HEIGHT CHANGES ALONG SELECTED LINES THROUGH THE DEATH VALLEY REGION, CALIFORNIA AND NEVADA, 1905-1984

_By_ Robert O. Castle[1], Thomas D. Gilmore[1], James P. Walker[1], _and_ Susan A. Castle[2]

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U.S. GEOLOGICAL SURVEY
U.S. DEPARTMENT OF THE INTERIOR

[1] U. S. Geological Survey, Menlo Park, CA 94025
[2] 456 W. 12th Street, Claremont, CA 91711

ABSTRACT

Comparisons among repeated levelings along selected lines through the Death Valley region of California and adjacent parts of Nevada have disclosed surprisingly large vertical displacements. The vertical control data in this lightly populated area is sparse; moreover, as much as a third of the recovered data is so thoroughly contaminated by systematic error and survey blunders that no attempt was made to correct these data and they were simply discarded. In spite of these limitations, generally episodic, commonly large vertical displacements are disclosed along a number of lines. Displacements in excess of 0.4 m, with respect to our selected control point at Beatty, Nevada, and differential displacements of about 0.7 m apparently occurred during the earlier years of the 20th century and continued episodically through at least 1943. While this area contains abundant evidence of continuing tectonic activity through latest Quaternary time, it is virtually devoid of historic seismicity. We have detected no clear connection between the described vertical displacements and fault zones reportedly active during Holocene time, although we sense some association with several more broadly defined tectonic features.

INTRODUCTION

Almost casual geologic reconnaissance through the area within and around Death Valley suggests that this region has been characterized by major tectonic activity through latest Quaternary time. This view is supported by a number of independent investigations, several of which we cite here (Noble and Wright, 1954; Denny,1965; Hill and Troxell, 1966; Hunt and Maybe,1966; Hooke, 1972; Bull and McFadden, 1977; Butler and others, 1988; Brogan and others, 1991;Wright and others, 1991; Jennings, 1994; Peterson and others, 1995; Knott and others,1997; Knott and others ,1999; Morison, 1999; Frankel and others, 2001; Machette and Crone, 2001). While only a handful of these studies argue, if only implicitly, for continuing activity into historic time, the gross physiography in itself supports this notion. For example, the 3.5-km height difference between Badwater and Telescope Peak, about 26 km apart (fig. 1), is clearly consistent with a high relief index characteristic of youthful terrains. Similarly, well developed Holocene (?) fault scarps characterized by offsets of the order of 2-3 m constitute equally significant evidence of continuing tectonic activity in the Death Valley region.

Even though the Death Valley region has sustained major tectonic deformation during Neogene and Quaternary time, it was not until relatively recently that this position became generally accepted. One of the reasons that this likelihood received so little attention may lie in one of the many geologic conundrums identified with this area. Specifically, while it is especially difficult to dismiss the likelihood that we are dealing with one of the most tectonically active areas in California, this region is at the same time associated with trivial historic seismicity westward nearly to the Sierras (Goter and others, 1994; Toppozada and others, 2000).

In this report we attempt to test the geologic presumption that Quaternary deformation in and around Death Valley has persisted into historic time through examination and

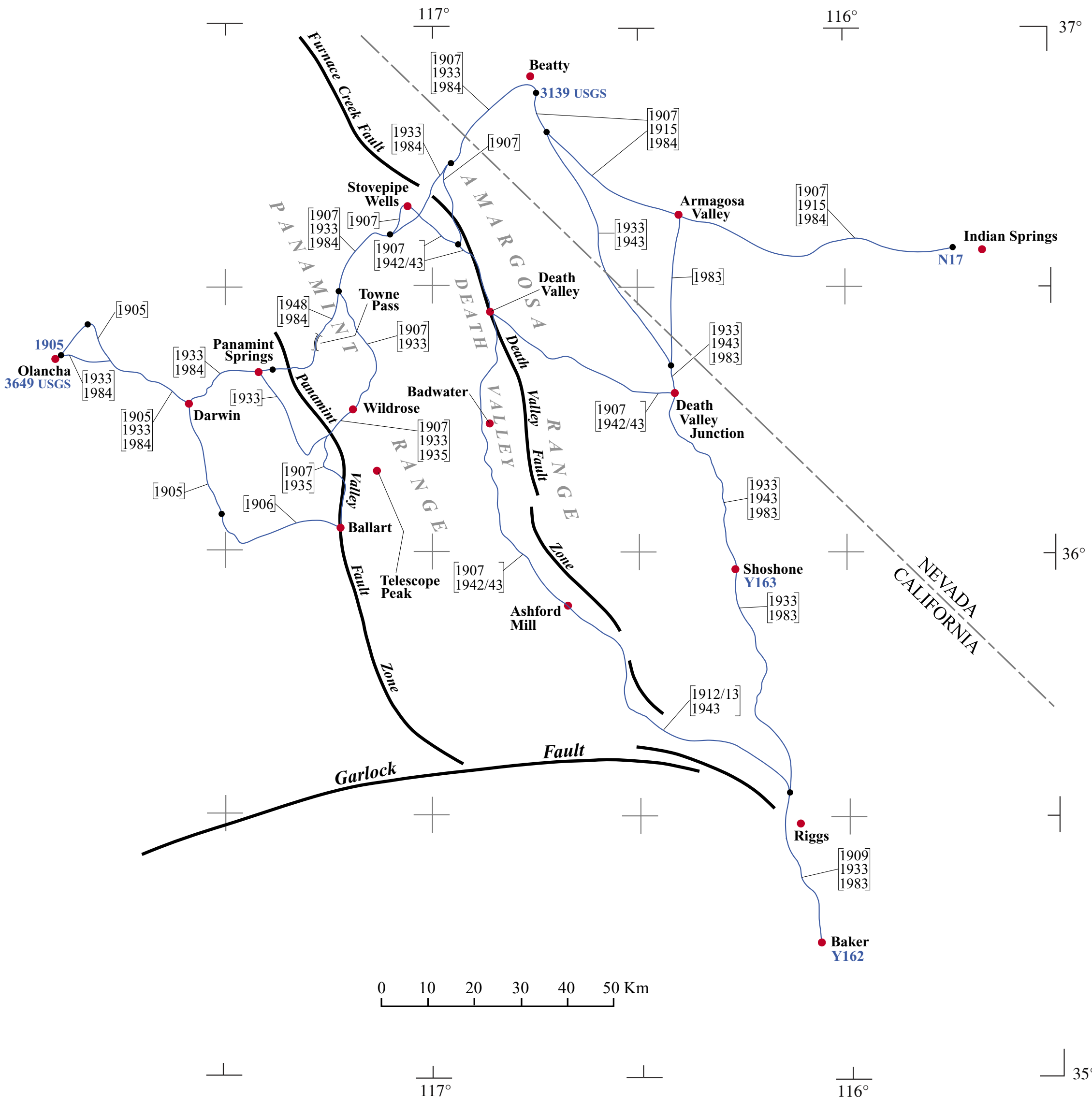

Figure 1. Index map of the greater Death Valley region, California and Nevada, showing approximate routes and dates of compared levelings, major physiographic features, and major faults and fault zones. Junction marks indicated by black dots; locally coincident with red dots showing towns or other geographic features.

analysis of the very limited terrestrial geodetic record. Moreover, our initial examination of the data identified a number of early surveys so highly contaminated by systematic error or simple blunders that they did not lend themselves to credible correction and were discarded for

purposes of this study. Finally, all, or nearly all, of the early Geological Survey field books, from which the early summary books were compiled, were destroyed by fire. Thus the source of and our ability to correct for several of these recognized errors was effectively foreclosed. In spite of these restrictions, the retained survey data included with the summary books revealed a number of surprising results in which we have a fairly high degree of confidence. Had we discarded all of the early baseline data it would have produced a sharply diminished argument for bringing this report to completion.

VERTICAL CONTROL DATA

The height changes reported here are based on the results of comparisons between successive geodetic levelings ranging upward from third- to first-order, including several “classes” associated with second- and first-order work. While the higher-order surveys are generally characterized by greater precision, they are not necessarily more accurate in the sense that they more perfectly conform to some stipulated measurement standard. For example, while the precision of most third-order work could not be expected to match that of double-run first-order or second-order leveling, because the maximum permitted sight length has never fallen below 92 m for third-order single-run Geological Survey leveling, whereas until 1961 the same requirement for first-order leveling was, set at 150 m. In other words, in considering a sample size as small as the one on which this study is based, the accuracy of each survey should be independently assessed.

Procedures intended to control the accuracy of the several orders and classes of geodetic leveling can be found in the publications of Hayford (1904), Gannett and Baldwin (1908), Bowie and Avers (1914), Rappleye (1948), and the Federal Geodetic Control Committee (1980). A detailed examination of the procedures intended to limit both systematic and random error, as well as blunders (or “busts”) in elevation measurements, is considered in Professional Paper 1362 (Castle and others, 1987, p. 4-14), a discussion that focuses on the earlier level surveys of both the Geological Survey and the Coast and Geodetic Survey. This summary, while it is thought to be especially useful in the context of the present investigation, need not be reiterated here.

Ultimate control on the accuracy of any leveling is dependent in large measure on the rejection criteria stipulated for various orders and classes of surveys. The accuracy of the third-order leveling of the Geological Survey was controlled by a circuit-rejection criterion of 0.05 ft$\sqrt{}$distance in miles [12 mm(km)$^{1/2}$], a restriction that remained unchanged from the beginning of the 20th century until at least 1980 (Wilson, 1898, p. 345; Federal Geodetic Control Committee, 1980, p. 28). Because third-order leveling was rarely double run, there was never a formally defined section-rejection limit for third-order work. Where double run, the earlier second-order leveling of the Geological Survey was controlled by a section-rejection criterion of either 7.2 mm(km)$^{1/2}$ or 8.0 mm(km)$^{1/2}$ (Gannett and Baldwin, 1908, p.6, 9), although it was subsequently relaxed to 8.4 mm(km)$^{1/2}$, a figure that matched that adopted by the Coast and Geodetic Survey (Rappleye, 1948, p. 8). No circuit-rejection criterion is known to have existed for the double-run leveling of the Geological Survey. Through at least 1948, the circuit rejection criterion for single run second-order leveling of the Coast and Geodetic Survey matched the section-rejection limit for double-run work of 8.4 mm(km)$^{1/2}$ (Rappleye, 1948. p. 8). Because no post-1948 second-order work of either the Geological Survey or Coast and Geodetic Survey has been included with this study, we need explore this issue no further here. Through a period ending around 1980, all of the first-order work of the Coast and Geodetic Survey (or its successor, the National Geodetic Survey) was double run to a section-rejection criterion at least as restrictive as 4 mm(km)$^{1/2}$ (Hayford, 1904, p. 213; Rappleye, 1948, p. 8). During this same period, the circuit-rejection criterion for all class

II first-order work was at least as restrictive as 5.00 mm(km)$^{1/2}$ (Federal Geodetic Control Committee, 1980, p. 68). With the adoption of both double-scale rods and double-simultaneous leveling procedures, about or shortly after 1980, single run leveling was accepted as the equivalent of class II first-order work; it was, nonetheless, still governed by a circuit–rejection criterion of 5.00 mm(km)$^{1/2}$ (Federal Geodetic Control Committee, 1980,p. 24, 28, 31-32). Justification for including single-run leveling that meets several specifically defined procedural controls with first-order work (originally identified as class III first-order leveling) can be found in the report of Whalen and Balazs (1976). All of the post-1980 first-order leveling data incorporated in this report were based on single-run leveling.

ERRORS IN HEIGHT DETERMINATIONS

Geodetic leveling, of whatever order and class, is thought to be an inherently accurate measurement system; it is compromised chiefly by the fact that it is time consumptive. That is, should any surface movements occur along the course of a given survey, whether at a junction point or elsewhere, it could lead to distorted elevation differences between the starting bench mark and marks elsewhere along the line (see, for example, Castle and others, 1987, p. 12-13). The longer the elapsed time between the initiation and completion of any leveling, the greater the likelihood of errors attributable to continuing crustal deformation.

Since we are interested here in height changes rather than heights as such, the gravity-dependent orthometric correction required to convert observed elevation differences into true height differences (see, for example, Vanicek and others, 1980) is not generally a point of concern. That is, because this correction is path dependent, and because we can disregard such changes as may have occurred in geoidal relief over periods of several decades or more, we can safely assume that direct comparisons between successively determined elevation differences over the same route will almost precisely match comparisons between the corresponding height differences. Because our comparisons, with only one significant exception, are based on successive surveys over the same route, errors associated with imprecisely defined orthometric corrections do not seriously impact reported characterizations of height changes dealt with in this region.

The most commonly invoked criticism of geodetic leveling centers on elevation (rod)- or refraction (slope)-dependent systematic error (Jackson and others, 1980; Strange, 1981; Stein and others, 1986). Because our baseline data consist largely of the results of early 20th-century third-order leveling based on wooden rods, the focus of any serious challenge to the reconstructions developed in this report is most apt to be on rod error.

The first line of defense against wooden-rod error consists of both frequent laboratory and field calibrations of rod excess (nominal minus measured length) on which any rod corrections must be based. Because the generally paraffin-coated wooden rods were subject to humidity- as well as temperature-dependent length changes, regular tape-based field calibrations were especially important. Calibrations at least as far back as 1897 were always read to values at least as accurate as ± 0.1 mm and changes between successive laboratory calibrations were generally much less than 1 x 10^{-4} m/m. Thus, even in the absence of regular calibrations, worst-case errors of as much as 100 mm over a height difference of 1000 m might occur. However, with regular calibrations, rod error in wooden rods probably held to 3-4 x 10^{-5} m/m or even less

With the adoption of invar rods about 1916, the rod excess was based exclusively on successive laboratory calibrations. Although the pre-1965 calibrations of invar rods were read to the nearest 0.01 mm, they were generally reported to the nearest 0.1 mm. However, it was not until 1975 that the rod excess was based on a least squares regression of all of the calibrated points along the full length of the graduated section of the rod, rather than simply a nominal minus measured cumulative length divided by 3. Nonetheless, Mark and others (1981, p. 2787-2790) showed that the traditional computation of rod excess was generally sound, such that it differed from the least-squares computation by a mean value of about 0.0093 mm/m with a standard deviation of 0.018mm/m. Moreover, the cumulative evidence developed by Mark and others (1981) argues that residual rod error attributable to inadequate calibration measurements was generally of the order of 2-3 x 10^{-5} m/m.

Several attempts have been made to hindcast rod error by comparing the results of successive levelings against the corresponding height differences between marks (Jackson and others, 1980; Stein, 1981; and Craymer and others, 1995). These attempts were necessarily limited by the inability to categorically discriminate between signals attributable in whole or in part to rod error and those attributable to actual height changes between marks. Moreover, one could not legitimately simply cast aside still other evidence, such as that obtained through calibration measurements. The hindcast corrections of Jackson and others (1980) were so seriously flawed that they were categorically dismissed by Mark and others (1981), a conclusion that, to the best of our knowledge, has never been challenged. Stein (1981) developed a slope-dependent hindcast procedure that suggests that rod errors of the order of 0.3 ± 2.3 x 10^{-5} m/m were the norm, although he identified several exceptions to this generalization. Craymer and others (1995) produced the most rigorous hindcast analysis, which proceeded from a refinement of Stein's (1981) technique. Nonetheless, the results of the Craymer and others (1995) study demonstrate that a number of stringent conditions must be met in defending any statistically based arguments, not the least of which is a clear demonstration that "independent checks indicate that caution should be exercised before accepting these results as evidence of scale error." Hence the calibration data remain as the most reliable control on rod error.

The slope-dependent unequal-refraction error is a theoretically expectable error that argues that in any given setup the atmospheric refractive deviation error is greater in the upslope reading, thereby producing a differential error that diminishes the error-free elevation difference in the compared rod readings (see, for example, Castle and others, 1994). While several experiments seem to support the accumulation of such errors, none of these experiments met the procedural requirements identified with geodetic leveling of whatever specified order, nor did they consider the observer's experience in ensuring that refraction error, whether viewed upslope or down, be minimized. That these two considerations have suppressed any accumulation of the path-dependent accumulation of the unequal-refraction error to values that no more than compete with random error has been demonstrated by Mark and others (1987) through an analysis of field data drawn from around the world. Pertinent to the problem at hand, the unequal-refraction error is proportional to the square of the sight length and inversely proportional to slope. That is, the longer the sight lengths, the greater the error; the shallower the slope below some unspecified limit, the less the error--disappearing with zero slope. Because steep slopes limit sight lengths and very shallow slopes diminish the error to insignificant values, this error tends to reach maximum values with modest slopes falling within the 1-2 percent range. Because, with at least one exception, slopes that fit this limitation are relatively uncommon in the Death Valley region, we can, for these and the earlier cited arguments of both Mark and others (1987) and Castle and others (1994), legitimately disregard the unequal-refraction error as a significant contaminant in our data.

Yet another source of systematic error is attributable to a proclivity towards a directionally dependent staff- or instrument-dependent settlement error (see, for example, Hayford, 1904, p. 215). Because it is directionally dependent, it is generally contained, if not eliminated, by double running or deliberately and regularly reversing the direction of running.. However, even with turn-of the-20th century single-run leveling the rods were supported by steel plates about 0.15 m in diameter, thereby distributing the load in such a way as to minimize settlement. Moreover, even with a degree of randomness introduced into the direction of running and a naturally well compacted ground surface (of whatever nature), this error is further minimized. While certainly a plausible contaminant in the Death Valley region, staff or instrument settlement is much more likely to impact broadly defined regional networks. Thus even though settlement errors summing to a few millimeters, or perhaps a centimeter or two, may be distributed along one or of the described lines, they are certainly much less troublesome than residual rod error.

Random error (noise), which impacts all of our measurements in varying degree, is generally described by an expression of the form $\alpha L^{1/2}$, where α is in units of mm/km$^{1/2}$ and L is the distance in kilometers from the reference mark (Table 1). Characterizations of random error are experienced based and provide a measure of expected error in any geodetic leveling, even were systematic error to be disregarded. Random error is a function of both the order of leveling and period during which it took place. Thus it may be thought of as procedurally based, since the various orders of leveling generally have been associated with procedural changes through time (Table 1). Experienced-dictated random error estimates are insensitive predictive tools in considering any given level survey. One might assume, for example, that the random error associated with 200 km of third-order leveling is necessarily of much greater magnitude than that associated with 200 km of first-order leveling over the same line. This need not be the case, however, especially when it is recalled that the random nature of this error affords no evidence of the sense of the error as it accumulated. Thus, if other evidence is available, such as circuit closures, it should certainly be used in attempting to more accurately gauge the magnitude of any cumulative random error.

Table 1. Random error estimates (α) for levelings of various orders and epochs (adapted from Vanicek and others, 1980, p.507-508).

Order	Period	α (mm/km$^{1/2}$)
1st order	before 1917	2.0
	1917-1955	1.5
	1956 and later	1.0
2nd order	1917-1955	3.0
	1956 and later	2.0
3rd order	before 1956	6.0
	1956 and later	4.0

R (random error over a distance L in km) = $\alpha L^{1/2}$

Blunders or "busts" in any survey are gross errors generally attributable to misreadings of the rod or transcription errors. Busts are extremely uncommon in double-run or double-scale rod double simultaneous leveling; they are much more common in single-run third-order work, but they are by no means uncommon in single-run second-order leveling as well. Busts are usually detected through recognition of unacceptably large misclosures, abrupt offsets between adjacent marks disclosed through comparisons against subsequent surveys along the same line, or relatively large and balanced circuit closures that share a common leg or segment. Because single-run third-order work is thought to be much more susceptible to busts, several instrumental design features have been incorporated in third-order equipment that have clearly minimized reading errors. For example, the widely used yard rods dating from the early 20th century were color coded by yard on one side of the rod and were read in feet on the opposite side of the rod. In spite of these and other ingenious design features, gross errors in both readings and recordings are not precluded.

We have identified four busts in the work retained for use in this investigation, all of which have been resolved with varying degrees of confidence. Because one can rarely "prove" the efficacy of the hindcast nature and magnitude of any bust correction, we have chosen to present our results both with and without the removal of the identified busts. However, at least one of the busts, the easternmost shown in figure 2, can be disregarded since no comparisons are made against the linewhich includes this error. Parenthetically, the magnitude of the closure around the relatively large circuit that is achieved through summing of the balanced loops that isolates this bust argues that the leveling that excludes the isolated segment is of clearly acceptable accuracy.

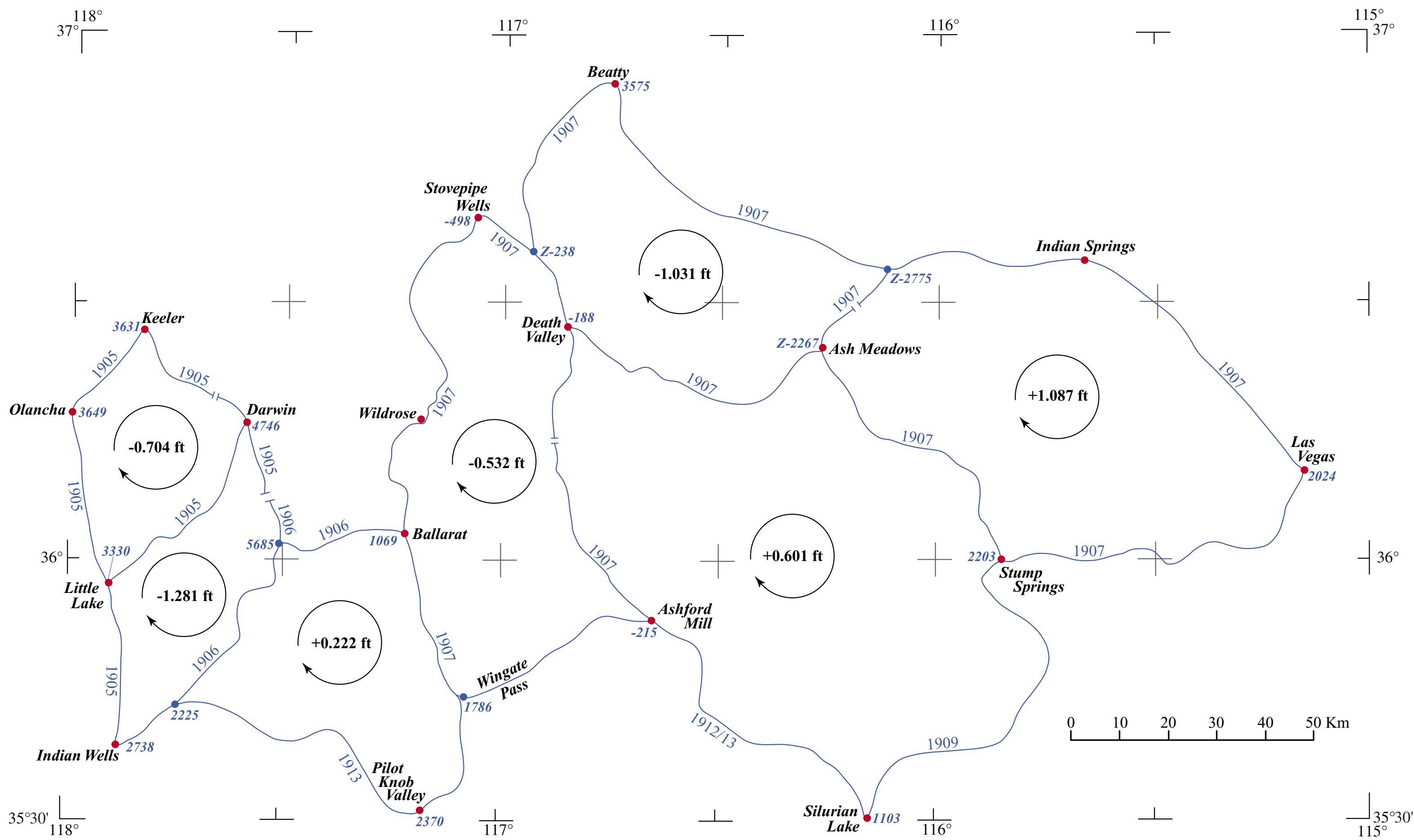

Figure 2. Misclosures around selected circuits in the Death Valley Region developed from the results of largely third order (single-run) rod-corrected leveling of the Geological Survey during the period 1905-1913. The line shown between Indian Wells and Keeler, along the western edge of the figure, is the only higher order (second-order, double-run) survey included with this figure. Because the original observations were chiefly in feet (or yards), and because our chief purpose here is the dection of, and correction for, blunders (or "busts")--shown as interruptions in the level line--based on single-run leveling, the misclosures are given in feet, rather than their metric equivalents. Data sources: U.S. Geological Survey summary books 6132, 7698, A6668, A8101, A9149, and A9151. See text for details.

REFERENCE MARK

All but one of the profiles of height changes developed in this report have been reconstructed with respect to a single reference bench mark or control point; we have selected bench mark 3139 USGS, located abut 4 km south of Beatty, as a useful, even if imperfect reference mark. This mark, which has been in place since first established in advance of the1907 leveling, has, apparently remained undisturbed since surveyed in 1907. This reference mark serves our purpose quite well, since it lies at the edge of the study area and virtually all of the profiled levelings hit this or adjacent marks, marks that show no movement which matches or exceeds expected random error measured with respect to 3139. While this mark is assumed to have remained fixed in height at 956.2778 m (the 1933 record elevation), and even though our reconstructions are based on this presumption, there is clearly defined evidence that 3139 sustained at least modest height changes during the 20th century. For example, an earlier investigation shows that while this same Beatty mark has, as here, been arbitrarily fixed in height, it is flanked on both the northwest and east by height changes of a somewhat episodic nature beginning about or shortly after the 1907 baseline leveling (Gilmore, 1992). Thus this exercise requires that we at least attempt to define any height changes of 3139 with respect to some tectonically near invariant datum point, such as one closely fixed with respect to the geoid of specified date or the reference ellipsoid. One such point is bench mark M57, tied to the San Diego tide station, a point that has probably remained very close to invariant in height during most or all of the 20th century (Castle and Vanicek, 1980).

The eight separately determined heights for bench mark 3139 (fig. 3), suggest that this mark has sustained modest episodic movement, together with at least one possible reversal, with respect to M57. This history is quite unlike that of several other marks equally distant from San Diego (22Q, Bill Williams River and O10, Hassayampa, both in Arizona) that seem to have remained very close to fixed in height over periods of more that 70 years—see figure 4 (Gilmore, 1986, figure 3). The individually determined heights for these two marks have remained so close to unchanged with respect to M57 that we can make use of their simple arithmetic means as approximate surrogates for M57 and thereby provide several alternative, independently determined heights for 3139. All of the heights produced for 3139 are based on combinations of levelings of various orders and periods associated with a range of estimated random errors (table 1). Moreover, several of these heights are based on assumptions of invariance at critical junction marks over periods of as much as 50 years and less than rigorous evaluations of systematic error, particularly rod error. Nonetheless, we are reasonably certain that none of the indicated levelings are contaminated by significant busts. Thus, with one exception, there is enough redundancy among more or less temporally equivalent heights that the history of height changes for 3139 described below is thought to represent a reasonable characterization of the nature of the tectonic activity at this mark through most of the 20th century.

The period included by the several heights for 3139 represented in figure 3, is of sufficient length as to provide a degree of confidence in the “absolute” signals referred to this mark. We view this as an important consideration, even though our primary purpose here is a description of the relative height changes that have occurred in the Death Valley region over a remarkably short segment of historic time (think Mesopotamia or the Nile Valley).

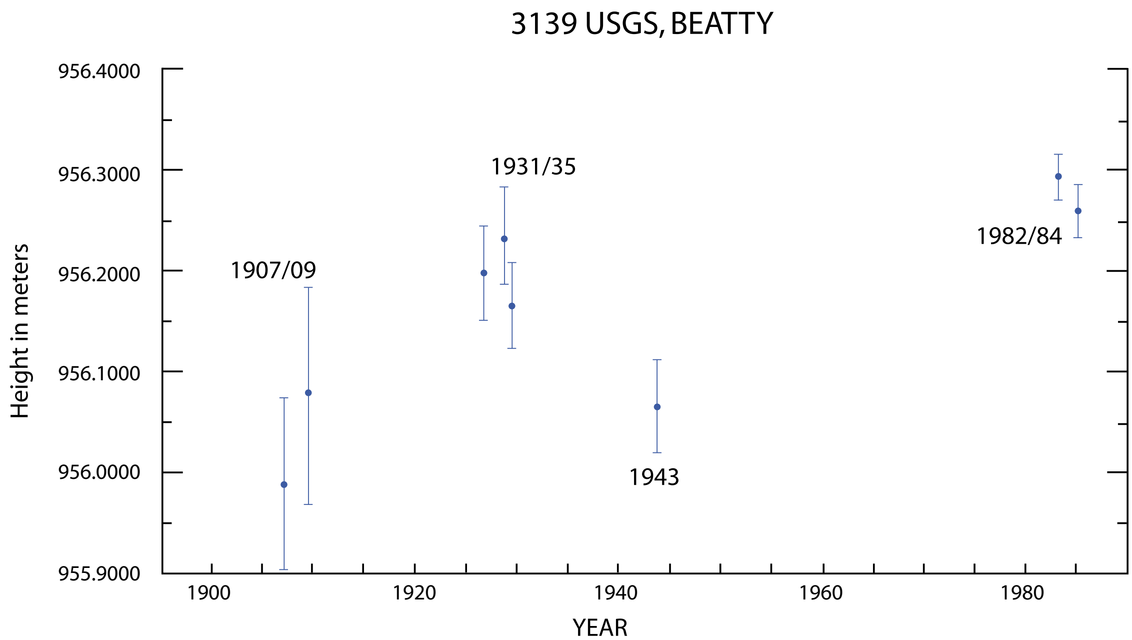

Figure 3. Successive orthometric heights for bench mark 3139 USGS, Beatty, with respect to tidal bench mark M57, San Diego, as fixed in height. The orthometric corrections are based on observed or interpolated gravity values.

The 1907 height is both the earliest and the lowest developed for bench mark 3139 USGS (fig. 3). It was obtained through 1906/07 first-order leveling between San Diego (M57) and Las Vegas, with an approximate 6-month interuption at Barstow, joined with 1907 third-order work between Las Vegas and Beatty. Had the 1907 Las Vegas-Beatty leveling been replaced by 1915 first-order leveling between these locales, it would have dropped the 1907 height by 0.0131 m. The 1909 height (fig. 3) is based on levelings propagated out of bench mark 22Q on the Bill Williams River, where the starting height (186.6954 m) is taken as the simple arithmetic mean of the several heights generated for this mark (Gilmore, 1986, Figure 3A, Table A1-A4; see also Castle and others, 1987, p. 58-59 and Castle and Gilmore, 1992, p. 1585). The indicated levelings used in producing the 1909 height include 1931 first-order work between 22Q and Yucca Junction, 1927 first-order leveling between Yucca Junction and Yucca, 1909 first-order leveling between Yucca and Goffs, 1906/07 first-order leveling between Goffs and Las Vegas, and 1907 third-order leveling between Las Vegas and Beatty. Again, were the results of the1915 leveling between Las Vegas and Beatty substituted for the 1907 work, it would have dropped the 1909 height by 0.0131 m.

There is a gap of about 20 years between the 1909 height for 3139 and the next earliest height developed for this mark (fig. 3). The 1931 height is again developed from leveling propagated out of the Bill Williams River mark (22Q) and acceptance of the simple

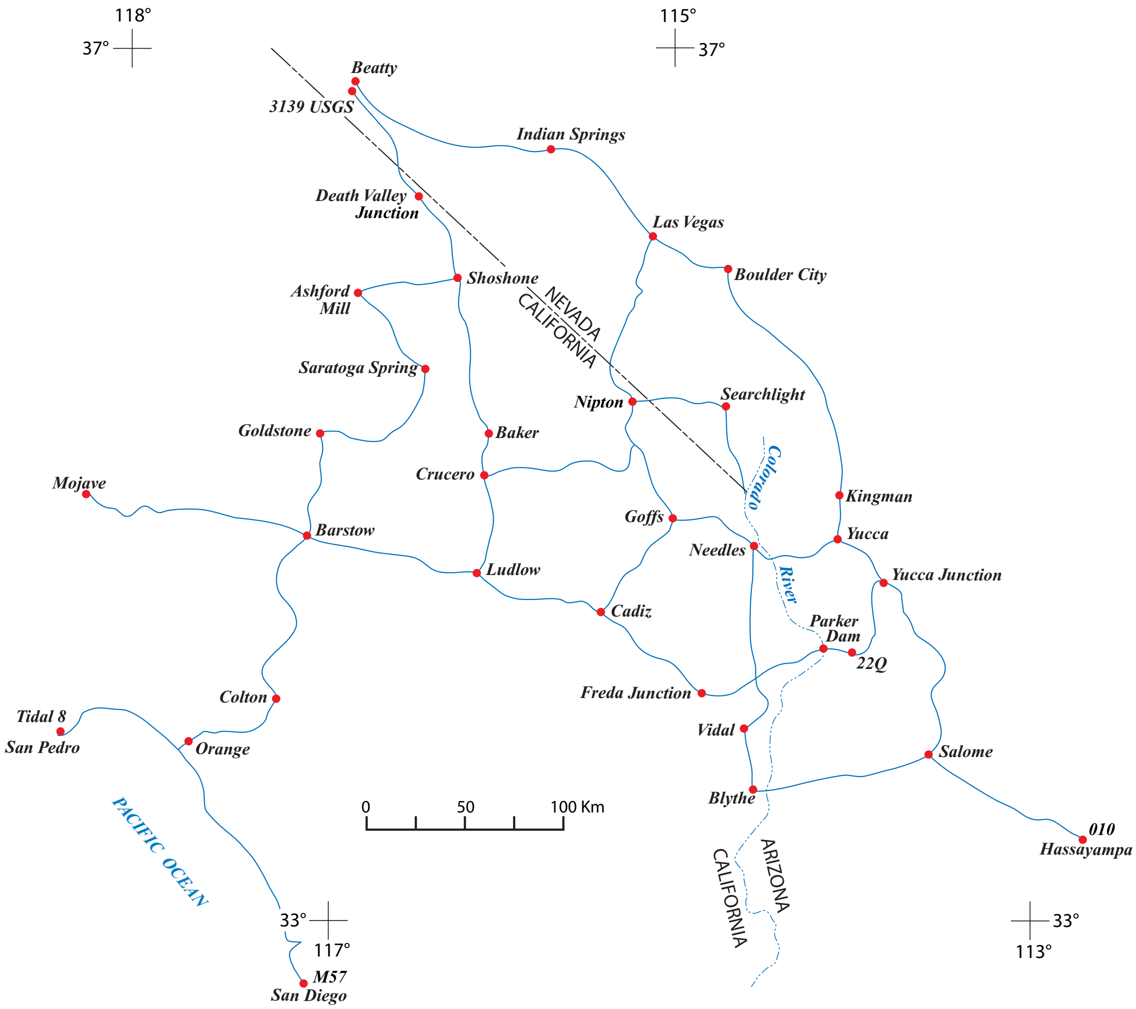

Figure 4. Sketch map showing approximate routes of levelings and junction locations used in the reconstruction of successive heights given in figure 3.

arithmetic mean for 22Q as a reasonable surrogate starting height for M57. The 1931 height is based on 1931 first-order leveling westward from 22Q to Cadiz, 1944 first-order work between Cadiz and Ludlow, coupled with an assumption of invariance over the Cadiz to Ludlow reach during the period 1931-1944, and 1933 first-order leveling northward from Ludlow via Shoshone into Beatty. The 1933 height for 3139 was again derived from our surrogate starting height at 22Q on the Bill Williams River. It was produced from 1931 first-order work between 22Q and Vidal, 1933 first-order leveling between Vidal and Needles, a 1909 tie between adjoining junction marks at Needles,1934 second-order work from Needles via Searchlight to Nipton, 1935 second-order leveling from Nipton to Crucero, and 1933 first-order leveling between Crucero and Beatty via Baker and Shoshone. The 1935 height for 3139 is based on leveling emanating out of O10, Hassayampa, where the stating height (274.5589 m) is again based on the simple arithmetic mean of the several heights for this mark (Gilmore, 1986, Figure 3B, Tables B1-B4; see also Castle and Gilmore, 1992, p. 1585). It is derivative from1927 first-order leveling extending westward from Hassaympa to Salome, 1933 first-order work from Salome to Blythe, second-order leveling between Blythe and Needles, the previously identified 1909 first-order tie between junction marks in Needles, 1934 second-order leveling from Needles via Searchlight to Nipton, second-order work from Nipton to Crucero, and the 1933 first-order line from Crucero to Beatty via Baker and Shoshone.

The 1943 height for 3139 (fig. 3) is based on a previously determined 1935 height for bench mark E43, Barstow (Mark and others, 1987, p. 2785), with respect to bench mark Tidal 8 at the San Pedro tide station, reconstructed with respect to M57. The reconstruction requires: (1) that we calculate the 1935 height for Tidal 8, San Pedro with respect to M57, San Diego, by means of a previously established geodetic tie between these two marks; and (2) that we subtract about 3 mm from the this geodetically determined height difference owing to continuing uplift of San Pedro with respect to the San Diego Municipal Pier tide station. Differencing the record height for Tidal 8 against this newly generated height for Tidal 8 permits the construction of a starting height for E43 with respect to M57, as opposed to Tidal 8 on which the initial value for E43 was based. The 1943 height for the junction mark at Beatty (B86) is thus based on this reconstructed height for E43, coupled with an assumption of invariance at E43 between 1935 and 1942/43, and the results of 1942/43 first-order leveling between Barstow and Beatty via Goldstone, Saratoga Springs, Ashford Mill, and Shoshone into Beatty. The last few kilometers between B86 and 3139 are based on 1933 first order leveling and an assumption of invariance between B86 and 3139 during the interval 1933-42/43.

Although starting from different Arizona reference points and based in large measure on independent levelings, the 1982 and 1984 heights for 3139 agree to within 0.04 m, well within either allowable limits or the estimated random error difference. The 1982 height for 3139 has been developed from temporally restricted first-order levelings referred to bench mark O10, Hassayampa, where the fixed starting height for O10 (274.5589 m) is based on the simple arithmetic mean for four successively determined heights for this stable mark (Gilmore,1986, Figure 3B, Tables B1-B4). The leveling used in the 1982 reconstruction consists of 1981/82 first-order work between Hassayampa and Boulder City via Salome, Yucca, and Kingman, 1980 first-order leveling from Boulder City to Indian Springs via Las Vegas, and 1983/84 first-order leveling from Indian Springs via Lathrop Wells into Beatty. The 1984 height for 3139 is based on the results of less temporally well constrained leveling proceeding from the fixed height for bench mark 22Q on the Bill Williams River (see above). The tie between 22Q and Beatty is based on 1931 first-order leveling between 22Q and Yucca Junction, a 1927 first-order join between adjacent marks at Yucca Junction, an assumption of invariance at Yucca Junction with respect to 22Q during the period 1927/31-82, 1982 first-order leveling between Yucca Junction and Boulder City via Kingman, 1980 first-order leveling from Boulder City to Indian Wells via Las Vegas, and 1983/84 leveling between Indian Wells and Beatty via Lathrop Wells.

While we believe that the represented height changes at 3139 USGS (fig. 3) constitute a reasonably valid characterization of the vertical history of this mark with respect to a near invariant tidal bench mark at San Diego, this history invites several questions and comments. At least two of the heights shown here (fig, 3) seem inconsistent with the cumulative history for 3139. The remarkably low 1907 height, while associated with fairly large error bars, suggests either an error in our reconstruction or leveling of questionable quality. For example, were our assumption of invariance at the Barstow junction mark between June and December of 1906 invalid, the join between the 1906/07 and 1907 levelings would produce a diminished height at 3139. However, the history of 22Q (Castle and others, 1987, p. 58) strongly supports the preceding assumption of invariance at Barstow and our other attempts to dismiss the validity of the1907 height of 3139 are devoid of merit. A similar question surrounds the 1943 height of 3139, which argues for a sharp drop below the 1930's heights. Again, the presumption of invariance at E43 Barstow may be invalid, and there is always the possibility of arithmetic error in our reconstruction. Regardless, the only option for increasing the 1943 height for this mark hangs on the likelihood of unrecognized uplift of E43 between 1935 and 1942/43. While clearly a possibility, uplift at Barstow during this interval is inconsistent with other evidence which either supports the stability of E43 or, more likely, argues for tectonic subsidence rather than uplift during the period 1935-1943 (Mark and others, 1987, p. 2785, 2787; Castle and others, 1987, p. 62-67). Thus, unless we were to resort to unspecified assertion, we would have to conclude that the Beatty area--at least bench mark 3139 USGS--was characterized by a history of modest episodic uplift, marked by at least one apparently oscillatory displacement during the 20th century. Perhaps surprisingly, episodic uplift and partial collapse may be the rule rather than the exception in the southwestern United States (see, for example, Castle and others, 1984; Gilmore, 1986; Castle and others 1987; Castle and Gilmore, 1992).

Accepting the successively indicated heights for 3139 (fig. 3) as a valid approximation of the height history for this mark with respect to M57, it argues toward several biases in comparing sequentially determined heights for any arbitrarily selected mark referred to 3139. For example, if the indicated mark is assumed to have remained unchanged in height with respect to some fixed datum, such as the reference ellipsoid, the height for this mark based on 1907/09 leveling versus 1931/35 leveling referred to 3139 would produce apparent subsidence. Similarly, were we to compare the heights for this same mark based on 1931/35 versus 1943 levelings referred to 3139, our selected mark would appear to have experienced modest uplift. Because we are concerned here chiefly with *relative* height changes, these biased height changes are generally not a problem. However, in attempting to assess any tectonic implications derivative from the height changes described in this report a built-in bias attributable to the mobility of 3139 may introduce some severely limiting complications.

HEIGHT CHANGES ALONG THE SELECTED LINES

Our characterizations of height changes along the several lines through the Death Valley region are in many, if not most cases based on new minus old comparisons among levelings of differing orders and various combinations of temporal constraints. In spite of a variety of uncertainties predictably introduced by such characterizations, the results of the described comparisons are sufficiently compelling as to provide a degree of insight into the nature of any continuing tectonic activity in this region.

BEATTY TO OLANCHA LINE

Height changes along the Beatty to Olancha line (fig. 5) are among the most illuminating reported here. They are also associated with several troubling problems, two of which we believe to be quite significant but still susceptible to reasonable interpretation.

An issue that is thought to be of trivial significance relates to height changes along parts of the Beatty-Olancha line based on comparisons among observed elevations, rather than appropriately corrected orthometric heights, where the baseline survey follows a different route from that of several subsequent levelings. The route divergence of concern is limited to the region between the Wildrose area and Darwin (fig. 1). Because the two sides of the involved circuit (Darwin-Panamint Springs-Ballarat-Darwin) are characterized by similar terrain and both modest and comparable Bouguer gravity relief, it is doubtful that the observed gravity othometric corrections around this circuit would sum to more than 2-3 cm. More to the point, however, to even bother to include properly computed orthometric corrections with these comparisons would impart a false sense of confidence in the results, since the third-order western leg (the baseline survey) of this circuit could be expected to be identified with random errors that would dominate the closure and might greatly exceed the difference between the orthometric corrections along the two sides of the circuit. It was for precisely this reason that we did not even consider the tedious computation of orthometric corrections in calculating the misclosures in the essentially third-order baseline network for the Death Valley region (fig. 2). This argument, however, would carry little or greatly diminished validity in considering comparisons among first-order or largely first-order work (see Vanicek and others, 1980, p. 510-513). This point has already been made, at least implicitly, in our calculation of successive heights for 3139 (fig. 3), whether emanating directly from tidal bench mark M57 or through the stable marks at Hassayampa and along the Bill Williams River.

The most challenging problem encountered in our reconstruction of height changes along the Beatty-Olancha line, and possibly the most challenging encountered in the preparation of the entire report, centers on the recognition of two fairly large busts detected along the western end of this line (fig. 2). While we believe that we can provide reasonable explanations and plausible corrections for both busts, because the field books were destroyed our confidence in the applied corrections is necessarily limited. Nevertheless, the corrected figures can in both cases be tested against the results of one of the most meticulous early 20th-century surveys in the western United States, where the accuracy of the compared precise survey (second-order or better) can itself be independently assessed by comparisons with a first-order survey that was completed only two years later (Los Angeles Department of Water and Power, 1907). Both of the indicated busts emerged from a fairly careful examination of data recovered from the same 1905 summary book (U.S.G.S. summary book 7698), which is believed to include some of the earliest third-order leveling in the entire region.

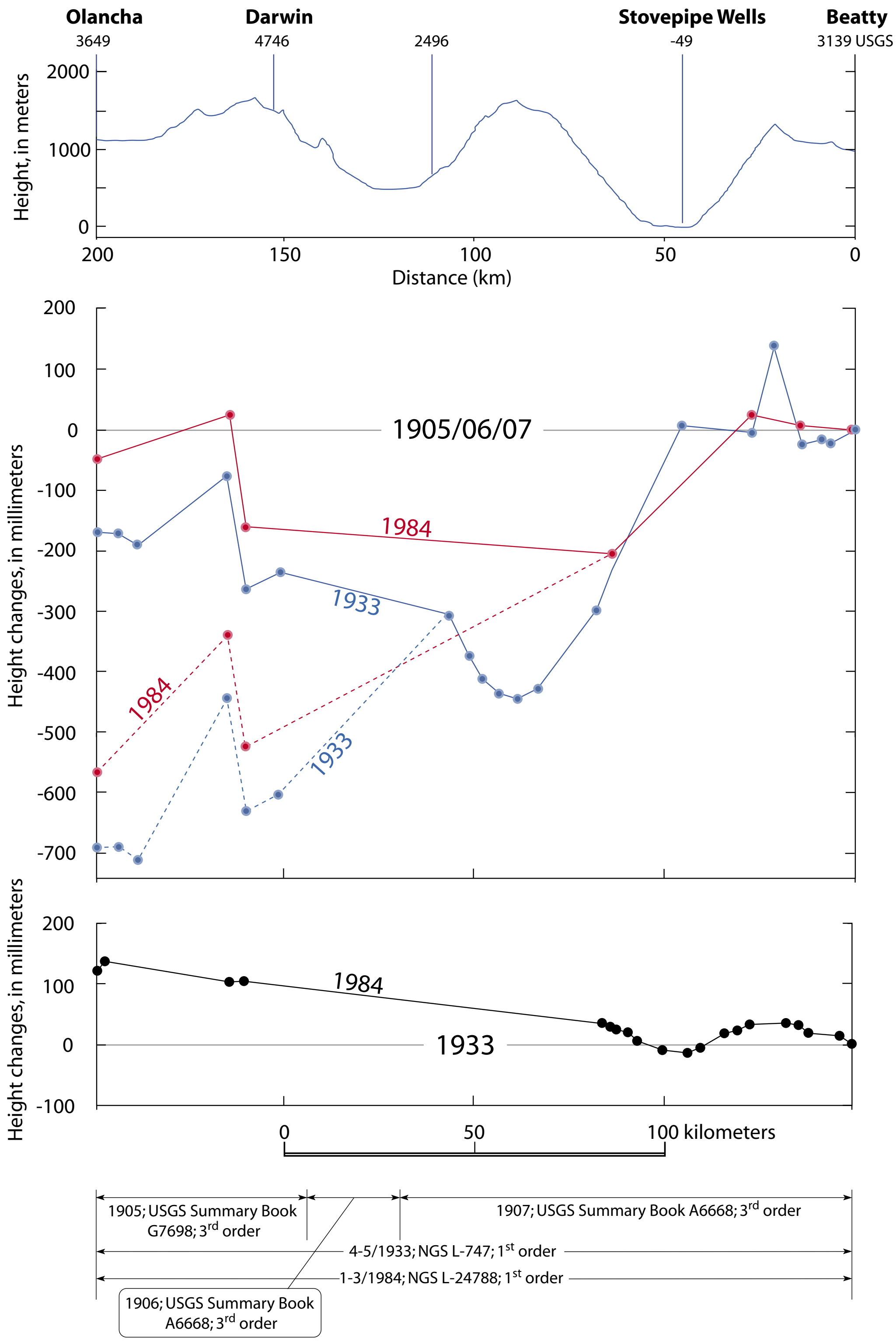

Figure 5. Profiles showing terrain and changes in height along the Beatty to Olancha line with respect to bench mark 3139 USGS, Beatty. The correction and datum shift to 3139 USGS, to NGS L-24788, is made through banch mark S408, about 6.7 km distant from 3139 USGS, through NGS L-24792. Dotted lines show changes in height had no busts been removed from 1905 datum.

The 1.281-ft misclosure, near the western edge of the map showing misclosures in the Death Valley baseline network (fig. 2), includes one of the two significant busts contaminating the Beatty-Olancha line. The culpable leg, which can be fairly easily identified, includes the reach between bench marks 4746, Darwin, and 5605 (said to be at Mount Vernon Mill--Gannett and Baldwin, 1908, p. 94). While certainty is hardly the hallmark of this analysis, the cumulative evidence indicates that the bust occurred at or about bench mark 4815B, located about 17 km south of Darwin, where a change was made in both instrumentation and crew. This bust, however, can not be easily dismissed as some sort of instrumental malfunction. Because we were unable to find a direct tie through the junction mark, 4815B, between the line extending south from Keeler, based on New York rods, with that extending north from 5685, based on yard rods (U.S.G.S. summary book 7698, p. 7-8), we suspect that the tie between the two segments of this survey must have been made by means of leveling through an improperly selected supplementary or temporary bench mark (SBM). That this could explain this bust is supported by a hiatus of weeks or perhaps months between the join based on New York rods with that based on yard rods (U.S.G.S. summary book 7698, p. 7-8). If the later work based on yard rods and an apparently different crew picked up on the wrong SBM (several were probably set), an error consistent with the elevation difference between the properly selected SBM and the one that was actually used could easily explain this bust. The correction applied to a bust of this type is necessarily arbitrary, since the data that tied the two segments are now missing. We can assume a bust of about -1.2 ft between bench marks 4746 and 5685. If we accept this as an approximately valid value, we can generate a conter-clockwise corrected loop, which starts with the 2740.161-ft value for bench mark "B" at Indian Wells, based on the 1905 precise level line of R.A. Farmer, and closes on the 3329.511-ft value for the "aluminum tablet" bench mark at Little Lake (Gannett and Baldwin, 1908, p.10), which produces a closure of +0.081 ft. While we accept the subjectivity of this procedure, additional evidence (see below) supports the validity of this subjective judgment.

There is always the possibility that the indicated +1.2 ft bust was derivative from a transposition error, possibly in transferring data from the field books to the summary book, or even less likely, in transferring the field observations to the appropriate field book(s). However imperfect our judgment regarding an improperly selected SBM, we believe that an appeal to transposition error in this case borders on special pleading. Nevertheless, we cite at least one case in this report where transposition error seems especially likely.

The second bust contaminating the Beatty-Olancha line occurs within the reach between bench marks 3631 and 4746 (fig. 2). While the misclosure around this loop sums to only -0.704 ft and is conceivably attributable to a concatenation of errors of various sorts, a bust provides a much more likely explanation of the indicated misclosure.

A comparison of new (1933 first-order work) minus old (1905 precise and 1905 third-order) leveling extending east from Olancha through Keeler (precise) and south to Darwin (third-order) discloses a jump in the profiled elevation changes of something less than 0.5

ft., localized between bench marks 3631, Keeler, and 4878B, about 16-17 km south of Keeler. We interpret this break in the profiled changes as a bust in the third-order work between these two marks. Even though the 3631 mark was not hit in the1933 first-order survey, because we view the precise work of R.A. Farmer as virtually unassailable (see above and Gannett and Baldwin, 1908, p. 9), it restricts the bust to somewhere between 3631 and the reach based on 1905 New York rod-leveling extending south from Keeler. Because the 1905 third-order leveling, which began at 3631 (U.S.G.S. summary book 7698, p. 1), was among the earliest third-order surveys in this region, the likelihood of a blundered reading by an inexperienced rodman seems especially likely.

The nature of this blunder is not easily assessed. The use of New York extensible rods in the 1905 third-order leveling suggests that the most likely explanation is an even 1-ft misreading on the back of the targeted New York rod when the rod was fully extended--thus the reading on the downhill rod. However, a complicating factor in attempting to explain this misclosure as a simple 1-ft misreading appears on the first page of summary book 7698: “Red figures are the mean of two N.Y. rod lines”, the observed values that we used in our reconstruction. That two New York rod lines were run south from Keeler suggests that a bust was suspected in the earlier third-order leveling, somewhere between the Keeler mark (3631) and bench mark 4815B, where the join occurred between the New York- and yard-rod lines. Thus the second running of the New York-rod line should have picked up any bust and actually may have done so. Accordingly, at least one section between 4631 and 4815B was run not twice but three times in order to correct the bust and still accommodate the requirement that the values used were the “mean of the two N.Y. rod lines.” If the observer, or whomever, inadvertently selected the contaminated sectional difference (rather than the bust-free corrected value) as one of his three possible choices, the meaning of the two utilized sections would result in a residual error of 0.5 ft. Correction for this postulated error between bench marks 3631 and 4878B would reduce the indicated misclosure to -0.204 ft.

We can test the validity of the -1.2-ft and -0.5-ft corrections to the line segments described above by summing the several legs, including the corrected legs, around each of the individual or combined loops (fig, 2), closing each of these summations on the 1905 precise (R. A. Farmer) line. Thus, referring to either U.S.G.S. summary book 6132 or Gannett and Baldwin (1908): starting at 2738 (2740.161 ft), Indian Wells, and closing on 3330 (3329.511 ft), Little Lake, produces a value of 3329.592 ft; starting at 2738 and closing on 3631 (3631.009), Keeler, produces a value of 3631.294 ft; finally, starting at 3330 and closing on 3631 produces a value of 3631.213 ft--all of which at least roughly support our provisional analyses and corrections for the indicated busts. We can further test the applicability of our corrections by comparing the resulting observed elevation of the westernmost mark on this line at Olancha, 3649B (with respect to the fixed height for 3139 USGS), against the corresponding observed elevation of 3649B based on1933 first-order leveling, again with respect to the fixed height for 3149 USGS. The 1905/06/07 observed elevation of 3649B based on our described reconstruction is 1111.9089 m; that based on the 1933 first-order work (NGS line L-747) is 1111.7336 m. Thus, with respect to 3139 USGS, 3649B at Olancha apparently subsided 0.17058 m between 1905/06/07 and 1933. Because 3139 is thought to have increased in height by 0.10-0.20 m between the early 1900's and the early 1930's, the apparent subsidence at Olancha could have been anticipated even if it had actually remained unchanged in height with respect to an invariant datum. An independent argument supportive of subsidence at 3649 is based on repeated levelings emanating from bench mark Tidal 8 at the San Pedro tide station. The first two levelings between Tidal 8 and 3649B, based on 1905 and 1926 connections, suggest subsidence of almost exactly 0.025 m (Castle and others, 1987, pl. 5)--virtually zero when allowing for error in the first of the two levelings, especially (Castle and others, 1987, pl. 5). Two successive surveys out of Tidal 8, in addition to the 1926 connection, produce the following observed elevations for Q45, Olancha, a little less than 2 km removed from 3649B:

1926—1151.3506 m

1935—1151.2312 m

1962—1151.2046 m.

These changes are again consistent with collapse of something more than 0.10 m at Olancha during the critical interval 1905/06/07-1933. While we cannot state whether, actual versus apparent subsidence is the more persuasive argument, that they are both in the same sense supports the validity of our corrections for the 1905 busts through the western part of the 1905/1906/1907 Beatty to Olancha line. Whether this consistency lends coherence to our reconstruction of height changes in the Death Valley region is a separate issue.

Ballarat Spur

A short spur off the Beatty to Olancha line has been developed from a comparison between a 1935 single-run second-order line (NGS line L-4887) against our 1905/06/07 datum. While this 18-km, essentially north-south spur discloses down-to-the-south differential displacement of only about 40 mm (fig. 6), because our data base is so sparse, we are inclined to include any reliable information available to us.

We can provide no direct evidence that our join at bench mark 2496 along the Beatty-Olancha line (fig. 5) remained unchanged in height during the 1933-35 interval. Nevertheless, our analysis of the Beatty to Riggs line (see below) suggests little, if any movement through this region between 1933 and 1935.

Height Changes

The profiled height changes along the Beatty to Olancha line referred to the fixed height of 3139 USGS, suggest little height-or slope-dependent systematic error along this line (fig. 5). Specifically, the absence of any clearly defined correlation between terrain and signal is indicated in comparisons against even the baseline turn-of-the-century

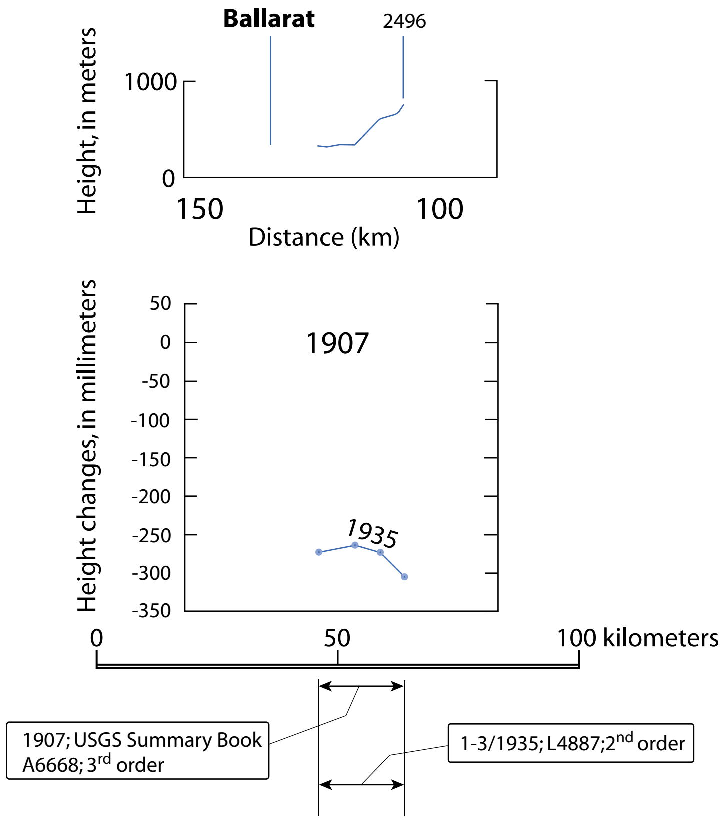

Figure 6. Profiles showing terrain and changes in height along the Ballarat spur with respect to bench mark 3139 USGS, Beatty.

work (see especially the reach between Beatty and Panamint Springs). The results of comparisons of the1984 fist-order surveys against 1933 first-order work along the eastern end of the line suggest modest height-dependent error of the order of 5 x 10^{-5} m/m in one or the other or in some combination of these two surveys. Nevertheless, and while the absence of any common marks between Towne Pass and Darwin preclude sweeping generalizations, if rod error amounted to even as much as suggested here, the increased magnitude of the signal at Darwin and beyond (fig. 5) is at variance with the likelihood that it should have no more than matched that in the Towne Pass area.

Based on acceptance of the square-root law, expected random error (1 σ) in the signal accumulated between Beatty and Olancha developed from a comparison of the 1933 survey against the 1905/06/07 baseline survey would be about 90-95 mm. Nevertheless, because this random error estimate is dominated by the earlier third-order work, and because the observed misclosures around the baseline network, when stripped of recognized busts, are all below their estimated random error values (fig. 2), it could be argued that this is an exaggerated estimate. The cumulative random error obtained from a comparison between the 1984 survey against the 1933 line is estimated to be of the order of 25 mm.

If our error estimates are no more than approximately correct, the vertical displacements along this line are striking in terms of both their magnitude and their episodic nature during the indicated periods of comparison . This history is much like that shown through and beyond the Long Valley region (Castle and others, 1984), some 100 km north-northwest of Death Valley, or that disclosed through the much more detailed investigations in southern California (Castle and others, 1984; 1987).

BEATTY TO RIGGS LINE

In terms of their importance to the narrative developed in this report, the height changes along the Beatty to Riggs line (fig. 7) probably match those along the Beatty to Olancha line. While several significant problems emerged in developing the profiled height changes along the Beatty to Riggs line, they are less challenging than those encountered along the Beatty to Olancha line. Moreover, even though the baseline leveling along the Beatty to Riggs line includes one segment that was surveyed about five years later (1912/13) than most of the other leveling around the eastern circuits (fig. 2), the associated misclosures argue that the third-order leveling along this line is free of major problems. Allowance for the corrections for or the discarding of the busts in those segments between Death Valley and Ashford Mill and between Z-2267 and Z-2775, respectively, suggests that this earlier leveling approached excellent (see below).

The chief problem addressed here is the magnitude and nature of an apparent bust between Death Valley and Ashford Mill (fig. 2). The two misclosures that share this segment are almost precisely balanced, and even though both closures are within limits for third-order leveling of this vintage, the balanced nature of these two loops virtually demands a bust along the common leg between the two. The issue is analogous to that disclosed by the balanced closures (-1.037 ft versus +1.057 ft) to the northeast. The balanced nature of these misclosures is again clearly consistent with a bust between Z-2775 and Z-2267, such that combining the loops lends credence to the accuracy of the leveling that defines the larger loop.

Not only are the loops that include the Death Valley-Ashford Mill segment closely balanced, the absolute magnitudes of these misclosures (~ 0.6 ft) suggests, if it does not compel, the source of the presumed bust. All of the ”1907 lines were run single with prism level and yard rods” (Gannett and Baldwin, 1908, p.86-94). Because yard rods are graduated in 0.01-yd intervals, conversion of 0.6 ft yields a value of 0.20 yd. Thus it is near certain that there was a 0.20-yd bust between Death Valley and Ashford Mill. Given the tightly balanced closures of almost exactly 0.6 ft, to argue otherwise would be asking too much of chance coincidence. Whether the 0.20-yd error is attributable to a 0.20-yd misreading of the rod, a recording error of 0.20 in the since destroyed field book, or a transposition error in transferring the data from the field book to the summary book (A-6668) is not directly determinable. Because the rod readings are (or should be) checked by back of the rod readings in feet, we suspect a simple transposition error in or in transferring data to the summary book. Although we can clearly identify the reach over which this bust must have occurred, we are less certain which bench mark pair includes the bust. Profiling of subsequent (1943) leveling against the 1907 datum indicates the error probably occurred between bench marks -235 and -215; the alternative option puts a spike at -235.

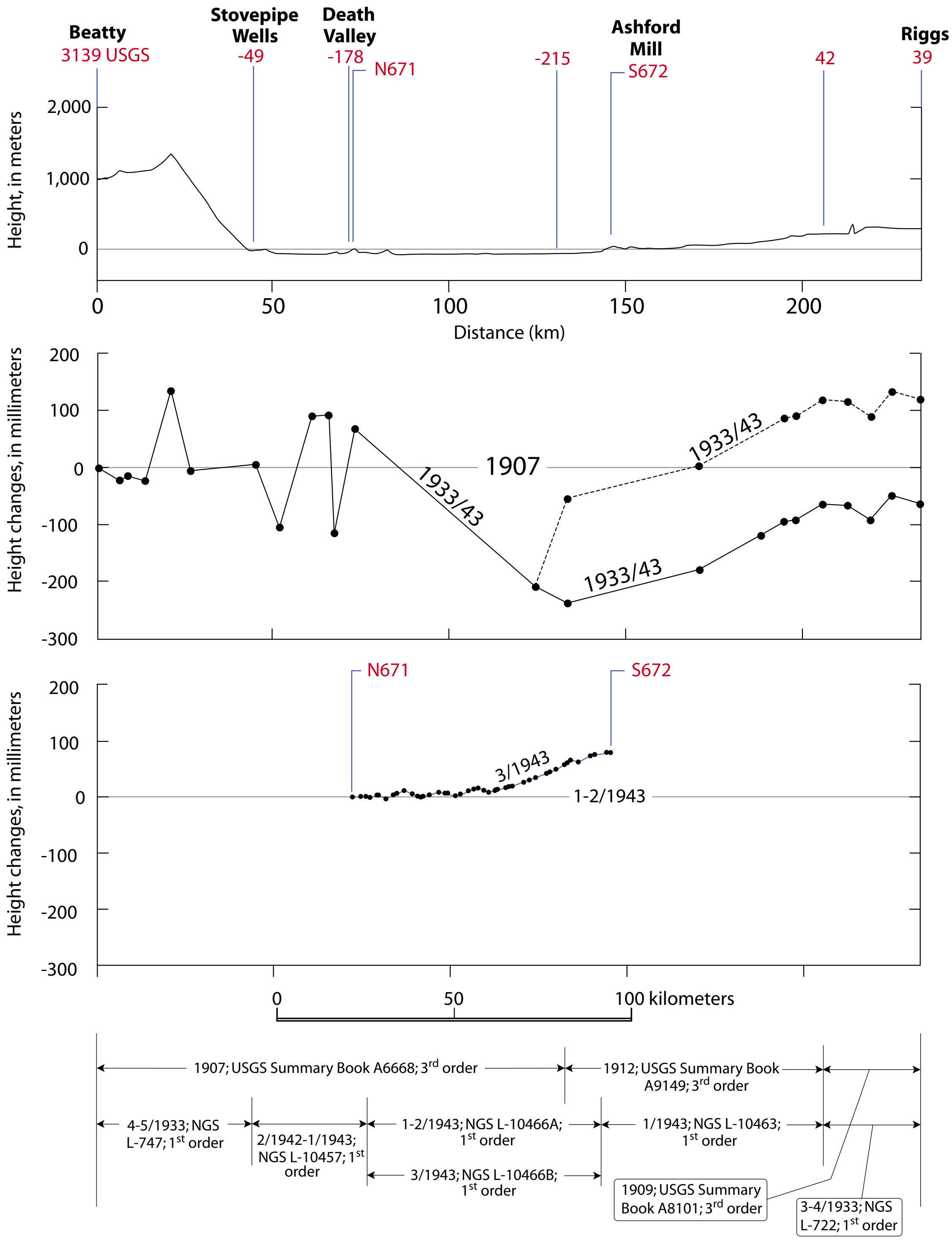

Figure 7. Profiles showing terrain and changes in height along the Beatty to Riggs line with respect to bench mark 3139 USGS, Beatty. 3/1943 comparison against datum based on 1-2/1943 leveling. Dotted line shows changes in height had no bust been removed from 1907 datum.

A second problem is associated with the recognition of a sharp up-to-the-south tilt along the southern end of the Death Valley-Ashford Mill segment of the Beatty to Riggs line that occurred sometime between January and March, 1943 (fig. 7). This apparent problem is disclosed by the sequential substitution of the two 1943 observed elevation values between Death Valley and Ashford Mill in the two adjacent circuits that include this segment (fig. 8).

Beginning with the western of the two circuits (fig. 8), which includes about 65-70 km of 1935 second-order leveling, as well as 40-50 km of 1933 first-order work, the earlier of the two indicated closures is well within first-order limits. With the substitution of the later leveling between N671 and S672, the misclosure is enlarged by 0.0783 m, as could be easily imagined with an elevation difference between N671 and S672 that increased by the same amount between January or February and March of 1943. A similar sequence of operations in the eastern circuit might be expected to produce a similar enlargement of the later circuit, which obviously it does not. If it is assumed that the elevation differences elsewhere around the earlier eastern circuit remained unchanged through March, uplift of S672 would lead to an increased elevation difference northwest to N671 of -7.5243 m to -7.6027 m, and thus a diminished positive misclosure. Alternatively, the above limits earlier misclosure might be attributable to east to west migration of tectonic activity. For example, uplift of Y163 with respect to K164 during the late February to early March interval would produce an increased elevation at S672 and, hence, impact the misclosures in such a way as to simulate error in the earlier leveling between S672 and N671. It is for this reason, we suspect, that the reach between N671 and S672 was rerun and did, in fact, produce a reduced closure around the eastern loop. Nevertheless, there is no basis for suggesting that the quality of the earlier leveling was either better or worse than that of the later leveling.

The preceding exercise again highlights the chief limitation of geodetic leveling: it is time consumptive, such that any movement around a circuit during the course of the leveling may distort the closure. We cannot say, accordingly, that the later misclosure associated with the eastern circuit argues for collectively more accurate leveling around this circuit. Regardless of which explanation one might choose, the abrupt up-to-the-south-tilt disclosed by the1943 comparisons cannot, or certainly should not be dismissed as a measurement artifact. We shall revisit this issue in our consideration of height changes along the Beatty-Baker line.

Spur from Furnace Creek Ranch (Death Valley)

The short spur off the Beatty to Riggs line from Furnace Creek Ranch (fig. 9) has been developed from comparison of a 1942/43 first-order line (NGS line L-10457) against our 1907 third-order baseline datum. While only 30 km long, this comparison discloses a surprisingly large down-to-the-southeast tilt of almost 0.29 m between bench marks -178 (Death Valley) and 3031 developed during the 1907-1942/43 interval (fig. 9).

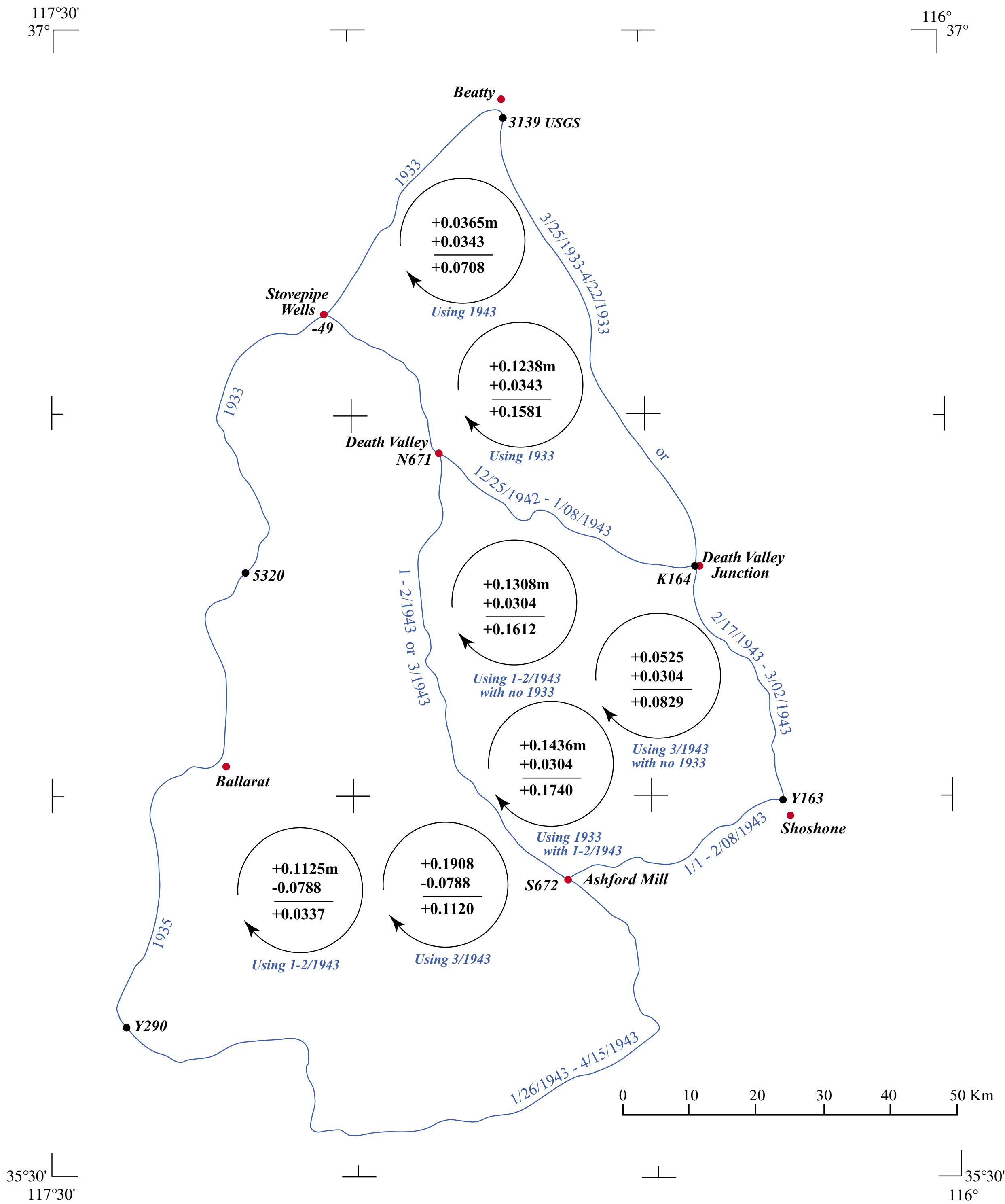

Figure 8. Misclosures around adjacent circuits obtained from first- and second-order levelings in the Death Valley region during the period 1933-1943. The 1935 survey between bench marks Y290 and 5320 is the only leveling included here that did not meet first-order standards. The upper figure shows the rod, instrument, and temperature corrected field values summed around the circuit; the second figure is the corresponding observed-gravity orthometric correction; the lower figure is the resultant orthometrically corrected value.

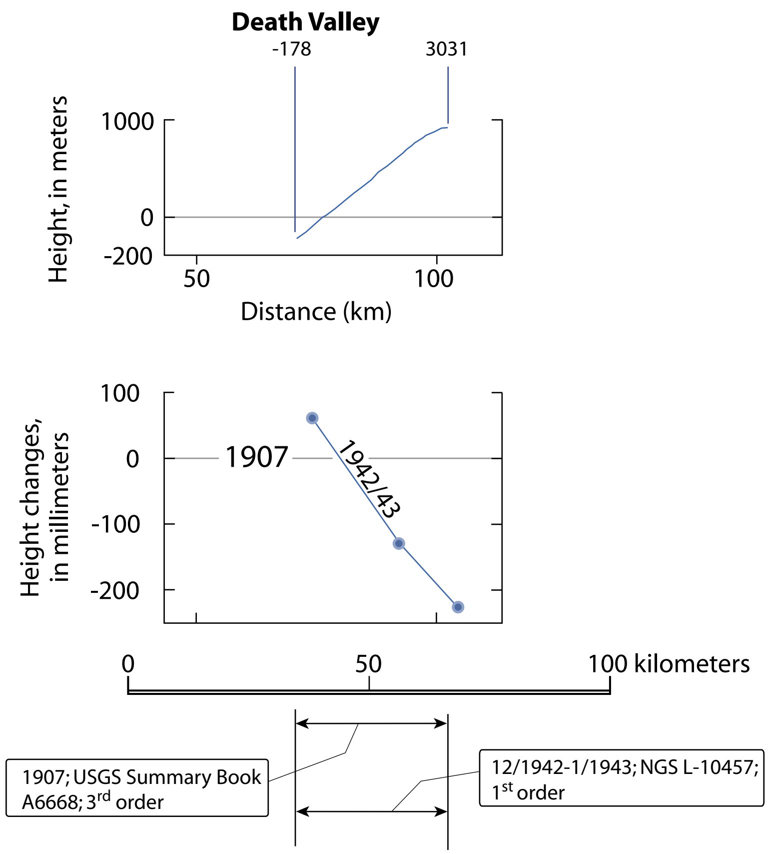

Figure 9. Profiles showing terrain and height changes along the spur from Furnace Creek Ranch with respect to bench mark 3139 USGS, Beatty

We are markedly skeptical of the indicated signal (fig. 9), if only because it shows such a striking correlation with terrain. This invites the suspicion of rod error in the earlier work, even though the misclosure that includes the 1907 segment (-0.601 ft., fig. 2) is remarkably tight, especially after removing the presumed bust between Death Valley and Ashford Mill which drops it to –0.001 ft (see above). Moreover, the indicated correlation is based on comparisons between only three marks, one or more of which may have been disturbed. Nevertheless, because as much as two-thirds or more of the leveling around this loop is based on the same rod pair, and because rod error may cancel when the upslope height difference is balanced against the downslope difference around the same circuit, we are hesitant about putting too much confidence in the misclosure argument as an index of the absence of height-dependent error. We are finally left, in any event, with the possibility that the signal disclosed by the comparison along the Furnace Creek Ranch spur may be real, such that we have provisionally accepted it here (see below).

Height Changes

The height changes along the Beatty to Riggs line, together with those along the Furnace Creek Ranch spur, are more or less consistent with what one might expect through this unusual regime. That is, for Death Valley to have continued to subside should not be viewed as especially surprising, since it is one of only two locales in North America currently below sea level. It must be admitted, however, that propagation of increasing subsidence southeastward from Furnace Creek Ranch (Death Valley) upslope from the valley floor toward the crest of the Amargosa Range, is not what one might have anticipated.

While Death Valley apparently subsided significantly during the1907-1942/43 period, that it had begun to recover very shortly thereafter is suggested by the modest early 1943 uplift centering on Ashford Mill (fig. 7).

BEATTY TO INDIAN SPRINGS

The represented height changes along the Beatty to Indian Springs line (fig. 10) repeat in part those previously described by Gilmore (1992); they are included here in order to contrast the character of the deformation eastward from Death Valley with that in and around the immediate Death Valley area. None of the survey results along the Beatty to Indian Springs line seem to be contaminated by significant measurement error.

The three compared surveys involve the easternmost lines included with our third-order, largely 1907 network (fig. 2) and two subsequent first-order levelings, the second of which was separated from its predecessor by about 68 years.

The baseline survey, as described earlier, forms part of a combined loop with a +0.027 ft (or about +0.009 m) observed misclosure (fig. 2)--or an observed gravity orthometrically corrected misclosure of +0.07 m (or about +0.229 ft) (Gilmore, 1992, fig. 5). In either case, the subsequent first-order surveys disclose significant signals when compared against the1907 datum, but relatively modest signals when compared against each other. Because there seems to be little correlation between terrain and signal among any of these comparisons, height- and slope-dependent error can be treated as near negligible. The accumulation of predicted random error in the1907-1915 signal at Indian Springs (referred to Beatty) is given as 66 mm and that for the 1907-1983/84 signal over the same reach is only slightly less. Nevertheless, because the misclosures suggest that the 1907 datum was particularly accurate, the 66-mm figure probably exaggerates the actual random error. The predicted random error in the 1915-1983/84 signal at Indian Springs (again referred to Beatty) is given as 20 mm.

Height Changes

Although clearly subdued, the relatively large magnitude vertical displacements disclosed by comparison within the more immediate Death Valley area seem to have propagated eastward--or occurred concurrently (fig. 10). Moreover, the sharply episodic nature of these displacements is again indicated here, as it was along the Beatty to Olancha line. However, while height changes along the Death Valley axis may have been equally episodic, and disregarding the limited evidence disclosed by the early 1943 comparison, we have no direct evidence of episodicity along the Beatty to Riggs line.

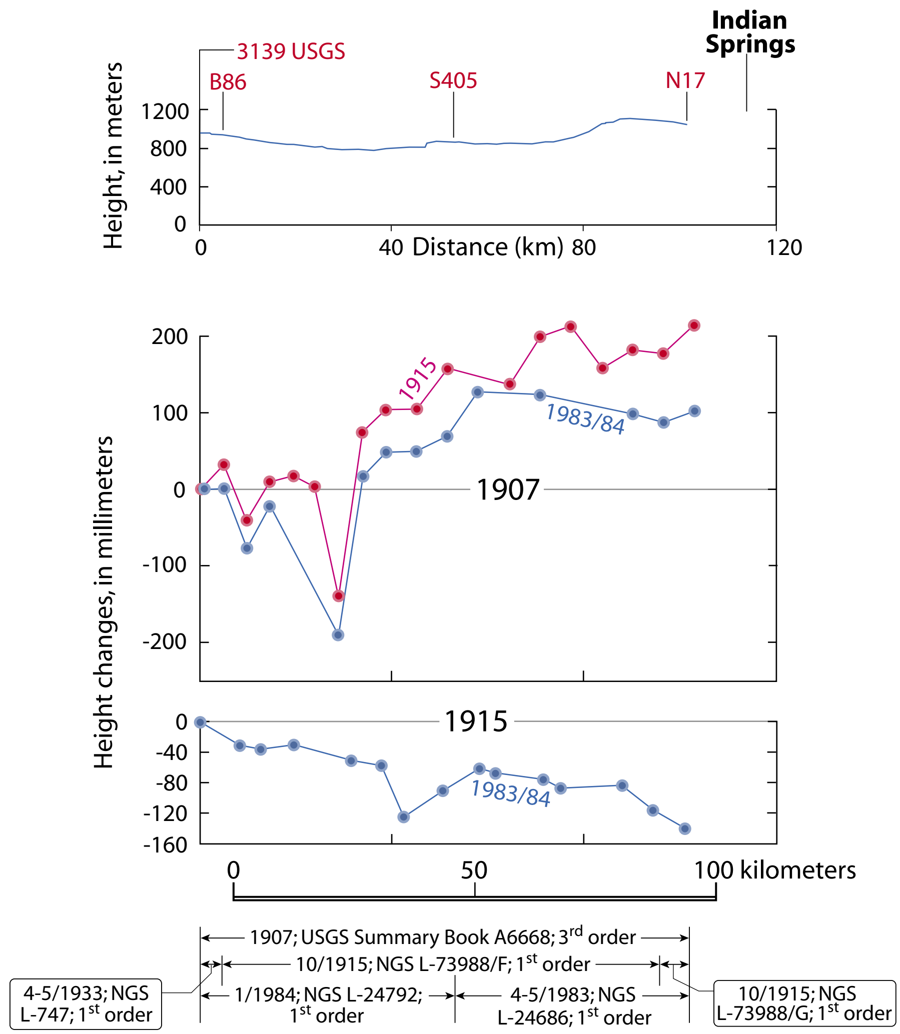

Figure 10. Profiles showing terrain and changes in height along the Beatty to Indian Springs line with respect to 3139 USGS, Beatty.

BEATTY TO BAKER LINE

Height changes along the Beatty to Baker line (fig. 11) comprise one of two sets described in this report that are not compared against our early 20th-century third-order datum. The Beatty-Baker height changes are referred instead to a 1933 first-order datum between Beatty and Baker and, thus provide us with at least some evidence of such deformation as may have occurred along the east flank of what we characterize here as the Death Valley regime, well after that period during which the early 20th–century surveys were carried out.

Comparisons between signal and terrain (fig. 11) suggest little height- or slope-dependent error along the Beatty to Baker line. For example, the break in the apparent 1933-1943 tilt near Death Valley Junction, where the continuing signal southward toward Shoshone is near flat, argues that neither the 1933 nor the1943 surveys were contaminated by height- or slope-dependent error. Moreover, the studies of Mark and others (1981), Stein (1981), and Craymer and others (1995), all indicate that even the earliest invar-rodded surveys (which all of these are) were generally contaminated by errors on the order of 2-3 x 10^{-5} m/m. Similarly, the investigations of Castle and others (1983), Castle and others (1985), and especially Mark and others (1987) cast doubt on significant unequal-refraction error in first-order leveling. One could argue that the correlation between terrain and signal is somewhat better developed in comparing the 1982/83 leveling against either the 1933 or 1943 survey, appealing perhaps to staff settlement in the 1982/83 single-run leveling. Nevertheless, such an appeal to systematic error in leveling of this era of as much as a third of a meter over a distance of 200 km and a height difference of about 700 m in the 1982/83 leveling, would be viewed as an egregious example of special pleading. Cumulative random error in the 1933-1943 signal between Beatty and Shoshone is estimated to be about 21 mm; that between Beatty and Baker, based on the 1933-1982/83 comparison, is estimated to be about 25 mm.

Height Changes

The height changes disclosed by the comparisons along the Beatty to Baker line (fig.11) are seemingly inconsistent with what we might have anticipated from our understanding of height changes along either the Beatty to Riggs line (fig. 7) or the Beatty to Indian Springs line (fig. 10). That is, the well-defined subsidence along this line (fig. 11) compares with that along the Death Valley axis; we might more reasonably have expected to see height changes along the elevated terrain identified with the Beatty to Baker line as matching those that characterize the uplift eastward from Beatty to Indian Springs (fig.10). Although we need not speculate here as to any physical explanation for this suggested contradiction, some attention should be given to how the displacements along the Beatty to Baker line may tie in with what we have seen both here and elsewhere.

We noted earlier that height changes referred to a control point that was subsiding with respect to an invariant datum would be biased toward the recognition of uplift. Or to restate the same conclusion in somewhat different terms, any such changes would be biased toward diminished subsidence—less than that which would have been recognized had our control point actually remained fixed in height . Because our selected reference mark subsided on the order of 0.15 m between the early 1930's and 1943 (fig. 3), the actual rather than the relative 1933-1943 subsidence between Beatty and Shoshone was apparently underestimated with respect to the 1930's value for 3139 USGS by about the same amount (fig. 11, red line representation). We can test this argument by examining the misclosure based on a combination of 1933 and 1943 levelings clockwise around the circuit -49 (Stovepipe Wells)-Beatty-Death Valley Junction-Shoshone-Ashford Mill-Death Valley-Stovepipe Wells ((fig. 8). The clockwise orthometrically corrected misclosure based on 1933 leveling out of Stovepipe Wells to Shoshone, coupled with 1943 leveling out of Shoshone produces relative uplift of Stovepipe Wells of about one-third meter. Viewed counter-clockwise, Shoshone subsided about about one-third meter between 1933 and1943. Recognizing that we have violated our stipulated requirement

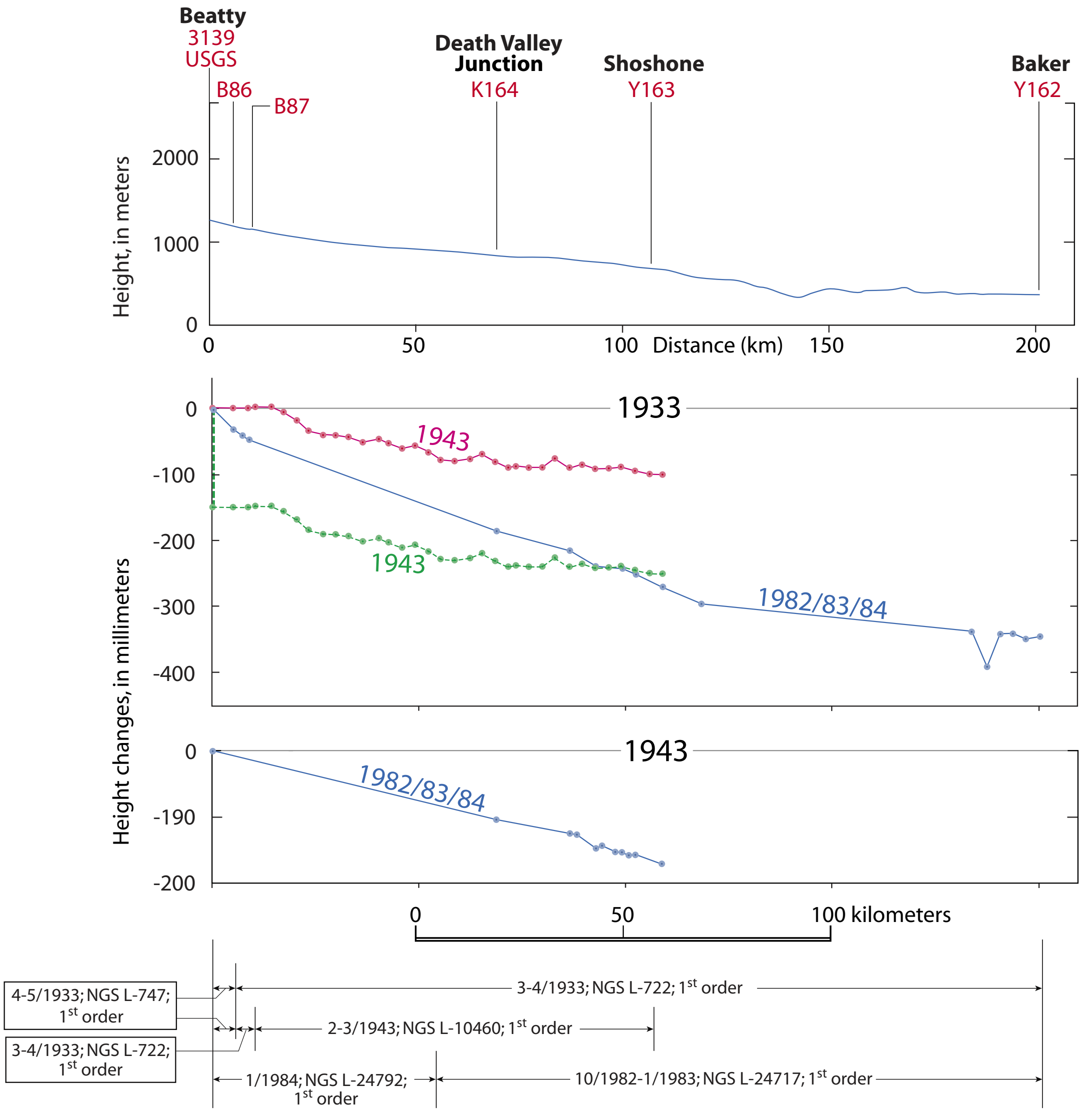

Figure 11. Profiles showing terrain and changes in height along the Beatty to Baker line with respect to bench mark 3139 USGS, Beatty. 1943 green line comparison against 1933 datum intended to accomodate about 150 millimeters of collapse at 3139 USGS between 1933 and 1943.

that we view 3139 USGS as fixed in height, acceptance of the 1943 drop (and subsequent recovery) of 3139 USGS (fig. 3) permits a more coherent characterization of the1933-1943 height changes east of Death Valley (fig. 11, green-line representation) than had we held our control point to its 1933 record elevation through at least 1943 (see below).

A corollary conclusion emerges from the preceding observation. Nearly all of the height changes along the Beatty to Shoshone (and perhaps the Beatty to Baker) line had occurred by 1943, demonstrating once again the episodic character of the height changes in this region.

The 1933-1943 subsidence reaches its near maximum in the vicinity of Death Valley Junction (fig. 11), whichever option we choose. Had we been able to extend the Furnace

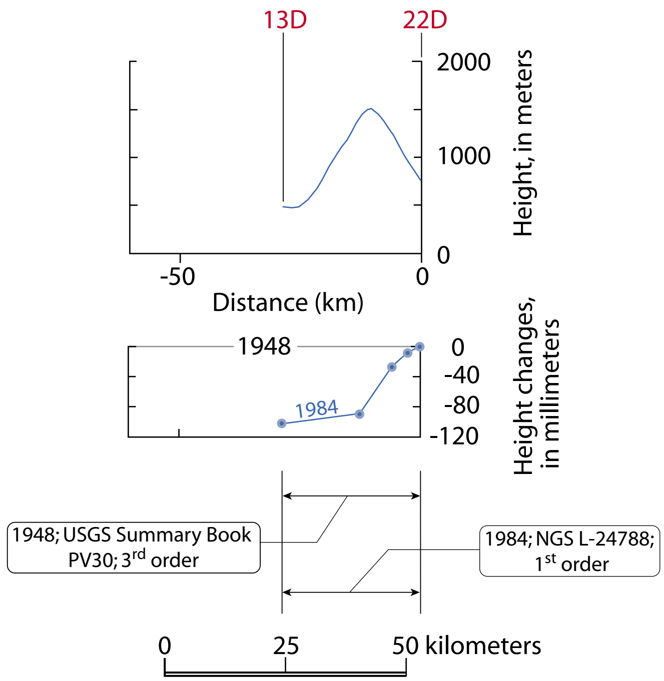

Figure 12. Profiles showing terrain and changes in height along the Towne Pass line with respect to bench mark 22D, Towne Pass.

Creek spur (fig. 9), off the Beatty to Riggs line, eastward toward Death Valley Junction, we might have seen that the subsidence along this spur continued eastward beyond our easternmost point of comparison. We have no way of knowing, of course, whether much, if any, of this subsidence occurred after 1933, but it is likely that a significant fraction did, and that the 1933-1943 height change at Death Valley Junction along the Beatty to Baker line represents an approximate expression of the possible or probable subsidence along the Furnace Creek spur projected eastward to Death Valley Junction.

TOWNE PASS LINE

The Towne Pass line is the only line described here (fig. 12) which is referred to a control point other than 3139 USGS, Beatty. We include it here simply because there is evidence of Holocene faulting within the pass (Jennings, 1994), coupled with fairly unambiguous evidence of significant height changes through the pass during the 1948-1984 interval.

There is hardly a hint in the indicated comparison of the1984 first-order work against a 1948 third-order datum (fig. 12) of any height- or slope-dependent systematic error. Moreover, the estimated cumulative random error in the signal at bench mark 13D, with respect to our selected control point at 22D, is given as 22 mm. Thus it seems very unlikely that more than a very small fraction of the described signal can be dismissed as measurement artifact.

The most intriguing feature disclosed by the comparison along the Towne Pass line is the sharply defined break in the signal that occurs no more than about five kilometers east of the Panamint Valley fault zone, which is at the same time bracketed between the two westernmost marks in the comparison. This comparison, accordingly, is unique among those described in this report in that it is identified with a break that at least approximately coincides with a previously recognized active fault system.

TECTONIC CONSIDERATIONS

Both abundant geologic evidence and considerable 20th-century geodetic evidence argue that the Death Valley region is a remarkably active tectonic regime. Attempting to model the deformation described here is beyond the scope of this report. Nevertheless, several compelling questions ultimately should be addessed. Why, for example, has the Death Valley region remained free of significant historic seismicity, given the compelling evidence of continuing or even accelerating tectonic activity during Holocene time? Again, can or even should one attempt to reconcile the apparently episodic and large magnitude vertical-displacement pattern in the Death Valley region with low elastic strain accumulation rates? Or is it likely that elastic strain accumulation is being continuously released with the concomitant absence of even moderate-magnitude earthquakes? Or, finally, while large-magnitude earthquakes may occur, are they so infrequent in this particular tectonic regime that no historic record of their occurrence survives?

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