Measurement of ridge-spreading movements (Sackungen) at Bald Eagle Mountain, Lake County, Colorado, II: continuation of the 1975-1989 measurements using a Global Positioning System in 1997 and 1999

by D.J. Varnes[1], J.A. Coe[1], J.W. Godt[1], W.Z. Savage[1], and J.E. Savage[2]

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Trench southeast of station 3, which is on the rocky hill with 2 standing persons. View to the southwest.

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[1]USGS, Denver, CO; [2]Colorado School of Mines, Department of Geology and Geological Engineering

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ABSTRACT

Measurements of ridge-spreading movements at Bald Eagle Mountain in north-central Colorado were reported in USGS Open-File Report 90-543 for the years 1975-1989. Measurements were renewed in 1997 and 1999 using the Global Positioning System (GPS). Movements are generally away from a ridge-top graben and appear to be concentrated along 3 or 4 trenches with uphill facing scarps that are parallel with slope contours. A point just below the lowest trench has moved the most—a total of 8.3 cm horizontally and slightly downward from 1977 to 1999 relative to an assumed stable point on the periphery of the graben. Movements from 1997 to 1999 are less than 1 cm or within the error of measurement.

INTRODUCTION

Geologic and geomorphic studies in many of the mountainous parts of the world during the last 30 years have shown that large mountain masses have undergone spreading movements under their own weight. The movements are inferred to be nearly horizontal near the base and both lateral and vertical near the crest of the mass. These displacements commonly produce linear trenches, upward-facing scarps on the flanks of ridges, and grabens along ridge crests. These features resemble those of recent tectonic faults and indeed spreading movements often make use of any preexisting faults or discontinuities that have an appropriate orientation. In areas where cultural activities require that nearby faults be identified and their recurrence intervals determined, careful studies may be necessary to decide whether scarps and trenches are the result of tectonic activity or gravitational spreading.

Spreading movements are most common in glaciated regions and may have begun when retreat of the ice from valleys left adjacent slopes oversteepened and unsupported. The ground surface offsets are generally one to a few meters at each scarp, rarely some tens of meters, and the movements at most places appear to have been completed long ago. However, in some localities, closed depressions and holes unfilled with soil or vegetation indicate that slow movements may be continuing.

Apparent gravitational spreading has been noted in several geologic settings. Where isolated masses of igneous rock lie on soft shale, as at some laccoliths of central Colorado, the overlying brittle crystalline rocks have broken into slices and spread on the underlying plastic shale. This is the situation at Crested Butte, the locale of a well-known ski resort. However, ridges composed entirely of homogeneous granitic rock also appear to have spread. In all instances that we have observed, the spreading mass of whatever composition is closely divided by well-developed sets of joints. Such is the condition at Bald Eagle Mountain, a broad ridge of gneissic Precambrian granite extending northeastward from Mount Massive, one of the high peaks of the Sawatch Range of west-central Colorado (fig. 1).

The Bald Eagle Mountain study area is one of moderate relief between elevations 3200 and 3660 m (10,500 to 12,000 ft) (See fig. 2). Access to the foot of the slope is by hard-surface road westward from the city of Leadville, past Turquoise Lake, and thence by a gravel road up Busk Creek to the portal of the Carlton Tunnel, a trans-Continental Divide water diversion project (See fig. 3). The unimproved road continues north and westward over Hagerman Pass at the Continental Divide and on to the town of Basalt. Access on foot toward the trenches east of Busk Creek is by a Forest Service trail that begins at the parking lot near the east portal of the Carlton Tunnel and zigzags up the slope to the southeast.

Geologic study of the gravitational spreading features at Bald Eagle Mountain and several nearby ridges began in 1975. The relation of these features to local topography and geologic structures here and elsewhere in the western United States has been described by Varnes and others (1989). At the beginning of our study, a few surveyed points were placed to determine if any movements were occurring. In succeeding years, more points were added to create a survey net, which is shown in figure 2, and measurements of the net were discussed in Open File Report OF 90-543 (Varnes and others, 1990). As in all previous surveys, station 4 was assumed to be stable and, in a local coordinate system, to have coordinates 10,000 m N, 10,000 m E, and altitude 3645.415 m (from estimate of 11,960 feet on the topographic sheet). The azimuth of line 4-6 was assumed to be constant at 155.93634 degrees. During surveys in all years, slope distances were converted to horizontal distances at the elevation of station 2, and coordinate positions were determined at that elevation.

The surveys made in 1975, 1977, 1982, and 1984 were made with helicopter support to transport heavy electronic distance measuring (EDM) equipment. When the area under survey became included within the Hunter-Fryingpan and Mount Massive Wildernesses, access by helicopter was prohibited. So, in 1989 only tripods, targets, and a 1-second theodolite were carried up to the site to measure horizontal and vertical angles but not distances. Computation of coordinates in 1989 therefore required that one distance and one direction in the net be assumed unchanged since 1984. For this purpose, not only the azimuth of the line between stations 4 and 6 but also the distance between stations 6 and K were assumed to remain unchanged from their 1984 values. The results of recalculating the network were not entirely satisfactory; moreover GPS measurements in 1997 indicated that the distance between stations 6 and K could not be assumed constant. Therefore, 1989 positions are not accepted and reported in the present paper.

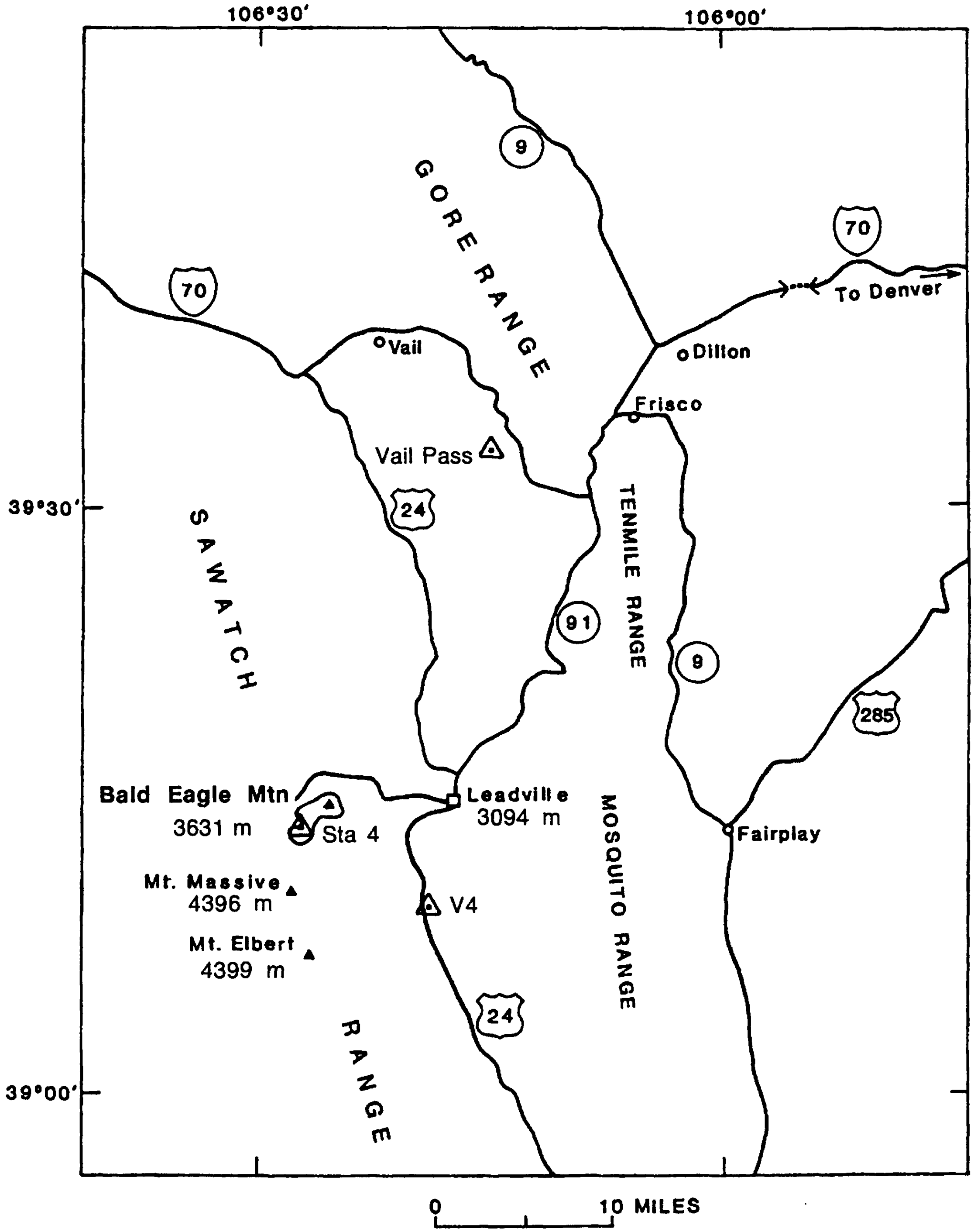


Figure 1. Location of Bald Eagle Mountain in the Sawatch Range of Colorado.

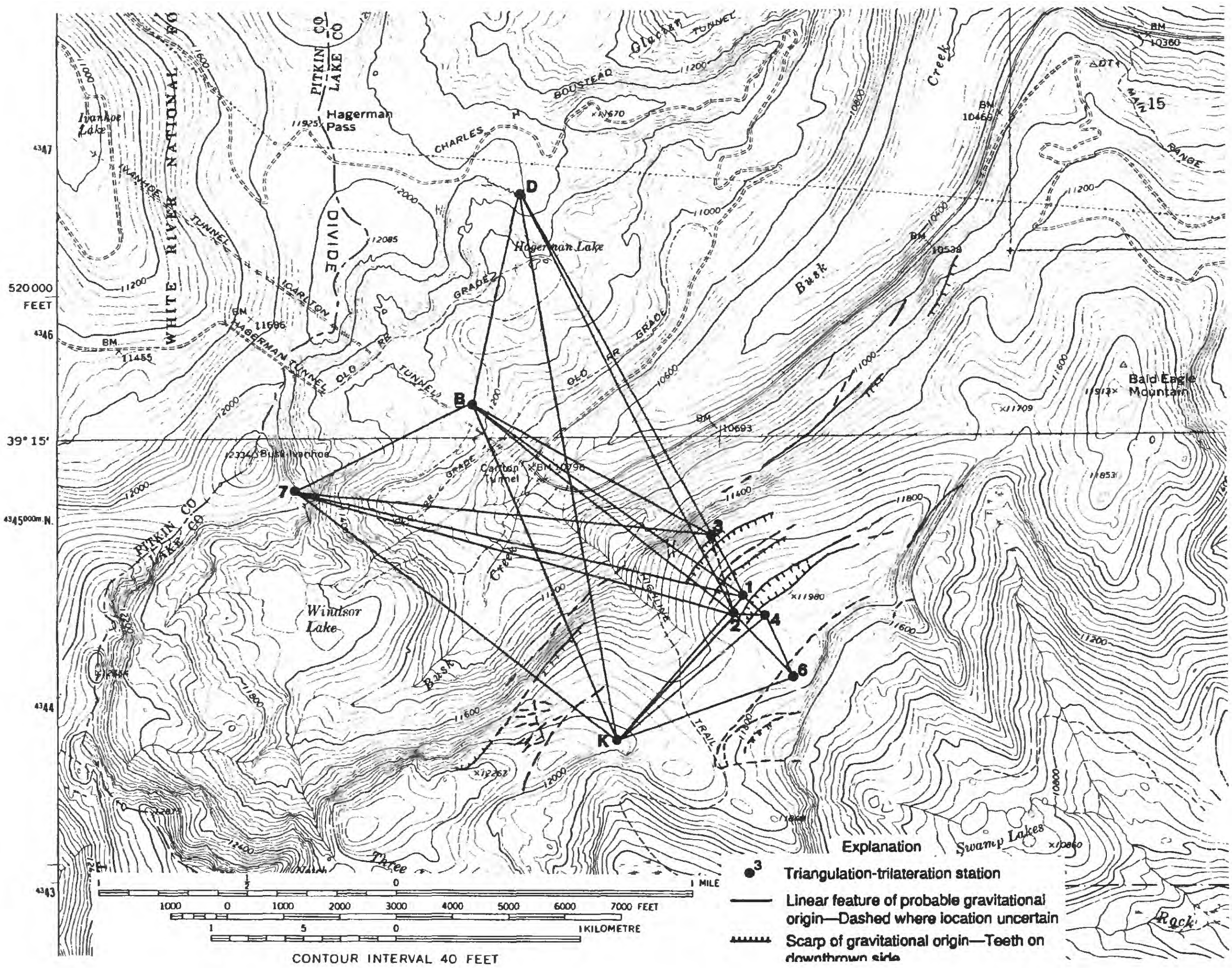


Figure 2. Survey net at Bald Eagle Mountain and valley of Busk Creek, Lake County, Colorado. Base map is from the Homestake Reservoir, 1970, and Mount Massive, 1967, 1:24,000 topographic sheets, U.S. Geological Survey.

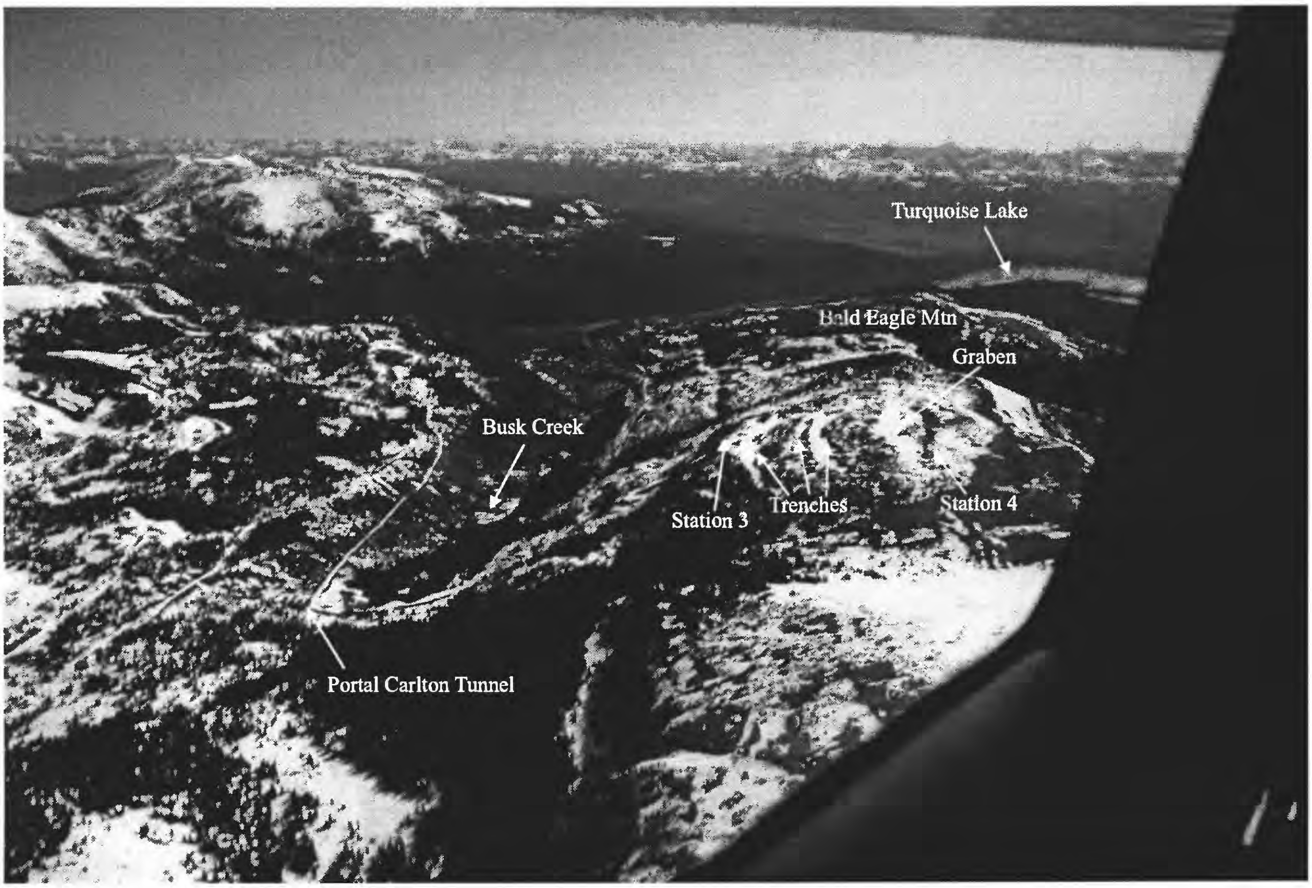


Figure 3. Oblique aerial view looking northeast down the valley of Busk Creek, showing the area of study at right center.

CONVERSION TO THE GLOBAL POSITIONING SYSTEM

In August 1997, the previously surveyed stations were again occupied and their positions redetermined with a portable but precise Global Positioning System (GPS). The resurvey served to determine if there had been additional movements and allowed comparison of the ease and accuracy of the GPS survey with that of the earlier surveys that used conventional electronic distance measuring (EDM) methods in the triangulation-trilateration net shown in figure 2. The 1997 GPS survey was made with three Ashtech Model Z-12, dual frequency receivers using a rapid-static GPS surveying technique with relative positioning (Van Sickle, 1996). The rapid-static technique consists of using at least one receiver at a known base station and the other(s) on remote stations. The minimum occupation time at each station is about 15 minutes, but is dependent on the distance from the base station to the remote station, as well as the number and positions of observable satellites. When rapid-static techniques are used, and the number and configuration of satellites is optimal, the GPS system of receivers and data reduction software (PNAV software, Ashtech, 1997) is reported by Ashtech to consistently determine relative positions to 5 mm plus 1ppm of the baseline length for latitude and longitude. The GPS position of base station 4 was initially determined by a static GPS survey (one hour simultaneous occupation) of station 4 and two benchmarks with known coordinates provided by the National Geodetic Survey—"Vail Pass" at Vail Pass and "V 4" near Leadville (fig. 1). The position of station 4 was determined by least squares adjustment of the triangle formed by the three points, using Ashtech Prism software.

TRANSFORMATION OF GPS POSITIONS INTO LOCAL COORDINATES

To compare results from earlier surveys with station locations determined in 1997 and 1999 by GPS the data must be reduced to a common coordinate system. GPS locations (Table 1) are primarily given in geodetic latitude and longitude and height above a standard ellipsoid. Secondarily, the Colorado State Plane coordinates (NAD 83) and height above mean sea level (NAVD88) were determined using the "Transform" module of Ashtech Prism software. Additional values given for each base and remote station pair include the horizontal grid distance in the State Plane Coordinate system, its azimuth, the horizontal ground distance at the mean elevation between the base and remote station, and the slope distance between the two.

The simplest method to compare the GPS positions with the earlier surveys is to transform the GPS positions into the local coordinate system, using the slope distance between stations, which is independent of the coordinate system in which it is measured. The slope distances of seven lines were compared, 1984 EDM with 1997 GPS. Four of those were chosen for which the changes in slope distance were 3 mm or less. The azimuths of those lines in the two systems were compared and a weighted average of the differences computed. This indicated that GPS azimuths need to be rotated clockwise 1.003163 degrees to align with the local coordinate system. A comparison of the local coordinate system elevation for station 4 of 3645.415 m with the GPS height above mean sea level (NAVD88) of 3646.651 m indicated that all GPS heights need to be lessened by 1.236 m to be compared with elevations in the local coordinate system.

The detailed procedure for transforming GPS positions into the local coordinate system is given below and in figure 4 by an example of computing the position in 1997 of station 3 from the base station 4.

1. Make a sketch (fig. 4), not to scale, showing in vertical section the relative positions of stations 3 and 4, the earth curvature (exaggerated), and the reported GPS data that may be necessary for the transforming procedure. This includes the slope distance, horizontal distance at the mean elevation between stations 3 and 4, and heights above mean sea level.

2. Determine the value of θ, which is the angle subtended at the Earth's center by half of the horizontal distance at mid-elevation between 3 and 4, reported in Table 1. Compute sin $(90-\theta)$ and cos $(90-\theta)$.

3. In the triangle A-4-3, and using the law of sines, compute the angle A-4-3, which is shown as α, and determine sin α and cos α.

4. Using again the law of sines in the triangle A-4-3, compute the length of HD, which is the horizontal distance A-4 at the elevation of station 4.

5. Reduce HD to HD', the horizontal distance at elevation of station 2, in order to make comparison with the earlier EDM triangulation net, which is at the elevation of station 2.

6. Correct the reported GPS azimuth of the line 4 to 3 by adding 1.003163 degrees to obtain 327.690464, thus rotating HD' into the orientation of the EDM net.

7. Using the distance HD' and its azimuth from station 4, compute the GPS position of station 3 in the EDM net coordinates.

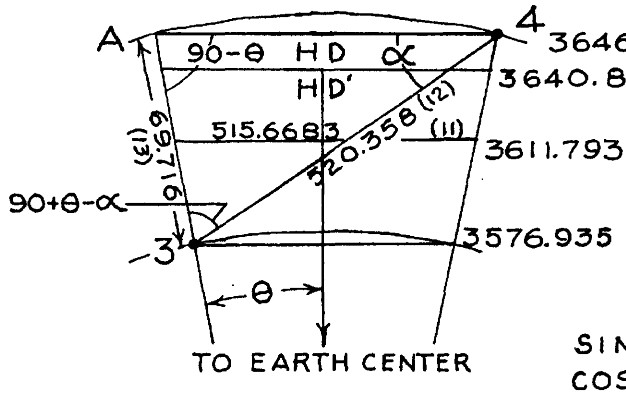
8. Subtract 1.236 m from the reported GPS elevation of station 3 (NAVD88) to compare with earlier elevations in the EDM coordinate system.

Horizontal and vertical coordinates of all the stations with the year of observation are given in Table 2. Plots of the horizontal positions and elevations of the stations are shown in figures 5 to 9.

Station 7 was established in 1984 on a high promontory west of Busk Creek to replace the intended stable point B, which had been showing large and erratic movements of unknown origin. Because station 7 was difficult to reach without a helicopter it was not occupied or observed in 1989. But there is close agreement, within less than 3 mm, of the horizontal positions of station 7 in 1984, determined by EDM over a distance of 2.5 km from station 2, and by GPS in 1997. This agreement allows the following inferences: 1) that both station 4 and station 7 can be assumed to be stable, 2) that the surveying procedures used for locating station 7 with the EDM in 1984 are satisfactory and, by extension, the agreement lends support to the locations of other stations determined by EDM, 3) that the GPS surveying procedures used for locating station 7, and probably other points, relative to station 4 are satisfactory, and 4) that the method presented above and in figure 4 is satisfactory for transforming GPS data to positions in the earlier EDM triangulation-trilateration net.

( ) MEMORY POSITION IN CALC.

EARTH RADIUS=6367445 m (10)



$$\tan\theta = \frac{\frac{515.6683}{2}}{6367445 + 3611.793}$$

$\tan\theta = 0.000040470$ (14)

$\theta = 0.0023187$ (15)

$90-\theta = 89.99768$ (16)

$\sin(90\pm\theta) = 0.999\,999\,999 \approx 1$ (17)

$\cos(90+\theta) = -0.000040470$ (18)

$$\frac{520.358}{\sin(90-\theta)} = \frac{69.716}{\sin\alpha}$$

$\sin\alpha = (13)/(12) = 0.133977$ (19)

$\alpha = 7.699469$ (20) $\quad \cos\alpha = 0.990984$ (21)

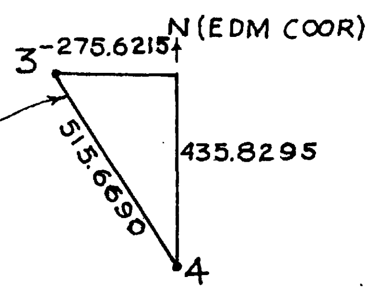
$$\frac{(12)}{(17)} = \frac{HD}{\sin(90+\theta-\alpha)} = \frac{HD}{\sin(90+\theta)\cos\alpha - \cos(90+\theta)\sin\alpha}$$

$$(12) = \frac{HD}{(17)(21)-(18)(19)}$$

HD = 515.6695 AT ELEV. OF STA. 4 (22)

$$(22)\,\frac{(10)+3640.816}{(10)+3646.651} = 515.6690 = HD' \text{ AT ELEV. OF STA. 2}$$

TABLE I AZIMUTH 4→3	=	326.687301
ROTATION		1.003163
AZIMUTH 4→3	=	327.690464



COORDINATES OF STA. 3

	N	E
1984 EDM	10435.8060	9724.4071
1997 GPS	10435.8295	9724.3785
CHANGE	+0.0235 m	−0.0286 m

ELEV. BY GPS 1997	3576.935
	−1.236
	3575.699
EDM 1984	3575.706
CHANGE	−0.007

FIG. 4 PROCEDURE FOR TRANSFORMING GPS DATA INTO EDM NET COORDINATES

Table 1. GPS observations of points in EDM network. WGS84 is the World Geodetic System 1984. NAD83 is the North American Datum 1983. NAVD88 is the North American Vertical Datum 1988. WGS84 coordinates of V4 are Latitude N 39 09 42.40829, Longitude W 106 19 27.12173, Ellipsoid Height 2823.400. WGS84 coordinates of Vail Pass are Latitude N 39 31 44.04349, Longitude W 106 13 03.17196, Ellipsoid Height 3221.81. NA= not applicable because solution was by least squares adjustment.

Point Name	Base Station	Date Observed (m/d/y)	Slope Distance from Base Station (m) and standard deviation (m)	Latitude (WGS84, degrees minutes seconds) and standard error (m)	Longitude (WGS84, degrees minutes seconds) and standard error (m)	Ellipsoid Height (m) and standard error (m)	Northing, NAD83, Colorado State Plane Coordinate, central zone (m)	Easting, NAD83, Colorado State Plane Coordinate, central zone (m)	Mean Sea Level Height (NAVD88, m)	Horizontal Grid Distance, base station to remote station (m)	Horizontal Ground Distance, base station to remote station (m)	Azimuth, base station to remote station (degrees)
4	V4/Vail Pass	8/17/97	NA	N 39 14 29.40594 ±0.006	W 106 27 21.54368 ±0.006	3633.767 ±0.008	461552.296	831877.161	3646.650	NA	NA	NA
D	4	8/18/97	2638.932 ±0.009	N 39 15 42.63574 ±0.005	W 106 28 18.34450 ±0.005	3600.227 ±0.007	463824.812	830539.343	3613.062	2637.060	2638.718	329.5149
1	4	8/18/97	166.742 ±0.006	N 39 14 32.97799 ±0.003	W 106 27 26.73916 ±0.003	3623.117 ±0.005	461663.753	831753.745	3635.999	166.295	166.400	312.0852
1	4	8/25/99	166.742 ±0.008	N 39 14 32.97816 ±0.004	W 106 27 26.73901 ±0.004	3623.121 ±0.006	461663.758	831753.748	3636.001	166.297	166.402	312.0872
2	4	8/18/97	178.159 ±0.007	N 39 14 29.80207 ±0.003	W 106 27 28.94719 ±0.003	3627.934 ±0.005	461566.381	831699.768	3640.816	177.951	178.064	274.5398
6	4	8/18/97	352.729 ±0.006	N 39 14 19.11191 ±0.003	W 106 27 15.18151 ±0.003	3618.966 ±0.005	461233.272	832026.380	3631.857	352.197	352.419	154.9328
B	4	8/18/97	1965.567 ±0.008	N 39 15 05.12776 ±0.004	W 106 28 28.85164 ±0.003	3432.060 ±0.006	462670.939	830275.065	3444.918	1953.989	1955.192	304.9242
1	6	8/18/97	509.890 ±0.006	N 39 14 32.97799 ±0.003	W 106 27 26.73913 ±0.003	3623.116 ±0.005	461663.753	831753.745	3635.998	509.552	509.873	327.6528
B	D	8/18/97	1196.358 ±0.007	N 39 15 05.12766 ±0.004	W 106 28 28.85177 ±0.004	3432.070 ±0.005	462670.936	830275.062	3444.929	1183.754	1184.479	192.9004
3	4	8/19/97	520.358 ±0.009	N 39 14 43.27431 ±0.005	W 106 27 33.53580 ±0.004	3564.062 ±0.006	461982.963	831594.129	3576.935	515.346	515.668	326.6873
3	4	8/25/99	520.358 ±0.009	N 39 14 43.27432 ±0.005	W 106 27 33.53588 ±0.004	3564.069 ±0.007	4619982.963	831594.127	3576.940	515.347	515.670	326.6871
2	4	8/19/97	178.160 ±0.008	N 39 14 29.80204 ±0.004	W 106 27 28.94723 ±0.003	3627.943 ±0.005	461566.380	831699.767	3640.824	177.952	178.065	274.5394
7	4	8/19/97	2626.953 ±0.007	N 39 14 49.76553 ±0.004	W 106 29 07.84914 ±0.003	3653.638 ±0.005	462207.327	829334.975	3666.510	2625.219	2626.881	284.4488
K	4	8/19/97	1049.526 ±0.010	N 39 14 06.79170 ±0.005	W 106 27 54.19417 ±0.005	3661.307 ±0.007	460863.258	831086.858	3674.202	1048.500	1049.165	228.9159
3	7	8/19/97	2273.456 ±0.008	N 39 14 43.27436 ±0.004	W 106 27 33.53575 ±0.003	3564.059 ±0.006	461982.964	831594.130	3576.932	2270.269	2271.693	95.6716
K	2	8/19/97	933.944 ±0.009	N 39 14 06.79174 ±0.005	W 106 27 54.19414 ±0.005	3661.305 ±0.006	460863.259	831086.858	3674.200	932.759	933.350	221.0786

Sta	Coords	1975	1977	1982	1984	1997(GPS)	1999(GPS)
	North	10113.662	10113.662	10113.676	10113.671	10113.672	10113.677
1	East	9878.485	9878.497	9878.479	9878.481	9878.478	9878.481
	Alt.	3634.764	3634.774	3634.772	3634.770	3634.763	3634.765
	North	10017.212	10017.208	10017.206	10017.194	10017.199	
2	East	9822.782	9822.792	9822.770	9822.771	9822.769	
	Alt.	3639.574	3639.594	3639.586	3639.590	3639.580	
	North	10435.774	10435.781	10435.798	10435.812	10435.830	10435.829
3	East	9724.410	9724.444	9724.414	9724.404	9724.379	9724.377
	Alt.	3575.708	3575.729	3575.709	3575.706	3575.700	3575.704
	North	10000.000			Assumed		
4	East	10000.000			Stable		
	Alt	3645.415					
	North	9678.218	9678.220	9678.217	9678.209	9678.210	9678.220
6	East	10143.695	10143.694	10143.696	10143.699	10143.701	10143.714
	Alt.	3630.613	3630.615	3630.625	3630.624	3630.621	3630.635
	North				10699.8	10699.879	
7	East				7468.081	7468.076	
	Alt.				3665.185	3665.275	
	North		11147.526	11147.263	11147.243	11147.241	
B	East		8417.152	8416.754	8416.734	8416.741	
	Alt.		3443.327	3443.597	3443.595	3443.682	
	North					12297.037	
D	East					8701.355	
	Alt.					3611.826	
	North		9324.484	9324.488	9324.4730	9324.478	
K	East		9197.226	9197.220	9197.231	9197.249	
	Alt.		3672.961	3672.901	3672.922	3672.966	

Table 2. Coordinates in the local EDM system and altitudes, in meters, of the Bald Eagle Mountain survey stations at the years of observation.

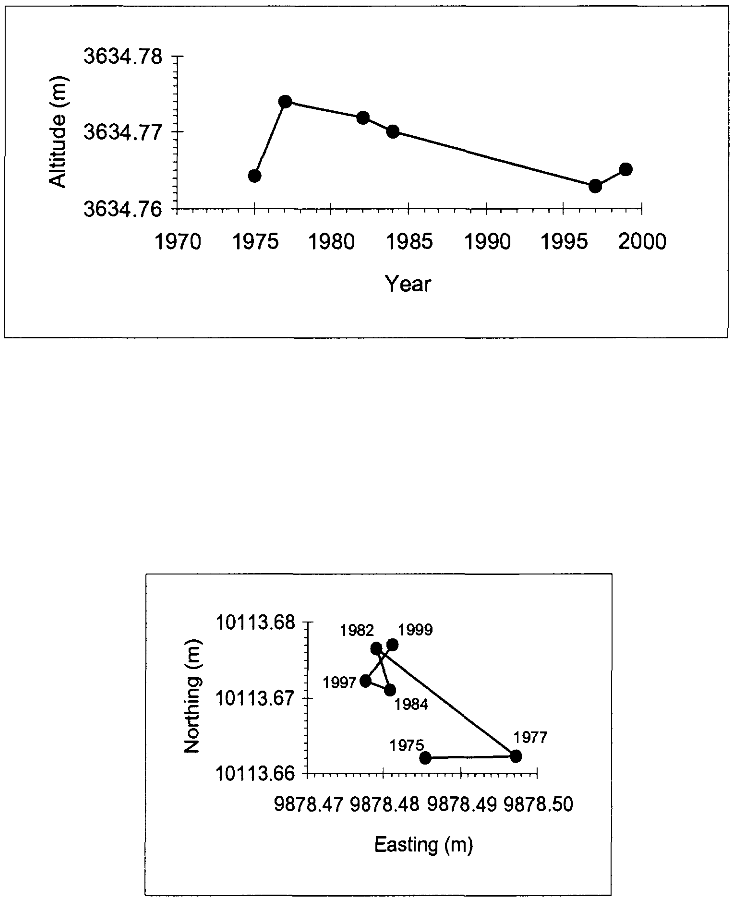
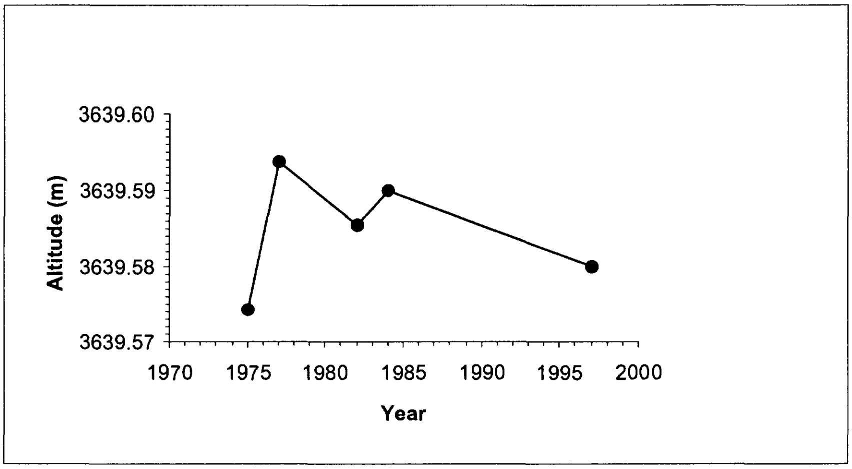


Figure 5. Coordinate positions of station 1.



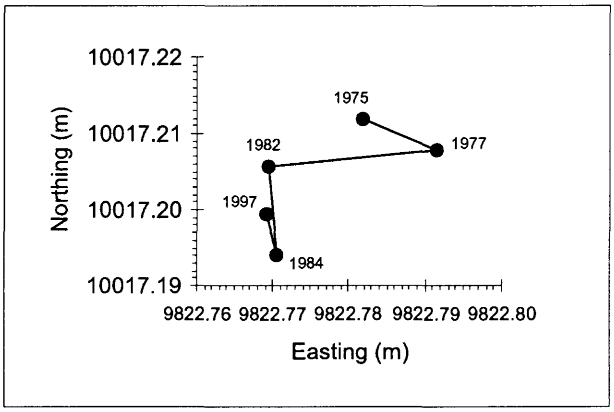
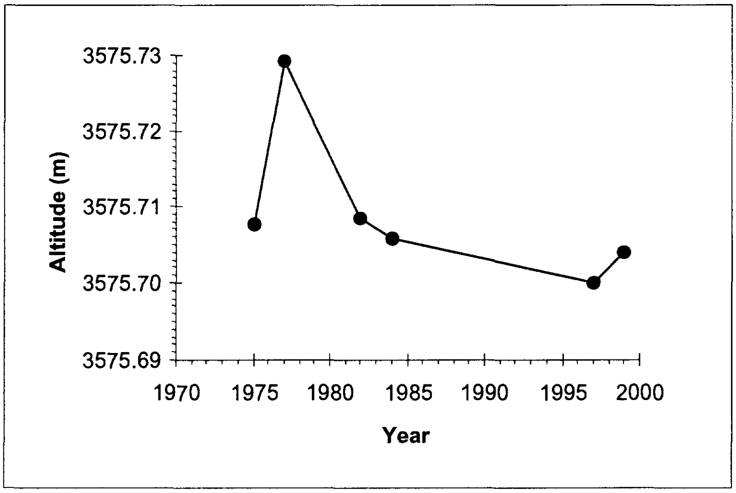


Figure 6. Coordinate positions of station 2.



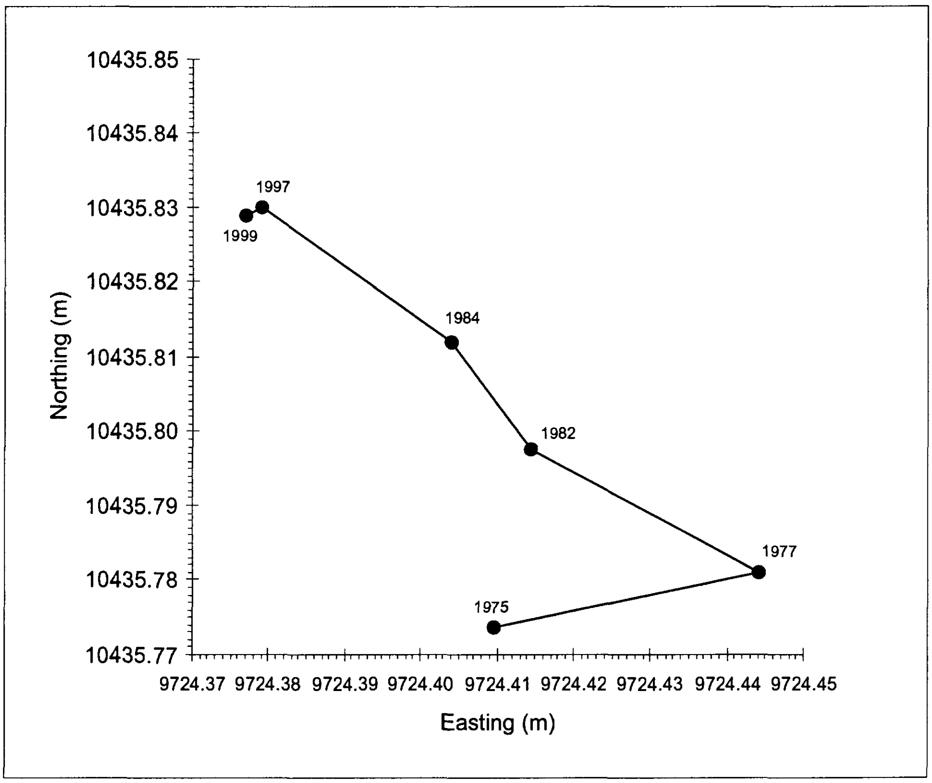
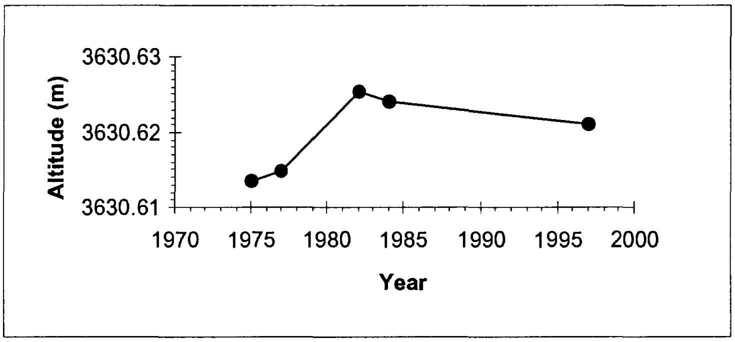


Figure 7. Coordinate positions of station 3.



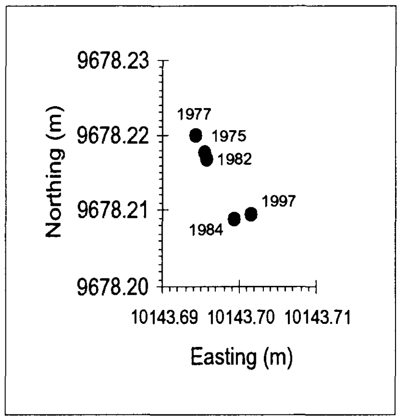
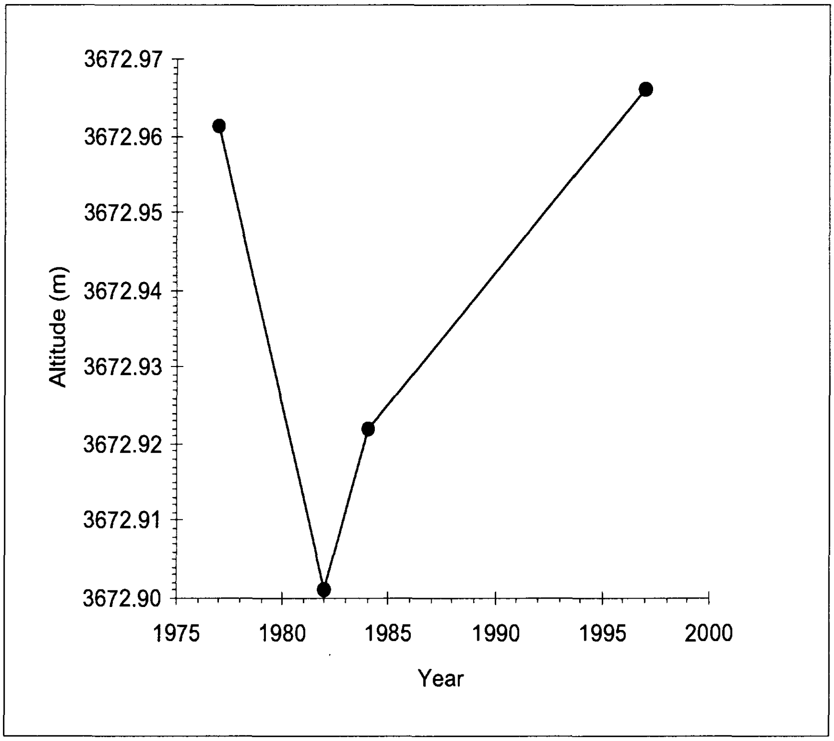


Figure 8. Coordinate positions of station 6.



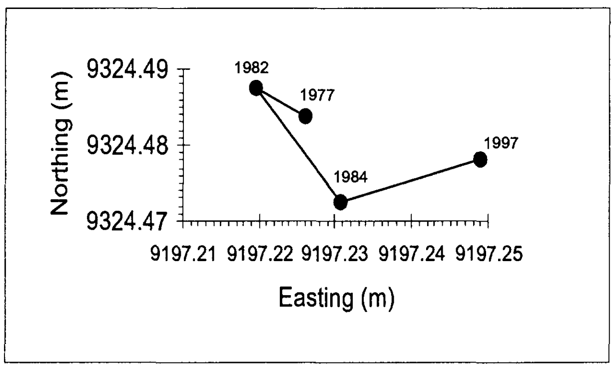


Figure 9. Coordinate positions of station K.

MEASURED DISPLACEMENTS
(Refer to figures 5 to 9)

Most observation points are 18-inch copper-clad steel stakes with a flat head marked with a center punch. These were driven until the heads were flush with the ground or to refusal. Station 1, in a place that might be subject to disturbance by passers-by, is the head of a small screw cemented in a rock.

Station 1. Net movement from 1977 to 1997 was 2.1 cm in the direction N 62 W., directly away from the ridge-top graben and normal to the local contours. The movement from 1975 to 1982, to the east and then to the northwest about 1.6 cm, may in part be the result of changing the type of EDM instrument from AGA to K&E. From 1982 to 1997 the horizontal movement was less than 0.5 cm, and the vertical movement from 1977 to 1997 was steadily down at the rate of about 0.5 mm per year. Between 1997 and 1999 station 1 moved about 6 mm to the northeast and 2 mm up.

Station 2. Net movement from 1975 to 1997 was 2.0 cm S 52 W, downhill normal to the local contours. The average vertical displacement has been down at a rate of about 0.6 mm per year.

Station 3. This station is immediately northwest of the lowest of the trenches that have resulted from spreading of the ridge, and is at the upper edge of a very steep bare rock slope to the west (see photo on title page). Expectedly, its horizontal movement has been more than that of any other station—8.3 cm from 1977 to 1999 in a N 54 W direction, which is nearly perpendicular to the trenches uphill and to the contours of the slope below. The net vertical displacement has been 0.2 cm down from 1975 to 1999, although measurements through the years for vertical movements have been erratic over a range of 5 cm and less accurate than horizontal movements. The distance of station 3 from station 7, which is to the west on the opposite side of the valley of Busk Creek, has lessened 2.7 cm between 1984 and 1997, which is just what would be expected from the movement of station 3 in that period.

Station 4. Assumed to remain stable. Movements of all other stations are relative to station 4.

Station 5. Has been abandoned. This station was a mirror reflector mounted close to the ground, facing toward station 3, above the road to Hagerman Pass, about five hundred meters north of the portal of the Carlton Tunnel.

Station 6. In the period 1975-1997 station 6 moved 1.0 cm S 37 E and 0.8 cm up. The direction of horizontal movement has been opposite to that of Station 1 on the other side of the ridge-top graben and obliquely toward the headwall of a large cirque a few hundred meters to the southeast.

Station 7. This station was placed in 1984 on a high rocky promontory, after the apparent erratic behavior of station B, to serve as a stable reference point on the west side of the valley of Busk Creek across from the area of spreading trenches. There appears to have been no horizontal movement from 1984 to 1997.

Station B. This station was set in 1977 on a granite outcrop to serve as a stable reference point on the west side of Busk Creek valley. Its apparent large and erratic movements 1977-1984, discussed in Open File 90-543, remain a mystery. However, movement may have ceased, because the 1997 GPS position is less than 4 mm from the EDM position in 1984.

Station D. This station was established in 1989 to furnish a stable point west of Busk Creek that was more easily accessible than station 7 and to which EDM equipment could be carried from a vehicle on the Hagerman Pass road. Its position in 1989 could not be accurately determined but it was accurately located by GPS in 1997.

Station K. This station was placed in 1977 on the south side of the broad valley south of stations 4 and 6. Its movements 1977-1997 were irregular with a net horizontal displacement of 2.3 cm S 76 E and vertical displacement of 0.5 cm up. It is on a gentle slope, not on a rock outcrop, and may be subject to freeze and thaw movements of ground at an altitude of 3673 meters (12050 ft).

During the August, 1997, surveys a continuous profile, extending down from station 4 across all the trenches to station 3 was measured using real- time GPS. Eight permanent stations were placed along the profile. The locations of the profile stations are shown in figure 10, and the topography along the profile in vertical section is shown in figure 11. The stations of the profile were reoccupied two years later in August, 1999; their coordinates and changes during the interval 1997-1999 are shown in Table 3. Some of the differences in northing and easting exceed 1 cm (for example, P433, table 3) and may represent small real movements. For the most part, however, results from 1999 suggest that little or no movement occurred along the profile between 1997 and 1999.

EDM AND GPS COMPARED

Comparison of EDM positions of points that are stable or nearly so with positions determined by GPS suggests that the precision of horizontal positions in the two methods is comparable, of the order of 1 cm or less, in the relatively small net of a few kilometers extent. The precision of vertical positions is much less for both methods, although relative differences in elevations between nearby stations are probably defined better by EDM than by GPS. The absolute elevation of stations far above distant benchmarks is better and more easily done by GPS.

The ease of field operations is considerably greater with GPS than it was in our EDM operations, owing to lighter loads to be carried at high altitudes, no tedious pointing of optics and reading or recording of angles and distances, and especially, no requirement for intervisibility between stations. Reduction of raw EDM data to forms suitable for computer solution of triangles and quadrilaterals appears to be more time consuming than reduction of GPS data with the computer and special software programs. GPS measurements are, however, subject to their own possible sources of error including variation in the propagation properties of the upper atmosphere and ionosphere and, more rarely, to the deliberate degradation of signals by the Defense Department. Most of these sources of error can be corrected by using currently available software.

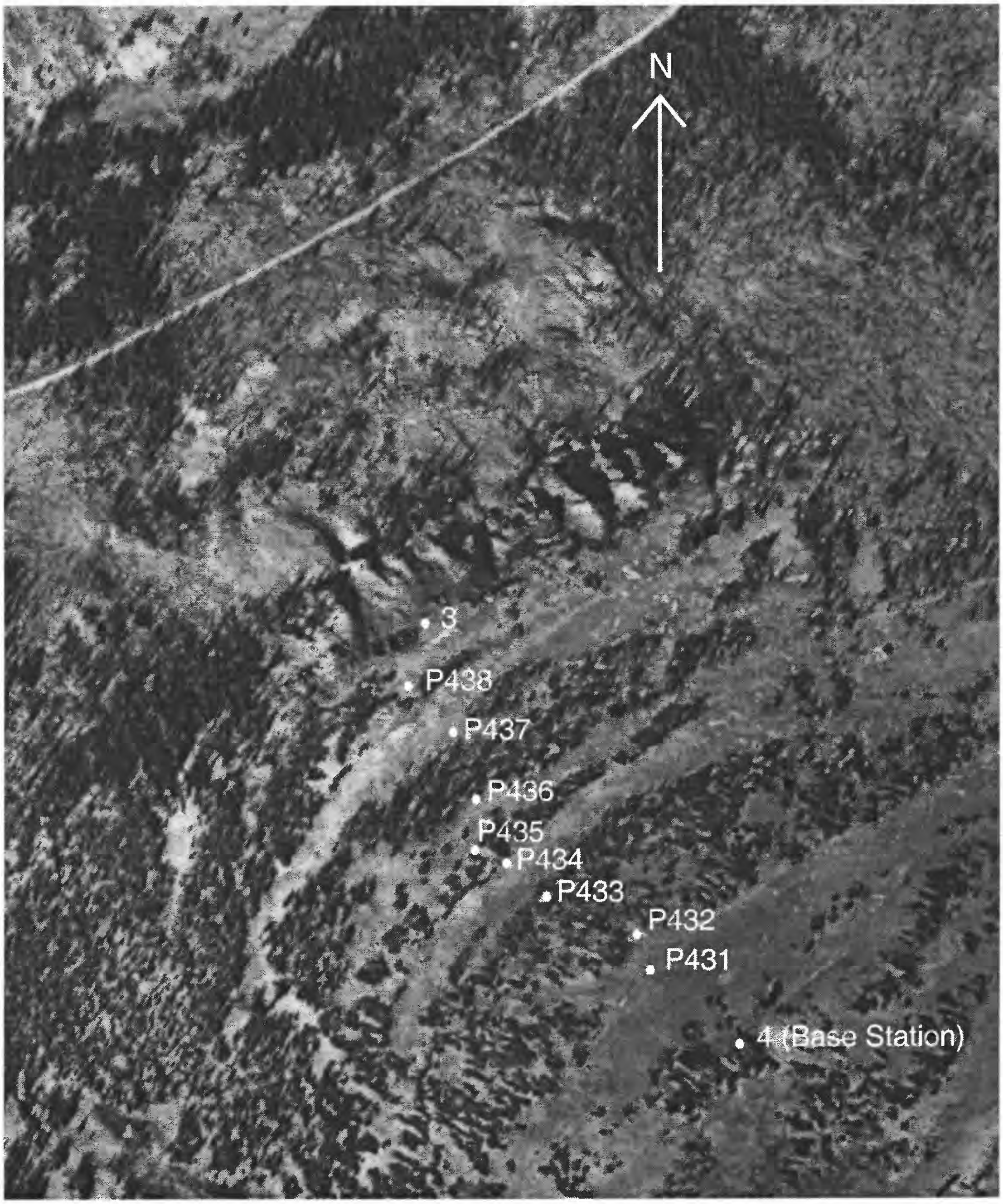


Figure 10. Location of profile points.

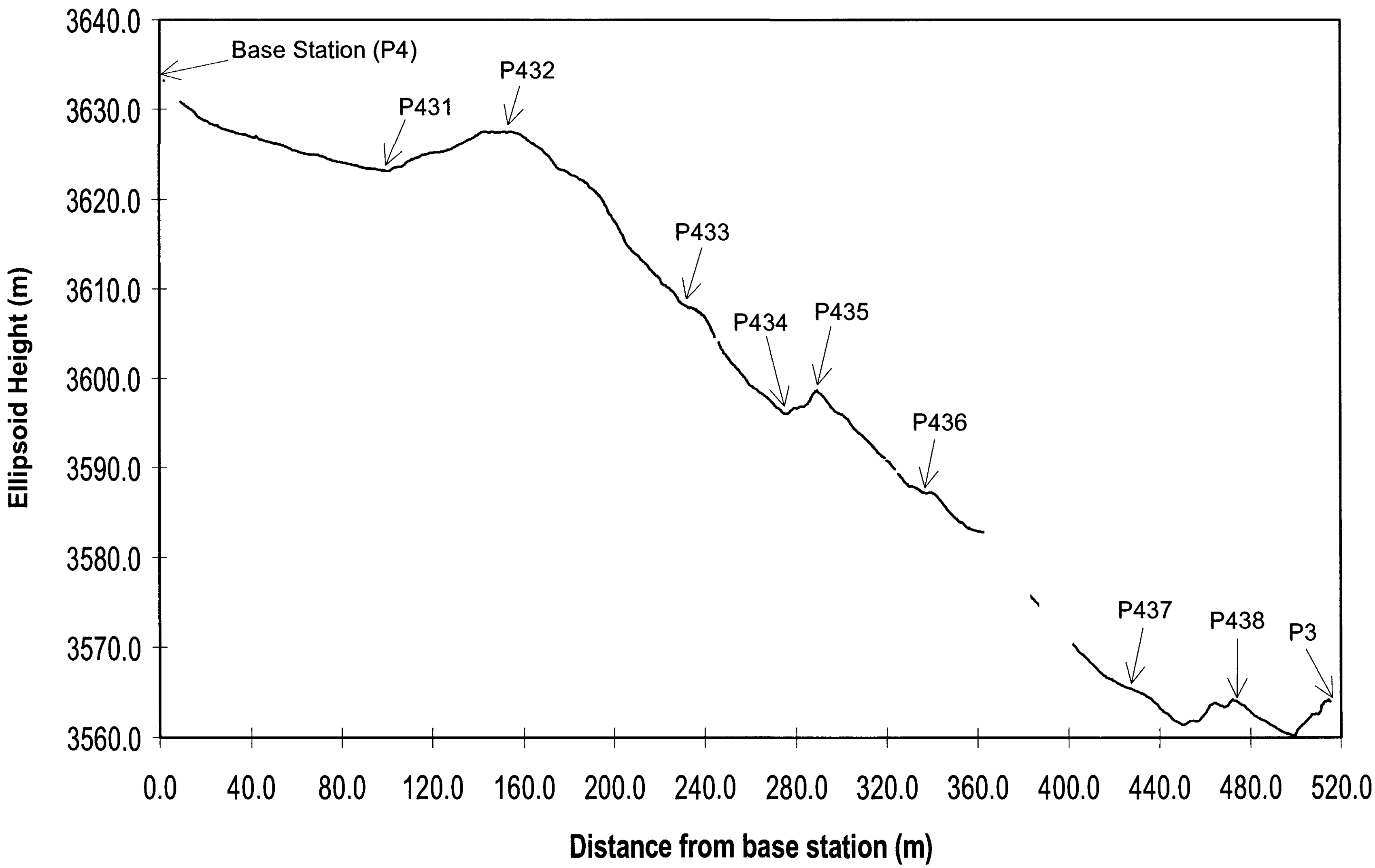


Figure 11. Real-time GPS profile data projected onto a vertical plane between the point 4 (base station) and point P3. Point locations measured using rapid static GPS methods are shown. Gaps in the profile are caused by poor GPS signal in heavy tree cover. Vertical exaggeration is 4x.

Table 3. Profile Point Data. WGS84 is the World Geodetic System 1984. NAD83 is the North American Datum 1983. NAVD88 is the North American Vertical Datum 1988. NA=Not applicable because the point is a base station (P4) or data is from the initial GPS observation.

Point Name	Date Observed (m/d/y)	Slope Distance from Base Station (m) and standard deviation (m)	Latitude (WGS84, degrees minutes seconds) and standard error (m)	Longitude (WGS84, degrees minutes seconds) and standard error (m)	Ellipsoid Height (m) and standard error (m)	Northing, NAD83, Colorado State Plane Coordinate, central zone (m)	Easting, NAD83, Colorado State Plane Coordinate, central zone (m)	Mean Sea Level Height (NAVD88, m)	Difference in Northing values (1997-1999, m)	Difference in Easting values (1997-1999, m)	Difference in Mean Sea Level Height values (1997-1999, m)
4	8/17/97	NA	N 39 14 29.40594	W 106 27 21.54368	3633.767	461552.296	831877.161	3646.650	NA	NA	NA
P431	8/20/97	101.845 ±0.009	N 39 14 32.30475 ±0.005	106 27 23.52463 ±0.004	3623.169 ±0.007	461642.182	831830.603	3636.052	NA	NA	NA
P431	8/25/99	101.853 ±0.009	N 39 14 32.30514 ±0.005	106 27 23.52438 ±0.004	3623.165 ±0.006	461642.194	831830.609	3636.046	+0.012	+0.006	-0.006
P432	8/20/97	156.061 ±0.009	N 39 14 33.90033 ±0.005	W 106 27 24.51538 ±0.004	3627.570 ±0.006	461691.632	831807.365	3640.449	NA	NA	NA
P432	8/25/99	156.063 ±0.008	N 39 14 33.90043 ±0.004	W 106 27 24.51527 ±0.004	3627.566 ±0.006	461691.635	831807.368	3640.446	+0.003	+0.003	-0.003
P433	8/20/97	235.720 ±0.008	N 39 14 35.51555 ±0.004	W 106 27 27.34237 ±0.003	3607.977 ±0.006	461742.152	831740.106	3620.856	NA	NA	NA
P433	8/25/99	235.743 ±0.010	N 39 14 35.51639 ±0.005	W 106 27 27.34259 ±0.004	3607.983 ±0.008	461742.178	831740.101	3620.862	+0.026	-0.005	+0.006
P434	8/20/97	279.691 ±0.009	N 39 14 36.44962 ±0.005	W 106 27 28.71080 ±0.004	3596.139 ±0.006	461771.301	831707.598	3609.017	NA	NA	NA
P434	8/25/99	279.684 ±0.009	N 39 14 36.44957 ±0.005	W 106 27 28.71034 ±0.004	3596.130 ±0.006	461771.299	831707.609	3609.008	-0.002	+0.011	-0.009
P435	8/20/97	292.381 ±0.009	N 39 14 36.78378 ±0.005	W 106 27 29.04901 ±0.004	3598.690 ±0.006	461781.690	831699.597	3611.568	NA	NA	NA
P435	8/25/99	292.376 ±0.007	N 39 14 36.78369 ±0.004	W 106 27 29.04870 ±0.004	3598.678 ±0.005	461781.687	831699.605	3611.555	-0.003	+0.008	-0.013
P436	8/20/97	344.718 ±0.007	N 39 14 38.08869 ±0.004	W 106 27 30.37316 ±0.003	3587.205 ±0.005	461822.262	831668.272	3600.082	NA	NA	NA
P436	8/25/99	344.718 ±0.009	N 39 14 38.08891 ±0.005	W 106 27 30.37287 ±0.004	3587.216 ±0.007	461822.269	831668.279	3600.092	+0.007	+0.007	+0.010
P437	8/20/97	434.953 ±0.010	N 39 14 40.74580 ±0.006	W 106 27 31.92601 ±0.004	3565.269 ±0.007	461904.588	831631.904	3578.143	NA	NA	NA
P437	8/25/99	434.954 ±0.012	N 39 14 40.74588 ±0.006	W 106 27 31.92582 ±0.005	3565.259 ±0.008	461904.590	831631.908	3578.133	+0.002	+0.004	-0.010
P438	8/20/97	482.425 ±0.010	N 39 14 42.00709 ±0.005	W 106 27 33.08087 ±0.004	3563.636 ±0.007	461943.773	831604.624	3576.509	NA	NA	NA
P438	8/25/99	482.430 ±0.011	N 39 14 42.00747 ±0.006	W 106 27 33.08066 ±0.005	3563.644 ±0.008	461943.784	831604.630	3576.517	+0.011	+0.006	+0.008
3	8/19/97	520.358 ±0.009	N 39 14 43.27431 ±0.005	W 106 27 33.53580 ±0.004	3564.062 ±0.006	461982.963	831594.129	3576.935	NA	NA	NA
3	8/25/99	520.358 ±0.009	N 39 14 43.27432 ±0.005	W 106 27 33.53588 ±0.004	3564.069 ±0.007	461982.963	831594.127	3576.940	0.000	+0.002	-0.005

DISCUSSION AND CONCLUSIONS

Theoretical analyses of spreading mechanics have been made (Savage and Varnes, 1987), but measurements in the field over an extended time are uncommon. In particular, knowledge of vertical movements of points on a spreading mountain, to an accuracy comparable with that of horizontal movements, is becoming essential to our further understanding of the relatively unknown mechanics of sackungen. We recommend, therefore, that precise determination of horizontal movements be supplemented with precise leveling, wherever practical, between stations in the Bald Eagle Mountain triangulation net and GPS profile. The bar-code-reading level system would be lightweight, fast, and sufficiently accurate.

We believe that spreading movements of the ridge under study are probably still taking place; these are slow by standards of human activity, but are quite rapid for a geologic process. The evidence is:

1. The horizontal movement by station 3 of 8.3 cm in the 20 years from 1977 to 1997 is in a direction directly away from the trenches uphill and the ridge-top graben, as should be expected if spreading is taking place.

2. The movement of station 1 just west of the ridge-top graben, although only 1.3 cm in the interval 1975-1997, was down and directly away from the graben.

3. The movement of station 6, which is about 400 m southeast of the graben, although only 1.0 cm in the interval 1975-1997, was to the southeast away from the graben and opposite in direction to the movement of station 1.

To speculate a little, the movement of station 3 of about 4 mm per year, if constant over about 10,000 years since the valley of Busk Creek was deglaciated, would amount to about 40 meters. Distributed over the 3 or 4 trenches below the graben, this is not an unreasonable amount, considering the present size of the trenches (See fig. 11 and fig. 12)

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Figure 12. One of the large trenches, showing the asymetric form of a steep upward-facing scarp on the left, downhill, side, and a smooth slope to the right on the uphill side.

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