Maine Geological Survey
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Geodetic Evidence of Current Crustal Motion in Maine

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ABSTRACT

Geodetic surveys, completed in Maine on numerous occasions since 1859, reveal a record of recent earth crustal motion. Repeated first order level lines throughout Maine, and horizontal first order triangulation surveys and satellite surveys in eastern Maine, indicate significant subsidence in the Passamaquoddy Bay region of the coast. Horizontal survey data, while less conclusive than the vertical data, indicate evidence of detectable strain accumulation.

VERTICAL DATA

The national first order vertical leveling network surveyed and maintained by the National Geodetic Survey (formerly the U.S. Coast and Geodetic Survey) was extended into Maine in 1916. Parts of the network, shown in Figure 1, have been releveled as many as four times between 1916 and 1978. All first order leveling data in Maine which could be located by the National Geodetic Survey in 1979 were collected and analyzed in order to provide a coherent picture of vertical crustal motion within the State (Tyler, Ladd and Borns, 1979; Tyler and Ladd, 1980). A number of computational techniques for combining disjointed segments of level lines surveyed and resurveyed at different epochs have been proposed (Vanicek and Christodulidis, 1974; Holdahl, 1978). A variation of Holdahl's method 5 was selected for the Maine data.

VERTICAL VELOCITY SURFACE MODEL

The elevation of benchmark a at time t_i is given by

$$h_{a,i} = h_{a,o} + V(x_a,y_a)(t_i - t_o) \qquad (1)$$

where:

$h_{a,i}$ = elevation of benchmark a at time t_i
$h_{a,o}$ = elevation of benchmark a at time t_o
V = vertical velocity
x_a, y_a = plane coordinates of benchmark a
t = time

The velocity function $V(x_a,y_a)$ is assumed to be independent of time and can be expressed as a two dimensional algebraic function:

$$V(x_a,y_a) = C_1x_a + C_2y_a + C_3x_ay_a + C_4x_a^2 + \ldots\ldots \qquad (2)$$

The difference in elevation between two benchmarks, a and b, at time t_i can now be written:

$$\Delta h_{b,a,i} = (h_{b,i} - h_{a,i}) + V_{b,a,i} \qquad (3)$$

where:

$\Delta h_{b,a,i}$ = observed difference in elevation at time t_i
$h_{b,i}$ and $h_{a,i}$ are as defined in equation 1
$V_{b,a,i}$ = a residual

The unknown parameters in equation 3 are the elevations of benchmarks a and b at time t_o and the coefficients of the polynomial. Equation 3 in expanded form is:

$$\begin{aligned}\Delta h_{b,a,i} = {} & (h_{b,o} - h_{a,o}) + C_1(x_b - x_a)(t_i - t_o) + C_2(y_b - y_a)(t_i - t_o) \\ & + C_3(x_b^2 - x_a^2)(t_i - t_o) + C_4(y_b^2 - y_a^2)(t_i - t_o) \\ & + C_5(x_by_b - x_ay_a)(t_i - t_o) + \ldots\ldots + V_{b\text{-}a,i} \qquad (4)\end{aligned}$$

and is linear in the parameters.

All releveled lines in the state were examined, and observed elevation differences between adjacent benchmarks included in at least two surveys were put into a least-squares solution to solve the velocity surface model. The resulting surface coefficients and equation 2 were used to generate point velocities which are

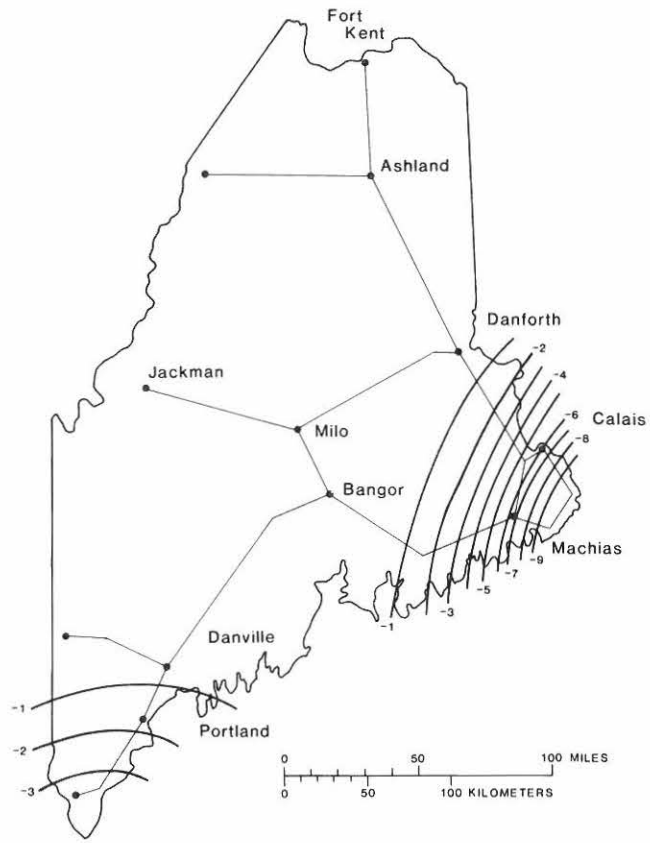

Figure 1. Map showing the first-order level network in Maine and the relative vertical crustal velocity surface (contours in mm/yr) relative to Bangor, Maine.

contoured in Figure 1. Benchmark V8 in Bangor was arbitrarily assigned a velocity of 0 mm/yr, making the velocity values in Figure 1 relative to Bangor.

In order to test the fit of the velocity surface, observed velocity differences between adjacent benchmarks were compared to predicted velocity differences, and root mean square (RMS) errors are tabulated for each segment of the state-wide level network in Table 1.

TABLE 1. RMS ERRORS IN RELATIVE BENCHMARK VELOCITIES

Line	Location	RMS Error mm/yr
1	Portland (south) to N.H. border	0.21
2	Maine-N.H. border to Danville	0.69
3	Danville to Portland	0.35
4	Danville to Bangor	0.78
5	Milo to Bangor	11.49
6	Bangor to Calais	3.08
7	Machias via Eastport to Calais	2.27
8	Jackman to Danforth	2.36
9	Fort Kent to Calais	1.11
10	Ashland via Clayton Lake to Canadian border	0.46

As might be expected, the velocity surface does not fit uniformly well throughout the state. With the exception of line 5, the largest velocity residuals are in the eastern part of the state, where the model predicts the largest velocities. These residuals must be attributed to random and uncorrected systematic errors in the level data and errors in the velocity model. Only those velocity contours which appear to be significant are shown in Figure 1.

Horizontal Data

In the spring of 1982 engineers from a consulting geology and soils engineering firm brought to the attention of the Maine Geological Survey what they believed to be evidence of recent horizontal crustal motion in the vicinity of Grand Falls Dam on the St. Croix River. The evidence was based on foundation problems encountered at the dam site and a resurvey of International Boundary Commission (IBC) stations by a local surveying firm (Anderson, 1982). The movement was described as being as much as 11 feet since 1900.

A study initiated at the University of Maine concentrated on existing geodetic stations located ten or more miles from the dam site (Tyler and Leick, 1985). If there is or has been horizontal motion of the magnitude suggested, a pattern of regional strain should emerge from the repeated observations on distant first order geodetic stations. A quadrilateral of first order triangulation stations Rye, Neal, Oak and Chamcook, shown in Figure 2, covers the site. These stations were first established between 1857 and 1890 by the United States Coast and Geodetic Survey, now the National Geodetic Survey (NGS). Surveys were repeated in the region in 1859, 1887, 1890, 1917, 1928, 1946, and 1975. Unfortunately, these surveys were performed for the purpose of extending the control network rather than to monitor suspected crustal motion and no attempt was made to remeasure directions and angles that had already been measured. In August, 1983, three stations of the quadrilateral, Rye, Oak and Neal, were occupied on two consecutive nights with Macrometer Global Positioning System (GPS) receivers. Geodetic analysis of horizontal crustal motion must at this point rest on a comparison of these three macrometer observations with the earlier triangulation surveys.

Observations from the Macrometer, one of several surveying instruments developed to use the GPS for precise positioning, are processed to produce estimates of vectors between simultaneously occupied stations. This is a fundamentally different kind of observation than the triangulation originally employed to locate the first order stations, and any comparison must be done very cautiously. The salient points of the comparison of the triangulation and GPS results are summarized below:

1) In 1975 the distance between stations Neal and Oak was measured with a model 8 Geodimeter. The reduced mark-to-mark distance was 27,965.914 m. The adjusted 1983 Macrometer distance between the two stations was 27,965.753 m, a

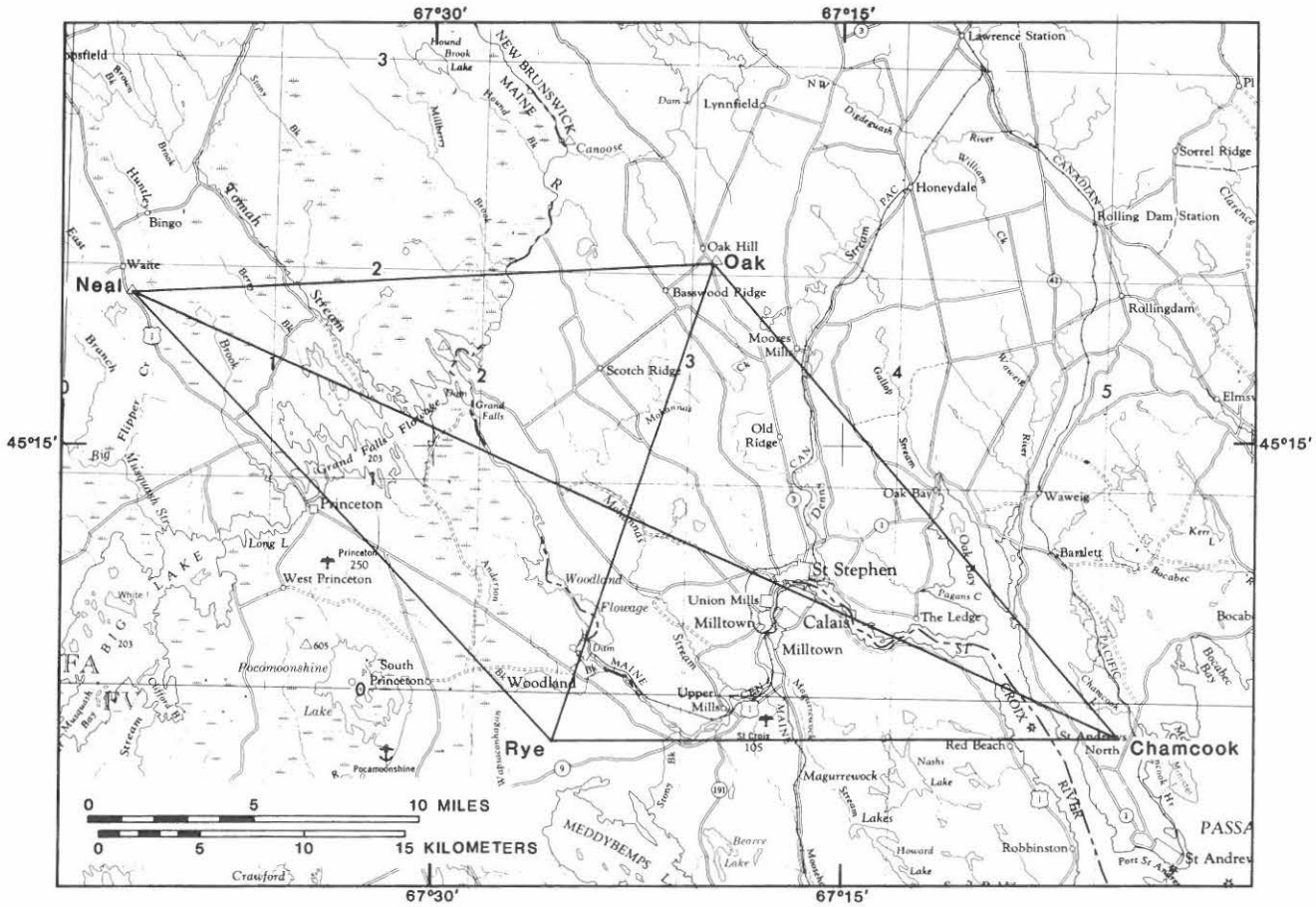

Figure 2. Map showing location of the Rye-Neal-Oak-Chamcook quadrilateral.

difference of 0.161 m. The NGS estimates the standard error in the Geodimeter measurement to be 0.032 m. The estimated standard error of the Macrometer distance, based on a 1983 survey of a twenty-station network in Germany using the same instruments (Bock and others, 1984) is 1 to 2 ppm or 0.045 m. If we accept these estimates of the standard errors of both measurements, we must reject the hypothesis that the two measured distances are equal at the 5% confidence level.

2) Geodetic latitudes and longitudes were computed with the NGS triangulation data and the Macrometer data. The lengths of geodesic lines between the three stations and the angles between geodesic lines were computed for each data set and the differences are shown in Figure 3 in the sense of Macrometer minus NGS data. The NGS estimates that angle changes of 3.5 seconds are the maximum that should be expected with these data (McKay, 1984). McKay also mentions a scale problem in the St. Croix area which could cause consistent length errors of up to one-half meter. Both angle and distance differences are significantly larger than can be explained by expected measurement errors.

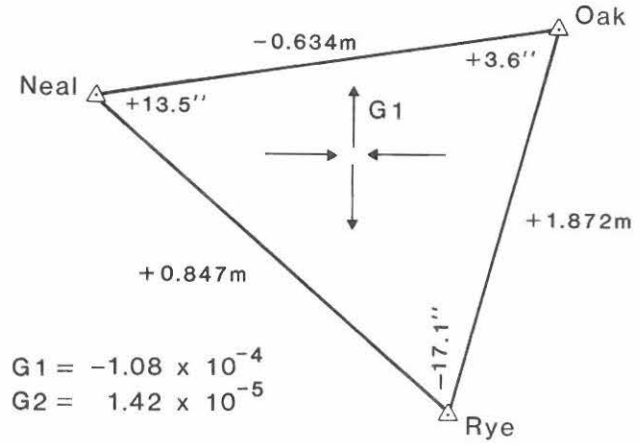

Figure 3. Differences in distance and angles in the sense of Macrometer (1983) minus triangulation (1890) survey data. Strain shown is based on angles only.

3) Angles computed from Macrometer observations can be compared with observed angles from the triangulation data to obtain an estimate of shear strain, but not of dilation or rotation. Geodesic lengths may be compared to estimate dilation, but as noted above, there may be a regional scale problem in the triangulation data. F. C. Frank (1966) has developed a method of computing shear components of strain from the repeated observations of the three angles of a single triangle. Frank's method has been applied to the triangle Rye, Neal, Oak with the results shown in Figure 3. G1 measures a pure shear corresponding to east-west elongation and north-south compression, and G2 measures a pure shear corresponding to NE-SW elongation and NW-SE compression. Gm is the square root of the sum of the squares of G1 and G2 and is the total shear strain. In this triangle G1 dominates with a negative sign indicating extension in the north-south direction and compression in the east-west direction. The maximum extension occurs along a line with an azimuth of 4 degrees from north. Because dilation cannot be deducted from the angle changes alone, a value of the maximum extension cannot be computed.

In a triangle reasonably close to equilateral, as the Rye, Neal, Oak triangle is, an angular error of one second will produce an erroneous strain of as much as 9×10^{-6}. The NGS estimates that 3.5 seconds is the maximum error to be expected in the triangulation angles and the Macrometer observations should introduce angular errors considerably smaller than 3.5 seconds. The expected accumulation of error cannot explain the computed crustal strain.

CONCLUSIONS

Both the vertical and horizontal geodetic data reviewed indicate significant crustal motion in eastern Maine. The relative vertical subsidence of up to 9 mm/yr indicated in the eastern region of the state can be attributed to: a) the accumulation of random errors, b) incorrectly modeled systematic errors, c) local movement and instability of individual marks, or d) crustal warping. The NGS estimates that random errors in a first order level line will be $1.5\ (L)^{0.5}$ mm for lines observed between 1917 and 1955 and $1.0\ (L)^{0.5}$ mm for lines observed after 1955 where L is the length of the line in km. This could account for between 1 and 2 mm per year of the indicated subsidence. A considerable amount of geodetic literature has been devoted to the study of systematic errors or effects in level lines. While a detailed analysis of the Maine data to isolate systematic effects has not been done, it is possible that the systematic errors could be equal in size to the accumulated random error and thus account for another 1 to 2 mm/yr. Locally unstable benchmarks will show spikes in the data but will not contribute to regional trends. Therefore, at least 5 mm/yr of the indicated relative subsidence would seem to be caused by crustal deformation.

Horizontal data from a single triangle cannot yield enough information to provide unequivocal evidence of crustal deformation. However, the Rye, Neal, Oak triangle shows an accumulation of strain which cannot be explained by expected random errors. While the horizontal motion indicated is not as great as that initially suspected at the Grand Falls Dam Site, the motion is large enough to be detected by future surveys using GPS technology. A network of 16 stations has been established in eastern Maine by the University of Maine and the NGS. The first set of observations on this network were accomplished in October, 1986. Future surveys of this network should define the pattern of crustal warping developing in eastern Maine.

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