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THE SELECTIVE SALVATION OF ZEISS NI 1 LEVELINGS

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An analysis of the results of a representative sample of earlier Zeiss Ni 1 levelings suggests that a number of these earlier levelings were free of any significant magnetic error

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ABSTRACT

Examination of the results of a relatively small sample of the more than 25,000 km of Zeiss Ni 1 levelings in the United States suggests that a large fraction of the earlier Ni 1 surveys were devoid of measurably significant magnetic error. This period of apparently error-free operation involved at least four instruments whose use extended from 1972 into the early months of 1975. Determination of the degree of magnetic contamination is based on both objective and subjective considerations. The least equivocal assessments are obtained from closures on either sea level or lake levels, such that crustal deformation can be disregarded as a significant contaminant. Alternatively, the results of the Ni 1 surveys can be compared against the results of earlier non-Ni 1 levelings, where both the sense and magnitude of any intervening vertical displacements can be independently estimated. Our clearly limited analyses of magnetic contamination are based on: 1) closures against sea level along the California coast and lake levels along the west side of Lake Michigan, where the meaned primary-station lake levels are idealized as points on the same equipotential surface; 2) sequentially determined heights for a representative mark at El Centro, California; and 3) comparisons against earlier levelings in eastern New York and along the west side of Lake Michigan, where crustal tilting can be inferred from geologic evidence and/or differenced water-level trends. The results of our investigations indicate that nine Ni 1 instruments were free of magnetic error above noise level during various periods ranging through April 1975. Discrimination of those Ni 1 surveys devoid of significant magnetic error should not only restore confidence in the results of these particular surveys, but could lead to an improved formulation of the empirically-based correction factors as well.

INTRODUCTION

The discovery of a magnetic-deflection error associated with the Zeiss Ni 1 automatic level (Rumpf and Meurisch, 1981) provoked understandable dismay in the geodetic community. This instrumental flaw was responsible for the most enigmatic and probably most troublesome systematic error ever recognized in any terrestrially based geodetic measurement system. Specifically, the Ni 1 magnetic-deflection error, which reaches its theoretical maximum along magnetic-north azimuths, may accumulate to values of at least as much as 0.15 m over no more than about 100 km (Packard and MacNeil, 1983). Thus the potentially enormous magnitude of this error clearly constitutes cause for concern in considering the acceptability of any leveling based on the Ni 1. Because about 25,000 km of precise leveling in the United States through the period 1972-1980, were based on the Ni 1 (Holdahl and others, 1987, p. 28), several serious efforts were directed toward the development of a hindcast correction for this error. However, owing to the instrument-specific and, especially, time-dependent nature of this error, these efforts commonly produced equivocal or at least coarsely defined correction factors.

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Hindcast Corrections

Evidence developed from several earlier studies (Whalen, 1984; Holdahl and others, 1987; Castle and Gilmore, 1992) suggests that a sizable but undetermined fraction of the earlier Ni 1 surveys in the United States were trivially, if at all, contaminated by magnetic error. "Correction" for a nonexistent error carries with it the obvious likelihood of contamination attributable to the correction model. Thus, if it can be shown that a significant fraction of Ni 1 levelings were free of magnetic error and, in fact, met otherwise stipulated standards of accuracy, their identification should assist in the development of an improved and generally more acceptable correction procedure. Thus we begin this report with a brief discussion of previously developed procedures intended to correct for the Ni 1 magnetic-deflection error.

Laboratory calibrations of the magnetic-deflection error (Whalen, 1984) provided relatively accurate corrections where they coincided closely in time with the surveys in question (see, for example, Holdahl and others, 1987, p. 35-36). However, these same calibrations failed dramatically where they were widely-separated in time from the pertinent surveys--several years as opposed to several months (see, for example, Holdahl and others, 1987, p. 28, 35-36). The empirical calibrations of the National Geodetic Survey improve upon the laboratory calibrations, but they too suffer from the unpredictable, time-dependent nature of this error, even though an attempt was made to weight the data as a function of elapsed time between the Ni 1 survey and the comparative survey(s) on which the empirical calibration depends. Specifically, as Holdahl and others (1987, p. 39) observed, the magnetic sensitivity of this instrument apparently changed with age, possibly doubling over no more than a few years. This generalization, moreover, is no less applicable in a number of cases where the compensator remained unchanged. Perhaps the clearest example of a failed empirical calibration is one provided by Holdahl and others (1989, p. 38), which shows that the correction underestimates the actual magnetic error by about 70 mm over a distance of only 60 km. Although the laboratory calibrations indicate that the magnetic-deflection error is consistently in the same down-to-the-north sense (Whalen, 1984, Table 2), because we have no clear idea how this error changes as a function of time, existing hindcast techniques are almost certain to fail in specific cases if not more generally.

Empirical calibrations currently in use are suspect for several other reasons as well. Probably the most questionable assumptions involved in these calibrations arise from either: 1) presumed crustal stability between surveys; or 2) uncertainties as to the nature of any presumed instability. For example, the weighting procedure adopted by Holdahl and others (1987) does not and probably cannot provide for episodic or oscillatory displacements, a consideration that effectively precludes use of comparative data gathered from areas of recognized tectonic activity. Although certain areas of continuing surface deformation were screened out in the analyses of Holdahl and others (1987, p. 32-33)--notably the Great Lakes region, the Houston area, and the Mississippi delta--all of the comparative data from along the Pacific-North American plate margin, as well as eastern New York and northern New England, were apparently included in the development of the empirical calibrations. While any selectivity designed to minimize the influence of crustal deformation is necessarily subjective, it is difficult to understand why plate-margin data were retained, whereas those from such places as the Mississippi delta were discarded. Still another complication is introduced through the incorporation of the untested assumption that the results of the comparative levelings on which the empirical calibrations depend were devoid of all other systematic error (Holdahl and others, 1987, p. 28-29). Finally, the empirical calibrations are derived from the results of comparative surveys that incorporate the refraction corrections of the National Geodetic Survey, a procedure that could easily introduce significant errors into the data owing to the likelihood that these "corrections" adulterate the uncorrected data in varying degree (Mark and others, 1987; Castle and others, 1994).

DISCRIMINATION OF UNCONTAMINATED Ni 1 LEVELINGS

Accepting the potential magnitude of the Ni 1 magnetic-deflection error, we now believe that a sizable number of uncorrected surveys based on this instrument are still salvageable on a case-by-case basis. Owing to the time-dependent nature of this error and fairly clear evidence that it had not begun to significantly affect leveling accuracy associated with at least a few of the earlier Ni

1 levelings, any procedure that lends itself to the discrimination of no more than trivially contaminated survey data provides a basis for the retention of an undetermined number of Ni 1 surveys in their uncorrected mode. The likelihood that the magnetic-deflection error did not begin to seriously distort Ni 1 observations until the mid-1970's is suggested especially by the results of several comparisons and the sequentially generated correction factors developed by Holdahl and others (1987, p. 32, 36-37; table 1, this report). For example, comparisons among successive empirical correction factors for the same instrument show that these factors generally increased with time, commonly starting with very small values (table 1). The only apparent exceptions consist of: 1) those associated with compensator replacements (78300 and 90760); 2) those identified with values that are statistically indistinguishable from each other (90823, 90825 and 90760); or 3) both. Moreover, the correction intervals were selected arbitrarily, whereby it was assumed both that the magnetic susceptibility of each instrument changed only at the time of repair and that no repairs occurred before 1975 (owing to the absence of pre-1975 repair records--Holdahl and others, 1987, p. 33). However, it is just as likely that these changing values proceeded irregularly and unpredictably in time, and that the earlier Ni 1 levelings were largely uncontaminated by the magnetic virus.

A general test for the accuracy of any Ni 1 leveling is based, in simplest terms, on closures against alternatively developed height (or geopotential) differences that explicitly exclude use of the Ni 1 and are so constrained that crustal movement can be disregarded as a potential contaminant. If it can be shown that the discrepancies in the closures of the Ni 1 levelings on these independently developed height differences do not exceed the predicted random error estimates, the indicated Ni 1 levelings and any earlier levelings based on the same instrument(s) can be accepted as free of any measurably significant magnetic-deflection error. Full implementation of this procedure requires the acceptance of an obvious assumption: if a given instrument can be shown to have been free of measurably significant magnetic error at a particular time during its use history, it is unlikely that this instrument sustained earlier magnetic contamination from which it subsequently recovered.

Comparisons of Ni 1 Levelings in California Against Both Sea Level and Earlier and Later Levelings

Investigations of the results of several relatively early Ni 1 levelings in California indicate that at least four and probably six Ni 1 instruments used in these surveys were free of significant magnetic contamination through at least the first few months of 1974. Specifically, the 1973/74/75 leveling between the San Francisco and San Pedro tide stations closed within 6 mm of local mean sea level at San Pedro with respect to that at San Francisco (Castle and Elliott, 1982, p.

7009)--in close agreement with both steric leveling (20-30 mm--Sturges, 1974) and at least one earlier spirit leveling (24 mm--Castle and Elliott, 1982, p. 7000-7009). Since these surveys were based in large measure on six Ni 1 instruments (table 2), we infer that these six instruments were devoid of measurably significant magnetic contamination during the course of the indicated survey. Four of these six instruments (table 2) were also used during the period 1973/74 between Amboy and El Centro (fig. 1). Because use of these four instruments predated their use from anywhere along the San Francisco-San Pedro line (table 2), we can reasonably assume that it is even less likely that the 1973/74 Amboy-El Centro levelings were afflicted by a measurably significant magnetic-deflection error.

Several subjective determinations support the likelihood that the 1973/74 Amboy-El Centro surveys were uncontaminated by magnetic error. The 1976 height for bench mark R59, El Centro (height 9, fig. 2), which has been reconstructed from the results of 1976 leveling extending southwestward from Parker Dam into El Centro (fig. 1), closely matches the 1974 value and thus supports the credibility of the 1974 height. Because the history with respect to Tidal 8, San Pedro (see caption, fig. 2), of the starting mark (22Q, about 20 km east of Parker Dam) used in the reconstruction of the 1976 height for R59 is well known (Mark and others, 1987, p. 2761), the 1976 starting height can be accepted with a high degree of confidence. Regrettably, all but about 25 km of the 1976 leveling into R59 was based on six Ni 1 instruments (231-90760, 231-107293, 231-107367, 231-78300, 231-90834, and 231-90856; National Geodetic Survey lines L-24068, L-24071, L-24077, L-24080, L-24085 and L-24130.1), including three that were also used in the 1973/74 Amboy-El Centro leveling. Thus, the 1976 leveling might also have been distorted by a significant magnetic-deflection error. Nevertheless, because the mix of instruments was clearly disparate (Holdahl and others, 1987, p. 32), and because both the survey route and the directional character of the 1976 leveling differ sharply from that of the 1973/74 survey, it is doubtful that the correspondence between the 1974 and 1976 heights for R59 could be attributed to the chance accumulation of magnetic-deflection errors of almost exactly the same magnitude. Similarly, the close correspondence between the 1939 (pre-Ni 1) and 1974 (or 1976) heights (fig. 2) suggests that uplift of the magnitude disclosed by the 1974 leveling need not be viewed as unexpected.

The results of the California levelings described here indicate, as we have already suggested, that incorporation of the empirically based magnetic corrections of the National Geodetic Survey may, on occasion (and possibly in the general case), seriously adulterate the conventionally corrected field data. For example, inclusion of magnetic corrections enlarges the 1973/74/75 closure on mean sea level at San Pedro from +0.0054 m (Castle and Elliott, 1982, p. 7009) to -0.0906 m. Acceptance of these corrections, in other words, not only enlarges the misclosure by nearly a decimeter, but produces a sea slope of the opposite sense to that predicted from oceanographic measurements (Sturges, 1974, p. 826). Hence, the magnetically corrected heights for R59 (fig. 2) probably significantly distort the vertical-displacement signal at El Centro.

Subjective Evaluations and Checks of Ni 1 Levelings Against Earlier Levelings

Alternatively, we can proceed from a subjective evaluation of a comparison based on the results of an Ni 1 survey and then seek independent corroboration of the validity of the comparison. For example, Isachsen (1975) interpreted the results of a 1973 Ni 1 north-trending survey against a 1955 leveling (fig. 3) as reasonably anticipated doming over the eastern end of the Adirondack massif. This interpretation requires that the indicated doming, in effect, overwhelmed whatever displacements (if any) might have been associated with postglacial unloading. Support for the absence of significant displacements associated with unloading can be found in the observation that the general area of concern (fig. 3) lies essentially athwart the contemporary null line between post-glacial rebound on the north and subsidence on the south (Walcott, 1972, p. 873-876). The up-to-the-south tilt between Rouses Point and bench mark P357 (fig. 3) is obviously inconsistent with rebound, but it could be interpreted as an expression of magnetic error identified with one or more of the three Ni 1 instruments used in the 1973 survey (table 3). However, the down-to-the-south tilt between P357 and Saratoga Springs is inconsistent with its attribution to a magnetic-deflection error, yet is consistent with both Isachsen's interpretation and anticipated postglacial subsidence within the annulus that surrounds the rebounding area (Fairbridge and Newman, 1968, p. 302). Finally, the fine-scale features shown by this profile (fig. 3) lend additional support to the accuracy of the 1973 leveling. For example, the virtually flat north-south reaches between P2 and C363 and between N62 and E7 are certainly inconsistent with a magnetic-deflection error in the 1973 leveling. Moreover, were we to appeal to magnetic error in the 1973 survey in explanation of the up-to-the-south tilt between P2 and P357, we would be hard pressed to explain the reversal between P357 and E7. Thus the collective evidence obtained from this comparison (fig. 3) is consistent with the likelihood that the 1973 Ni 1 leveling between Saratoga Springs and Rouses Point was largely or entirely devoid of magnetic error.

Support for the preceding interpretation is obtained from comparisons against the results of an earlier (1916) first-order line that extended southward from Rouses Point to Whitehall, New York, about 60 km north of Saratoga Springs (fig. 3). Profiled comparisons against the 1916 leveling disclose an incredibly large number of spikes over a roughly 100-km segment, the ends of which lie both well north of Whitehall and well south of Rouses Point, respectively. While these spikes are reasonably interpreted as the products of frost heave during the period 1916-1955, the exceptionally noisy nature of the profiled comparisons against this early leveling preclude useful comparisons over the full length of the 1916 line. Nevertheless, determination of the changes in the relative height of bench mark W3, Whitehall, are generally inconsistent with significant magnetic contamination of the 1973 leveling (table 4). Because the 1955-1973 comparison suggests that reference mark Q1 may be characterized by aberrant displacements (fig. 3), we have also computed the observed elevations of W3 with respect to bench mark U1, about 13 km south of Q1 (table 4). It clearly makes very little difference which reference mark we choose. That is, the 1916-1973 displacements of W3 are well within the estimated random error range of the discrepancy between these surveys (about 30 mm) with respect to either Q1 or U1 (table 4). The history of W3 during the period 1955-1973 is obviously more equivocal in the sense that W3 was characterized by displacements of +0.0722 m and +0.0572 m with respect to Q1 and U1, respectively. Because both of these values are above the estimated random error associated with the discrepancy between the 1955 and 1973 surveys (about 20 mm), the sense of these apparent displacements is such that they could be interpreted as an expression of magnetic contamination of the 1973 leveling. They could, of course, be just as reasonably interpreted as an expression of episodic doming over the Adirondacks. We are, in any case, left with the problem of explaining the excellent correspondence between the 1916 and 1973 values for W3 (with respect to either Q1 or U1) if we appeal to magnetic error in explanation of the 1955-1973 signals over the same reach.

Resumption of Ni 1 leveling southward from Saratoga Springs between mid-1974 and 1975 disclosed an apparent 0.34-m 1955-1974/75 up-to-the-south tilt between Saratoga Springs and New York City (Holdahl and others, 1987, p. 57). Because this continuation was based largely on the same instruments as those used between Saratoga Springs and Rouses Point (table 3), it is near certain that one or more of the three Ni 1 instruments used in the 1973 leveling (National Geodetic Survey lines L-23483 and L-23486) had by no later than mid- to late-1974 been seriously infected by the magnetic virus. Accordingly, an element of doubt clearly clouds the provisional interpretation developed in the preceding paragraphs.

Evidenced Obtained from Ni 1 Levelings in Combination with Earlier Levelings and Lake-Level Measurements in Lake Michigan Area

Evidence developed from almost exclusively Ni 1 levelings along the west side of Lake Michigan indicates that the utilized instruments--including one common to the 1973 Saratoga Springs-Rouses Point leveling--were free of measurably significant magnetic contamination through much of the summer of 1973. The correspondence between the results of the 1972/73 Ni 1 Lake Michigan surveys with those developed during the preceding epoch (largely the early 1930's) is quite good (fig. 4)--especially when allowance is made for the large amount of second-order leveling that characterized the baseline survey. That is, the estimated random error (1σ) in the discrepancy between the baseline and subsequent 1972/73 observed elevations of F52 (St. Ignace), with respect to C18 (Chicago), is about 76 mm, whereas the actual closure on F52 is about 50 mm (fig. 4). Moreover, and disregarding spikes, many of the short-wavelength signals disclosed in this comparison (fig. 4) are reasonably interpreted as localized crustal adjustments following unloading of the massive Wisconsin ice sheet. Thus, based on no more than this comparison (fig. 4), we would be inclined to conclude that the Ni 1 instruments used in the 1972/73 Chicago-Mackinaw City (St. Ignace) leveling (table 3) were essentially devoid of magnetic contamination in excess of that which could be expected to be associated with reasonably anticipated random error--a conclusion strongly reinforced by the close correspondence between the magnetic-north azimuth and the lengthwise trend of Lake Michigan (fig. 5).

Holdahl and others (1987, p. 34, 36) developed a comparison similar to that shown in figure 4, but one that differs in detail. In our comparison (fig. 4), we attempted to minimize any contamination in the measured elevation differences attributable to intrasurvey deformation (see, for example, Castle and Elliott, 1982) by restricting the time frame of the baseline leveling to the shortest possible interval. In order to meet this goal, we made use of 1934 leveling over the entire reach between Escanaba and St. Ignace, a determination that required that we remove a demonstrable 0.268-m bust in the 1934 leveling between bench marks J54 and H54 (fig. 4). Owing either to their recognition of an error in the 1934 leveling or some other unspecified reason, Holdahl and others (1987, p. 36) apparently included the results of 1938 leveling between B56 and K51 (fig. 4) in developing their baseline datum, a determination that resulted in a 1972/73 closure on F52 of about -50 mm. Thus even though the magnitude of the two closures is about the same (compare with fig. 4), the negative aspect of the latter closure introduces a complication that impacts the interpretation of Holdahl and others. Specifically, they argue that the agreement defined by their comparison is "misleading", since the "analysis of historical lake level records yields a relative uplift rate of approximately +243 mm per century at Mackinaw City relative to Milwaukee"--or an inferred 40-year uplift of about 100 mm between Chicago and Mackinaw City (Holdahl and others, p. 1987, p. 34,36). It is obvious, of course, that the 50-mm uplift of F54 shown in figure 4 provides the agreement that eluded Holdahl and others. The apparent disagreement between these two interpretations highlights a characteristic of glacial rebound that is bound to create a potential for divergent results of this sort. That is, based on time scales of centuries or millennia, postglacial rebound has proceeded relatively smoothly in both space and time. However, as shown here (fig. 4) and can be shown elsewhere, this generalization breaks down over time scales of months and years or even decades. This same conclusion, moreover, could be inferred from an examination of the differenced lake-level means between Milwaukee and

Mackinaw City shown by Holdahl and others (1987, p. 36). In other words, the measured 1934-38 tilt between B56 and K51 (fig. 4) accounts for nearly the entire discrepancy between our interpretation and that of Holdahl and others.

The sensitivity of the magnitude (and even the sign) of continuing rebound to both the spatial and temporal sample can be demonstrated quite independently through an examination of differenced water-level trends at seven stations, all but one of which are located along the west side of Lake Michigan (fig. 5). The computed trends depend on differenced means obtained for the four-month period June-September as annual-mean equivalents, thereby minimizing aberrations attributable to heavy spring run-off, winter gales, ice jams, etc.--an apparently standard procedure in studying variations in water-level trends in the Great Lakes (Tait and Bolduc, 1985, p. 194). Linear regressions were fitted to the differenced values for various station pairs for various intervals within the representative 30-year period 1956-1985. The option of increasing the number of stations (which we have adopted here) carries with it an automatic limitation on the baseline period, since only five of the utilized stations operated during the full 1956-1985 interval. However, comparison with the results of Holdahl and others (1987, p. 36) suggests that an increased period of observation would not seriously impact either the regressions or their interpretation. All of the published data for the period 1956-1985 were included in the development of the computed water-level trends (table 5); we have made no attempt to cleanse the data through removal of outliers. In fact, however, we discovered only two significant outliers, both of which emerged from comparisons against water-level means at Green Bay. Specifically, with respect to Calumet City, one of these outliers (1971) was -0.174 m and the other (1978) +0.253 m. In any case, the physical isolation of the Green Bay station from the main body of Lake Michigan (fig. 5) indicates that this station is more apt to produce aberrant water-level means than any of the other primary stations considered here. Thus less credence should be attached to the regression results obtained from comparisons against Green Bay than those obtained from other stations around Lake Michigan--regardless of statistical significance.

The results of this relatively simple exercise (table 5) produce several conclusions that clearly impact any interpretation of the profiled height changes shown in figure 4. For example, if we consider the full period 1956-1985, about 75 percent of the inferred up-to-the-north tilt at Mackinaw City, whether referred to either Calumet City or Milwaukee, is confined to the area north of Sturgeon Bay Canal; there is evidence of no more than a small fraction of the inferred crustal motion in the Lake Michigan area within the southern two-thirds of the lake (table 5). Similarly, while only two of the seven trends based on comparisons between Calumet City and Milwaukee are statistically significant (1970-1985 and 1974-1985), all but one of these trends disclose rising water levels at Milwaukee, (table 5)--that is, down-to-the-north tilting. Thus one might reasonably anticipate negative vertical displacements of the order of a few tens of millimeters at Milwaukee during a roughly 40-year interval--much as shown in figure 4. Again, and even though it is not shown directly in the profiled comparison, the statistically significant temporal variations in the Sturgeon Bay Canal values, whether referred to either Calumet City or Milwaukee, range between -0.57 mm/yr and -2.44 mm/yr (table 5), which suggests that diminished subsidence (if not uplift) at the latitude of Sturgeon Bay Canal is a reasonable expectation. This generalization seems to be consistent with both the relative uplift in the Green Bay area and the modest uplift northeastward from Escanaba (fig. 4)--neither of which can be attributed to the accumulation of a magnetic-deflection error.

The magnitude of the trends and the generally good agreement between the trends for Port Inland and Mackinaw City indicate that it is only toward the northern end of Lake Michigan that we can expect to see any significant expression of uplift (with respect to southern Lake Michigan stations) based on comparative surveys at least several decades apart. Moreover, because the survey route along the northern edge of Lake Michigan traverses irregularly across the isobases of uplift (Walcott, 1972, p. 873), the vertical signal based on successive surveys should be rather irregular in character--as, indeed, it seems to be (fig. 4). Taken together, all of these observations suggest that the degree of conformity between the two sets of surveys profiled in figure 4 is not only not "misleading", but generally consistent with what could have been predicted.

An objective but qualified assessment of the accuracy of the Ni 1 surveys along the west side of Lake Michigan can be obtained through closures against lake level, where the meaned lake-level values at the several primary stations (fig. 5) are idealized as points on the same equipotential surface. The objectivity of this approach is self evident; the qualification stems from the degree of departure of these meaned values from a true equipotential surface and the error inherent in the measured equipotential difference between water-level stations based on first-order leveling (devoid of magnetic contamination) and appropriately accurate gravity measurements. We have dealt with the first of these problems in much the same way that we did in computing the differenced water-level trends. That is, the lake-level mean at each station is based on a nine-year mean of the June-September "annual" mean, thereby minimizing the effects of expected seasonal aberrations. With respect to the second problem, we provide two solutions, where we can reasonably expect close agreement between the two. The first of these is based on closures of the observed elevation differences against the meaned lake-level means at the several stations with respect to the Calumet City mean. Neither refraction corrections nor, quite obviously, magnetic corrections have been applied to any of the leveled differences. Use of traditionally-corrected observed elevation differences as close approximations of the potential differences between stations is based on two considerations: 1) Nearly all of the 1972/73 leveling hugs the western edge of the lake and traverses through very modest relief (fig. 4). 2) First-order sight lengths of this vintage were so short that any refraction errors, even in the absence of the obviously modest relief (fig. 4), can be treated as infinitesimal. The second solution is based on the differences between the assumed zero geopotential difference derivative from the lake-level measurements at the several stations and the geodetically determined geopotential differences based on the 1972/73 leveling and integrated gravity measurements--again with respect to Calumet City. The geopotential difference between the meaned lake-level surface and the water-level station reference mark is computed simply as the product of the meaned gravity value between the reference mark and the lake level and the observed elevation difference between these points.

The results of the assessment described in the preceding paragraph indicate that any magnetic contamination of the Ni 1 instruments used in the 1972/73 Lake Michigan leveling was generally negligible--at least as far north as Sturgeon Bay Canal (table 6; fig. 5). The closure on the Milwaukee water-level station is marginally above the expected noise range and the sense of the closure is consistent with a postulated magnetic error. Moreover, because the tie between Calumet City and Milwaukee was based on the latest of the Lake Michigan Ni 1 levelings, there is a greater likelihood that this segment might have been contaminated by magnetic error than those to the north. This likelihood is diminished, however, by the fact that the closures northward to Sturgeon Bay Canal, which necessarily depended on the Calumet City-Milwaukee segment, are quite good (table 6). The closures on both Port Inland and Mackinaw City, on the other hand, are significantly above the expected error range, and the sign of the misclosures is again consistent with a magnetic-deflection error. However, because the instruments used in the levelings northward from Green Bay into St. Ignace were subsequently used on those levelings extending northward from Chicago into Green Bay, to conclude that these larger than expected misclosures were attributable to a magnetic error would challenge our basic assumption, whereby it is very unlikely that any magnetically contaminated instrument might subsequently undergo a spontaneous decontamination. Finally, the average azimuth of the line eastward from Escanaba is almost exactly orthogonal to magnetic north (fig. 5), such that virtually all of the magnetic error to which one might appeal in explanation of the Port Inland and Mackinaw City misclosures would have to have accumulated between Green Bay and Escanaba. Accordingly, because the relatively large misclosures on the Port Inland and Mackinaw City stations are probably unrelated to large leveling errors, we speculate here that they may be attributable to wind-generated pileup at these stations.

When combined with our analysis of the water-level trends and the profiled height changes between leveling epochs along the west side of Lake Michigan, the described closures (table 6) lead to the conclusion that any magnetic error associated with the Ni 1 instruments used in the 1972-73 leveling can be discounted as negligible through the periods of each of the surveys (table 3).

This finally brings us back to the 1973 Saratoga Springs-Rouses Point leveling. Two of the three instruments used in this leveling were also used along National Geodetic Survey line L-23087 between Chicago and Racine (table 3). Accordingly, because the 1973 Lake Michigan survey and the New York leveling were separated by only 2-3 months, it is especially likely that at least one of the instruments used in the Saratoga Springs-Rouses Point leveling (231-90825--table 3) was devoid of magnetic contamination through the early fall of 1973--and thus consistent with our subjective determination of the general absence of magnetic error in the 1973 Saratoga Springs-Rouses Point survey. We cannot however, extend this supporting generalization to the second of the two common instruments (231-90823), since it was used along line L-23087 for only one day.

CONCLUSION

We have examined the results of only a small fraction of the of Ni 1 levelings in the United States in this assessment of magnetic contamination associated with the earlier use of this instrument. Nevertheless, it is especially likely that a number of these earlier levelings (and hence the instruments--and explicitly associated compensators--involved in these surveys) were free of measurably significant magnetic contamination through various stipulated periods (table 7). Further investigation of the inventory of Ni 1 surveys--especially those from along the Atlantic Coast and the central Mississippi Valley--based on the procedures outlined in this report probably will identify still other levelings essentially devoid of magnetic error. At the very least, winnowing of those surveys clearly free of magnetic contamination should permit the development of more rigorously formulated empirical correction factors. In the absence of much more accurately determined correction factors (based, for example, on comparisons against the results of at least two non-Ni 1 levelings in tectonically inactive areas), the prudent course would be to simply discard those Ni 1 surveys where either hard evidence or statistically significant doubt attaches to the resulting empirically determined corrections.

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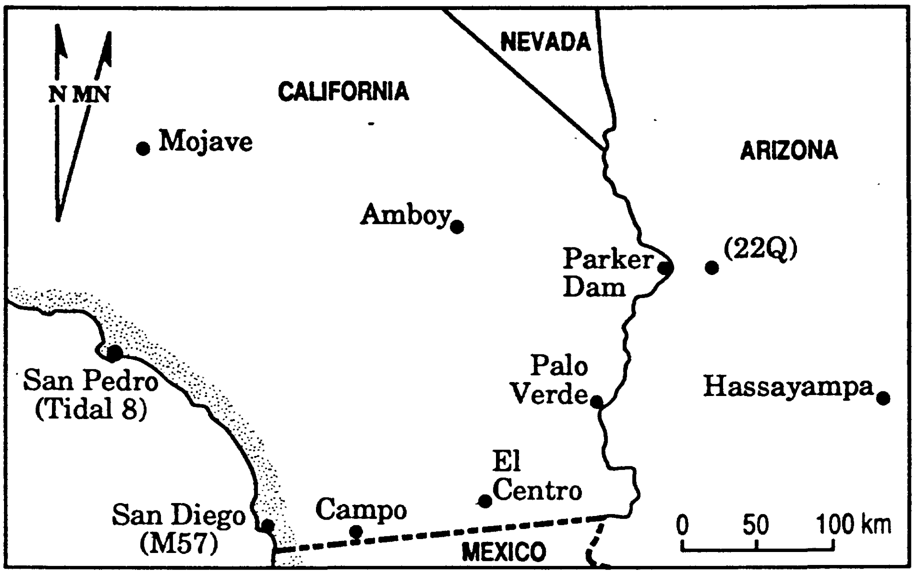

Figure 1. Index map of southern California showing referenced communities and principal control points used in the reconstruction of successive heights for bench mark R59, El Centro (fig. 2).

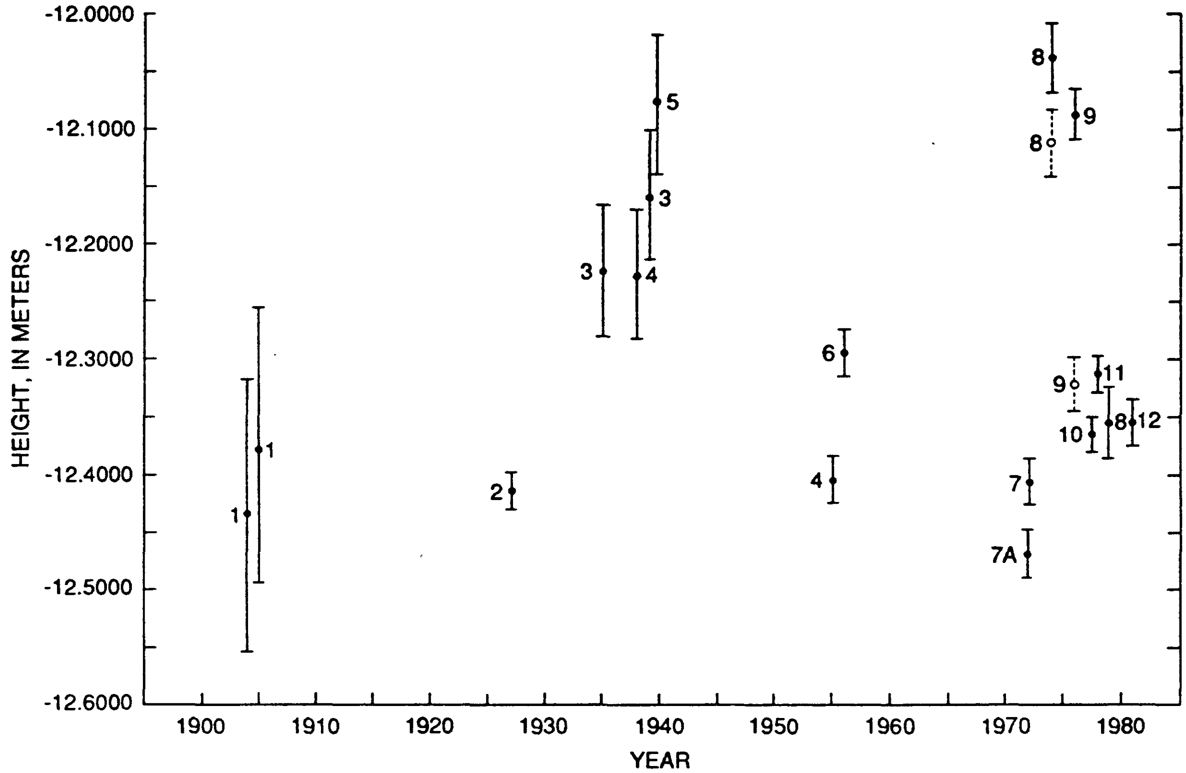

Figure 2. Sequentially determined heights for bench mark R59, El Centro, with respect to bench mark Tidal 8, San Pedro. The numbers adjacent to each height identify separately traversed leveling routes into R59. Height 7A is an alternative height based on a presumption of stability at Palo Verde (fig. 1) during the period 1933-1971/72. Heights "corrected" for magnetic-deflection error shown by dashed error bars. Orthometric corrections based on observed or interpolated gravity. Error bars show conventionally estimated random error only. Modified from Gilmore (1986).

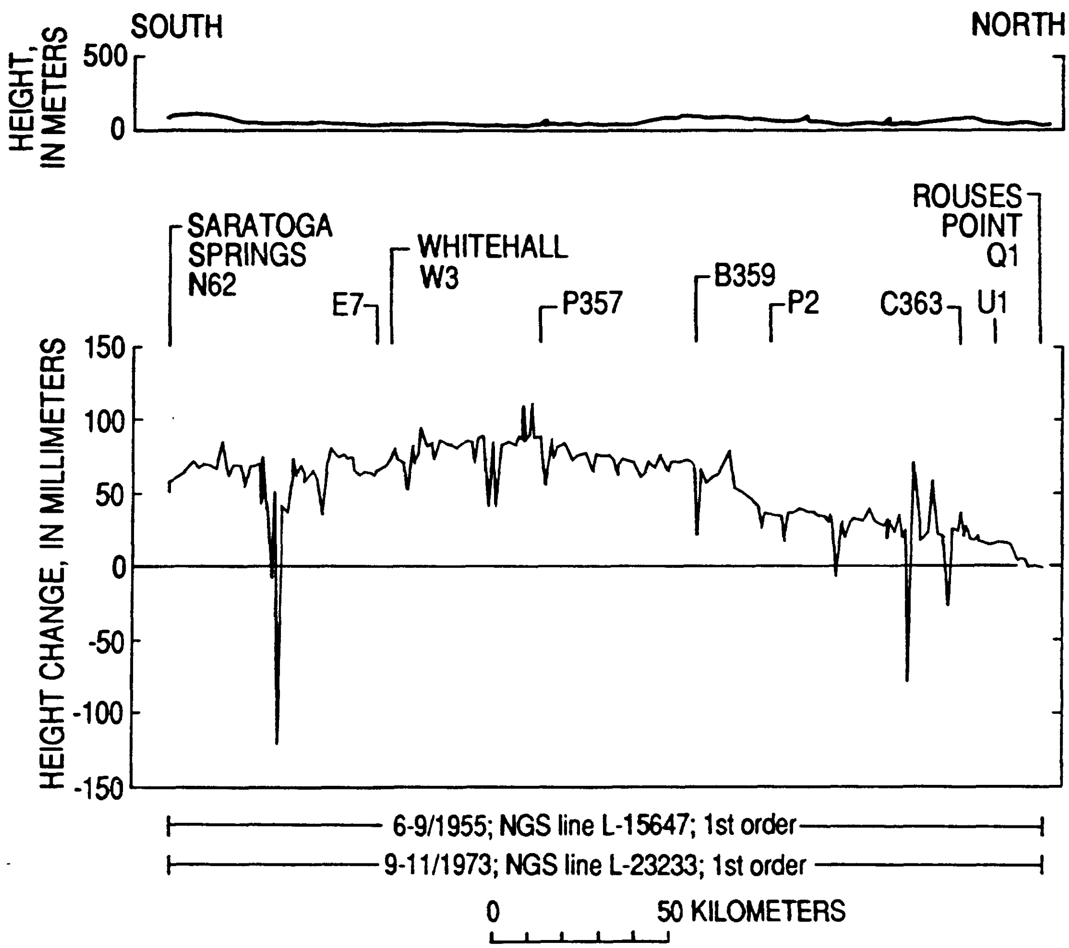

Figure 3. Height changes between Saratoga Springs and Rouses Point, New York, with respect to bench mark Q1 during the period 1955-1973.

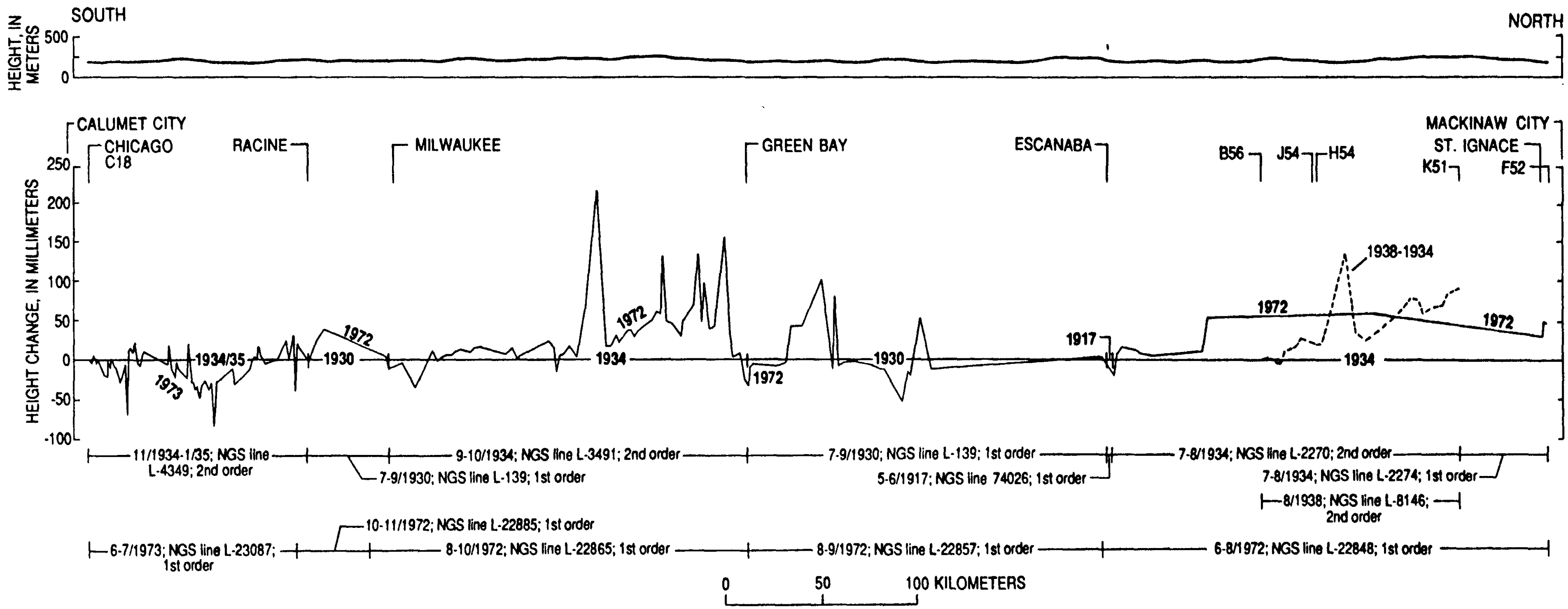

Figure 4. Height changes between Chicago, Illinois, and St. Ignace, Michigan, with respect to bench mark C18, Chicago. Based on the results of 1972/73 levelings against a composite datum developed largely from leveling completed during the period 1930-1934.

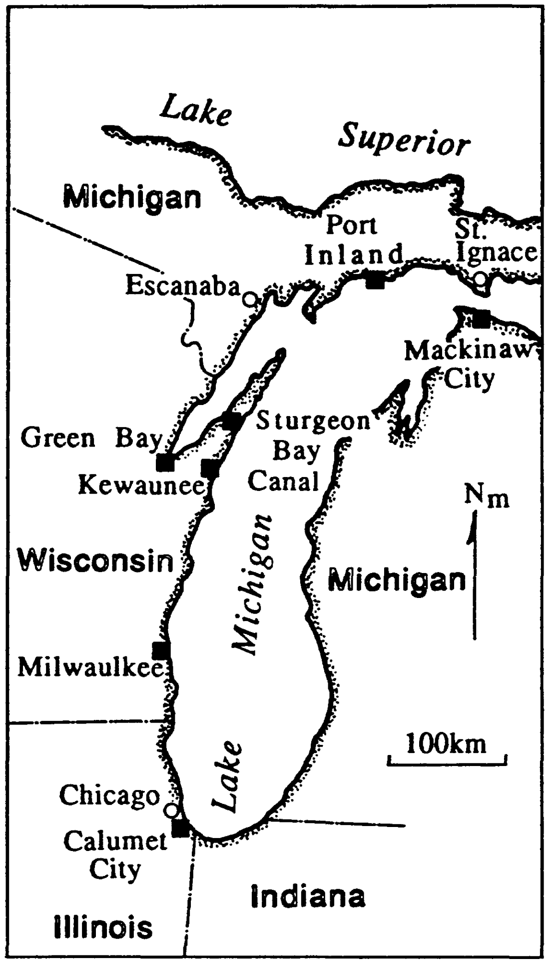

Figure 5. Index map showing primary water-level stations (blackened squares) located chiefly along the west side of Lake Michigan.

Table 1. Correction factors for those Ni 1 instruments for which two or more corrections have been computed.[1,2]

Instrument number	Correction interval	Correction factor (mm/km/gauss)	Standard deviation (mm/km/gauss
78300	1972.00-1975.70	-3.28	0.75
78300	1975.70-1978.59	-10.18	2.08
78300	1978.59-1980.00	-3.64	2.61
90760	1973.67-1975.73	-6.40	1.11
90760	1975.73-1979.24	-5.29	1.56
90760	1979.24-1980.00	-4.76	2.45
90823	1972.00-1974.46	1.28	1.14
90823	1974.46-1975.42	-5.24	1.85
90823	1975.42-1980.00	-4.10	1.85
90825	1972.00-1974.46	-2.13	1.12
90825	1974.46-1975.91	-5.83	1.39
90825	1975.91-1978.27	-4.68	1.81
90825	1978.27-1980.00	-8.48	2.13
90829	1972.67-1978.27	-3.93	0.76
90829	1978.27-1980.00	-5.57	1.31
90834	1972.67-1975.07	0.16	1.37
90834	1975.07-1979.05	-1.96	1.29
90834	1979.05-1980.00	-6.86	1.37
90856	1974.00-1975.04	-4.36	1.75
90856	1975.04-1978.78	-9.87	0.91

1 Modified from Holdahl and others (1987, p. 29, 32).

2 Dotted lines show times when new compensators were installed; new compensators effectively equate with new instruments.

Table 2. Distribution of Ni 1 instruments in 1973/74/75 San Francisco-San Pedro and 1973/74 Amboy-El Centro surveys.

Survey	National Geodetic Survey line number	Inclusive dates of leveling	Instrument number(s)
San Francisco-San Pedro	L-23297	June 1974	231-78300; 231-90834; 231-90856
	L-23596	November-December 1974	231-78300; 231-90834; 231-90856
	L-23611	January-March 1974	231-78298
	L-23644	January-February 1974	231-78298
	L-23760	January-May 1975	231-90829; 231-90856
	L-23763	January-March 1975	231-78300; 231-90829
	L-23781	March-April 1975	231-78300; 231-90829; 231-90856
	L-23784	April-May 1975	231-78300; 231-90879; 231-90856; 231-107367
Amboy-El Centro	L-23243	December 1973-February 1974	231-90829
	L-23215	March-May 1974	231-78300; 231-90834; 231-90856

Table 3. Distribution of Ni 1 instruments in 1973 Rouses Point-Saratoga Springs (New York) and 1972/73 Chicago-Mackinaw City (St. Ignace) surveys.

Survey	National Geodetic Survey line number	Inclusive dates of leveling	Instrument number(s)
Rouses Point-Saratoga Springs	L-23233	September-November 1973	231-90760; 231-90823; 231-90825;
Chicago-Mackinaw City (St. Ignace)	L-23087	June-July 1973	231-90823; 231-90825
	L-22885	October-November 1972	231-90823; 231-90825
	L-22865	August-October 1972	231-78300; 231-90823; 231-90825
	L-22857	August-September 1972	231-78300; 231-90825
	L-22848	June-August 1972	231-78300; 231-90825

Table 4. Height changes at bench mark W3, Whitehall (New York), with respect to bench marks Q1 and U1, Rouses Point (New York) obtained from three consecutive first-order levelings.[1,2]

Survey date	National Geodetic Survey line number	Observed elevation[3] difference (m)	Height change with respect to 1916 value (m)
		With respect to Q1	
1916	74007	+5.8038	–
1955	L-15647	+5.7563	-0.0475
1973	L-23233	+5.8285	+0.0247
		With respect to U1	
1916	74007	-5.7822	–
1955	L-15647	-5.8140	-0.0318
1973	L-23233	-5.7568	+0.0254

[1] Q1 and W3 are northernmost and southernmost marks, respectively, common to the indicated levelings.

[2] See figure 3 for locations of indicated bench marks.

[3] Traditionally corrected values devoid of either refraction corrections or magnetic corrections.

Table 5. Differenced water-level trends between gauge stations along west side of Lake Michigan with respect to indicated stations.[1]

Table Interval	Station	Trend (mm/yr)	Standard Deviation (mm/yr)	R^2	t-statistic
1956-1985[2]					
	(Referred to Calumet City[3])				
	Milwaukee[4]	0.34	0.22	0.08	1.52
	Green Bay	0.31	1.32	0.00	0.24
	Sturgeon Bay Canal[5]	-0.57	0.27	0.14	2.11
	Mackinaw City	-2.47	0.33	0.67	7.55
	(Referred to Milwaukee[4])				
	Green Bay	-0.03	1.28	0.00	0.02
	Sturgeon Bay Canal[5]	-0.91	0.27	0.30	3.43
	Mackinaw City	-2.81	0.27	0.79	10.34
	(Referred to Green Bay)				
	Sturgeon Bay Canal[5]	-0.88	1.31	0.02	0.67
	Mackinaw City	-2.78	1.27	0.15	2.19
	(Referred to Sturgeon Bay Canal)				
	Mackinaw City	-1.90	0.26	0.66	7.42
1956-1969[2,6]					
	(Referred to Calumet City)				
	Milwaukee	0.50	0.74	0.37	0.68
	Green Bay	-2.57	1.13	0.30	2.26
	Sturgeon Bay Canal	-1.94	1.05	0.22	1.85
	Mackinaw City	-3.92	1.19	0.48	3.30
	(Referred to Milwaukee)				
	Green Bay	-3.07	0.59	0.69	5.19
	Sturgeon Bay Canal	-2.44	0.64	0.55	3.79
	Mackinaw City	-4.42	0.83	0.70	5.33

(Continued)

(Referred to Green Bay)				
Sturgeon Bay Canal	0.62	0.73	0.06	0.86
Mackinaw City	-1.35	0.97	0.14	1.39
(Referred to Sturgeon Bay Canal)				
Mackinaw City	-1.98	0.94	0.27	2.10
1970-1985[6,7]				
(Referred to Calumet City[3])				
Milwaukee[4]	1.81	0.41	0.58	4.43
Green Bay	2.42	4.65	0.02	0.52
Sturgeon Bay Canal[5]	-0.57	0.46	0.10	1.24
Port Inland	-1.62	0.71	0.27	2.28
Mackinaw City	-1.65	0.67	0.30	2.46
(Referred to Milwaukee[4])				
Green Bay	0.61	4.56	0.00	0.13
Sturgeon Bay Canal[5]	-2.38	0.58	0.55	4.15
Port Inland	-3.44	0.59	0.71	5.85
Mackinaw City	-3.44	0.62	0.69	5.62
(Referred to Green Bay)				
Sturgeon Bay Canal[5]	-2.99	4.67	0.03	0.64
Port Inland	-4.04	4.61	0.05	0.88
Mackinaw City	-4.08	4.52	0.06	0.90
(Referred to Sturgeon Bay Canal[5])				
Port Inland	-1.05	0.55	0.21	1.92
Mackinaw City	-1.07	0.55	0.22	1.96
(Referred to Port Inland)				
Mackinaw City	-0.03	0.33	0.00	0.09
1965-1985[7]				
(Referred to Calumet City[3])				
Milwaukee[4]	0.55	0.37	0.11	1.49
Green Bay	1.52	2.66	0.02	0.57
Sturgeon Bay Canal[5]	-0.13	0.42	0.01	0.31
Port Inland	-1.33	0.49	0.28	2.72
Mackinaw City	-1.98	0.46	0.50	4.32

(Continued)

	(Referred to Milwaukee[4])			
Green Bay	0.96	2.61	0.01	0.37
Sturgeon Bay Canal[5]	-0.68	0.51	0.09	1.33
Port Inland	-1.89	0.48	0.44	3.89
Mackinaw City	-2.53	0.44	0.64	5.81
	(Referred to Green Bay)			
Sturgeon Bay Canal[5]	-1.65	2.68	0.02	0.61
Port Inland	-2.85	2.65	0.06	1.08
Mackinaw City	-3.50	2.59	0.09	1.35
	(Referred to Sturgeon Bay Canal[5])			
Port Inland	-1.20	0.35	0.39	3.47
Mackinaw City	-1.85	0.38	0.55	4.85
	(Referred to Port Inland)			
Mackinaw City	-0.65	0.29	0.20	2.20
1974-1985				
	(Referred to Calumet City[3])			
Milwaukee	1.57	0.57	0.44	2.77
Kewaunee	2.25	1.03	0.32	2.18
Green Bay	-4.46	7.43	0.04	0.60
Sturgeon Bay Canal	-0.18	0.68	0.01	0.27
Port Inland	-1.81	1.19	0.19	1.52
Mackinaw City	-1.58	1.12	0.17	1.41
	(Referred to Milwaukee)			
Kewaunee	0.68	1.00	0.04	0.68
Green Bay	-6.02	7.39	0.06	0.82
Sturgeon Bay Canal	-1.75	0.50	0.55	3.49
Port Inland	-3.38	0.94	0.56	3.58
Mackinaw City	-3.14	1.04	0.48	3.03
	(Referred to Kewaunee)			
Green Bay	-6.70	7.06	0.08	0.95
Sturgeon Bay Canal	-2.43	0.82	0.47	2.97
Port Inland	-4.06	0.98	0.63	4.13
Mackinaw City	-3.83	0.95	0.62	4.02

(Continued)

	(Referred to Green Bay)			
Sturgeon Bay Canal	4.27	7.37	0.03	0.58
Port Inland	2.64	7.31	0.01	0.36
Mackinaw City	2.87	7.15	0.02	0.40
	(Referred to Sturgeon Bay Canal)			
Port Inland	-1.63	0.72	0.41	2.63
Mackinaw City	-1.40	0.68	0.30	2.06
	(Referrd to Port Inland)			
Mackinaw City	0.24	0.56	0.02	0.42
1956-1979[2,8,9]				
	(Referred to Calumet City[3])			
Milwaukee[4]	-0.10	0.31	0.01	0.34
Green Bay	1.52	2.05	0.02	0.74
Sturgeon Bay Canal[5]	0.74	0.40	0.14	1.86
Mackinaw City	-2.82	0.45	0.64	6.26
	(Referred to Milwaukee[4])			
Green Bay	1.62	1.95	0.03	0.83
Sturgeon Bay Canal[5]	-0.63	0.40	0.10	1.59
Mackinaw City	-2.72	0.38	0.70	7.17
	(Referred to Green Bay)			
Sturgeon Bay Canal[5]	-2.25	2.02	0.05	1.12
Mackinaw City	-4.34	1.93	0.19	2.25
	(Referred to Sturgeon Bay Canal[5])			
Mackinaw City	-2.09	0.38	0.58	5.47
1980-1985				
	(Referred to Calumet City)			
Milwaukee	3.40	1.90	0.44	1.79
Kewaunee	3.05	2.23	0.32	1.37
Green Bay	1.13	1.75	0.10	0.65
Sturgeon Bay Canal	2.53	2.09	0.27	1.21
Port Inland	2.79	3.62	0.13	0.77
Mackinaw City	3.22	3.28	0.19	0.98

(Continued)

(Referred to Milwaukee)				
Kewaunee	-0.35	1.25	0.02	0.28
Green Bay	-2.28	0.70	0.72	3.24
Sturgeon Bay Canal	-0.87	1.80	0.06	0.48
Port Inland	-0.61	3.31	0.01	0.18
Mackinaw City	-0.17	3.48	0.00	0.05
(Referred to Kewaunee)				
Green Bay	-1.92	0.77	0.61	2.50
Sturgeon Bay Canal	-0.52	0.85	0.09	0.62
Port Inland	-0.26	2.16	0.00	0.12
Mackinaw City	0.17	2.39	0.00	0.07
(Referred to Green Bay)				
Sturgeon Bay Canal	1.39	1.35	0.21	1.03
Port Inland	1.66	2.72	0.09	0.61
Mackinaw City	2.09	2.85	0.12	0.73
(Referred to Sturgeon Bay Canal)				
Port Inland	0.26	1.97	0.00	0.13
Mackinaw City	0.70	1.94	0.03	0.36
(Referred to Port Inland)				
Mackinaw City	0.44	0.92	0.05	0.47

[1] Data from National Ocean Survey (1986).
[2] Two of the seven stations considered here (Kewaunee and Port Inland) did not operate during the full period 1956-1985.
[3] August and September 1973 and September 1977 means missing.
[4] August 1971 mean missing.
[5] September 1973 mean missing.
[6] 1956-1985 interval broken into two periods owing to relocation of Milwaukee station in 1970.
[7] One of the seven stations considered here (Kewaunee) did not operate during the full periods 1956-1985, 1956-1985, or 1970-1985.
[8] 1956-1985 interval broken into two periods owing to relocation of Green Bay station in 1980.
[9] Two of the seven stations considered here (Kewaunee and Port Inland) did not operate during the full period 1956-1979).

Table 6. Closures on lake level with respect to that at Calumet City developed from 1972/73 Ni 1 surveys along the length of Lake Michigan. [1,2,3]

Station	Closure	
	Based on observed elevation difference (m)	Based on geopotential difference (kGal m)
Milwaukee	-0.0275 ± 0.0161	-0.0275 ± 0.0161
Kewaunee	+0.0034 ± 0.0207[4]	+0.0026 ± 0.0207[4]
Sturgeon Bay Canal	+0.0088 ± 0.0217	+0.0054 ± 0.0217
Green Bay	-0.0104 ± 0.0219	-0.0158 ± 0.0219
Port Inland	-0.0544 ± 0.0288	-0.0582 ± 0.0288
Mackinaw City	-0.0528 ± 0.0303	-0.0575 ± 0.0303

[1] All but one of the lake-level pairs based on nine-year means centering on 1972.

[2] See Table 3 for National Geodetic Survey line numbers and instrument numbers.

[3] Error estimates based on the square root of the sum of the squares of: (1) the standard deviation in the meaned annual lake-level differences with respect to Calumet City; and (2) the estimated random error for first-order leveling of this vintage which is taken as $\alpha L^{1/2}$, where $\alpha = 1\ \text{mm}/L^{1/2}$ and L is the line length in kilometers.

[4] Based on nine-year means centering on 1978; Kewaunee did not operate as a primary station until 1974.

Table 7.
(A) Ni 1 instruments free of measurably significant magnetic error through indicated periods.

Instrument	Period devoid of magnetic contamination
231-90823	1972.0-1972.9
231-20825	1972.0-1972.6
231-78298	1972.0-1974.3
231-90834	1972.0-1974.9
231-78300	1972.0-1975.3
231-90829	1972.0-1975.3
231-90856	1972.0-1975.3
231-107367	1972.0-1975.3

(B) Ni 1 instruments probably free of measurably significant magnetic error through indicated periods.[1]

Instrument	Period devoid of magnetic contamination
231-90823	1972.0-1973.9
231-90825	1972.0-1973.9
231-90760	1972.0-1973.9

[1] Based on Saratoga Springs-Rouses Point analysis.