo taken in July, 1998.

GPS background

The following discussion of GPS surveying is summarized from Leick (1990) and Van Sickle (1996). The primary task of GPS surveying is to measure distances between 24 Department of Defense satellites in known orbits about 20,000 km above the earth and locations on the earth. Once distances have been measured, coordinates of positions on the earth are calculated by triangulation. Distances are measured based on the amount of time required for an electromagnetic GPS signal to travel from the satellites to ground-based antennas and receivers. Antennas collect the satellite signal and convert the electromagnetic waves into electric currents that can be recorded by the receiver.

Satellites transmit precise time and location information in three binary codes, precise code (P code), coarse and acquisition code (C/A code), and Navigation code. The codes are transmitted on two carrier waves that are part of the L-band of the microwave electromagnetic spectrum. The two carrier waves have frequencies called L1 (1,575.42 Mhz, 19 cm wavelength) and L2 (1,227.60 MHz, 24 cm wavelength).

There are two GPS observables that are used to determine distances from satellites to the ground, pseudorange and carrier phase. Pseudorange is a preliminary distance determined on the basis of a comparison of clock information contained in the C/A and P codes with a replica of the codes generated by the receiver. Pseudorange is used to determine approximate locations on the ground. Carrier phase is the cumulative number of phase cycles (including the fractional part of the last cycle) of the L1 and/or L2 carrier wave signal as measured at the receiver. Unlike pseudorange, use of the carrier phase allows for correction of atmospheric effects and clock offsets between the satellite and receiver. Carrier phase is used for high-precision GPS surveying.

There are two main GPS surveying methods, kinematic and static surveying. In kinematic applications, receivers are in motion during the measurement period and real-time positioning solutions are available based on the pseudorange observables. In static applications, receivers are stationary for long-measurement periods (generally > 30 minutes) and both pseudorange and carrier-phase data are post-processed for precise positioning solutions. Rapid-static applications are the same as static techniques except that occupation times are short, generally ranging from 5 to 20 minutes, and post-processing relies on code and L1 and L2 carrier phase observations.

The type and accuracy of positioning in kinematic and static surveying is dependent on the number of receivers available. There are two types of positioning, single point and relative. Single-point positioning is the determination of a ground position using one receiver and observables from one or more satellites. Single-point positioning relies on the pseudorange observable. The accuracy of the single-point positioning increases with the number of satellites available. Relative positioning is the determination of a ground position using two or more receivers and two or more satellites. Relative positioning allows for the elimination of clock and atmospheric errors in the carrier-phase signal by combining simultaneous observables (referred to as differencing in GPS terminology) from multiple receivers and satellites during post-processing. Relative positioning determines the precise vector (baseline) between receiver positions. When the coordinates of one of the receiver positions is known, that receiver is referred to as a base station, and the known coordinates and baseline can be used to determine the precise coordinates of the unknown points.

In relative positioning, data is stored in the receivers and is post-processed using computer software to calculate baselines, determine unknown coordinate positions, and estimate horizontal and vertical errors for calculated positions. If baselines are calculated from two or more base stations, the baselines and coordinates of unknown points can be further refined through the use of a least-squares adjustment performed by holding the base station positions fixed while adjusting the baselines and coordinate positions of the unknown positions.

A requirement of relative positioning is that the receivers are capable of recording at least one of the carrier phases. Although many types of receivers are available, dual-frequency receivers are commonly used for relative positioning because they record all GPS codes, as well as the L1 and L2 carrier phases. In addition to recording all components of the GPS signal, dual frequency receivers generally have 12 channels, which allows them to simultaneously record the signals of up to 12 satellites.

The coordinate system used by GPS is the World Geodetic System 1984 (WGS84). The WGS84 coordinate system is based on an ellipsoidal model of the earth's surface. Therefore, GPS receivers provide raw positional data in WGS84 coordinates consisting of latitude, longitude, and ellipsoid height. Transformations of latitude and longitude values into other datums, such as the North American Datum of 1983 (NAD83), followed by projections into local coordinate systems, such as state plane systems, is accomplished through the use of software containing conversion algorithms provided by the U.S. National Geodetic Survey (NGS). Ellipsoid heights can be transformed into other vertical datums, such as the North American Vertical Datum of 1988 (NAVD88), by subtracting a theoretical geoid height (see Van Sickle, 1996).

GPS observations

All control and monitoring points were surveyed using Ashtech Z-12 and Z-Surveyor, dual-frequency receivers equipped with Ashtech geodetic or marine antennas. Rapid-static GPS surveying with relative positioning was used for all points. Control points were surveyed one time, in July, 1998. Current plans (January, 2000) call for control points to be resurveyed at least one more time before the end of the project. Monitoring points were surveyed during six, 2-day GPS 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.

Two base stations, TP200 and Windy (fig. 2), were used for each GPS survey. Windy and TP200 consist of rebar with stamped bronze caps. Both stations were originally installed in the early 1990s (see Varnes and others, 1996). The WGS84 positions of Windy and TP200 were determined by a static GPS survey in May, 1997. Positions were determined using a Federal Base Network Control Station (Station Designation S424, located near the Blue Mesa reservoir about 50 km north of Lake City) as a base station.

All GPS data were post-processed using Ashtech Precise Navigation (PNAV) software, v. 2.4.00M. Baselines and positions were calculated from Windy and TP200 each of the control and monitoring points. By calculating baselines to each measured point from two base stations, a triangle was formed with one side known (TP200 to Windy), and two sides measured (Windy to measured point and TP200 to measured point). The measured baselines and point positions were then refined using a least-squares adjustment contained in Ashtech PRISM software, v. 2.1. During the adjustment, the positions of Windy and TP200 were held fixed and the baselines and positions of the measured points were adjusted. In general, positions of adjusted points did not change by more than 1 cm in horizontal and 2 cm in vertical from the original positions as determined from GPS data alone.

In some cases, the original, unadjusted point positions as determined by GPS alone were used as the final reported positions. These cases were the result of problems at base stations. Most commonly, problems were encountered during winter surveys and included dead receiver batteries and settling of tripod legs in thawing ground during daylight hours. Most problems were encountered at station Windy because of exposure to wind and solar extremes.

After surveying, post-processing, and adjustment, coordinate positions for all measured points were transformed into the NAD83 datum and then projected into the Colorado State Plane, southern zone, coordinate system using PRISM software. Ellipsoid heights were transformed into NAVD88 mean sea level heights using PRISM software and the GEOID96 model provided by the NGS. Standard errors of computed positions were derived from the least squares adjustment, or from PNAV in cases where GPS data alone were used for final positions.

Results

Base station, control point, and monitoring point positions

Dates of observation, coordinates, and heights of the two base stations, TP200 and Windy, as well as the eleven control points around the periphery of the landslide are given in table 1. Dates of observation, coordinates, heights, and positional errors for all monitoring points are given in table 2. Positional errors are given as standard errors and are always less than or equal to 1 cm in horizontal and 1.5 cm in vertical. At all points except MP1 and MP17, these errors are insignificant in comparison to the amount of movement that occurred between each GPS observation.

Movements and velocities of monitoring points

All monitoring points moved between each set of GPS observations (see table 3 for movement data and Appendix A for figures showing movement of each point). Total movement (combined horizontal and vertical movement) was largely dominated by the horizontal component (see annual combined and annual horizontal movement, table 3). 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. 4 and fig. 5). Annual horizontal movements ranged from 0.15 m at MP1 to 7.3 m at MP12 (fig. 4a). Average daily horizontal

Table 1. Coordinates of base stations (TP200 and Windy) and control points. See figure 2 for locations. Latitude and longitudes are given in WGS84 coordinates. Easting and Northing values are given in NAD83, Colorado State Plane coordinates, southern zone. Elevation is NAVD88 height above mean sea level. Point names incorporate the method used to determine the final position. Positions of points that end in adj were computed using a least-squares adjustment. Positions of points that end in TP200 or Windy were determined based on the baseline solution from the named station. For example, the position of CP2-Windy was determined using the baseline solution from Windy to CP2. TP200 and Windy were determined by a static survey using base station S424 located near Blue Mesa Reservoir, WGS84 coordinates, N 38 27 35.60861, W 107 18 12. 64275, Ellipsoid Height, 2299.46.

Point	Date(s) of GPS Observations (m,d,y)	Longitude (Degrees, Minutes, Seconds) and standard error (m)	Latitude (Degrees, Minutes, Seconds) and standard error (m)	Ellipsoid Height and standard error (m)	Easting (m)	Northing (m)	Elevation (m)
TP200	5/12/97	107 16 24.35915	37 59 9.92868	2930.482	758624.740	452715.056	2945.210
Windy	5/13/97	107 14 32.21986	37 59 10.37092	3315.033	761360.851	452677.197	3329.793
CROWN EAST-adj	7/28/98-7/30/98	107 14 11.87713 ±0.007	38 00 23.98378 ±0.005	3705.171 ±0.007	761899.344	454937.103	3719.980
LEVEE-adj	7/28/98-7/30/98	107 16 5.57084 ±0.006	37 59 26.70796 ±0.004	2987.935 ±0.006	759092.909	453223.590	3002.674
CP1-adj	7/28/98-7/30/98	107 14 17.50263 ±0.005	37 59 58.35631 ±0.004	3421.365 ±0.005	761747.435	454149.676	3436.169
CP2-Windy	7/28/98	107 14 46.68642 ±0.003	38 00 01.07886 ±0.004	3331.271 ±0.005	761037.136	454246.879	3346.014
CP3-adj	7/28/98-7/30/98	107 14 57.60740 ±0.006	37 59 43.83557 ±0.004	3280.737 ±0.006	760760.793	453720.333	3295.517
CP4-adj	7/28/98-7/30/98	107 14 35.55985 ±0.007	38 00 11.65818 ±0.005	3511.385 ±0.007	761314.625	454567.921	3526.180
CP5-adj	7/28/98-7/30/98	107 15 13.30739 ±0.006	37 59 42.31149 ±0.004	3222.357 ±0.006	760376.927	453680.535	3237.128
CP6-adj	7/28/98-7/30/98	107 15 19.60700 ±0.006	37 59 29.31424 ±0.004	3158.888 ±0.006	760215.724	453282.777	3173.655
CP7-adj	7/28/98-7/30/98	107 15 26.06481 ±0.005	37 59 33.75204 ±0.004	3150.379 ±0.005	760060.759	453422.536	3165.142
CP8-adj	10/28/98-10/29/98	107 15 52.43924 ±0.006	37 59 14.12107 ±0.004	3029.771 ±0.006	759405.928	452829.537	3044.506
A-adj	7/28/98-7/30/98	107 16 26.39955 ±0.006	37 59 17.63479 ±0.004	2944.243 ±0.006	758579.473	452953.543	2958.970

Table 2. Positions of monitoring points for each GPS observation. Positions given in NAD83, Colorado State Plane coordinates, southern zone. Elevation is NAVD88 height above mean sea level. See table 1 caption for point-naming convention.
NA = Not Applicable because initial observation.

Point	Date of GPS Observation (m,d,y)	Easting (m)	Standard Error of Easting value (m)	Northing (m)	Standard Error of Northing value (m)	Elevation (m)	Standard Error of Elevation value (m)	Days since previous observation
MP1 - adj	7/28/1998	761817.112	±0.007	454426.497	±0.005	3447.422	±0.007	NA
MP1 - adj	10/22/1998	761817.071	±0.007	454426.504	±0.005	3447.412	±0.007	86
MP1 - TP200	1/6/1999	761817.075	±0.004	454426.448	±0.005	3447.375	±0.008	76
MP1 - TP200	3/23/1999	761817.075	±0.004	454426.444	±0.004	3447.395	±0.006	76
MP1 - TP200	5/11/1999	761817.043	±0.006	454426.433	±0.006	3447.391	±0.009	49
MP1 - adj	7/27/1999	761816.970	±0.010	454426.438	±0.007	3447.417	±0.010	77
MP2 - adj	7/28/1998	761595.120	±0.007	454334.899	±0.005	3426.505	±0.007	NA
MP2 - adj	10/22/1998	761595.016	±0.007	454334.798	±0.005	3426.501	±0.007	86
MP2 - TP200	3/23/1999	761594.934	±0.003	454334.716	±0.005	3426.460	±0.008	152
MP2 - TP200	5/11/1999	761594.857	±0.003	454334.648	±0.005	3426.425	±0.007	49
MP2 - adj	7/27/1999	761594.683	±0.010	454334.467	±0.007	3426.423	±0.010	77
MP3 - adj	7/29/1998	761134.169	±0.007	454101.532	±0.005	3352.379	±0.007	NA
MP3 - adj	10/22/1998	761133.863	±0.007	454101.428	±0.005	3352.330	±0.007	85
MP3 - TP200	1/6/1999	761133.631	±0.005	454101.310	±0.006	3352.283	±0.008	76
MP3 - TP200	3/23/1999	761133.413	±0.005	454101.245	±0.005	3352.229	±0.008	76
MP3 - TP200	5/11/1999	761133.242	±0.005	454101.174	±0.007	3352.184	±0.009	49
MP3 - Windy	7/27/1999	761132.857	±0.005	454101.048	±0.005	3352.171	±0.007	77
MP4 - Windy	7/28/1998	761283.532	±0.004	454093.549	±0.005	3368.028	±0.006	NA
MP4 - adj	10/22/1998	761283.243	±0.007	454093.475	±0.005	3367.991	±0.007	86
MP4 - TP200	1/6/1999	761283.028	±0.005	454093.385	±0.005	3367.990	±0.007	76
MP4 - TP200	3/23/1999	761282.851	±0.006	454093.347	±0.006	3367.904	±0.008	76
MP4 - TP200	5/11/1999	761282.700	±0.004	454093.306	±0.004	3367.856	±0.006	49
MP4 - adj	7/27/1999	761282.293	±0.010	454093.213	±0.007	3367.781	±0.010	77

Table 2 - continued.

Point	Date of GPS Observation (m,d,y)	Easting (m)	Standard Error of Easting value (m)	Northing (m)	Standard Error of Northing value (m)	Elevation (m)	Standard Error of Elevation value (m)	Days since previous observation
MP5 - Windy	7/28/1998	761316.460	±0.004	454309.998	±0.004	3399.810	±0.006	NA
MP5 - adj	10/22/1998	761316.290	±0.007	454309.895	±0.005	3399.793	±0.007	86
MP5 - TP200	1/6/1999	761316.204	±0.004	454309.771	±0.004	3399.759	±0.007	76
MP5 - TP200	3/23/1999	761316.125	±0.004	454309.737	±0.005	3399.706	±0.006	76
MP5 - TP200	5/11/1999	761316.018	±0.004	454309.675	±0.005	3399.672	±0.007	49
MP5 - adj	7/27/1999	761315.730	±0.010	454309.530	±0.007	3399.638	±0.010	77
MP6 - Windy	7/28/1998	760923.503	±0.004	454057.002	±0.004	3335.298	±0.006	NA
MP6 - Windy	10/22/1998	760923.143	±0.006	454056.795	±0.007	3335.201	±0.010	86
MP6 - TP200	1/6/1999	760922.844	±0.003	454056.595	±0.004	3335.195	±0.005	76
MP6 - TP200	3/23/1999	760922.578	±0.003	454056.496	±0.004	3335.161	±0.005	76
MP6 - TP200	5/11/1999	760922.375	±0.004	454056.341	±0.004	3335.084	±0.006	49
MP6 - adj	7/27/1999	760921.903	±0.009	454056.110	±0.007	3335.029	±0.009	77
MP7 -adj	7/28/1998	760879.542	±0.007	453979.438	±0.004	3321.898	±0.007	NA
MP7 -adj	10/22/1998	760878.978	±0.006	453979.112	±0.004	3321.845	±0.006	86
MP7 -TP200	1/6/1999	760878.502	±0.004	453978.810	±0.004	3321.780	±0.005	76
MP7 - TP200	3/23/1999	760878.091	±0.003	453978.582	±0.004	3321.739	±0.006	76
MP7 - TP200	5/11/1999	760877.764	±0.006	453978.386	±0.006	3321.672	±0.009	49
MP7 - adj	7/27/1999	760877.060	±0.009	453977.997	±0.006	3321.630	±0.009	77
MP8 - adj	7/29/1998	760668.934	±0.006	453816.868	±0.004	3277.031	±0.006	NA
MP8 - adj	10/22/1998	760668.252	±0.006	453816.074	±0.004	3277.008	±0.006	85
MP8 - TP200	1/6/1999	760667.656	±0.003	453815.392	±0.004	3276.976	±0.005	76
MP8 - TP200	3/23/1999	760667.151	±0.003	453814.852	±0.004	3276.944	±0.006	76
MP8 - TP200	5/11/1999	760666.735	±0.004	453814.397	±0.004	3276.920	±0.006	49
MP8 - adj	7/27/1999	760665.919	±0.009	453813.506	±0.006	3276.899	±0.009	77

Table 2 - continued.

Point	Date of GPS Observation (m,d,y)	Easting (m)	Standard Error of Easting value (m)	Northing (m)	Standard Error of Northing value (m)	Elevation (m)	Standard Error of Elevation value (m)	Days since previous observation
MP9 - adj	7/29/1998	760544.534	±0.006	453801.449	±0.004	3268.326	±0.006	NA
MP9 - adj	10/22/1998	760543.867	±0.006	453800.736	±0.004	3268.254	±0.006	85
MP9 - TP200	1/6/1999	760543.317	±0.003	453800.102	±0.003	3268.220	±0.005	76
MP9 - TP200	3/24/1999	760542.811	±0.008	453799.583	±0.007	3268.146	±0.012	77
MP9 - TP200	5/11/1999	760542.431	±0.004	453799.170	±0.005	3268.091	±0.007	48
MP9 - adj	7/27/1999	760541.683	±0.009	453798.363	±0.006	3268.050	±0.009	77
MP10 - adj	7/29/1998	760502.406	±0.006	453589.948	±0.004	3236.037	±0.006	NA
MP10 - adj	10/21/1998	760501.310	±0.006	453588.924	±0.004	3235.747	±0.006	84
MP10 - TP200	1/5/1999	760500.345	±0.003	453588.023	±0.004	3235.464	±0.007	76
MP10 - TP200	3/23/1999	760499.542	±0.005	453587.311	±0.006	3235.279	±0.008	77
MP10 - TP200	5/11/1999	760498.861	±0.004	453586.673	±0.004	3235.042	±0.006	49
MP10 - adj	7/27/1999	760497.626	±0.009	453585.539	±0.006	3234.752	±0.009	77
MP11 -adj	7/29/1998	760318.933	±0.006	453603.010	±0.004	3209.846	±0.006	NA
MP11 -adj	10/21/1998	760318.088	±0.006	453602.369	±0.004	3209.694	±0.006	84
MP11 -TP200	1/5/1999	760317.279	±0.004	453601.734	±0.005	3209.381	±0.007	76
MP11 -TP200	3/24/1999	760316.634	±0.004	453601.258	±0.004	3209.201	±0.006	78
MP11- TP200	5/12/1999	760316.056	±0.006	453600.868	±0.005	3209.029	±0.011	49
MP11 - adj	7/28/1999	760315.019	±0.009	453600.158	±0.006	3208.727	±0.009	77
MP12 -adj	7/29/1998	760406.147	±0.006	453555.091	±0.004	3220.235	±0.006	NA
MP12 -adj	10/21/1998	760405.002	±0.006	453553.857	±0.004	3220.133	±0.006	84
MP12 -TP200	1/5/1999	760403.997	±0.005	453552.761	±0.006	3219.975	±0.008	76
MP12 -TP200	3/24/1999	760403.175	±0.006	453551.869	±0.006	3219.878	±0.008	78
MP12 - TP200	5/11/1999	760402.435	±0.006	453551.128	±0.007	3219.775	±0.009	48
MP12 - adj	7/28/1999	760401.133	±0.009	453549.799	±0.006	3219.564	±0.009	78

Table 2 - continued.

Point	Date of GPS Observation (m,d,y)	Easting (m)	Standard Error of Easting value (m)	Northing (m)	Standard Error of Northing value (m)	Elevation (m)	Standard Error of Elevation value (m)	Days since previous observation
MP13 - adj	7/29/1998	759961.451	±0.006	453273.791	±0.004	3142.627	±0.006	NA
MP13 - adj	10/21/1998	759960.514	±0.006	453273.240	±0.004	3142.409	±0.006	84
MP13 - TP200	1/5/1999	759959.683	±0.003	453272.737	±0.004	3142.203	±0.006	76
MP13 - TP200	3/24/1999	759959.000	±0.004	453272.375	±0.005	3142.030	±0.007	78
MP13 - TP200	5/12/1999	759958.371	±0.004	453272.021	±0.005	3141.873	±0.007	49
MP13 - adj	7/28/1999	759957.352	±0.009	453271.441	±0.006	3141.567	±0.009	77
MP14 -adj	7/29/1998	760063.201	±0.006	453235.801	±0.004	3156.650	±0.006	NA
MP14 -adj	10/21/1998	760062.099	±0.006	453235.108	±0.004	3156.423	±0.006	84
MP14 -TP200	1/5/1999	760061.112	±0.006	453234.442	±0.007	3156.166	±0.009	76
MP14 -TP200	3/24/1999	760060.335	±0.004	453233.962	±0.004	3155.989	±0.006	78
MP14 - TP200	5/12/1999	760059.599	±0.004	453233.509	±0.005	3155.822	±0.007	49
MP14 - adj	7/28/1999	760058.395	±0.009	453232.774	±0.006	3155.517	±0.009	77
MP15 -adj	7/28/1998	759613.286	±0.006	453037.319	±0.004	3086.041	±0.006	NA
MP15 -adj	10/21/1998	759612.424	±0.006	453036.766	±0.004	3085.806	±0.006	85
MP15 -TP200	1/5/1999	759611.660	±0.004	453036.228	±0.004	3085.606	±0.007	76
MP15 -TP200	3/24/1999	759611.050	±0.005	453035.879	±0.006	3085.405	±0.008	78
MP15 - TP200	5/12/1999	759610.452	±0.006	453035.510	±0.006	3085.232	±0.008	49
MP15 -Windy	7/28/1999	759609.513	±0.005	453034.897	±0.006	3084.978	±0.008	77
MP16 -adj	7/28/1998	759315.258	±0.006	452922.426	±0.004	3039.804	±0.006	NA
MP16 -adj	10/21/1998	759314.657	±0.006	452922.246	±0.004	3039.869	±0.006	85
MP16 -TP200	1/5/1999	759314.135	±0.004	452922.059	±0.004	3039.928	±0.006	76
MP16 -TP200	3/24/1999	759313.717	±0.005	452921.961	±0.005	3039.918	±0.007	78
MP16 - TP200	5/12/1999	759313.267	±0.004	452921.820	±0.005	3039.961	±0.006	49
MP16 - Windy	7/28/1999	759312.619	±0.005	452921.625	±0.005	3039.988	±0.009	77

Table 2 - continued.

Point	Date of GPS Observation (m,d,y)	Easting (m)	Standard Error of Easting value (m)	Northing (m)	Standard Error of Northing value (m)	Elevation (m)	Standard Error of Elevation value (m)	Days since previous observation
MP17 -adj	7/28/1998	759281.959	±0.006	453105.926	±0.004	3038.957	±0.006	NA
MP17 -adj	10/21/1998	759281.908	±0.006	453105.976	±0.004	3038.964	±0.006	85
MP17 -TP200	1/5/1999	759281.867	±0.006	453105.988	±0.006	3038.948	±0.009	76
MP17 -TP200	3/24/1999	759281.828	±0.006	453106.049	±0.006	3038.972	±0.008	78
MP17 - TP200	5/12/1999	759281.767	±0.005	453106.087	±0.006	3038.924	±0.009	49
MP17 - Windy	7/28/1999	759281.712	±0.005	453106.187	±0.005	3038.901	±0.007	77
MP18 - Windy	7/28/1998	759228.680	±0.005	452781.216	±0.009	3026.330	±0.010	NA
MP18 - adj	10/21/1998	759228.222	±0.006	452781.036	±0.004	3026.270	±0.006	85
MP18- TP200	1/5/1999	759227.826	±0.003	452780.808	±0.004	3026.246	±0.005	76
MP18 - TP200	3/24/1999	759227.512	±0.005	452780.708	±0.005	3026.227	±0.007	78
MP18 - TP200	5/12/1999	759227.182	±0.004	452780.578	±0.005	3026.191	±0.007	49
MP18 - Windy	7/28/1999	759226.688	±0.005	452780.380	±0.006	3026.141	±0.008	77
MP19 - Windy	7/28/1998	758987.607	±0.004	452819.390	±0.007	3008.896	±0.011	NA
MP19 - adj	10/21/1998	758987.077	±0.006	452819.267	±0.004	3008.808	±0.006	85
MP19 - TP200	1/5/1999	758986.623	±0.005	452819.114	±0.004	3008.782	±0.007	76
MP19 - TP200	3/24/1999	758986.239	±0.004	452819.060	±0.004	3008.742	±0.006	78
MP19 - TP200	5/12/1999	758985.847	±0.005	452818.952	±0.006	3008.675	±0.009	49
MP19 - Windy	7/28/1999	758985.236	±0.005	452818.826	±0.007	3008.606	±0.009	77

Table 3. Summary of movements, direction of movements, and velocities of monitoring points. See table 1 caption for point naming convention. Negative sign indicates vertical movement or velocity in a downward direction.

Point	Date of GPS Observation (m,d,y)	Seasonal Horizontal Movement (m, from previous position)	Seasonal Horizontal Velocity (m/day, since previous position)	Seasonal Horizontal Movement Direction (Degrees, from previous position)	Annual Horizontal Movement (m, net, 7/98 to 7/99 position)	Average Annual Horizontal Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Vertical Movement (m, from previous position)	Seasonal Vertical Velocity (m/day, since previous position)	Annual Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Vertical Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Combined Horizontal and Vertical Movement (m, from previous position)	Seasonal Combined Horizontal and Vertical Velocity (m/day, since previous position)	Annual Combined Horizontal and Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Combined Horizontal and Vertical Velocity (m/day, net, 7/98 to 7/99 position)
MP1 - adj	7/28/1998													
MP1 - adj	10/22/1998	0.042	0.0005	279.689			-0.010	-0.0001			0.043	0.0050		
MP1 - TP200	1/6/1999	0.056	0.0007	175.914			-0.037	-0.0005			0.067	0.0009		
MP1 - TP200	3/23/1999	0.004	0.0001	180.000			0.020	0.0003			0.020	0.0003		
MP1 - TP200	5/11/1999	0.034	0.0007	251.030			-0.004	-0.0001			0.034	0.0007		
MP1 - adj	7/27/1999	0.073	0.0010	277.326	0.154	0.0004	0.026	0.0003	-0.005	<-0.0001	0.078	0.0010	0.154	0.0004
MP2 - adj	7/28/1998													
MP2 - adj	10/22/1998	0.145	0.0017	225.838			-0.004	<-0.0001			0.145	0.0017		
MP2 - TP200	3/23/1999	0.116	0.0008	225.000			-0.041	-0.0003			0.123	0.0008		
MP2 - TP200	5/11/1999	0.103	0.0021	228.552			-0.035	-0.0007			0.109	0.0022		
MP2 - adj	7/27/1999	0.251	0.0033	223.870	0.615	0.0017	-0.002	<-0.0001	-0.082	-0.0002	0.251	0.0033	0.620	0.0017
MP3 - adj	7/29/1998													
MP3 - adj	10/22/1998	0.323	0.0038	251.229			-0.049	-0.0006			0.327	0.0038		
MP3 - TP200	1/6/1999	0.260	0.0034	243.041			-0.047	-0.0006			0.265	0.0035		
MP3 - TP200	3/23/1999	0.227	0.0030	253.397			-0.054	-0.0007			0.234	0.0031		
MP3 - TP200	5/11/1999	0.185	0.0038	247.452			-0.045	-0.0009			0.191	0.0039		
MP3 - Windy	7/27/1999	0.405	0.0053	251.878	1.398	0.0039	-0.013	-0.0002	-0.208	-0.0006	0.405	0.0053	1.414	0.0039

Table 3 - continued.

Point	Date of GPS Observation (m,d,y)	Seasonal Horizontal Movement (m, from previous position)	Seasonal Horizontal Velocity (m/day, since previous position)	Seasonal Horizontal Movement Direction (Degrees, from previous position)	Annual Horizontal Movement (m, net, 7/98 to 7/99 position)	Average Annual Horizontal Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Vertical Movement (m, from previous position)	Seasonal Vertical Velocity (m/day, since previous position)	Annual Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Vertical Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Combined Horizontal and Vertical Movement (m, from previous position)	Seasonal Combined Horizontal and Vertical Velocity (m/day, since previous position)	Annual Combined Horizontal and Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Combined Horizontal and Vertical Velocity (m/day, net, 7/98 to 7/99 position)
MP4 - Windy	7/28/1998													
MP4 - adj	10/22/1998	0.298	0.0035	255.638			-0.037	-0.0004			0.301	0.0035		
MP4 - TP200	1/6/1999	0.233	0.0031	247.286			-0.001	<-0.0001			0.233	0.0031		
MP4 - TP200	3/23/1999	0.181	0.0024	257.883			-0.086	-0.0011			0.200	0.0026		
MP4 - TP200	5/11/1999	0.156	0.0032	254.809			-0.048	-0.0010			0.164	0.0033		
MP4 - adj	7/27/1999	0.417	0.0054	257.129	1.284	0.0035	-0.075	-0.0010	-0.247	-0.0007	0.424	0.0055	1.307	0.0036
MP5 - Windy	7/28/1998													
MP5 - adj	10/22/1998	0.199	0.0023	238.789			-0.017	-0.0002			0.200	0.0023		
MP5 - TP200	1/6/1999	0.151	0.0020	214.743			-0.034	-0.0004			0.155	0.0020		
MP5 - TP200	3/23/1999	0.086	0.0011	246.714			-0.053	-0.0007			0.101	0.0013		
MP5 - TP200	5/11/1999	0.124	0.0025	239.910			-0.034	-0.0007			0.128	0.0026		
MP5 - adj	7/27/1999	0.322	0.0042	243.276	0.867	0.0024	-0.034	-0.0004	-0.172	-0.0005	0.324	0.0042	0.884	0.0024
MP6 - Windy	7/28/1998													
MP6 - Windy	10/22/1998	0.415	0.0048	240.101			-0.097	-0.0011			0.426	0.0050		
MP6 - TP200	1/6/1999	0.360	0.0047	236.222			-0.006	-0.0001			0.360	0.0047		
MP6 - TP200	3/23/1999	0.284	0.0037	249.586			-0.034	-0.0004			0.286	0.0038		
MP6 - TP200	5/11/1999	0.255	0.0052	232.637			-0.077	-0.0016			0.267	0.0054		
MP6 - adj	7/27/1999	0.525	0.0068	243.923	1.832	0.0050	-0.055	-0.0007	-0.269	-0.0007	0.528	0.0069	1.852	0.0051

Table 3 - continued.

Point	Date of GPS Observation (m,d,y)	Seasonal Horizontal Movement (m, from previous position)	Seasonal Horizontal Velocity (m/day, since previous position)	Seasonal Horizontal Movement Direction (Degrees, from previous position)	Annual Horizontal Movement (m, net, 7/98 to 7/99 position)	Average Annual Horizontal Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Vertical Movement (m, from previous position)	Seasonal Vertical Velocity (m/day, since previous position)	Annual Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Vertical Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Combined Horizontal and Vertical Movement (m, from previous position)	Seasonal Combined Horizontal and Vertical Velocity (m/day, since previous position)	Annual Combined Horizontal and Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Combined Horizontal and Vertical Velocity (m/day, net, 7/98 to 7/99 position)
MP7 -adj	7/28/1998													
MP7 -adj	10/22/1998	0.651	0.0076	239.972			-0.053	-0.0006			0.654	0.0076		
MP7 -TP200	1/6/1999	0.564	0.0074	237.607			-0.065	-0.0009			0.568	0.0075		
MP7 - TP200	3/23/1999	0.470	0.0062	240.981			-0.041	-0.0005			0.472	0.0062		
MP7 - TP200	5/11/1999	0.381	0.0078	239.062			-0.067	-0.0014			0.387	0.0079		
MP7 - adj	7/27/1999	0.804	0.0104	241.077	2.870	0.0079	-0.046	-0.0006	-0.272	-0.0007	0.806	0.0105	2.883	0.0079
MP8 - adj	7/29/1998													
MP8 - adj	10/22/1998	1.047	0.0123	220.661			-0.023	-0.0003			1.047	0.0123		
MP8 - TP200	1/6/1999	0.906	0.0119	221.150			-0.032	-0.0004			0.906	0.0119		
MP8 - TP200	3/23/1999	0.739	0.0097	223.082			-0.032	-0.0004			0.740	0.0097		
MP8 - TP200	5/11/1999	0.617	0.0126	222.436			-0.024	-0.0005			0.617	0.0126		
MP8 - adj	7/27/1999	1.208	0.0157	222.484	4.516	0.0124	-0.021	-0.0003	-0.132	-0.0004	1.208	0.0157	4.518	0.0124
MP9 - adj	7/29/1998													
MP9 - adj	10/22/1998	0.976	0.0115	223.091			-0.072	-0.0008			0.979	0.0115		
MP9 - TP200	1/6/1999	0.839	0.0110	220.942			-0.034	-0.0004			0.840	0.0111		
MP9 - TP200	3/24/1999	0.725	0.0094	224.273			-0.074	-0.0010			0.729	0.0095		
MP9 - TP200	5/11/1999	0.561	0.0117	222.617			-0.055	-0.0011			0.564	0.0117		
MP9 - adj	7/27/1999	1.100	0.0143	222.827	4.201	0.0116	-0.041	-0.0005	-0.276	-0.0008	1.101	0.0143	4.210	0.0116

Table 3 - continued.

Point	Date of GPS Observation (m,d,y)	Seasonal Horizontal Movement (m, from previous position)	Seasonal Horizontal Velocity (m/day, since previous position)	Seasonal Horizontal Movement Direction (Degrees, from previous position)	Annual Horizontal Movement (m, net, 7/98 to 7/99 position)	Average Annual Horizontal Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Vertical Movement (m, from previous position)	Seasonal Vertical Velocity (m/day, since previous position)	Annual Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Vertical Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Combined Horizontal and Vertical Movement (m, from previous position)	Seasonal Combined Horizontal and Vertical Velocity (m/day, since previous position)	Annual Combined Horizontal and Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Combined Horizontal and Vertical Velocity (m/day, net, 7/98 to 7/99 position)
MP10 - adj	7/29/1998													
MP10 - adj	10/21/1998	1.500	0.0179	226.945			-0.290	-0.0035			1.528	0.0182		
MP10 - TP200	1/5/1999	1.320	0.0174	226.964			-0.283	-0.0037			1.350	0.0178		
MP10 - TP200	3/23/1999	1.073	0.0139	228.437			-0.185	-0.0024			1.089	0.0141		
MP10 - TP200	5/11/1999	0.933	0.0190	226.867			-0.237	-0.0048			0.963	0.0196		
MP10 - adj	7/27/1999	1.677	0.0218	227.441	6.503	0.0179	-0.290	-0.0038	-1.285	-0.0035	1.702	0.0221	6.629	0.0183
MP11 -adj	7/29/1998													
MP11 -adj	10/21/1998	1.061	0.0126	232.817			-0.152	-0.0018			1.072	0.0128		
MP11 -TP200	1/5/1999	1.028	0.0135	231.871			-0.313	-0.0041			1.075	0.0141		
MP11 -TP200	3/24/1999	0.802	0.0103	233.573			-0.180	-0.0023			0.822	0.0105		
MP11- TP200	5/12/1999	0.697	0.0142	235.991			-0.172	-0.0035			0.718	0.0147		
MP11 - adj	7/28/1999	1.257	0.0163	235.602	4.843	0.0133	-0.302	-0.0039	-1.119	-0.0031	1.293	0.0168	4.971	0.0137
MP12 -adj	7/29/1998													
MP12 -adj	10/21/1998	1.683	0.0200	222.858			-0.102	-0.0012			1.687	0.0201		
MP12 -TP200	1/5/1999	1.487	0.0196	222.520			-0.158	-0.0021			1.495	0.0197		
MP12 -TP200	3/24/1999	1.213	0.0156	222.661			-0.097	-0.0012			1.217	0.0156		
MP12 - TP200	5/11/1999	1.047	0.0218	224.961			-0.103	-0.0021			1.052	0.0219		
MP12 - adj	7/28/1999	1.860	0.0239	224.412	7.290	0.0200	-0.211	-0.0027	-0.671	-0.0018	1.872	0.0240	7.321	0.0201

Table 3 - continued.

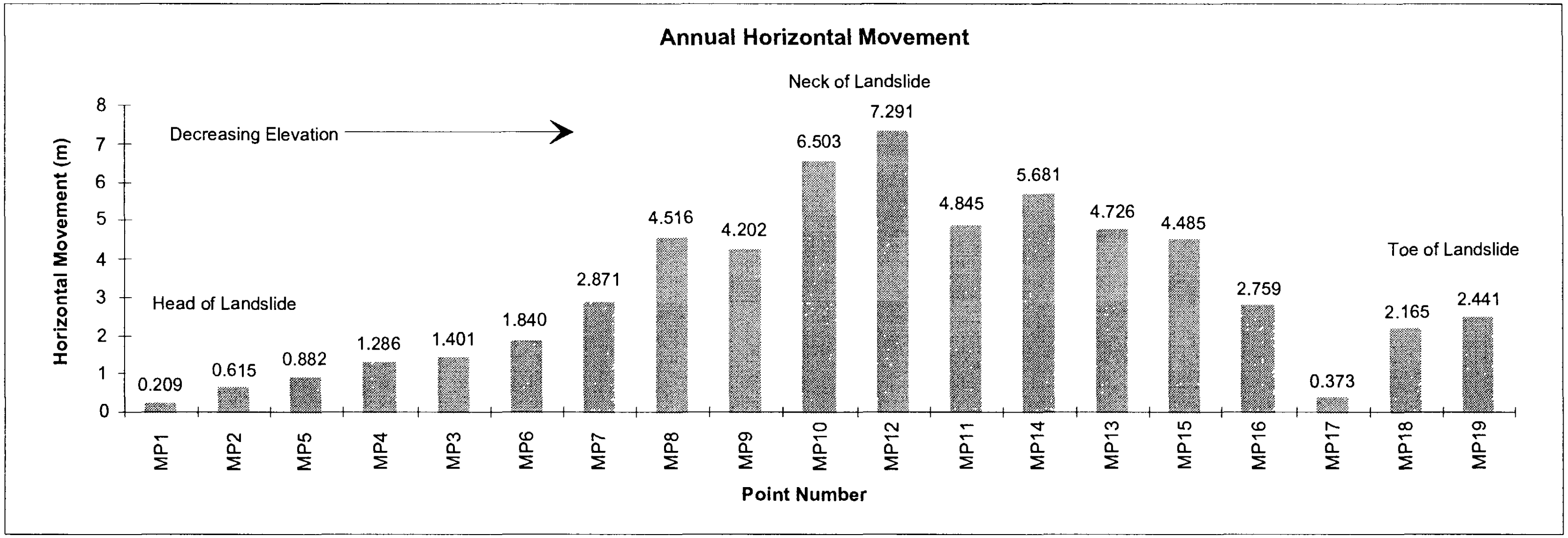
Point	Date of GPS Observation (m,d,y)	Seasonal Horizontal Movement (m, from previous position)	Seasonal Horizontal Velocity (m/day, since previous position)	Seasonal Horizontal Movement Direction (Degrees, from previous position)	Annual Horizontal Movement (m, net, 7/98 to 7/99 position)	Average Annual Horizontal Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Vertical Movement (m, from previous position)	Seasonal Vertical Velocity (m/day, since previous position)	Annual Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Vertical Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Combined Horizontal and Vertical Movement (m, from previous position)	Seasonal Combined Horizontal and Vertical Velocity (m/day, since previous position)	Annual Combined Horizontal and Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Combined Horizontal and Vertical Velocity (m/day, net, 7/98 to 7/99 position)
MP13 - adj	7/29/1998													
MP13 - adj	10/21/1998	1.087	0.0129	239.543			-0.218	-0.0026			1.109	0.0132		
MP13 - TP200	1/5/1999	0.971	0.0128	238.814			-0.206	-0.0027			0.993	0.0131		
MP13 - TP200	3/24/1999	0.773	0.0099	242.076			-0.173	-0.0022			0.792	0.0102		
MP13 - TP200	5/12/1999	0.722	0.0147	240.629			-0.157	-0.0032			0.739	0.0151		
MP13 - adj	7/28/1999	1.173	0.0152	240.352	4.725	0.0130	-0.306	-0.0040	-1.060	-0.0029	1.212	0.0157	4.842	0.0133
MP14 -adj	7/29/1998													
MP14 -adj	10/21/1998	1.302	0.0155	237.836			-0.227	-0.0027			1.321	0.0157		
MP14 -TP200	1/5/1999	1.191	0.0157	235.990			-0.257	-0.0034			1.218	0.0160		
MP14 -TP200	3/24/1999	0.913	0.0117	238.294			-0.177	-0.0023			0.930	0.0119		
MP14 - TP200	5/12/1999	0.864	0.0176	238.388			-0.167	-0.0034			0.880	0.0180		
MP14 - adj	7/28/1999	1.411	0.0183	238.597	5.680	0.0156	-0.305	-0.0040	-1.133	-0.0031	1.443	0.0187	5.792	0.0159
MP15 -adj	7/28/1998													
MP15 -adj	10/21/1998	1.024	0.0120	237.319			-0.235	-0.0028			1.051	0.0124		
MP15 -TP200	1/5/1999	0.934	0.0123	234.847			-0.200	-0.0026			0.956	0.0126		
MP15 -TP200	3/24/1999	0.703	0.0090	240.225			-0.201	-0.0026			0.731	0.0094		
MP15 - TP200	5/12/1999	0.703	0.0143	238.323			-0.173	-0.0035			0.724	0.0148		
MP15 -Windy	7/28/1999	1.121	0.0146	236.863	4.484	0.0123	-0.254	-0.0033	-1.063	-0.0029	1.150	0.0149	4.608	0.0126

Table 3 - continued.

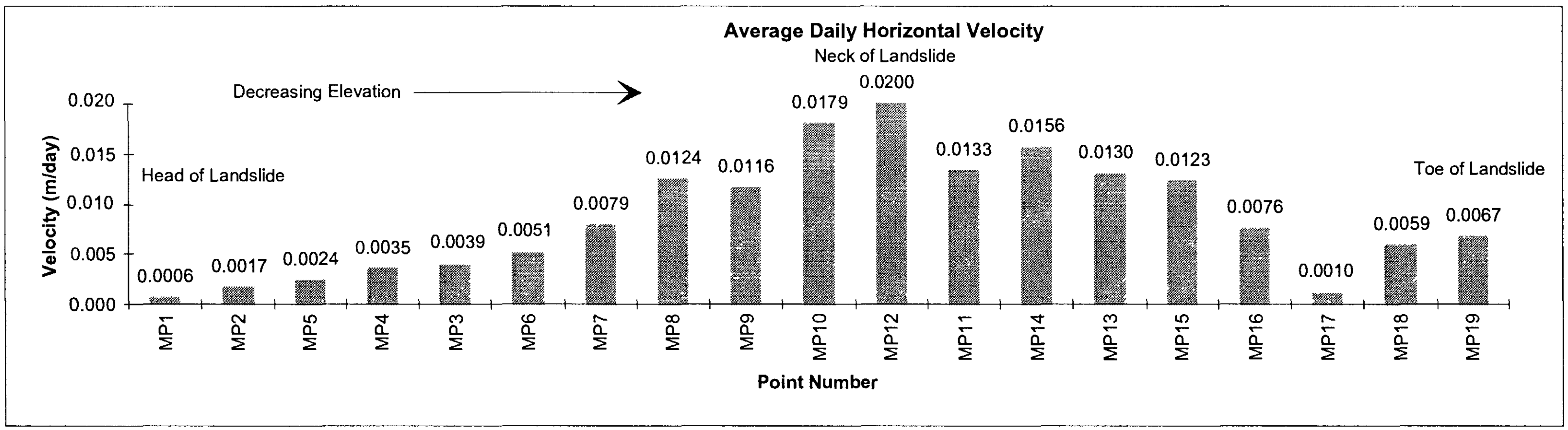
Point	Date of GPS Observation (m,d,y)	Seasonal Horizontal Movement (m, from previous position)	Seasonal Horizontal Velocity (m/day, since previous position)	Seasonal Horizontal Movement Direction (Degrees, from previous position)	Annual Horizontal Movement (m, net, 7/98 to 7/99 position)	Average Annual Horizontal Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Vertical Movement (m, from previous position)	Seasonal Vertical Velocity (m/day, since previous position)	Annual Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Vertical Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Combined Horizontal and Vertical Movement (m, from previous position)	Seasonal Combined Horizontal and Vertical Velocity (m/day, since previous position)	Annual Combined Horizontal and Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Combined Horizontal and Vertical Velocity (m/day, net, 7/98 to 7/99 position)
MP16 -adj	7/28/1998													
MP16 -adj	10/21/1998	0.627	0.0074	253.327			0.065	0.0008			0.631	0.0074		
MP16 -TP200	1/5/1999	0.554	0.0073	250.291			0.059	0.0008			0.558	0.0073		
MP16 -TP200	3/24/1999	0.429	0.0055	256.805			-0.010	-0.0001			0.430	0.0055		
MP16 - TP200	5/12/1999	0.472	0.0096	252.603			0.043	0.0009			0.474	0.0097		
MP16 - Windy	7/28/1999	0.677	0.0088	253.252	2.758	0.0076	0.027	0.0004	0.184	0.0005	0.677	0.0088	2.764	0.0076
MP17 -adj	7/28/1998													
MP17 -adj	10/21/1998	0.071	0.0008	314.433			0.007	0.0001			0.072	0.0008		
MP17 -TP200	1/5/1999	0.043	0.0006	286.314			-0.016	-0.0002			0.046	0.0006		
MP17 -TP200	3/24/1999	0.072	0.0009	327.407			0.024	0.0003			0.076	0.0010		
MP17 - TP200	5/12/1999	0.072	0.0015	301.921			-0.048	-0.0010			0.086	0.0018		
MP17 - Windy	7/28/1999	0.114	0.0015	331.189	0.359	0.0010	-0.023	-0.0003	-0.056	-0.0002	0.116	0.0015	0.364	0.0010
MP18 - Windy	7/28/1998													
MP18 - adj	10/21/1998	0.492	0.0058	248.545			-0.060	-0.0007			0.496	0.0058		
MP18- TP200	1/5/1999	0.457	0.0060	240.069			-0.024	-0.0003			0.458	0.0060		
MP18 - TP200	3/24/1999	0.330	0.0042	252.335			-0.019	-0.0002			0.330	0.0042		
MP18 - TP200	5/12/1999	0.355	0.0072	248.499			-0.036	-0.0007			0.357	0.0073		
MP18 - Windy	7/28/1999	0.532	0.0069	248.159	2.160	0.0059	-0.050	-0.0006	-0.189	-0.0005	0.535	0.0069	2.169	0.0059

Table 3 - continued.

Point	Date of GPS Observation (m,d,y)	Seasonal Horizontal Movement (m, from previous position)	Seasonal Horizontal Velocity (m/day, since previous position)	Seasonal Horizontal Movement Direction (Degrees, from previous position)	Annual Horizontal Movement (m, net, 7/98 to 7/99 position)	Average Annual Horizontal Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Vertical Movement (m, from previous position)	Seasonal Vertical Velocity (m/day, since previous position)	Annual Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Vertical Velocity (m/day, net, 7/98 to 7/99 position)	Seasonal Combined Horizontal and Vertical Movement (m, from previous position)	Seasonal Combined Horizontal and Vertical Velocity (m/day, since previous position)	Annual Combined Horizontal and Vertical Movement (m, net, 7/98 to 7/99 position)	Average Annual Combined Horizontal and Vertical Velocity (m/day, net, 7/98 to 7/99 position)
MP19 - Windy	7/28/1998													
MP19 - adj	10/21/1998	0.544	0.0064	256.934			-0.088	-0.0010			0.551	0.0065		
MP19 - TP200	1/5/1999	0.479	0.0063	251.376			-0.026	-0.0003			0.480	0.0063		
MP19 - TP200	3/24/1999	0.388	0.0050	261.995			-0.040	-0.0005			0.390	0.0050		
MP19 - TP200	5/12/1999	0.407	0.0083	254.597			-0.067	-0.0014			0.412	0.0084		
MP19 - Windy	7/28/1999	0.624	0.0081	258.348	2.437	0.0067	-0.069	-0.0009	-0.290	-0.0008	0.628	0.0082	2.454	0.0067



a



b

Figure 4. Bar graph showing the distribution of a) annual horizontal movement and b) average daily horizontal velocites over the year-long monitoring period.

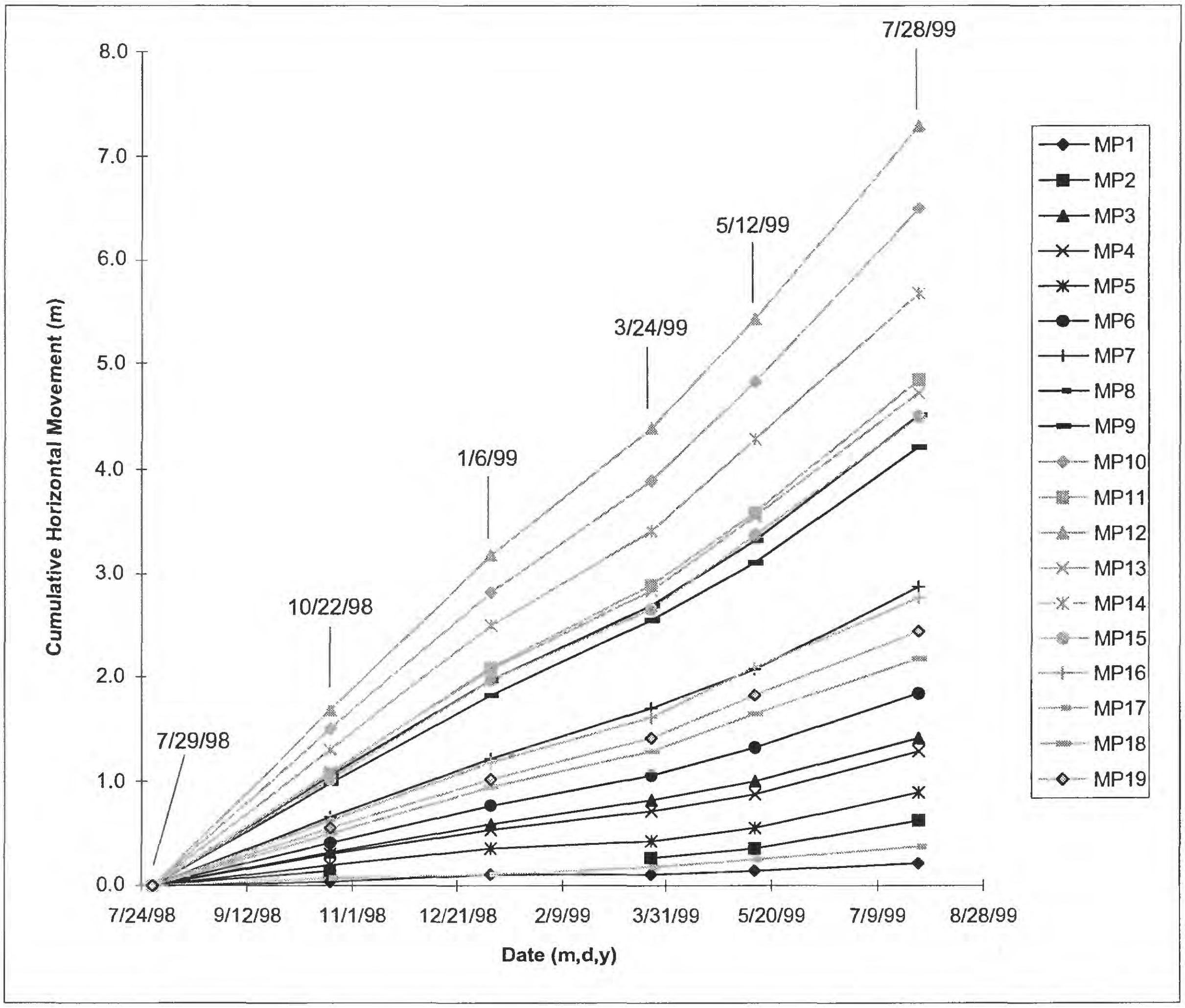


Figure 5. Diagram showing cumulative horizontal movement of monitoring points. Ending dates of GPS campaigns are shown.

velocities over the yearlong monitoring period ranged from <0.001 m/day at MP1 to 0.020 m/day at MP12 (fig 4b). 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 Appendix, MP16).

Velocities of individual points varied considerably according to the season, with minimum values ranging from 10-66 percent of maximum values (fig. 6). 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. The smallest differences occurred at points in the neck of the slide (MP9, MP10, MP12, MP11, MP14, and MP13) where the seasonal minimum velocities were 63-66 percent of the seasonal maximums.

Minimum and maximum velocities occurred at different times on different parts of the slide (fig. 7). At 15 of the 19 monitoring points (MP1-MP15), maximum velocities occurred between May 12 and July 28. 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. Minimum velocities at all points, except MP17, occurred between January 6 and March 24. At MP17, the minimum velocity occurred between October 22 and January 6.

Summary

Data presented in this report indicate that all parts of the active portion of the Slumgullion landslide moved throughout the 1998/1999 monitoring year. Daily velocities, however, were highly variable on a seasonal basis. Minimum velocities occurred between January and March, whereas maximum velocities occurred between March and May on the lower part of the slide, and between May and July on the middle and upper parts of the slide. Annual and seasonal velocities were greatest at the neck of the landslide and gradually decreased both upslope and downslope with the lowest velocities occurring at the head and toe of the slide.

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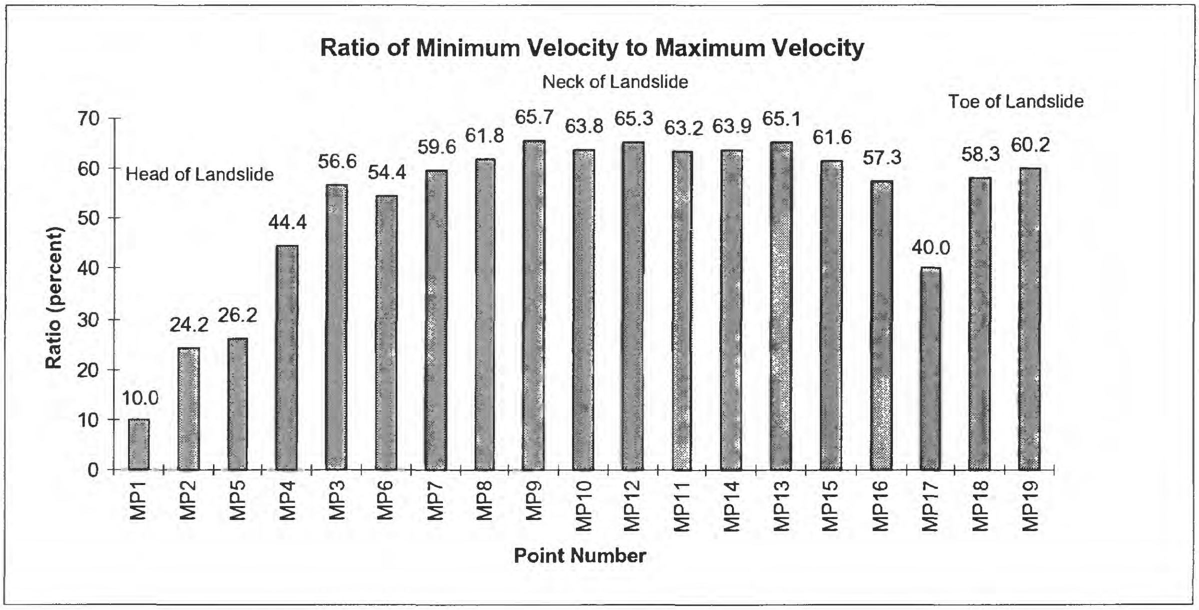


Figure 6. Bar graph showing the ratio of minimum velocity to maximum velocity at each monitoring point.

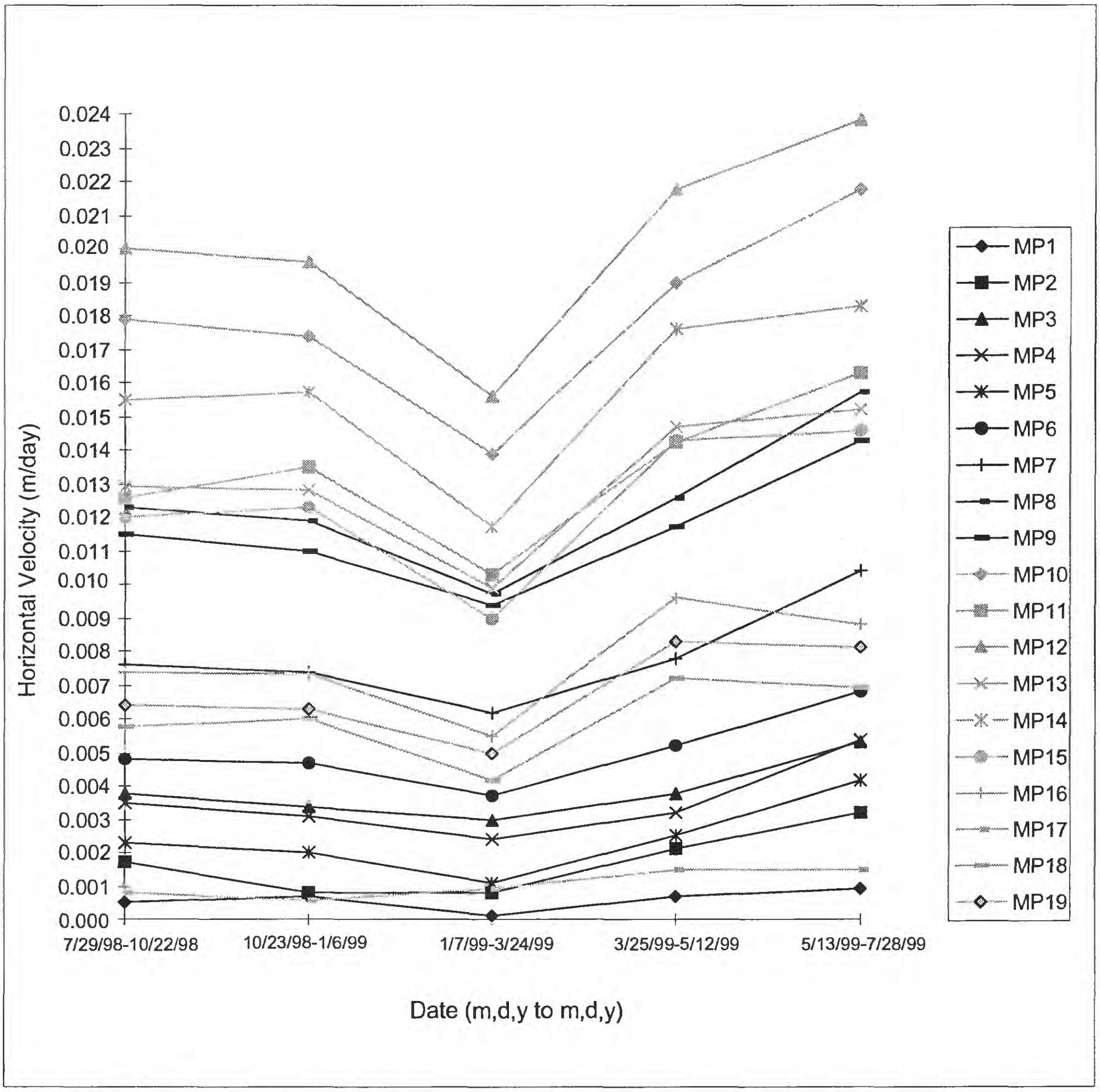


Figure 7. Diagram showing daily velocities of monitoring points. Dates shown are periods between GPS observations.

References Cited

Atwood, W.W. and Mather, K.F., 1932, Physiography and Quaternary geology of the San Juan mountains, Colorado: U.S. Geological Survey Professional Paper 166, 176 p.

Baum, R.L. and Fleming, R.W., 1996, Kinematic studies of the Slumgullion landslide, Hinsdale County, Colorado: *in* Varnes, D.J. and Savage, W.Z., eds., The Slumgullion Earth Flow: A large-scale natural laboratory, U.S. Geological Survey Bulletin 2130, p. 9-12.

Coe, J.A., Godt, J.W., Ellis, W.L., Savage, W.Z., Savage, J.E., Powers, P.S., Varnes, D.J., and Tachker, P., 2000, Preliminary interpretation of seasonal movement of the Slumgullion landslide as determined by GPS observations, July 1998 - July 1999: U.S. Geological Survey Open-File Report 00-102, 25 p.

Crandell and Varnes, 1961, Movement of the Slumgullion Earthflow near Lake City, Colorado, *in* Short papers in the geologic and hydrologic sciences: U.S. Geological Survey Professional Paper 424-B, p. B136-B139.

Endlich, F.M., 1876, Report of F.M. Endlich, in U.S. Geological and Geographical Survey (Hayden) of the Territories Annual Report 1974, p. 203.

Leick, A., 1990, GPS satellite surveying: Wiley and Sons, New York, 352 p.

Savage, W.Z. and Fleming, R.W., 1996, Slumgullion landslide fault creep studies, *in* Varnes, D.J. and Savage, W.Z., eds., The Slumgullion Earth Flow: A large-scale natural laboratory, U.S. Geological Survey Bulletin 2130, p 73-76.

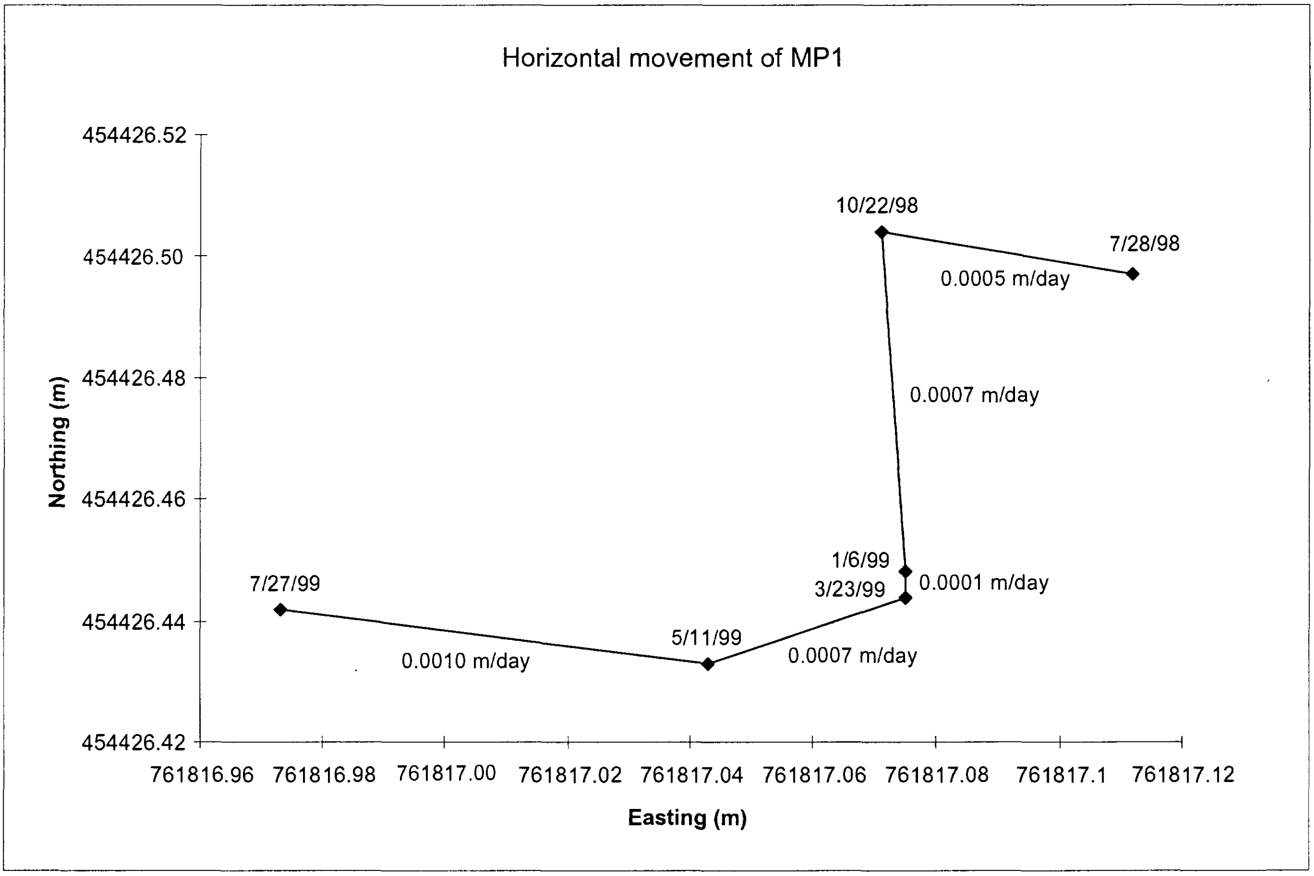
Van Sickle, J., 1996, GPS for land surveyors: Ann Arbor Press, Chelsea, Michigan, 209 p.

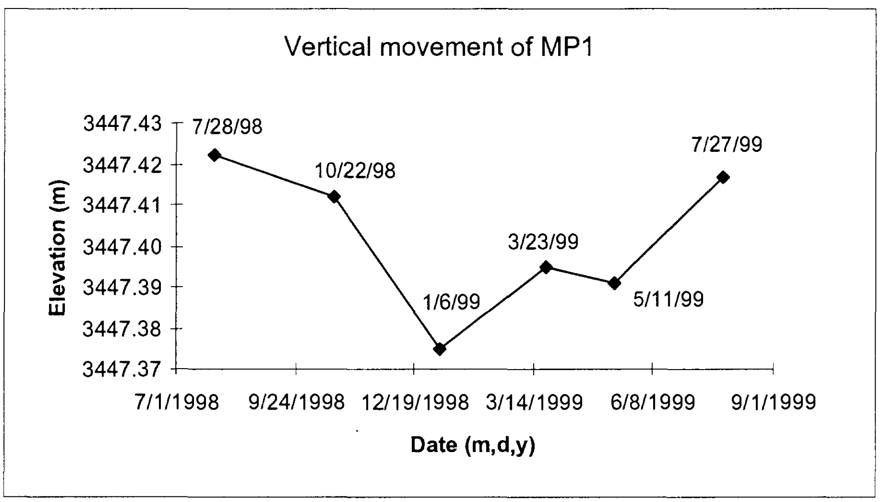
Varnes, D.J., Smith, W.K., Savage, W.Z., and Powers, P.S., 1996, Deformation and control surveys, Slumgullion landslide: *in* Varnes, D.J. and Savage, W.Z., eds., The Slumgullion Earth Flow: A large-scale natural laboratory, U.S. Geological Survey Bulletin 2130, p. 43-49.

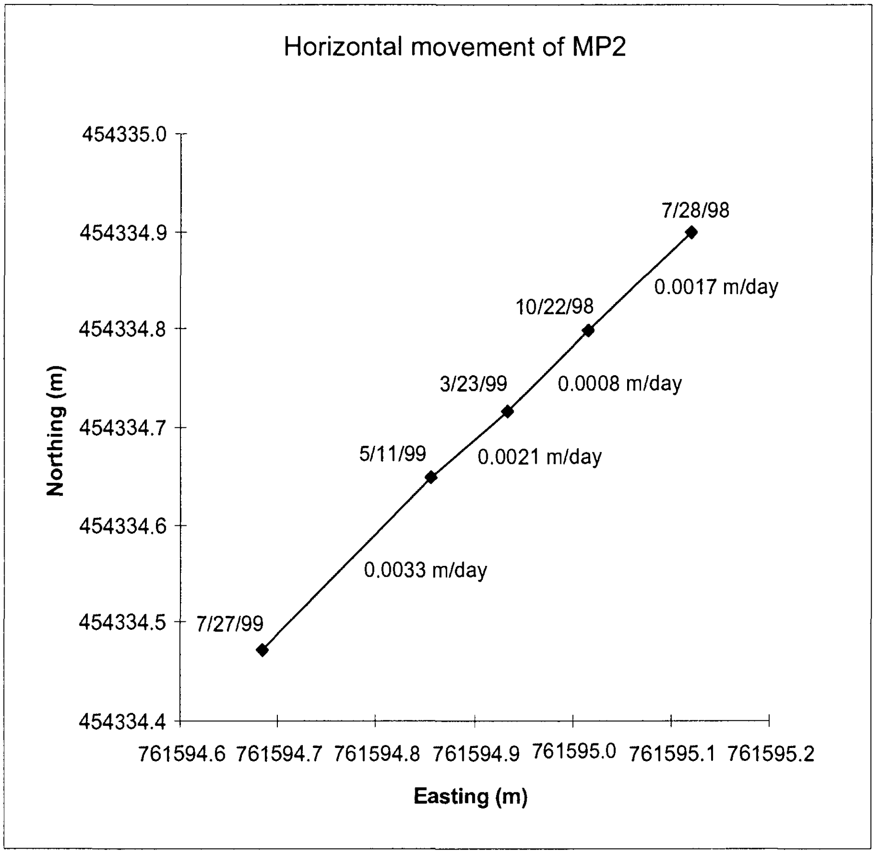
Varnes, D.J. and Savage, W.Z., 1996, The Slumgullion Earth Flow: A large-scale natural laboratory, U.S. Geological Survey Bulletin 2130, 95 p.

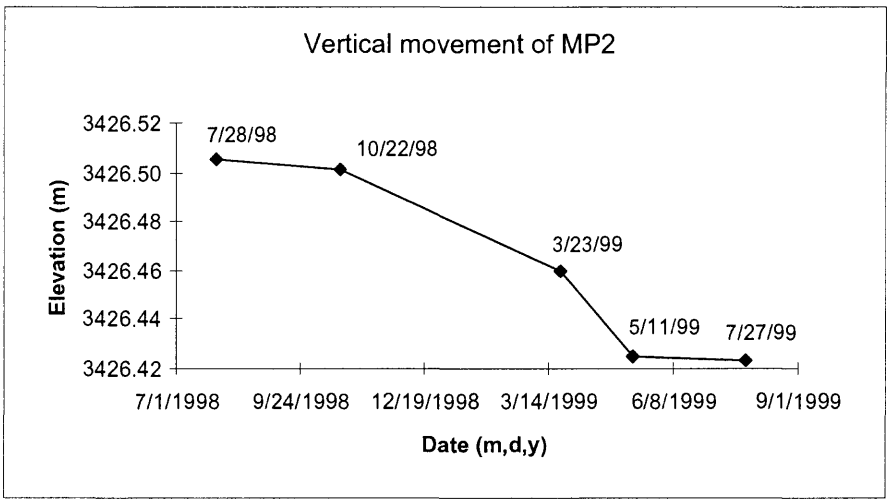
Appendix

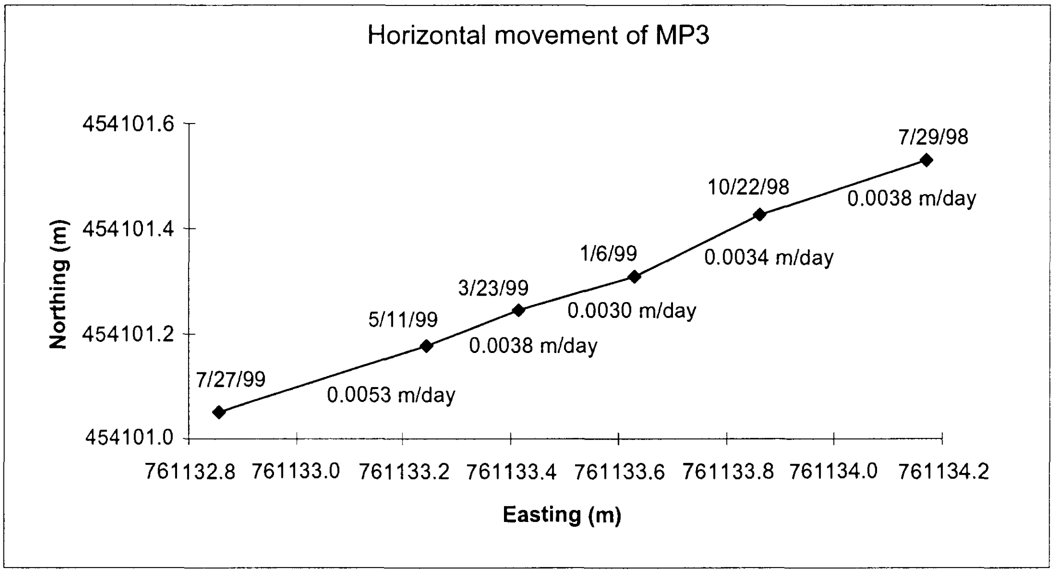
Diagrams showing horizontal and vertical movements of individual monitoring points.

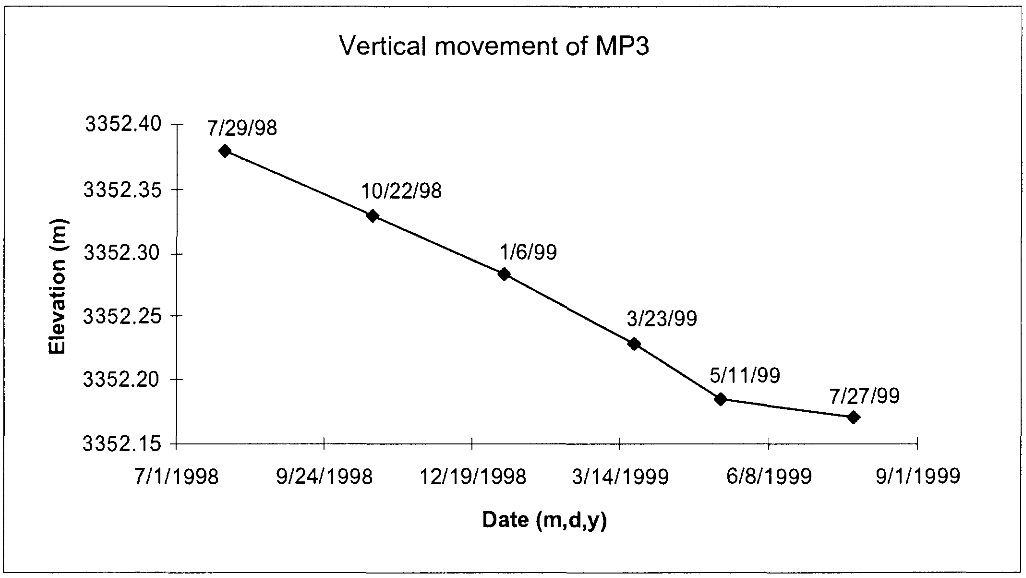

Horizontal movement of MP1
454426.52
454426.50
454426.48
454426.46
454426.44
454426.42
Northing (m)
761816.96
761816.98
761817.00
761817.02
761817.04
761817.06
761817.08
761817.1
761817.12
Easting (m)
10/22/98
7/28/98
0.0005 m/day
0.0007 m/day
1/6/99
3/23/99
0.0001 m/day
7/27/99
5/11/99
0.0010 m/day
0.0007 m/day


Vertical movement of MP1
3447.43
3447.42
3447.41
3447.40
3447.39
3447.38
3447.37
Elevation (m)
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
Date (m,d,y)
7/28/98
10/22/98
1/6/99
3/23/99
5/11/99
7/27/99


Horizontal movement of MP2
454335.0
454334.9
454334.8
454334.7
454334.6
454334.5
454334.4
Northing (m)
7/28/98
0.0017 m/day
10/22/98
3/23/99
0.0008 m/day
5/11/99
0.0021 m/day
0.0033 m/day
7/27/99
761594.6 761594.7 761594.8 761594.9 761595.0 761595.1 761595.2
Easting (m)


Vertical movement of MP2
3426.52
3426.50
3426.48
3426.46
3426.44
3426.42
Elevation (m)
7/28/98
10/22/98
3/23/99
5/11/99
7/27/99
7/1/1998 9/24/1998 12/19/1998 3/14/1999 6/8/1999 9/1/1999
Date (m,d,y)


Horizontal movement of MP3
Northing (m)
454101.6
454101.4
454101.2
454101.0
761132.8
761133.0
761133.2
761133.4
761133.6
761133.8
761134.0
761134.2
Easting (m)
7/29/98
10/22/98
0.0038 m/day
1/6/99
0.0034 m/day
3/23/99
0.0030 m/day
5/11/99
0.0038 m/day
7/27/99
0.0053 m/day


Vertical movement of MP3
Elevation (m)
3352.40
3352.35
3352.30
3352.25
3352.20
3352.15
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
Date (m,d,y)
7/29/98
10/22/98
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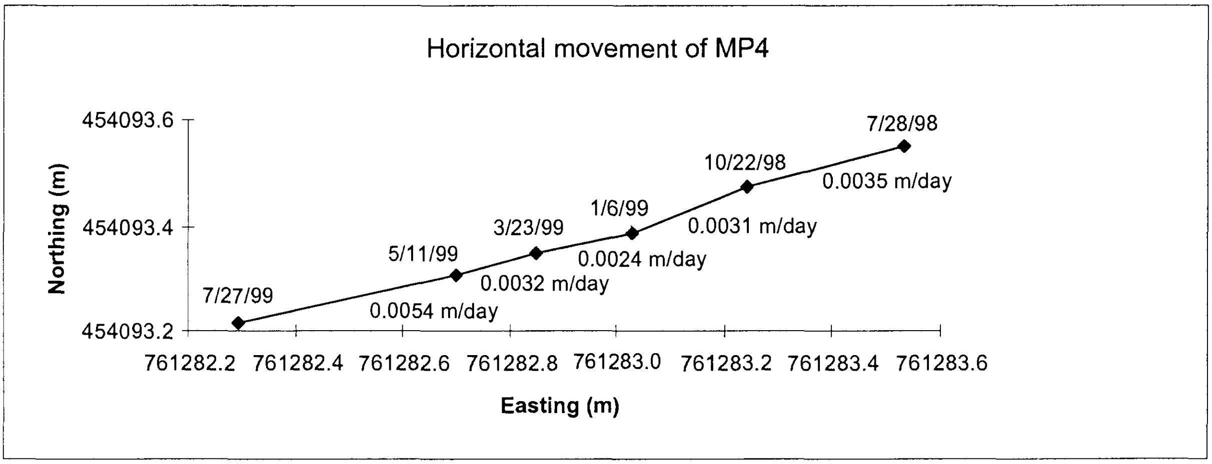
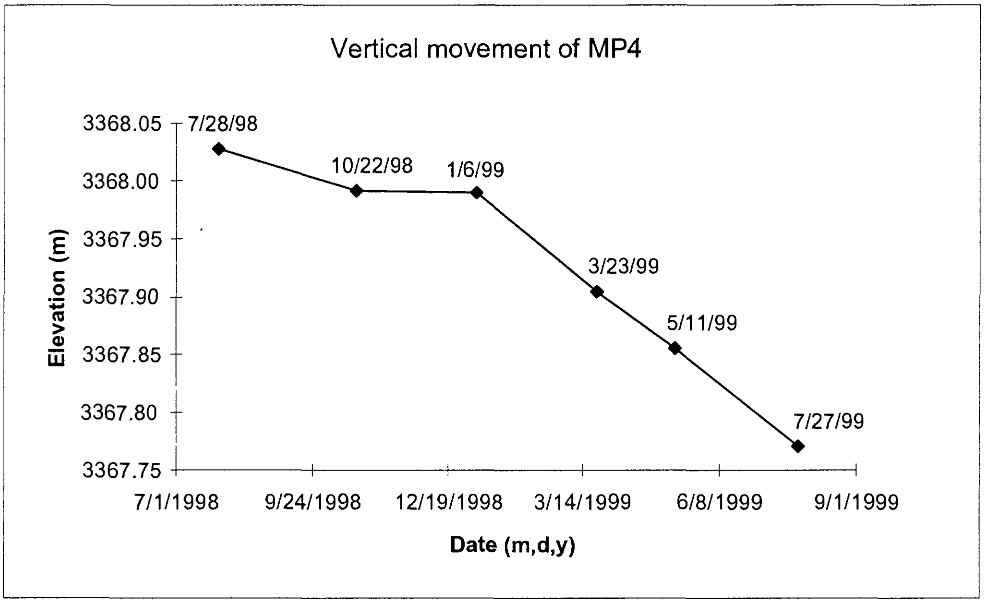
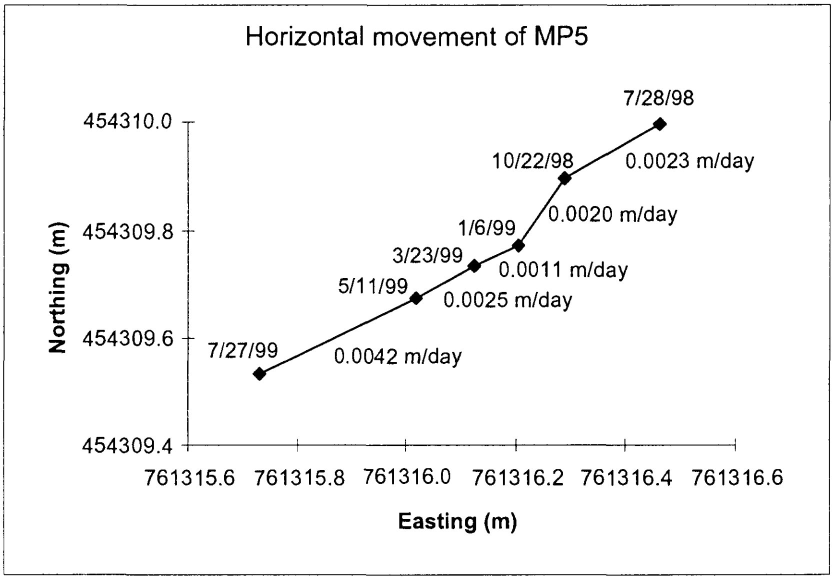
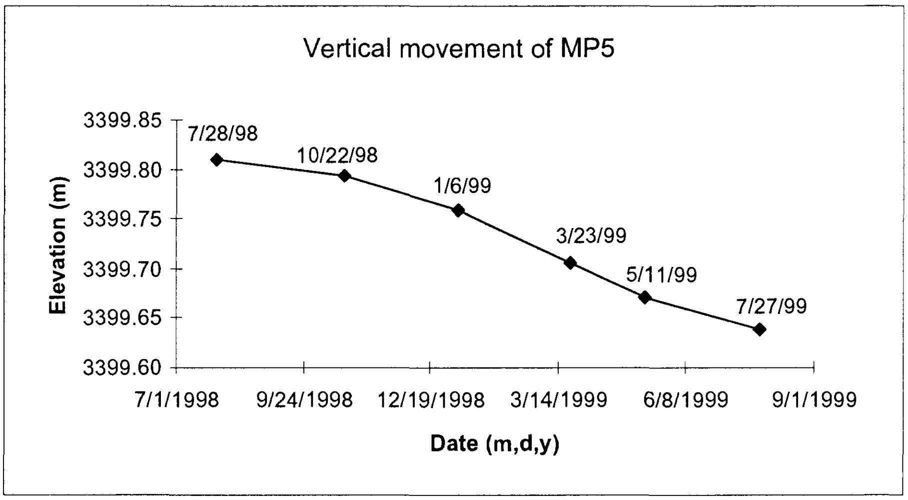
3/23/99
5/11/99
7/27/99


Horizontal movement of MP4
454093.6
454093.4
454093.2
Northing (m)
7/28/98
10/22/98
0.0035 m/day
1/6/99
3/23/99
0.0031 m/day
5/11/99
0.0024 m/day
0.0032 m/day
7/27/99
0.0054 m/day
761282.2 761282.4 761282.6 761282.8 761283.0 761283.2 761283.4 761283.6
Easting (m)


Vertical movement of MP4
3368.05
3368.00
3367.95
3367.90
3367.85
3367.80
3367.75
Elevation (m)
7/28/98
10/22/98
1/6/99
3/23/99
5/11/99
7/27/99
7/1/1998 9/24/1998 12/19/1998 3/14/1999 6/8/1999 9/1/1999
Date (m,d,y)



Horizontal movement of MP5
Northing (m)
454310.0
454309.8
454309.6
454309.4
7/28/98
10/22/98
0.0023 m/day
1/6/99
0.0020 m/day
3/23/99
0.0011 m/day
5/11/99
0.0025 m/day
7/27/99
0.0042 m/day
761315.6
761315.8
761316.0
761316.2
761316.4
761316.6
Easting (m)



Vertical movement of MP5
Elevation (m)
3399.85
3399.80
3399.75
3399.70
3399.65
3399.60
7/28/98
10/22/98
1/6/99
3/23/99
5/11/99
7/27/99
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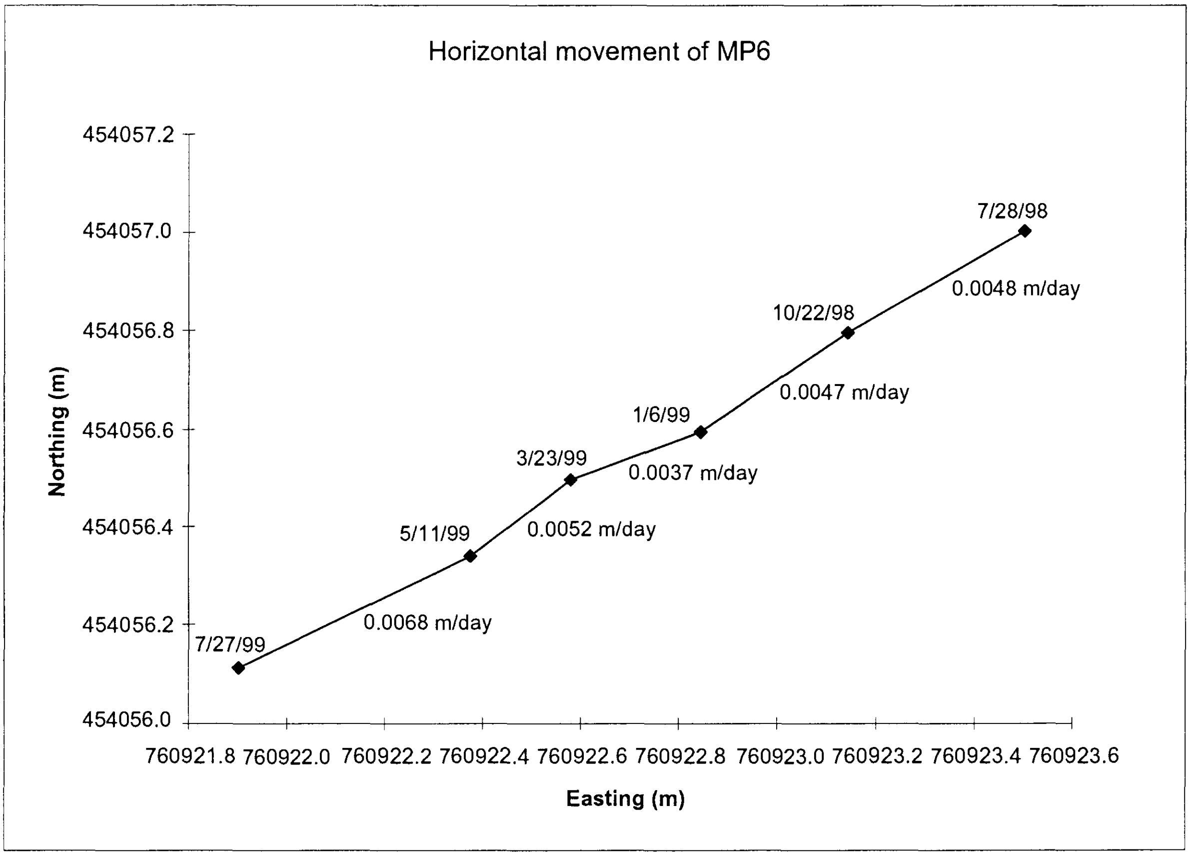
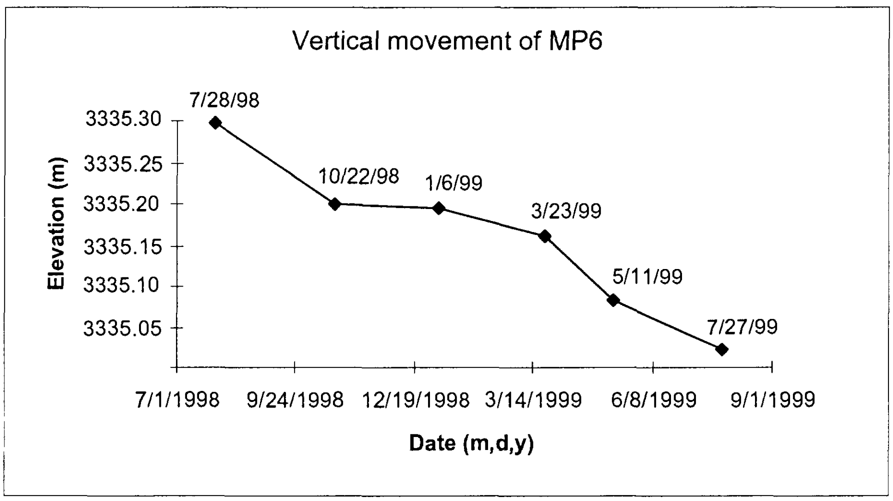
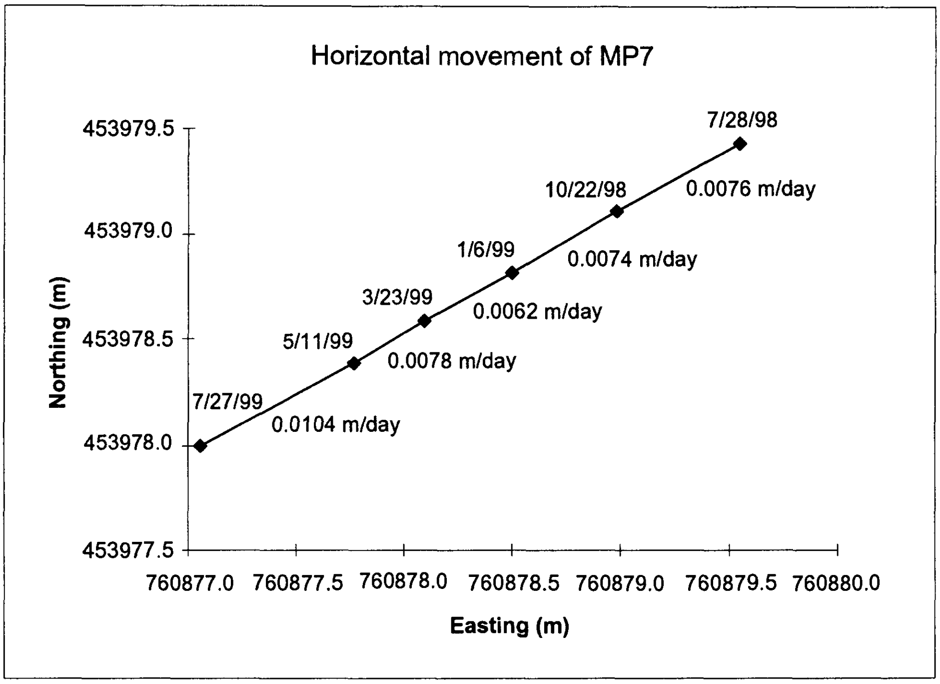
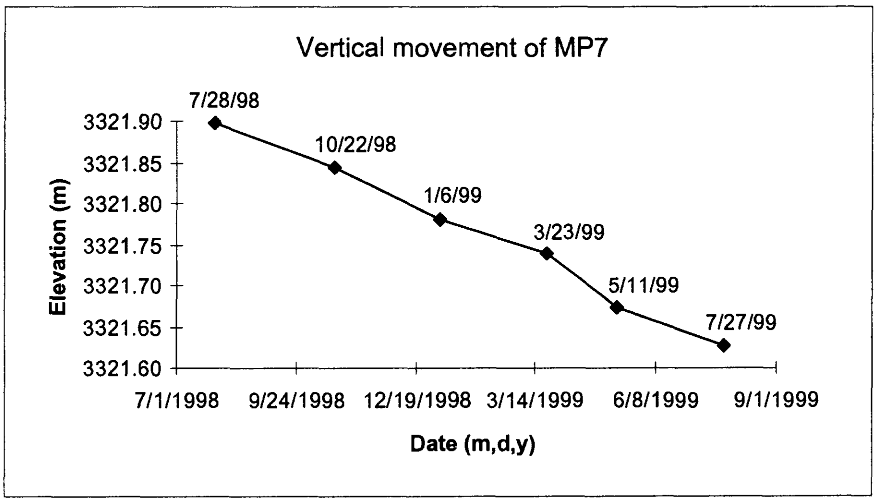
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
Date (m,d,y)


Horizontal movement of MP6
Northing (m)
454057.2
454057.0
454056.8
454056.6
454056.4
454056.2
454056.0
Easting (m)
760921.8 760922.0 760922.2 760922.4 760922.6 760922.8 760923.0 760923.2 760923.4 760923.6
7/28/98
0.0048 m/day
10/22/98
0.0047 m/day
1/6/99
0.0037 m/day
3/23/99
0.0052 m/day
5/11/99
0.0068 m/day
7/27/99


Vertical movement of MP6
Elevation (m)
3335.30
3335.25
3335.20
3335.15
3335.10
3335.05
Date (m,d,y)
7/1/1998 9/24/1998 12/19/1998 3/14/1999 6/8/1999 9/1/1999
7/28/98
10/22/98
1/6/99
3/23/99
5/11/99
7/27/99


Horizontal movement of MP7
Northing (m)
453979.5
453979.0
453978.5
453978.0
453977.5
Easting (m)
760877.0
760877.5
760878.0
760878.5
760879.0
760879.5
760880.0
7/28/98
10/22/98
0.0076 m/day
1/6/99
0.0074 m/day
3/23/99
0.0062 m/day
5/11/99
0.0078 m/day
7/27/99
0.0104 m/day


Vertical movement of MP7
Elevation (m)
3321.90
3321.85
3321.80
3321.75
3321.70
3321.65
3321.60
Date (m,d,y)
7/1/1998
9/24/1998
12/19/1998
3/14/1999
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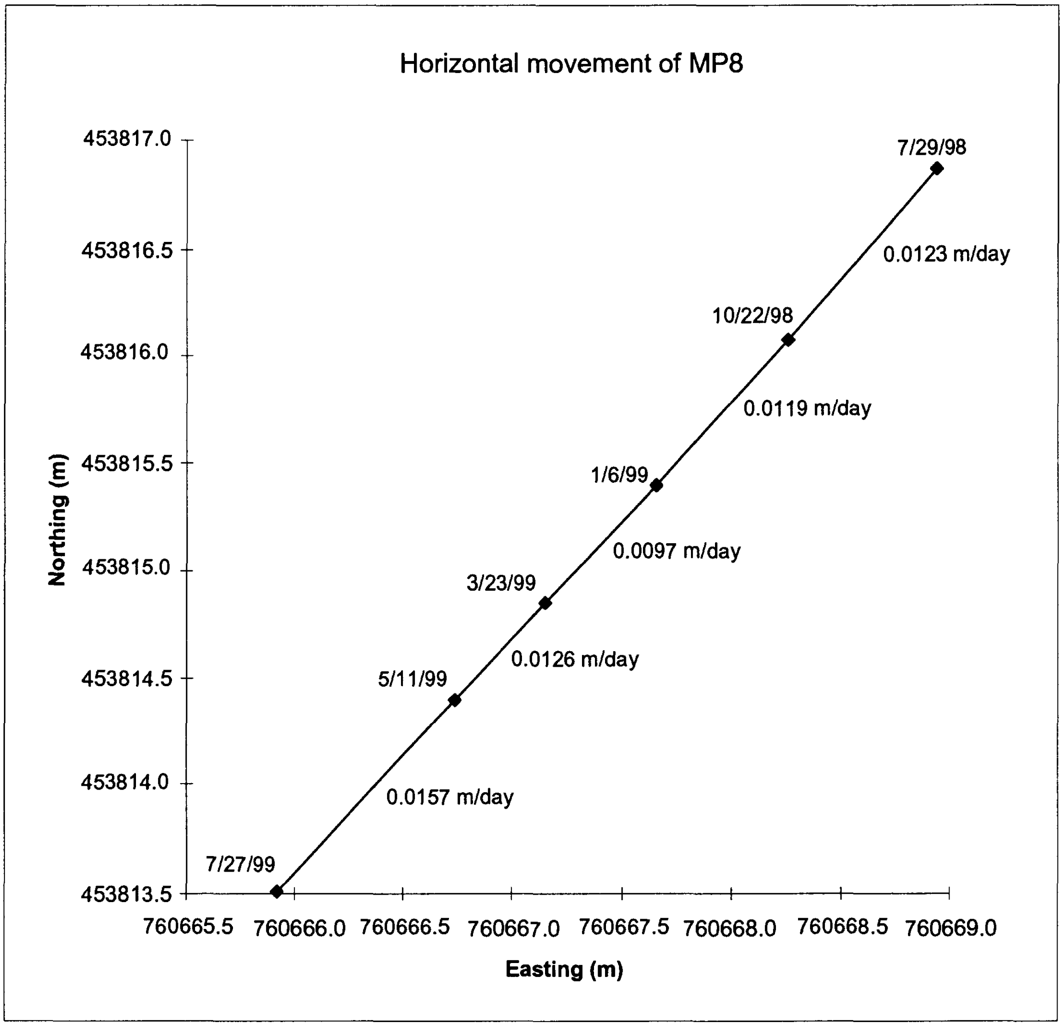
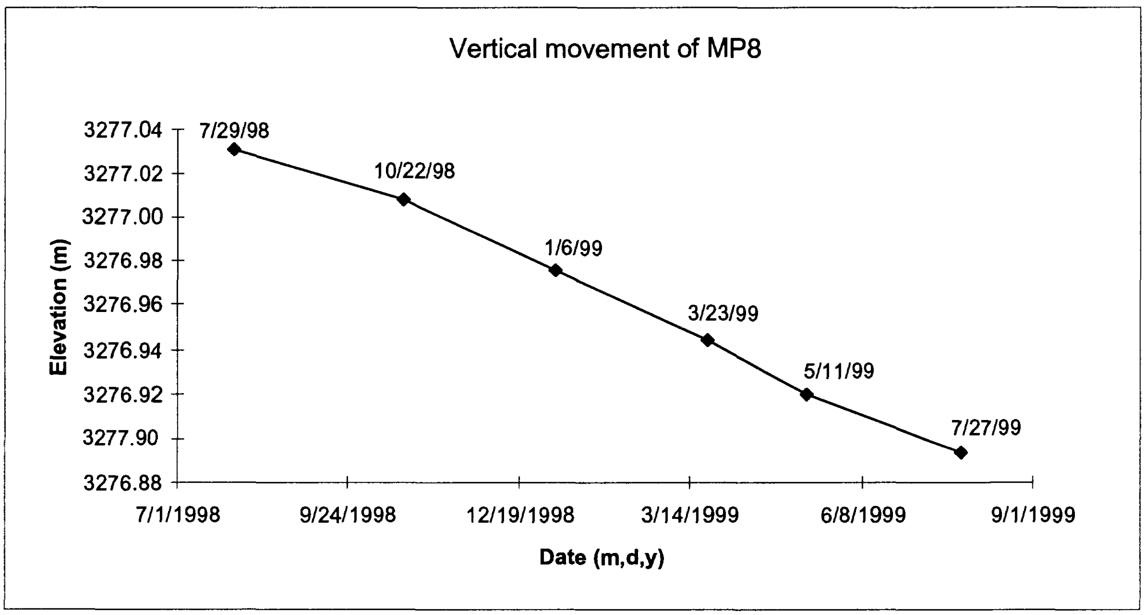
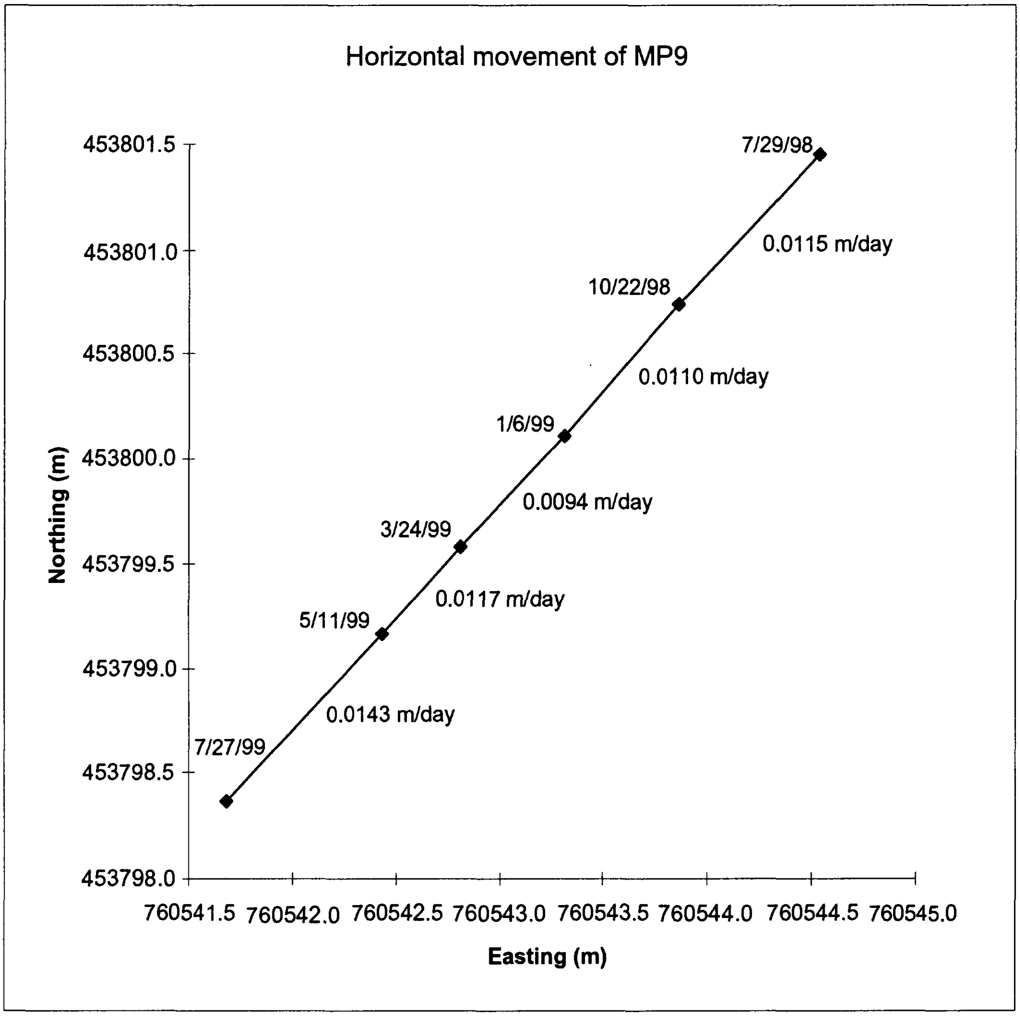
3/23/99
5/11/99
7/27/99



Horizontal movement of MP8
453817.0
453816.5
453816.0
453815.5
453815.0
453814.5
453814.0
453813.5
Northing (m)
760665.5
760666.0
760666.5
760667.0
760667.5
760668.0
760668.5
760669.0
Easting (m)
7/29/98
0.0123 m/day
10/22/98
0.0119 m/day
1/6/99
0.0097 m/day
3/23/99
0.0126 m/day
5/11/99
0.0157 m/day
7/27/99



Vertical movement of MP8
3277.04
3277.02
3277.00
3276.98
3276.96
3276.94
3276.92
3277.90
3276.88
Elevation (m)
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
Date (m,d,y)
7/29/98
10/22/98
1/6/99
3/23/99
5/11/99
7/27/99


Horizontal movement of MP9
Northing (m)
Easting (m)
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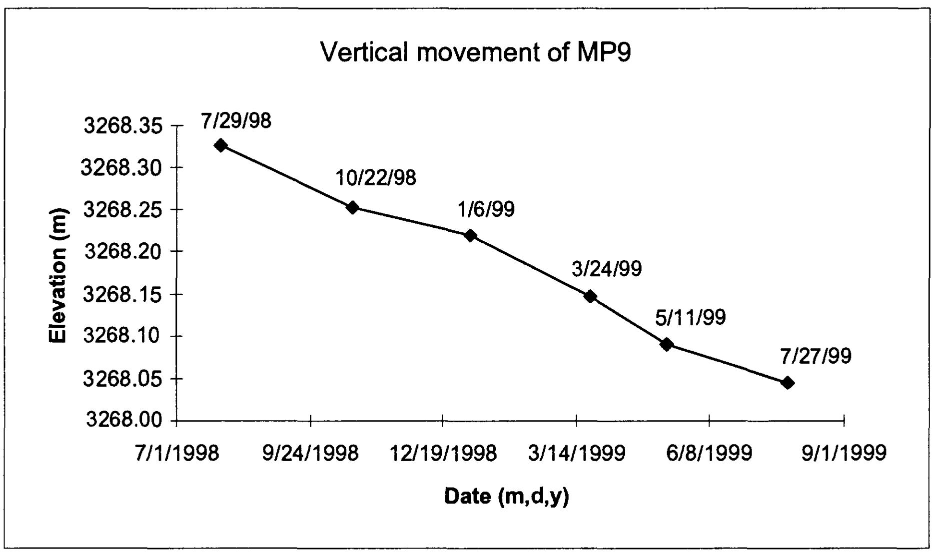
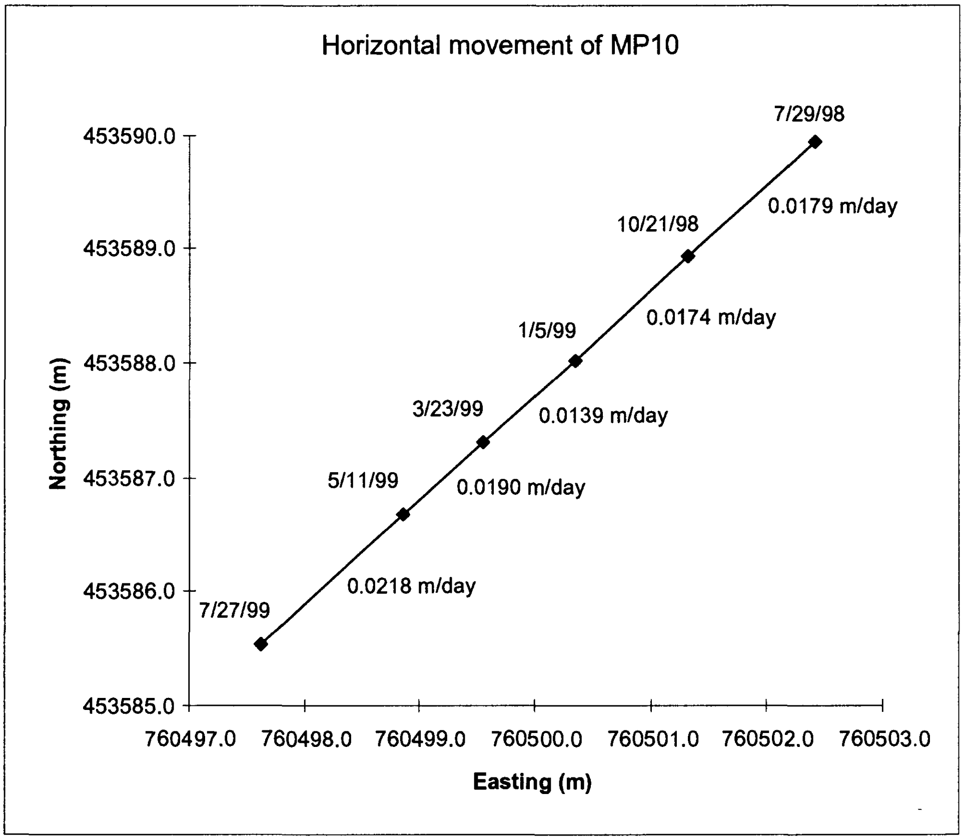
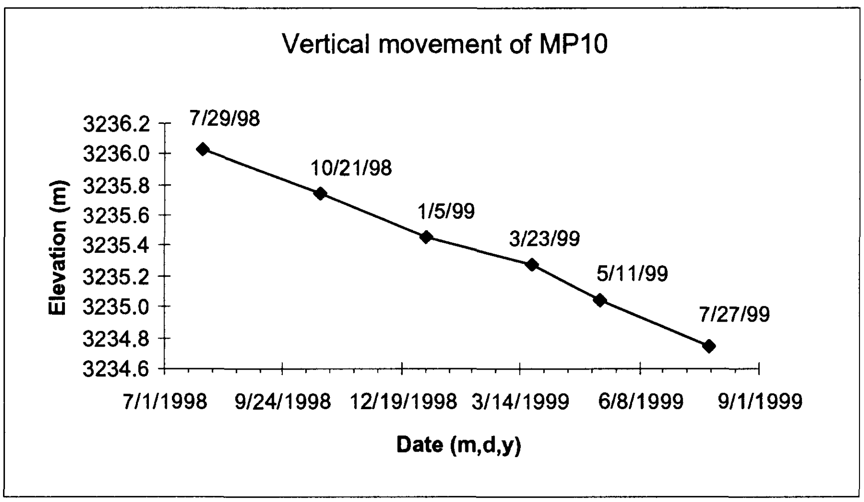
453801.0
453800.5
453800.0
453799.5
453799.0
453798.5
453798.0
760541.5
760542.0
760542.5
760543.0
760543.5
760544.0
760544.5
760545.0
7/29/98
0.0115 m/day
10/22/98
0.0110 m/day
1/6/99
0.0094 m/day
3/24/99
0.0117 m/day
5/11/99
0.0143 m/day
7/27/99

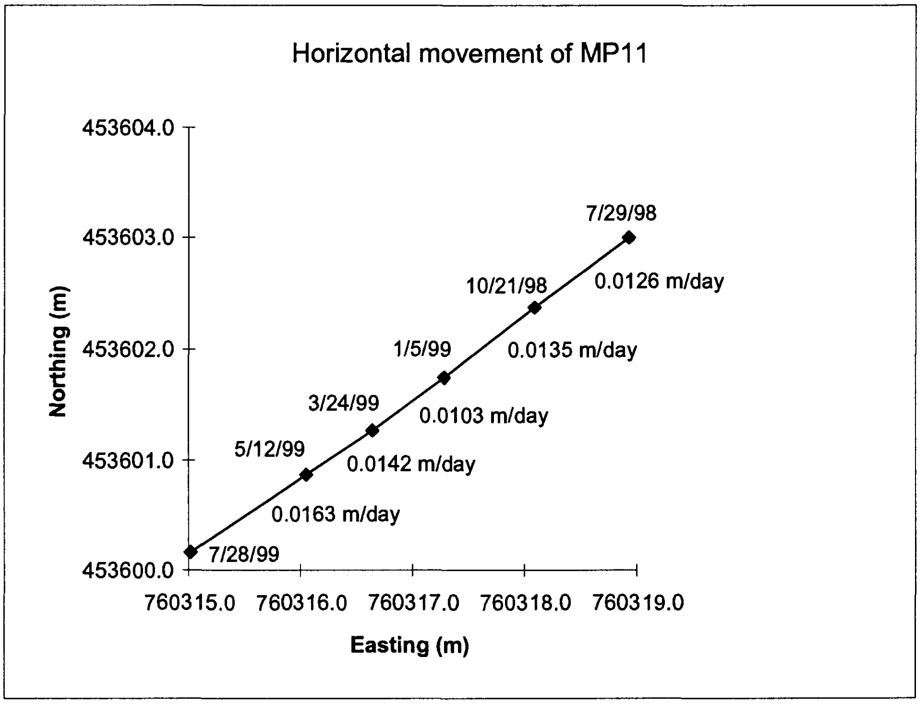

Vertical movement of MP9
Elevation (m)
Date (m,d,y)
3268.35
3268.30
3268.25
3268.20
3268.15
3268.10
3268.05
3268.00
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
7/29/98
10/22/98
1/6/99
3/24/99
5/11/99
7/27/99

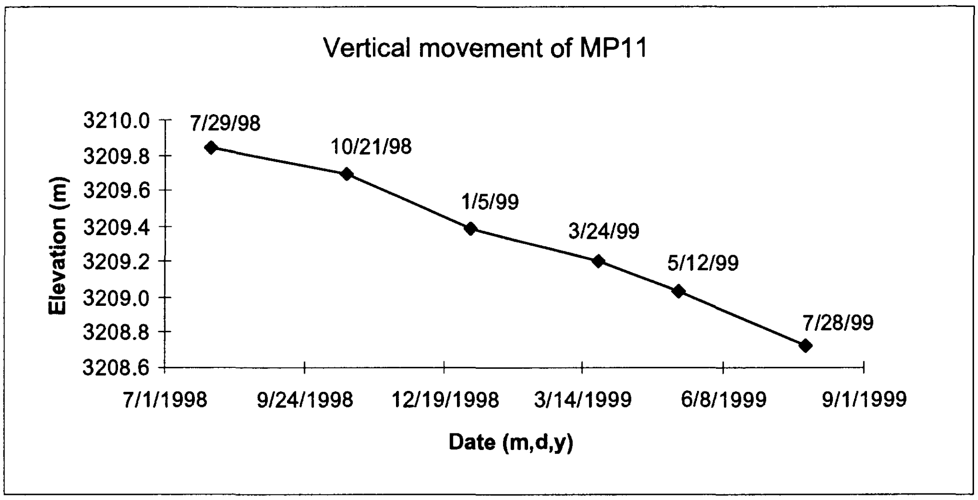


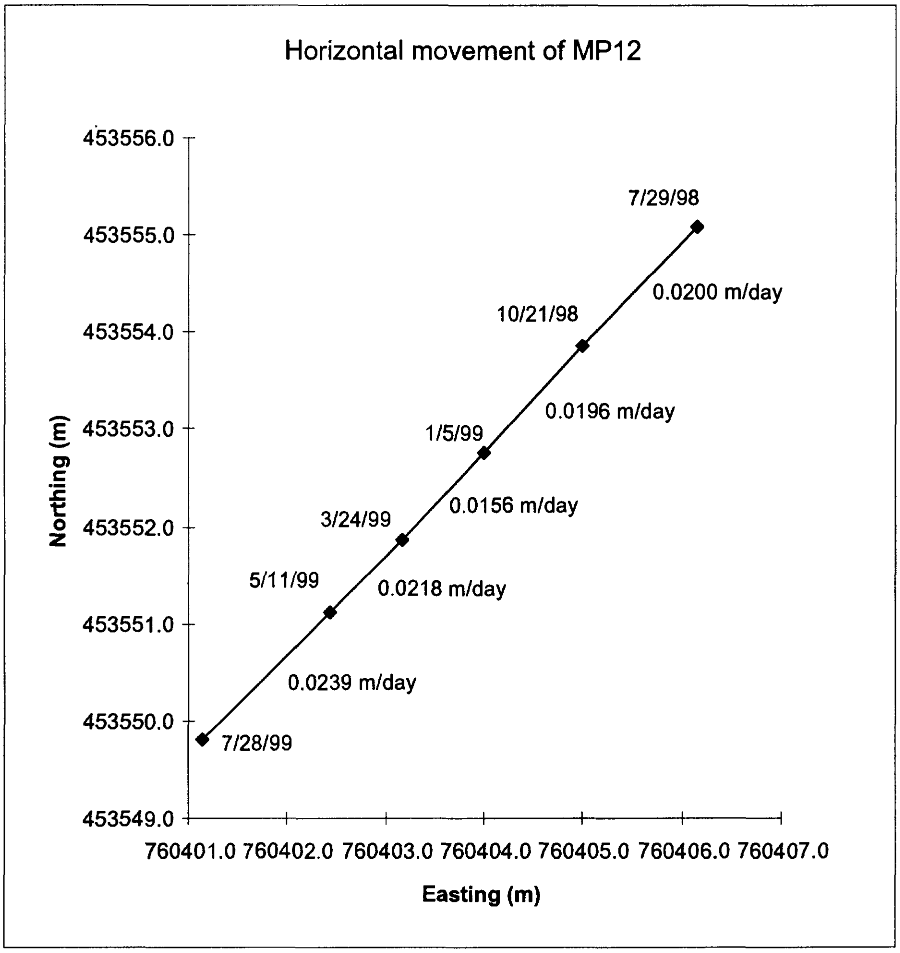
Horizontal movement of MP10
Northing (m)
Easting (m)
453590.0
453589.0
453588.0
453587.0
453586.0
453585.0
760497.0
760498.0
760499.0
760500.0
760501.0
760502.0
760503.0
7/29/98
0.0179 m/day
10/21/98
0.0174 m/day
1/5/99
0.0139 m/day
3/23/99
0.0190 m/day
5/11/99
0.0218 m/day
7/27/99



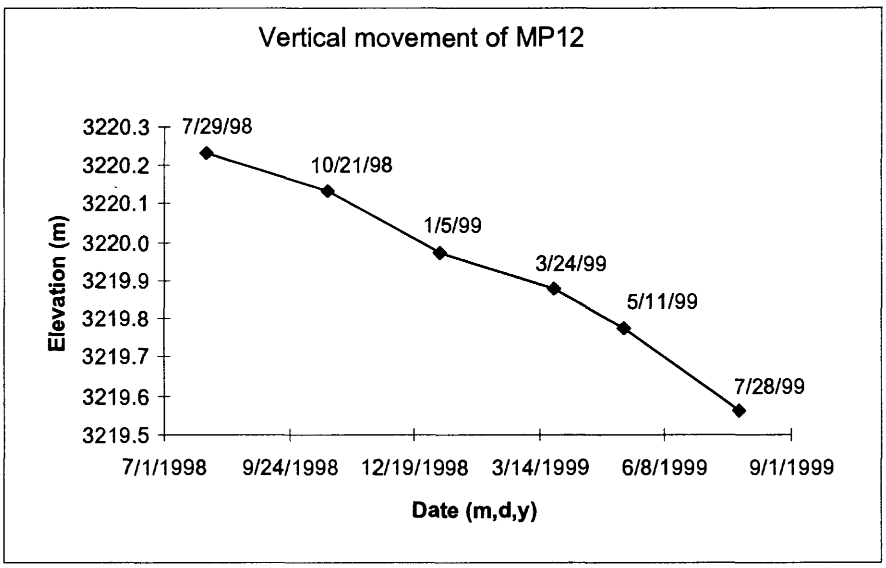
Vertical movement of MP10
Elevation (m)
Date (m,d,y)
3236.2
3236.0
3235.8
3235.6
3235.4
3235.2
3235.0
3234.8
3234.6
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
7/29/98
10/21/98
1/5/99
3/23/99
5/11/99
7/27/99


Horizontal movement of MP11
453604.0
453603.0
453602.0
453601.0
453600.0
Northing (m)
7/29/98
10/21/98
0.0126 m/day
1/5/99
0.0135 m/day
3/24/99
0.0103 m/day
5/12/99
0.0142 m/day
0.0163 m/day
7/28/99
760315.0
760316.0
760317.0
760318.0
760319.0
Easting (m)

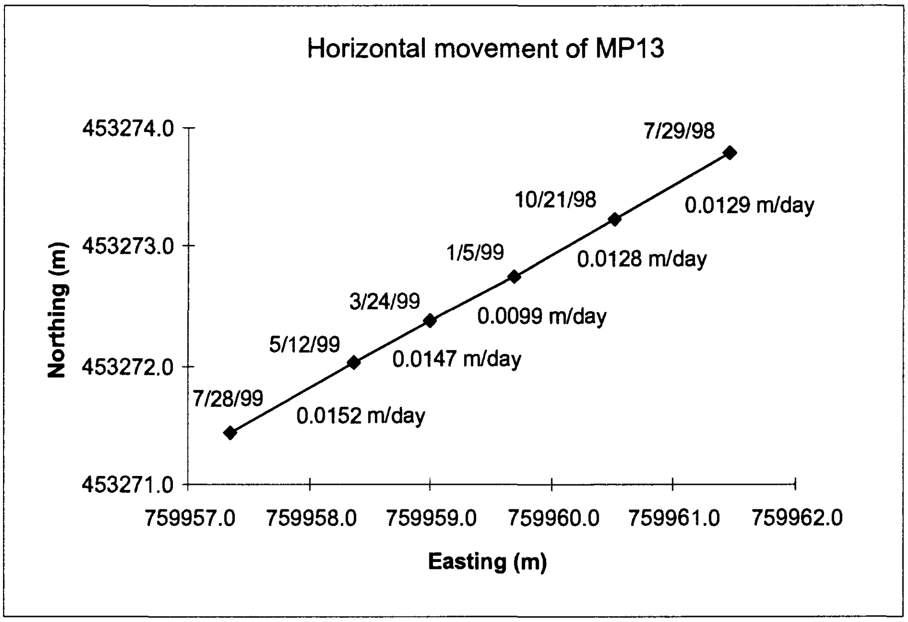

Vertical movement of MP11
3210.0
3209.8
3209.6
3209.4
3209.2
3209.0
3208.8
3208.6
Elevation (m)
7/29/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
Date (m,d,y)

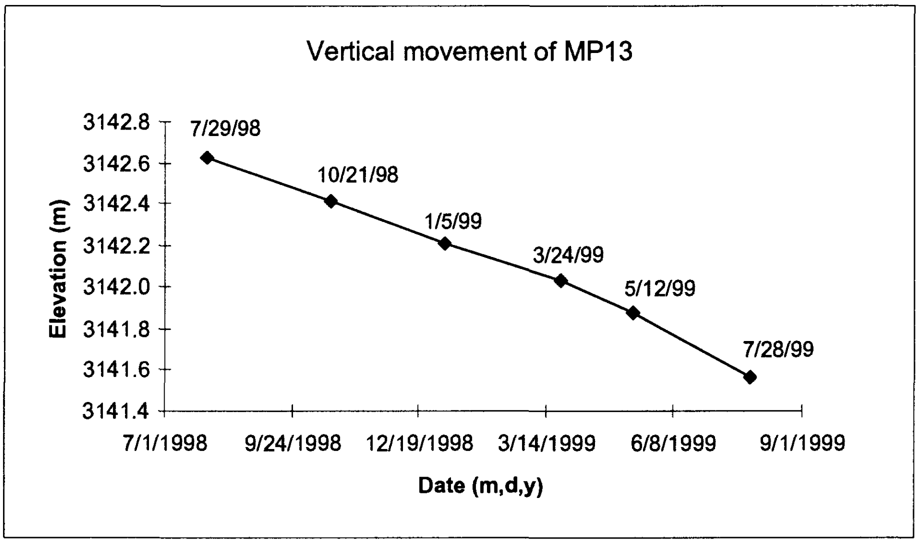


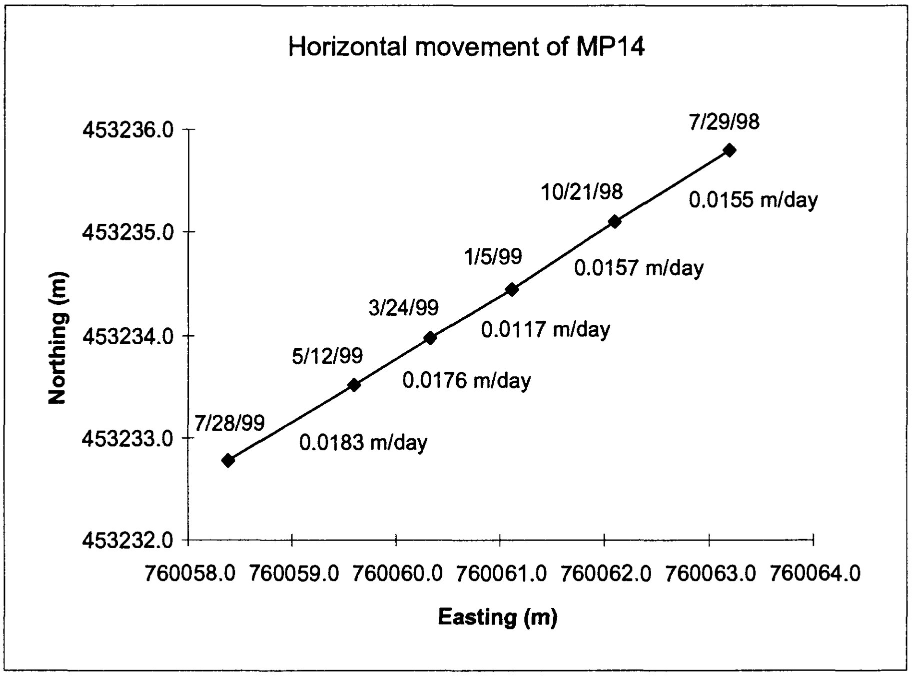
Horizontal movement of MP12
Northing (m)
Easting (m)
453556.0
453555.0
453554.0
453553.0
453552.0
453551.0
453550.0
453549.0
760401.0 760402.0 760403.0 760404.0 760405.0 760406.0 760407.0
7/29/98
0.0200 m/day
10/21/98
0.0196 m/day
1/5/99
0.0156 m/day
3/24/99
5/11/99
0.0218 m/day
0.0239 m/day
7/28/99

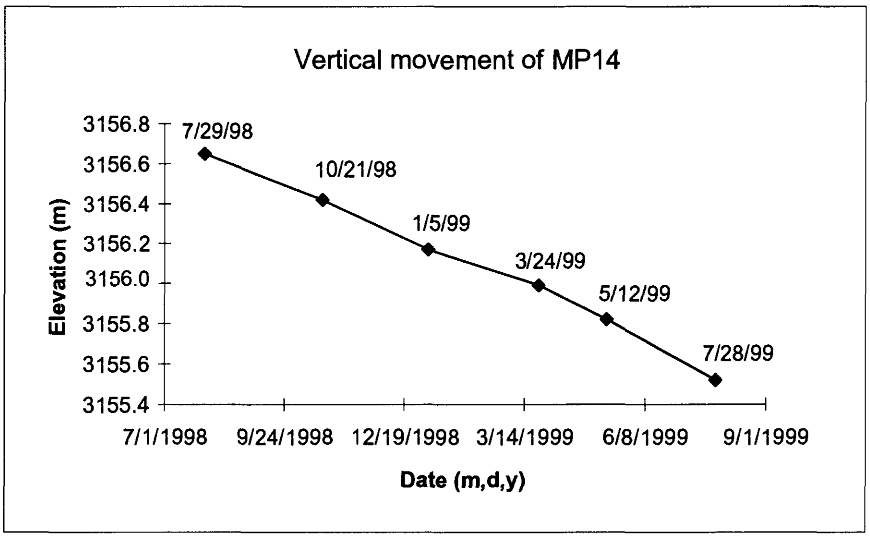


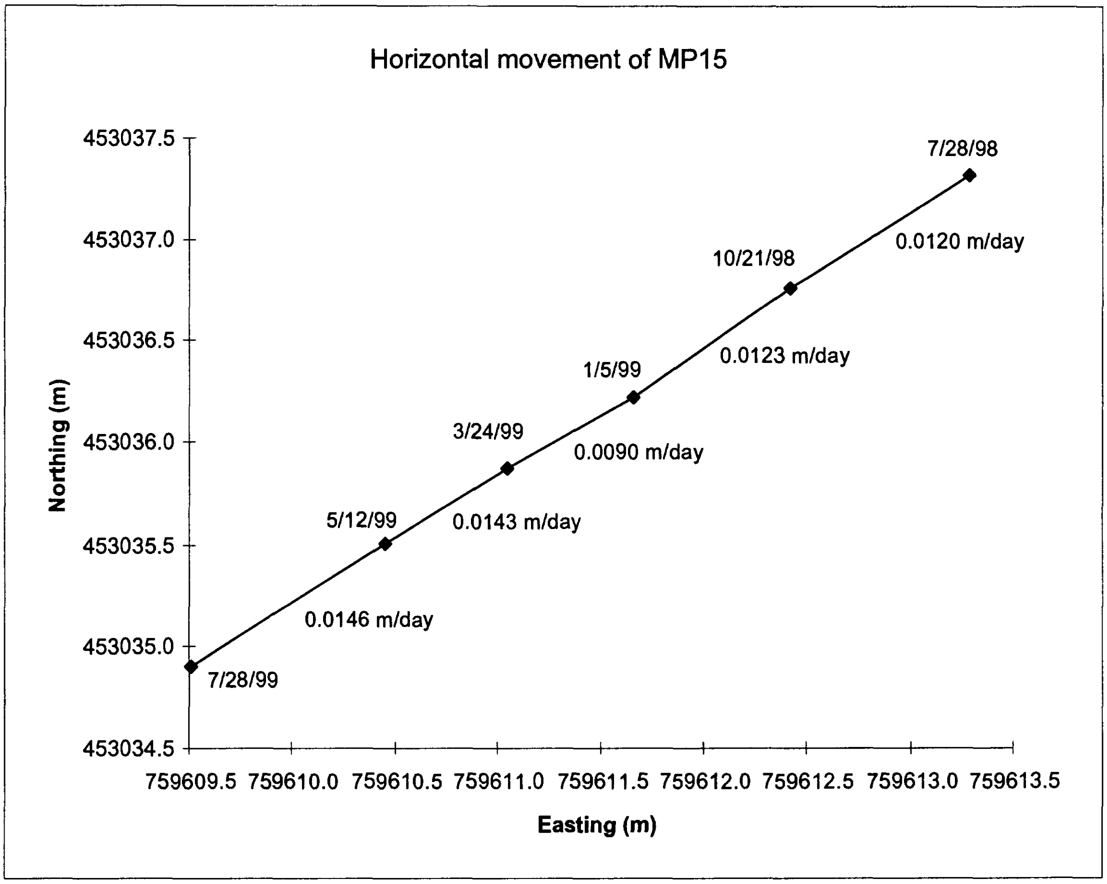
Vertical movement of MP12
Elevation (m)
Date (m,d,y)
3220.3
3220.2
3220.1
3220.0
3219.9
3219.8
3219.7
3219.6
3219.5
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
7/29/98
10/21/98
1/5/99
3/24/99
5/11/99
7/28/99

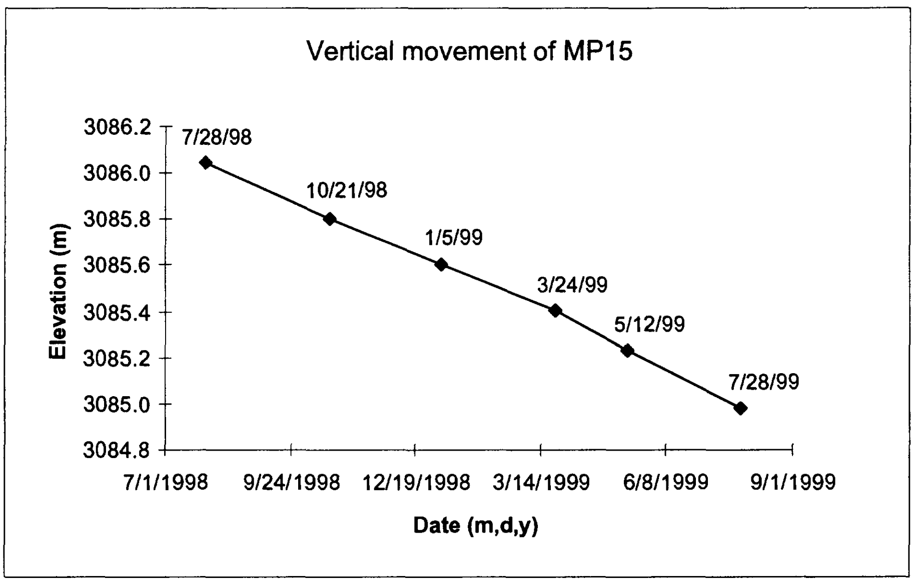

Horizontal movement of MP13
453274.0
453273.0
453272.0
453271.0
Northing (m)
7/29/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99
0.0129 m/day
0.0128 m/day
0.0099 m/day
0.0147 m/day
0.0152 m/day
759957.0
759958.0
759959.0
759960.0
759961.0
759962.0
Easting (m)

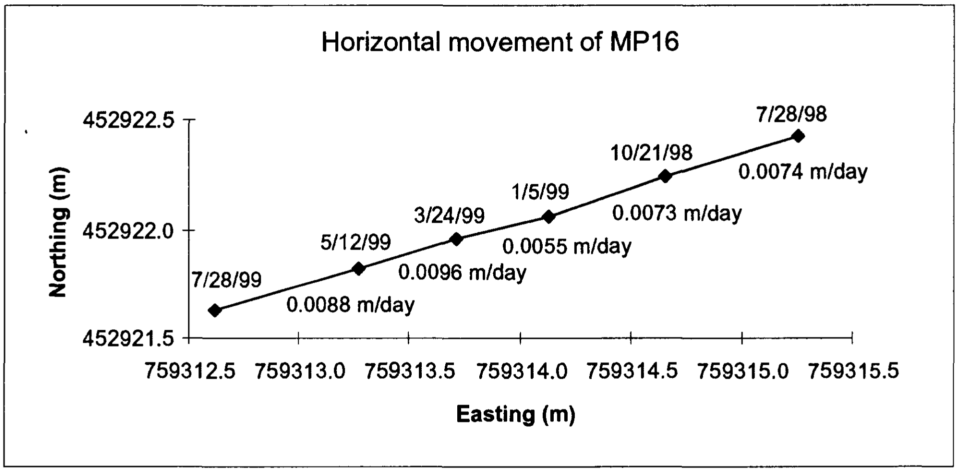

Vertical movement of MP13
3142.8
3142.6
3142.4
3142.2
3142.0
3141.8
3141.6
3141.4
Elevation (m)
7/29/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
Date (m,d,y)


Horizontal movement of MP14
453236.0
453235.0
453234.0
453233.0
453232.0
Northing (m)
760058.0 760059.0 760060.0 760061.0 760062.0 760063.0 760064.0
Easting (m)
7/29/98
10/21/98
0.0155 m/day
1/5/99
0.0157 m/day
3/24/99
0.0117 m/day
5/12/99
0.0176 m/day
7/28/99
0.0183 m/day

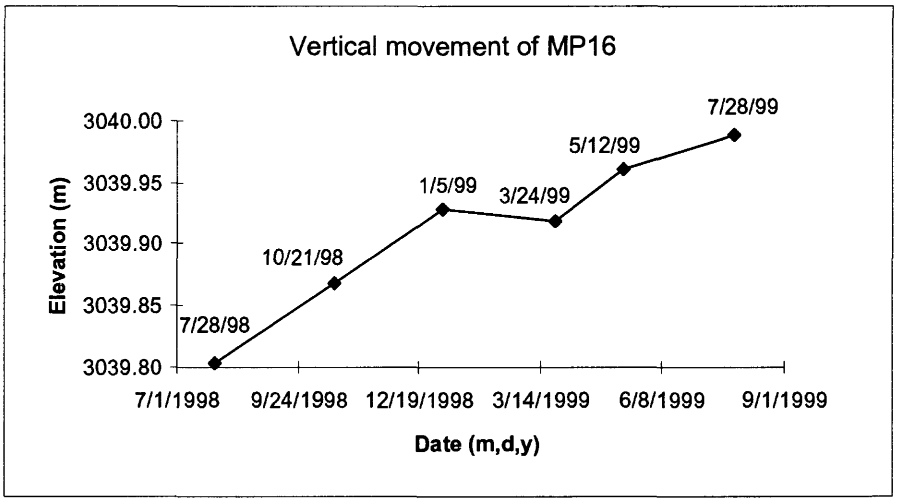

Vertical movement of MP14
3156.8
3156.6
3156.4
3156.2
3156.0
3155.8
3155.6
3155.4
Elevation (m)
7/1/1998 9/24/1998 12/19/1998 3/14/1999 6/8/1999 9/1/1999
Date (m,d,y)
7/29/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99


Horizontal movement of MP15
453037.5
453037.0
453036.5
453036.0
453035.5
453035.0
453034.5
Northing (m)
759609.5
759610.0
759610.5
759611.0
759611.5
759612.0
759612.5
759613.0
759613.5
Easting (m)
7/28/98
0.0120 m/day
10/21/98
0.0123 m/day
1/5/99
0.0090 m/day
3/24/99
0.0143 m/day
5/12/99
0.0146 m/day
7/28/99

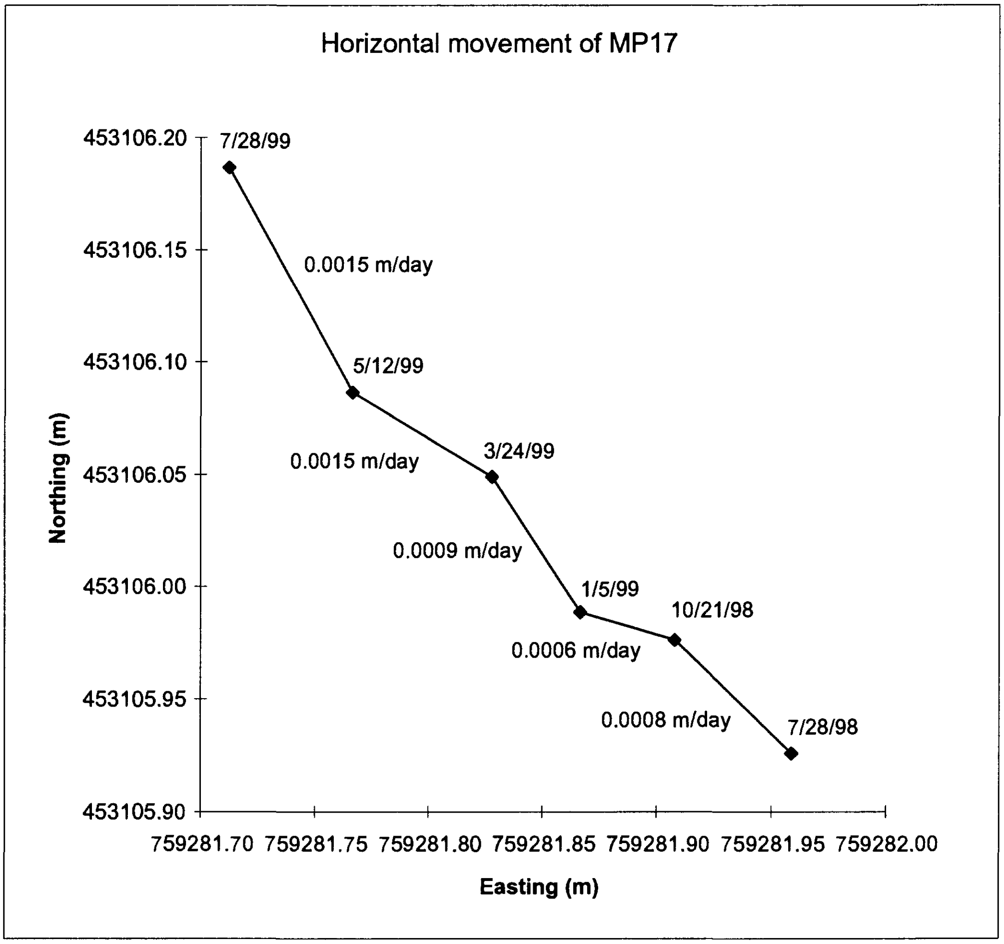

Vertical movement of MP15
3086.2
3086.0
3085.8
3085.6
3085.4
3085.2
3085.0
3084.8
Elevation (m)
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
Date (m,d,y)
7/28/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99



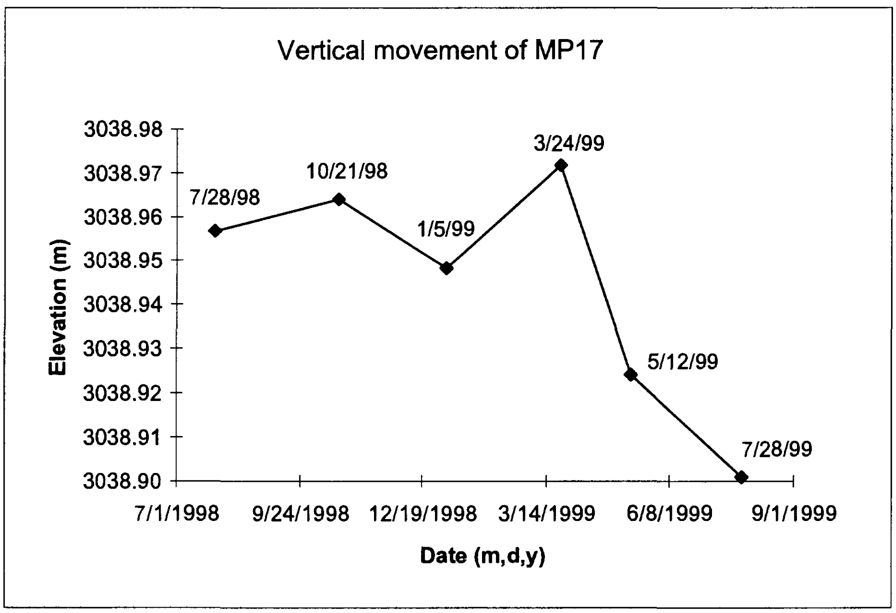
Horizontal movement of MP16
Northing (m)
452922.5
452922.0
452921.5
759312.5
759313.0
759313.5
759314.0
759314.5
759315.0
759315.5
Easting (m)
7/28/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99
0.0074 m/day
0.0073 m/day
0.0055 m/day
0.0096 m/day
0.0088 m/day



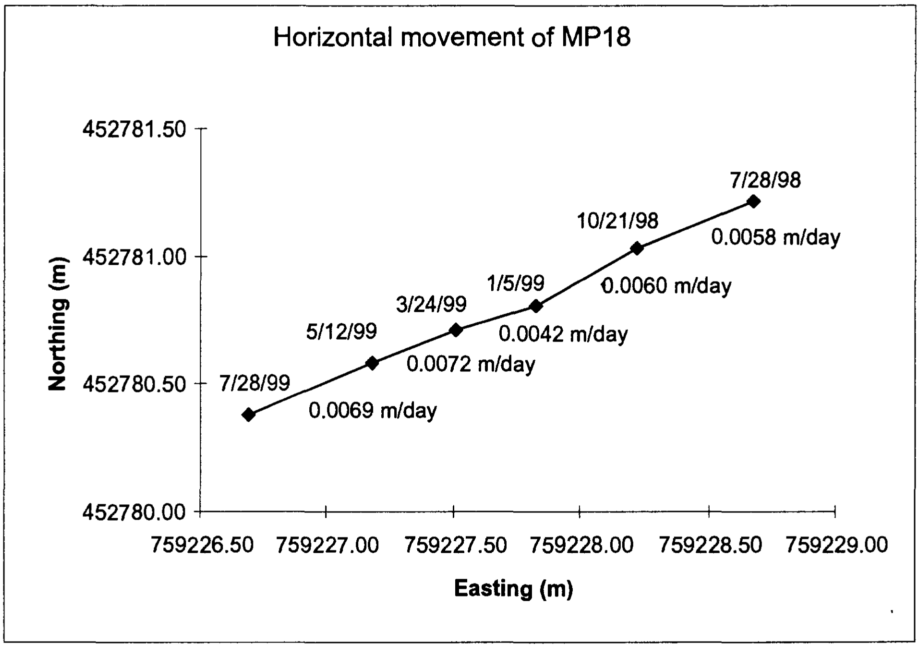
Vertical movement of MP16
Elevation (m)
3040.00
3039.95
3039.90
3039.85
3039.80
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
Date (m,d,y)
7/28/99
5/12/99
1/5/99
3/24/99
10/21/98
7/28/98



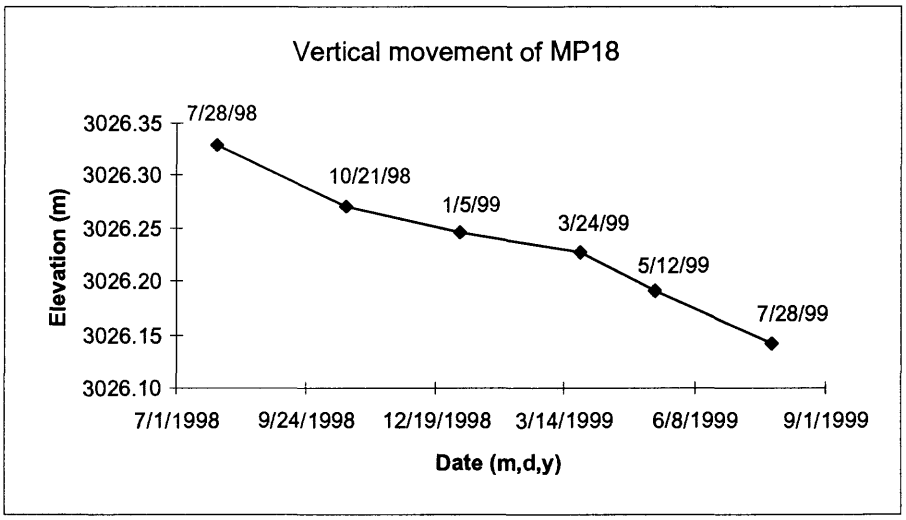
Horizontal movement of MP17
Northing (m)
Easting (m)
453106.20
453106.15
453106.10
453106.05
453106.00
453105.95
453105.90
759281.70
759281.75
759281.80
759281.85
759281.90
759281.95
759282.00
7/28/99
0.0015 m/day
5/12/99
0.0015 m/day
3/24/99
0.0009 m/day
1/5/99
10/21/98
0.0006 m/day
0.0008 m/day
7/28/98



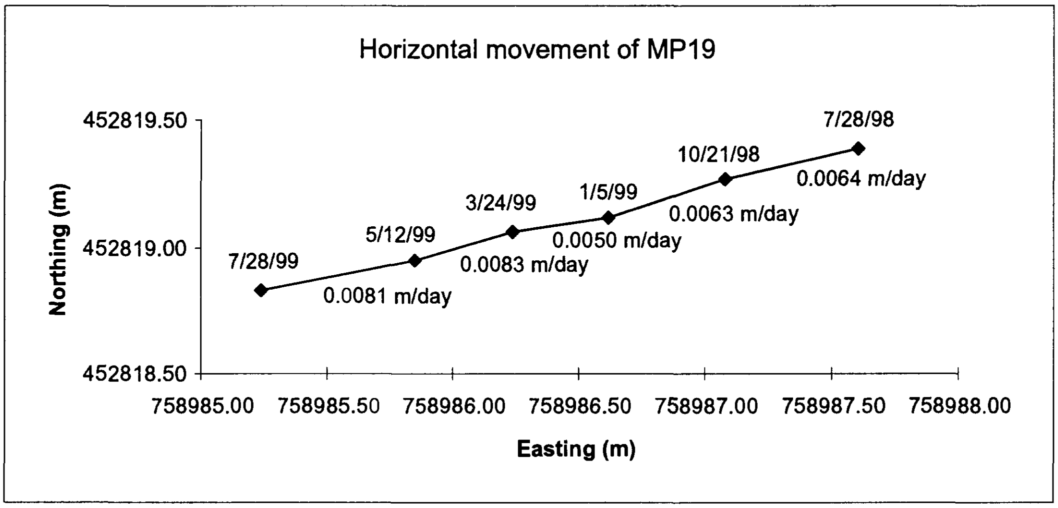
Vertical movement of MP17
Elevation (m)
Date (m,d,y)
3038.98
3038.97
3038.96
3038.95
3038.94
3038.93
3038.92
3038.91
3038.90
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
7/28/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99

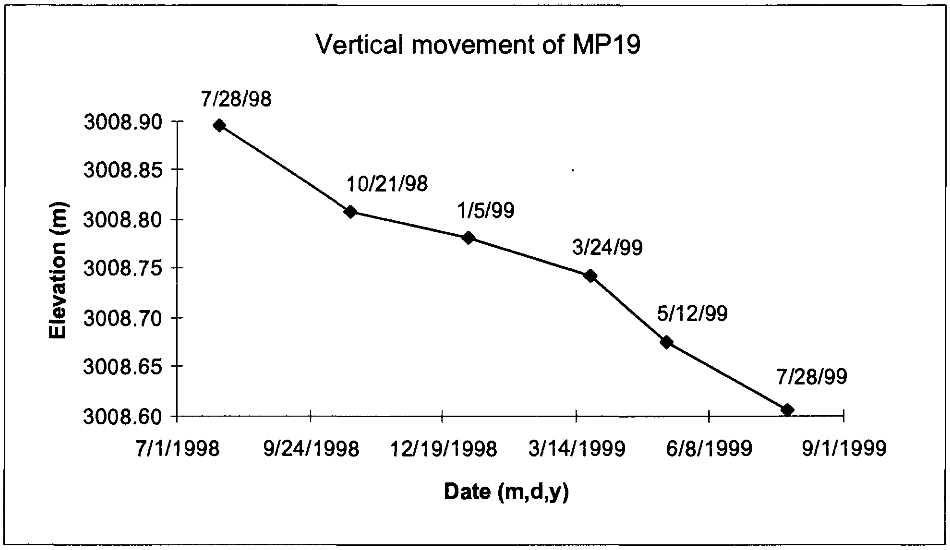


Horizontal movement of MP18
452781.50
452781.00
452780.50
452780.00
Northing (m)
759226.50
759227.00
759227.50
759228.00
759228.50
759229.00
Easting (m)
7/28/98
10/21/98
0.0058 m/day
1/5/99
0.0060 m/day
3/24/99
5/12/99
0.0042 m/day
0.0072 m/day
7/28/99
0.0069 m/day



Vertical movement of MP18
3026.35
3026.30
3026.25
3026.20
3026.15
3026.10
Elevation (m)
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
Date (m,d,y)
7/28/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99


Horizontal movement of MP19
Northing (m)
452819.50
452819.00
452818.50
Easting (m)
758985.00
758985.50
758986.00
758986.50
758987.00
758987.50
758988.00
7/28/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99
0.0064 m/day
0.0063 m/day
0.0050 m/day
0.0083 m/day
0.0081 m/day


Vertical movement of MP19
Elevation (m)
3008.90
3008.85
3008.80
3008.75
3008.70
3008.65
3008.60
Date (m,d,y)
7/1/1998
9/24/1998
12/19/1998
3/14/1999
6/8/1999
9/1/1999
7/28/98
10/21/98
1/5/99
3/24/99
5/12/99
7/28/99