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Reply

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INTRODUCTION

We would like to thank *Reilinger* [this issue] for pointing out that artificial subsidence could account for the 53±16 mm of refraction-corrected elevation change that we attributed to tectonic deformation at a bench mark (BM) N 899 10 km south of Palmdale, measured relative to Saugus (BM X 898) [*Stein et al.*, 1986]. Our reply to *Reilinger* [1980], the paper upon which *Reilinger*'s comment is predicated, was given by *Stein* [1981]. We are thus in the uncomfortable position of entering the second round of exchanges over so little deformation. Circumventing the Saugus basin, we find that BM N 899 at Palmdale rose 64±34 mm with respect to sea level during the period 1955–1965/1968, consistent with our previous estimate but no longer significant at the 95% confidence level.

SEA LEVEL REFERENCE FRAME

Reilinger [this issue] argues persuasively that because of pumping of groundwater aquifers, Saugus is a poor choice to reference any elevation change in southern California. The only way to get out of this hole would be to compare BM X 898 at Saugus, or BM N 899 near Palmdale, with an absolute reference frame. Although we lack such a reference frame, the BMs can be tied to mean sea level, the equipotential surface to which geodetic leveling is referenced, via the tidal gauge at San Pedro (Figure 1). BM Tidal 8 has remained approximately stable with respect to sea level for the past 134 years [*Wood and Elliot*, 1979]; the rate of elevation change of BM Tidal 8 (or of Tidal 8X, 44 m away) relative to mean annual sea level for the period 1924–1975 is −0.5±0.2 mm/yr, this small residual perhaps attributable to eustatic sea-level rise [*Hicks*, 1978; *Chelton and Enfield*, 1986]. The only penalty incurred by use of the sea level reference is that random and systematic errors will be larger for the link from Palmdale to San Pedro than from Palmdale to Saugus, owing to the greater distance and height difference between the end points. For this reason, we also consider a surrogate reference, BM W 786 at Burbank, which lies closer to Saugus and adjacent to exposures of a Precambrian metamorphic rock and Mesozoic granite, the oldest rocks along the leveling route (Figure 1).

The elevation change history of BM X 898 at Saugus relative to sea level (BM Tidal 8) and to the Precambrian outcrop (BM W 786) is shown in Figure 2. The National Geodetic Survey lines used to construct Figure 2 were corrected for errors from rod calibration and atmospheric refraction error using REDUC4 [*Holdahl*, 1981] and are listed in Table 1. It is evident that BM X 898 subsided 20–30 mm with respect to sea level from 1955 to 1961 but rebounded by the same amount between 1961 and 1968. The record of water table fluctuations in the alluvial aquifer beneath Saugus shows the same reversal in trend between 1945–1961 and 1962–1968 [*Robson*, 1972, Figure 8]. We doubt that this rebound is an artifact of unusually large survey errors between San Pedro and Burbank because Saugus displays a similar history with respect to the surrogate reference, BM W 786, which lies only 30 km south of Saugus (Figure 2). Our assumed 9±3 mm of subsidence for 1955–1965 [*Stein et al.*, 1986] is also shown in Figure 2. From this comparison we regard our former 9-mm estimate of the subsidence during 1955–1965 to be appropriate but our 3-mm assessment of its uncertainty to be much too small.

LOCAL REFERENCE BENCH MARKS

Reilinger [this issue] argues that BM X 898 subsided with respect to BM M 53, located 10 km to the south at the edge of the Saugus basin. The history of this reference bench mark is also shown in Figure 2; unlike the sea level reference, M 53 continues to rise with respect to X 898 through 1964. Contrary to the impression created by the top panel of *Reilinger*'s [this issue] Figure 2*a*, M 53 is anomolously uplifted with respect to all BMs on the 100-km-long line to San Pedro. This can be seen in Figure 3, a profile of elevation change between San Pedro and Saugus for 1955–1964 (the 1955–1968 elevation changes for the reference BMs are also shown with triangles). BM M 53 is located at the topographic peak of the leveling route (Figure 3, bottom). One possibility is that BM M 53 is stable and all BMs to the south undergo artificial subsidence. Alternatively, the apparent uplift of M 53 may result from a residual topographic or slope-dependent error in the 1955 survey (see, for example, *Jackson et al.* [1981], *Reilinger and Brown* [1981], and *Stein* [1981]), or it may be real uplift from preseismic slip on the adjacent Santa Susana fault (Figure 1), which slipped 1 m during the 1971 San Fernando earthquake. Deformation preceding the 1971 earthquake has been reported by *Castle et al.* [1974], *Thatcher* [1976], and *Strange* [1981]. Because these alternative explanations are not readily eliminated, we prefer to reference elevations to sea level.

Reilinger [this issue] suggests that 60 mm of subsidence at

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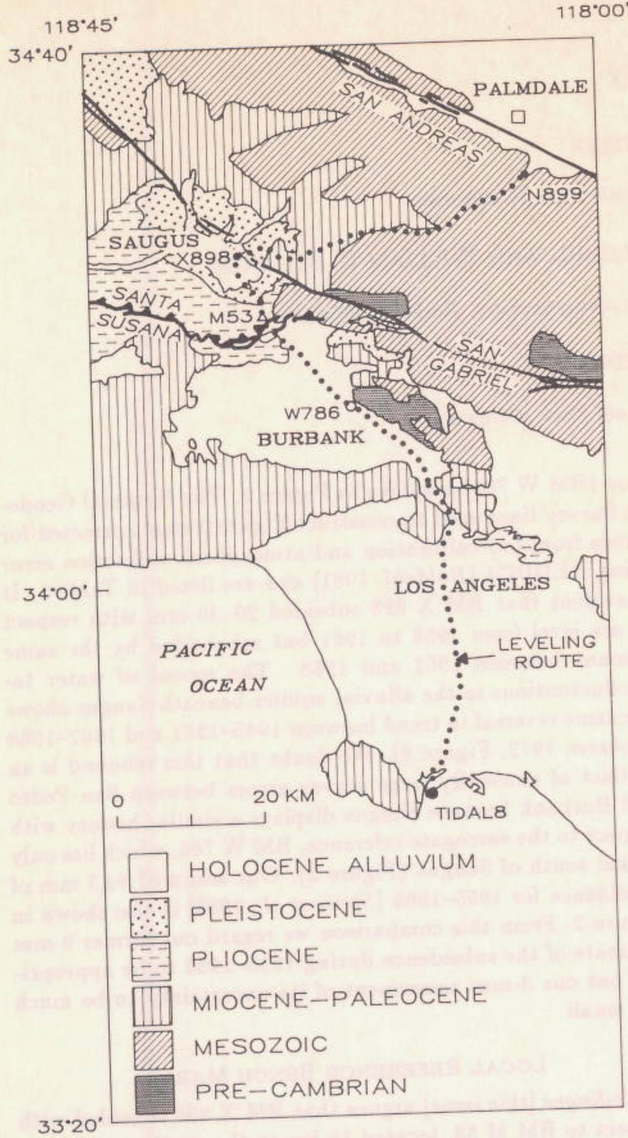

Fig. 1. Sketch map of geology and active faults along the leveling route (dotted line) from San Pedro to Palmdale, southern California. The Saugus basin is centered on BM X 898; other bench marks referred to in the text and shown in Figure 2 are also indicated.

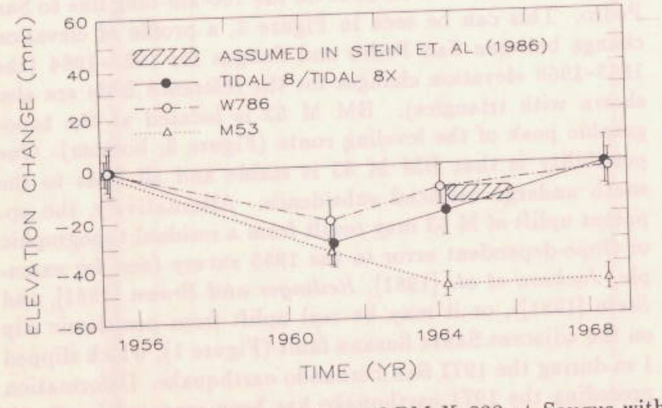

Fig. 2. Elevation change history of BM X 898 at Saugus with respect to three reference BMs. Surveys corrected for rod calibration and atmospheric refraction errors, with 1-sigma random error brackets shown.

TABLE 1. NGS Lines for Saugus–Tidal 8 Route

1955 April–May	1961 March–May	1964 March–June	1968 April–August
L15577	L18299	L19752*	L21723
	L18296		L21739
	L18364		L21731
			L21729

*X 898 – 1171 USGS (1 km) tied using L19781.

Saugus is consistent with the two well records if the decline in the water table in the surficial alluvial aquifer is applied to the deeper Saugus aquifer. The latter is a thicker, and presumably more compressible, fine-grained aquifer. Problems in estimating BM subsidence without local measurements of the aquifer compressibility and well drawdown, however, are evident from Figure 3. While BM X 898 has remained fairly stable with respect to sea level, BM 1171 USGS, just 1 km away, subsided 50 mm during 1955–1964. Varying displacement of adjacent BMs renders subsidence estimation imprecise, if not tenuous.

Conclusion

In sum, we agree with *Reilinger* [this issue] that the reference BM at Saugus (X 898) used by *Stein et al.* [1986] was inadequate because of subsidence caused by groundwater withdrawal, and we are grateful that he has brought this to our attention. We find that BM X 898 subsided 20±16 mm with respect to sea level during 1955–1964 and 1±16 mm for the period 1955–1968. Here we assume a random error of $(2S)^{1/2}$, where S is the one-way distance in kilometers and the error is in millimeters, a residual rod calibration error of 12 ppm $\times H$ based on *Stein* [1981], where H is the ele-

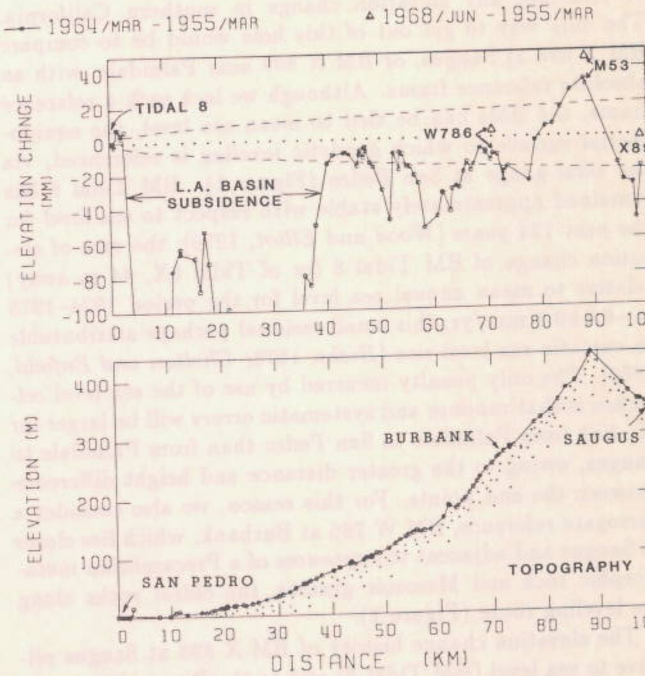

Fig. 3. (Top) Profile of elevation change from BM Tidal 8 (0 km) to BM X 898 (98 km), with 1-sigma random error envelope dashed. (Bottom) Route topography.

vation difference in meters; and a residual refraction error of 24 ppm×H, based on the discrepancy between the observed and predicted refraction error in the 1981 leveling experiment reported by *Stein et al.* [1986]. The elevation change of BM N 899 near Palmdale with respect to sea level for the period 1955–1964 is then 44±34 mm, and for 1955–1965/1968 it is 64±34 mm, larger but less significant (90% level of confidence) than our previously reported estimate of 53±16 mm for 1955–1965. The more important conclusion of our work is, however, unchanged: that the refraction correction reduced the observed 150-mm elevation change by 60%.

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