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Comment on "The Impact of Refraction Correction on Leveling Interpretations in Southern California" by William E. Strange

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I would like to point out and correct some errors and inconsistencies central to the contention of Strange (1981) that "Uplift at Palmdale and Gorman-Lebec relative to Los Angeles (BM V32) during 1953-1978 is no greater than 10 cm", and that "The bulk of the motion occurs as localized motion on the San Gabriel fault during 1953-1964". Neither of these statements from his abstract find support in the refraction corrected elevations presented in his paper. Strange fails to consistently link elevation changes to his most distant reference station at Los Angeles, and combines corrected and uncorrected data. Using Strange's refraction corrected elevations, I have done this and find that aseismic uplift north of the San Gabriel and San Andreas faults persisted from 1965 to 1971, reached a peak of 150 ± 19 mm, and was followed by partial collapse.

Refraction-corrected elevations from *Strange* [1981] can be assembled to yield all elevation changes relative to Los Angeles, which is south of the region under examination (Figure 1). Elevation change at Saugus (BM R370) relative to Los Angeles (BM V32), corrected for refraction from Table 4 of Strange, is shown in Figure 2*a*. One standard deviation random error brackets for surveys are shown in Figure 2 under the assumption that errors grow with $aL^{1/2}$, where L is distance in kilometers, and $a = 1.5$ mm km$^{-1/2}$ (1953-1955) and 1.0 mm km$^{-1/2}$ (1956-1978), after *Vaníček et al.* [1980]. To establish the elevation of Grapevine (BM Z365, 20 km north of the San Andreas fault) with respect to Los Angeles, the refraction-corrected elevations between Saugus (BM J52) and Sandberg (BM V53) from Table 5 of Strange are added to the corrected elevations between Sandberg and Grapevine in Figure 2*b*. Though Sandberg (BM V53) and Grapevine (BM Z365) are 39 km apart, they are both called "Lebec" by Strange. The refraction-corrected elevation differences between these two stations have been supplied to me by Strange, and I list them in Table 1. Adding the elevations of Figures 2*a* and 2*b* yields the elevation history of Grapevine relative to Los Angeles since 1953 (Figure 2*c*). It is apparent that Grapevine uplifted at least 130 ± 19 mm and remained elevated throughout the period 1965-1971. This result is independent of Strange's rejection of the 1973 and 1968 surveys because the uplift can be observed in 1965 and 1971.

The only basis offered by Strange to reject the 1968 survey from Saugus to Sandberg is that 40 mm of differential uplift measured over a distance of 5 km along bedrock bench marks could have been caused by "a leveling blunder" [see *Strange*, 1981, Figure 6]. Strange implies that the elevation change was documented between only two bench marks, whereas four bench marks (X370, P52, Z370rst67, and M450) actually record the tilt, making blunder untenable. In fact, Strange's profile of the refraction corrected elevation changes from Saugus to Sandberg [*Strange*, 1981, Figure 9] shows only 16 out of the 40 resurveyed BM's.

Strange dismisses the 1973 survey between Los Angeles and Saugus because he claims that the cumulative elevation change is correlated with the cumulative elevation or topography (*Strange* [1981, Figure 5]; see Stein [1981] for discussion of elevation-dependent errors in leveling). In fact, the observed elevation change at Saugus is less than 1 mm with respect to Los Angeles from 1971 to 1973, even without refraction correction. Thus the 44-mm uplift listed in Strange's Table 4 and shown in his Figure 5 is erroneous. There is no elevation-dependent uplift over this segment because there is no uplift.

If there is merit to Strange's thesis that the refraction correction is significant for routes resurveyed between 1953 and 1973 along

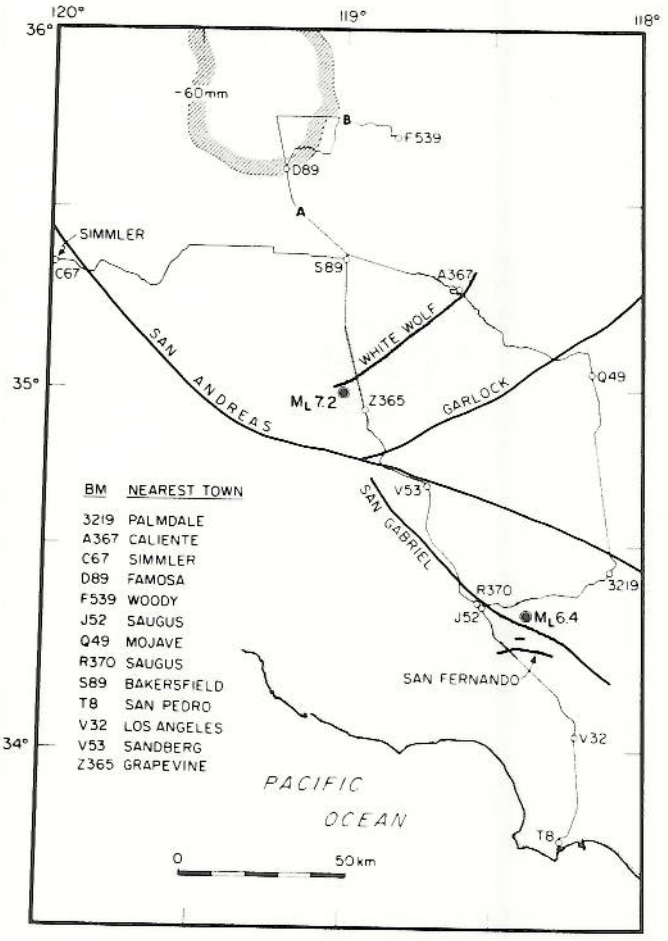

Fig. 1. Map of southern California leveling routes and reference BM's. Earthquake aftershock zones are stippled. Also shown is the −60 mm contour of 1954-1957 subsidence from *Lofgren and Klausing* [1969].

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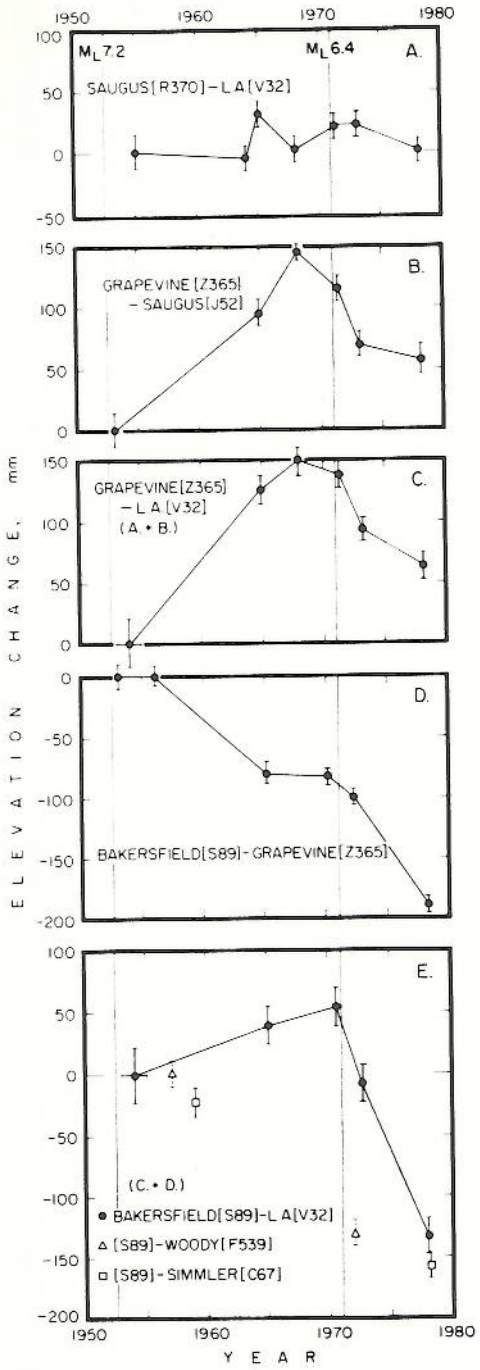

Fig. 2. Elevation change as a function of time. (*a*) From Table 4 of *Strange* [1981]. (*b*) Elevation differences from Table 5 of *Strange* [1981] are added to the differences from Sandberg to Grapevine listed in Table 1. J52 and R370 are adjacent BM's. (*c*) Sum of values in Figures 2*a* and 2*b*. (*d*) Elevation changes from Figure 12 of *Strange* [1981], corrected for refraction. Z365 is "Lebec" in Figure 12. (*e*) Sum of values in Figures 2*c* and 2*d*, with routes from Woody and Simmler uncorrected for refraction, from Strange's Figure 12, shown for comparison.

gently sloping terrain, then why has he neglected the corrections from Bakersfield (BM S89) to all four ties used to establish its movement history? Strange argues that Bakersfield, which is north of the uplift defined by *Castle* [1978], "can be presumed to have been subsiding with respect to all of the stations on the edge of the San Joaquin Basin since at least 1953." These stations include local ties to Grapevine (Z365) and Caliente (A367), and

TABLE 1. Refraction Corrected Elevation Differences Between Grapevine (BM Z365) and Sandberg (BM V53)

Year of Survey	Elevation Differences, m
1953	707.651
1964	707.666
1965	707.607
1968	707.629
1971	707.594
1973	707.605

more distant ties to Woody (F539) and Simmler (C67), shown in Figure 1. None of these four ties were corrected for refraction, despite the fact that all of the reference stations lie at altitudes greater than Bakersfield (heights of the BM's above Bakersfield are 457 m for Grapevine, 177 m for Caliente, 417 m for Woody, and 500 m for Simmler). Thus uncorrected elevations will create the appearance that Bakersfield subsided. In fact, because Grapevine uplifts more than 130 mm from 1953 to 1971 relative to Los Angeles (Figure 2*c*), it should not in any case be considered a stationary point for comparisons to Bakersfield.

To establish the movement of Bakersfield with respect to Los Angeles, the elevation change at Bakersfield (BM S89) relative to Grapevine (BM Z365) from Figure 12 of Strange has been corrected for refraction with values that have been supplied to me by Strange (Figure 2*d*). The data of Figures 2*c* and 2*d* are added to produce Figure 2*e*, the refraction-corrected elevation change of Bakersfield with respect to Los Angeles. Bakersfield does not subside below its 1953 value until after 1971. Holding BM's in the aftershock zone of the 1952 M_L7.2 Kern County earthquake (Figure 1) fixed during 1953-1973 for reference to Bakersfield, as was done in Strange's Figure 12, is inconsistent both with the geophysical evidence for postseismic deformation, and with the refraction corrected elevations from Los Angeles. *Dunbar et al.* [1980] find 2.5-3.0 m of coseismic slip (left-lateral and reverse) and interpert the postseismic 1953-1963 shear strains, which accumulated at twice the preseismic rate, to result from 2 m of postseismic fault slip.

Strange compares the elevation history of Bakersfield to that of Woody, in the Sierra Nevada foothills, as an alternative reference station. If used, this leveling survey would indicate uplift at Woody of 195 ± 27 mm relative to Los Angeles, using Strange's data (Figure 3). Surely, this is incompatible with Strange's use of the Woody station as a stable reference. The elevation change reflects either movement at Woody or refraction error. Because all of the elevation change on the Woody to Bakersfield route accumulates on sloped terrain, refraction may well be large. Strange states that Woody uplifts 100 mm, commenting that "these remainir.g apparent uplifts must be considered marginally significant."

In summary, Strange mixes elevations that are corrected and uncorrected for refraction, he has not linked elevations consistently to his reference station at Los Angeles, and his reasons for rejecting two surveys are wrong. Using only refraction-corrected elevations with respect to Los Angeles in 1953, I find more than 130 ± 19 mm of uplift both north and south of the San Andreas fault at Grapevine and Sandberg, between 1965 and 1971, contrary to the claims that Strange puts forth. Restoring the 1968 survey that Strange rejects yields 150 ± 19 mm uplift at Grapevine in 1968, north of the San Gabriel and San Andreas faults. Refraction-corrected elevations from Los Angeles show no subsidence at Bakersfield until after 1971. If Bakersfield in fact subsided 100

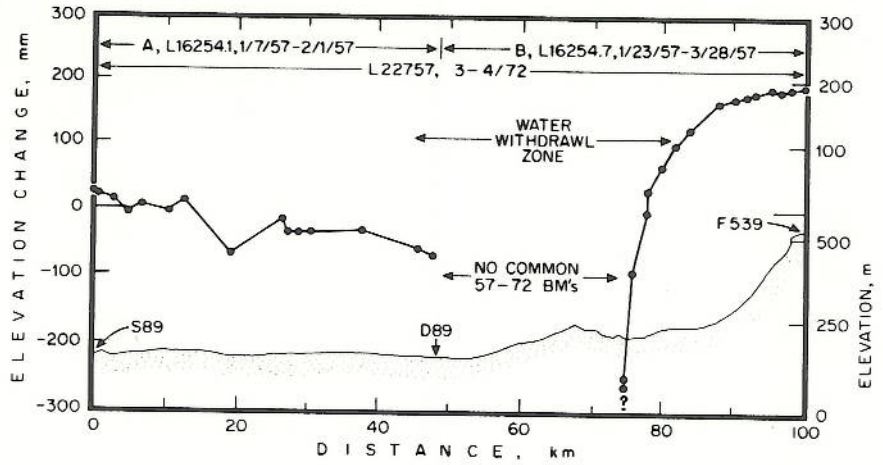

Fig. 3. Profile of elevation change uncorrected for refraction between Bakersfield (BM S89) and Woody (BM F539) with route topography. Elevation change is relative to Los Angeles (BM V32) in 1953. The time of each survey is shown with its National Geodetic Survey line number.

mm from 1953 to 1973 as Strange argues, then either (1) Los Angeles subsided more than 150 mm during the same period, a result incompatible with ties to mean sea level at BM T8, or (2) Strange's refraction correction accumulates a 150-mm error between Los Angeles and Bakersfield.

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Reply

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Stein [this issue] begins his comment by asserting there are errors and inconsistencies central to the validity of two statements in my paper [*Strange*, 1981]. He implies that these errors and inconsistencies arise because I failed to link elevation changes to Los Angeles and combined corrected and uncorrected data. Stein claims the statements are not supported by the refraction-corrected elevations given in the paper. In all respects he is wrong.

Table 1 of this reply summarizes the basis for the first questioned statement. Table 1 gives apparent uplifts of Gorman/Lebec (V53) and Palmdale (M899) relative to Los Angeles (V32) using data from Tables 4, 5, and 6 of *Strange* [1981]. For reasons specified by *Strange* [1981], I rejected the 1973 leveling between Los Angeles and Saugus, the 1968 leveling between Saugus and Gorman/Lebec, and the 1964 leveling between Saugus and Palmdale. With these rejections the remaining apparent uplift values of V53 and M899 relative to V32 were less than 10 cm. This led to the statement in my abstract: "Uplift at Palmdale and Gorman/Lebec relative to Los Angeles (V32) during the 1953–1978 time period is no greater than 10 cm."

The basis for the second questioned statement can be found in Figures 8 and 10 of *Strange* [1981]. These figures show a 4- to 6-cm discontinuity in apparent uplift where the Saugus-Palmdale and Saugus-Gorman/Lebec profiles cross the San Gabriel fault. This fact, together with the fact that the total uplift values at Palmdale (M899) and Gorman/Lebec (V53) for the unrejected levelings were less than 10 cm, was the basis for my statement: "The bulk of the motion occurs as localized motion on the San Gabriel fault during 1953–1964."

Tables 4, 5, and 6 and Figures 8 and 10 of *Strange* [1981] are derived from refraction-corrected elevations. Also, as shown in Table 1 of this reply, my statements were based entirely on elevation changes of Palmdale and Gorman/Lebec relative to Los Angeles. Thus Stein's claim that I failed to consistently link elevation changes to Los Angeles and that I combined corrected and uncorrected data when arriving at the two statements he questions is clearly wrong. Indeed, Stein presents nothing in his comment to support these claims.

Stein's discussion, aimed at proving that the two statements were incorrect, addresses two points which are unrelated to any failure to link elevation changes to Los Angeles or to use refraction corrected data. First, he questions my use of V53 as representative of uplift in the Gorman/Lebec area and shows that bench mark Z365, lying between Lebec and Grapevine, has apparent uplifts in the 10–15 cm range, 3–5 cm greater than V53. Second, he questions my rejections of the 1973 Los Angeles to Saugus and 1968 Saugus to Gorman/Lebec levelings.

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I was aware that there were larger apparent uplift values at Z365 than V53. In fact, Figure 8 of *Strange* [1981] shows that the movements of Z365 relative to Saugus at about the 90-km point on the profile. Using Figure 8 and Table 4 of *Strange* [1981], one can obtain the 1965, 1971, and 1978 uplift values shown in *Stein*'s [this issue] Figure 2*c*.

My reasons for not using bench mark Z365 as representative of aseismic uplift in the Gorman-Lebec-Grapevine area are brought out by Stein, himself, elsewhere in his comment. Bench mark Z365 is near the Pleito fault where considerable vertical movement occurred during the 1952 Kern County earthquake. As indicated by Stein, there is reason to believe that bench mark Z365 experienced localized postseismic movement in the years immediately following the 1953 leveling. The 3–5 cm of localized uplift involving bench mark Z365 shown in Figure 8 of *Strange* [1981] is compatible with this conclusion. But the focus of my paper was on the extensive aseismic uplift which *Castle* [1978] postulated to have occurred between 1959 and 1973. Thus I did not consider motion at Z365 because I felt a part of the uplift at this bench mark was localized postseismic uplift occurring in the 1953–1959 time frame. I find it puzzling that Stein would argue at one point that postseismic motion had occurred at Z365 and, at another point, would use the entire motion at Z365 as indicative of aseismic uplift occurring during a later time period. Using Stein's momenclature, I consider this an "inconsistency."

Next, consider the questions Stein raises with regard to my rejection of data. While it may not be immediately obvious from reading his comment, Stein agrees with my rejection of the 1973 Los Angeles to Saugus leveling results I used when preparing my paper. What Stein points out is that if the 1973 Los Angeles to Saugus leveling is properly reduced, the differences between 1971 and 1973 levelings shown in Figure 5 of my paper disappear. In other words the problem with the 1973 Los Angeles to Saugus data I was using lay, not in the data itself, but rather in the fact that I was using an incorrect reduction of the data. While I am somewhat embarrassed at not identifying the problem as one arising from an incorrect reduction, I was correct in rejecting the data as being affected by height-correlated error.

If I had used a correct reduction of the 1973 Los Angeles to Saugus leveling, then I would have obtained 1973 uplifts of V53 and M899 relative to V32 which were less than 10 cm (see Table 1 of this reply). Thus, while Stein's point with regard to 1973 Los Angeles to Saugus leveling is correct, its impact is to provide further support for the two statements he questions. In passing, it should be noted that the 1973 uplift indicated in Stein's Figure 2*a* is derived from correctly reduced level data and not from data taken from Table 4 of *Strange* [1981], as stated by the caption.

Stein also questions my rejection of the 1968 Saugus to Lebec leveling. As illustrated in Figure 8*b* of *Strange* [1981], the 1965 and 1969 levelings over this route are in close agreement, while the intervening 1968 leveling indicated

TABLE 1. Uplift of Gorman/Lebec (V53) and Palmdale (M899) Relative to Los Angeles (V32) Since 1953–1955 From Strange [1981]

Location	Year					
	1964	1965	1968	1971	1973	1978
Gorman Lebec (V53)	+8.9	+8.2	+12.6*	+8.0	+8.9† (+4.6)	+1.8
Palmdale (M899)	+12.3‡	+6.8	+4.6	+6.7	+13.0† (+8.7)	+7.2

Movement in centimeters. Values in parentheses were obtained using correct Los Angeles to Saugus leveling.

*Rejected because of suspected error on Saugus to Lebec segment.

†Rejected because of suspected error on Los Angeles to Saugus segment.

‡Rejected because of calibration error on Saugus to Palmdale segment.

about 8 cm greater uplift of V53 relative to J52. As I stated, "The alternative to assuming leveling error in the 1968 leveling is to assume uplift across a localized zone occurring between 1965 and 1968 and disappearing by 1969." I consider an uplift which appears during one leveling interval and disappears during the next as highly unlikely. It was for this reason that I rejected the 1968 Saugus to Lebec leveling.

In searching for a source of error in the 1968 leveling, I suggested the possibility of leveling blunder because, as illustrated in Figure 6 of *Strange* [1981], the bulk of the difference between the 1965 and 1968 levelings occurred over a single bench mark interval lying between bench marks P52 and M450. The 1965 amd 1968 levelings I used had no observations at a common bench mark lying between P52 and M450. During the 1965 leveling, only bench mark Z370 was observed between P52 and M450; during the 1968 leveling, only bench mark Z370 RS 67 (a bench mark established to replace Z370 which had been destroyed) was observed between P52 and M450. In the levelings I used, there were no connections made between Z370 and Z370 RS 67. R. S. Stein (personal communication, 1982) found that in 1967, when bench mark Z370 RS 67 was established, it was connected to bench mark Z370 before Z370 was destroyed. Using this connection, it is possible to show that the 1965–1968 difference extends over two bench mark to bench mark intervals rather than one. This being the case, I am in agreement with Stein that my suggestion of a blunder in the 1968 leveling is no longer tenable. However, while I accept the fact that my speculation as to the cause of error in the 1968 leveling was not correct, I continue to believe that the probability is very high that this leveling is in error.

As may be seen from the above discussion, differences between Stein and myself regarding my conclusion concerning uplift in the Gorman-Lebec-Grapevine area are small (<5 cm) and are based on differences of opinion regarding whether I should have used a bench mark in the aftershock zone of the 1952 Kern County earthquake to define aseismic movements in the Gorman/Lebec/Grapevine area and whether or not I should have rejected the 1968 Saugus-Lebec leveling. To a large extent the question of who is "right" with regard to what I should have done, given the data available when I prepared my paper, is academic. Analyses in the past 2 years have shown that application of more accurate refraction corrections tends to reduce apparent uplifts below the values given in my paper. Table 2 of this reply illustrates the reduction.

Stein begins his comments on my discussion of movements in the Bakersfield area by asking why I "neglected the [refraction] corrections from Bakersfield (BM S89) to all four ties used to establish its movement history." There was no such neglect. In my paper I discussed both uncorrected and refraction corrected leveling in the Bakersfield area. Stein seems to have confused the two discussions. Discussion of the leveling results shown in Figure 12 of my paper concerned the consequences of accepting uncorrected leveling. Thus it was entirely proper that I should use uncorrected leveling in constructing Figure 12. On the basis of the uncorrected leveling results given in Figure 12 I made two points: (1) Using uncorrected leveling, one cannot postulate that Bakersfield remained stationary between 1959 and 1978 while postulating episodic uplifts and subsidences at Lebec (i.e., Z365) and Caliente/Mojave, and (2) using uncorrected leveling, acceptance of the southern California uplift of *Castle* [1978] forces one to postulate that much of the Sierra Nevada mountains and the area near Simmler also uplifted about 30 cm during the same time period. Nothing in Stein's comments challenges these conclusions.

One of the primary focuses of Stein's comments is an argument against treating Grapevine (Z365) and Caliente (A367) as stable or stationary reference points. Stein claims that I did this in analyzing Figure 12. I did not. As indicated above, the two points I made using Figure 12 had to do with the consequences of assuming there was motion at Grapevine and Caliente.

After discussing problems associated with interpreting uncorrected leveling in the Bakersfield area, I presented, in a brief paragraph [*Strange*, 1981, p. 2821], what I believed to be the consequences of applying refraction corrections to this leveling. As explicitely stated in my paper, these conclusions were based on refraction corrected data not on the uncorrected data shown in Figure 12.

Using refraction-corrected data, I concluded that there was an apparent uplift of Woody relative to Tidal 8 of about 10 cm. I noted that uncertainties in refraction correction and rod calibration made this apparent uplift marginally significant. Stein claims that he derives 19.5 cm of uplift of Woody using my data. This is not the case. The results shown in *Stein*'s [this issue] Figure 3 are not based on my numbers nor are they compatible with results presented in Figure 2 of *Stein* [this issue]. In preparing my paper I arrived at a refraction-corrected subsidence of Bakersfield relative to Los Angeles between 1953 and 1973 of about 2 cm. This is, as it should be, about the same value as Stein shows in his Figure 2*e* for 1973, the only difference being that I used the

TABLE 2. Apparent Movement Relative to Los Angeles During 1953–1957 to 1972–1974 Time Period Using Refraction-Corrected Data

	Strange [1981]*	Using Holdahl Refraction†
Lebec (V53)	+3.6	−2.9
Grapevine (Z365)	+9.4	+0.3
Bakersfield (S89)	‡	−11.7
Woody (F539)	+10.0	+3.1

Movement in centimeters.

*Values obtained using mean of 1971 and 1978 Los Angeles to Saugus Leveling.

†Values obtained using correct Los Angeles to Saugus leveling.

‡No values given. *Strange* [1981] states Bakersfield has subsided but gives no values.

mean of the 1971 and 1978 values for movement of Saugus relative to Los Angeles rather than the revised 1973 value shown in Stein's Figure 2*a*. To obtain the motion of Woody relative to Bakersfield, I used refraction-corrected 1957 and 1972 levelings. As may be seen in my Figure 12 and Stein's Figure 2*e*, my 1957–1972 apparent uplift of Woody relative to Bakersfield using uncorrected leveling was about 14 cm. I obtained a refraction correction of about 3 cm for this leveling. Combining these numbers and extending from Los Angeles to Tidal 8 gave me, in round numbers, 10 cm of uplift at Woody.

Stein shows in his Figure 3 that in arriving at 19.5-cm uplift of Woody, he accepts about 3 cm of uplift of Bakersfield relative to Los Angeles, but this value is not compatible with my refraction-corrected results, as shown in his own Figure 2*e*, and is not clear where he obtained it. Stein uses uncorrected leveling for the Bakersfield to Woody profile segment in arriving at 19.5 cm of uplift at Woody. The use of this uncorrected leveling would, in itself, make Stein's value of 19.5 cm unrelated to my refraction-corrected result. In addition, Stein shows in his Figure 3 uplift of Woody relative to Bakersfield of about 16.5 cm rather than the 14 cm I obtained using uncorrected leveling. In summary, Stein's value of 19.5 cm for uplift of Woody relative to Los Angeles is not based on my data and is based at least partially on data uncorrected for refraction. Thus the 19.5-cm result is not comparable to the 10-cm value I obtained, and without more information on how it was derived, its significance is obscure.

At this point is it worth noting that my statement that the 10 cm of uplift at Woody was marginally significant has been verified. As shown in Table 2 of this reply, using the more accurate refraction correction algorithms of *Holdahl* [1981, 1982], the apparent uplift of Woody is reduced from 10 to 3 cm.

In concluding this reply I will point out some errors in the final summary paragraph of Stein's comment.

In his summary, Stein makes an assertion which is unsupported by any discussion in his comment. Specifically, Stein claims that he finds more than 13 cm of uplift south of the San Andreas fault at Sandberg (V53) between 1965 and 1971 relative to 1953 leveling. However, nowhere in his comment does he give any basis for this claim. In fact (as may be seen from Table 1 of this reply), refraction-corrected data from my paper does not indicate more than 13 cm uplift at V53 at any time and shows less than 10 cm uplift in 1965 and 1971.

Stein in his summary states that I argued that Bakersfield subsided 10 cm from 1953 to 1973 relative to Los Angeles. Nowhere in my paper do I state Bakersfield subsided 10 cm from 1953 to 1973. I never give any specific value for the subsidence of Bakersfield during any time period. Although it is perhaps academic, I should also point out that, if I had claimed Bakersfield subsided 10 cm from 1953 to 1973, it is not clear how this would lead to a requirement that either Los Angeles subsided 15 cm or there was a 15-cm error in refraction. Stein's Figure 2*e* would indicate that if I postulated that Bakersfield subsided 10 cm, the resultant discrepancy would be 9 cm, not 15 cm.

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