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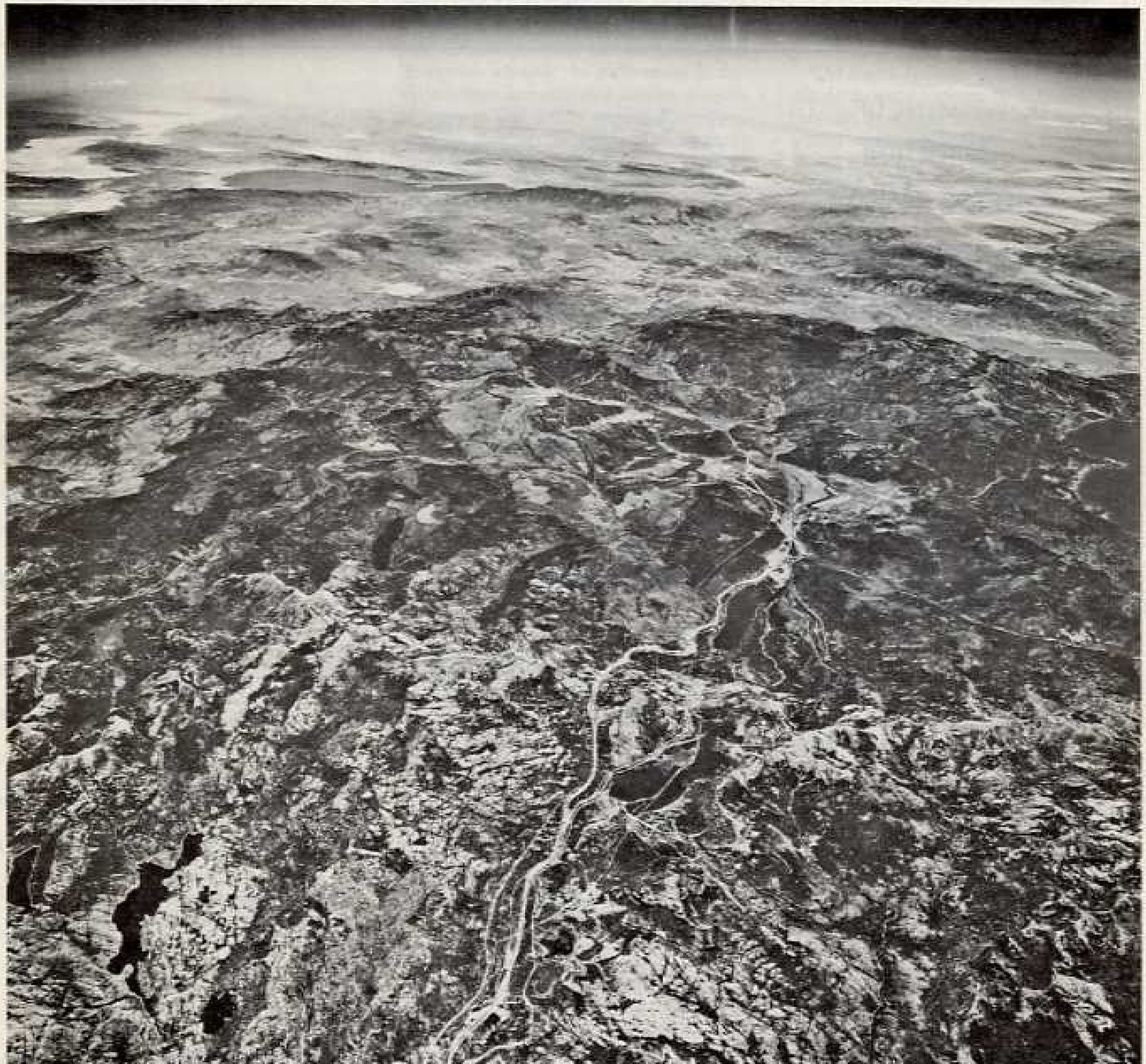

CRUSTAL MOVEMENT IN THE NORTHERN SIERRA NEVADA

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Figure 1. Location map showing outline of Sierra Nevada geologic province, the route of the leveling surveys and area (100 km radius from Alta) for which epicenters are plotted.

INTRODUCTION

Repeated precise leveling surveys across the Sierra Nevada at Donner Summit since 1912 reveal vertical crustal deformation within the Sierra Nevada province (figure 1). The observed elevation changes are generally closely associated with known faulting or contacts between major structural units (figure 2). On the western Sierra Nevada slope, vertical deformation is clearly localized in the immediate vicinity of the Melones fault zone near Alta. Significant elevation changes are also evident near the intrusive contact between metamorphic rocks of the Paleozoic Shoo–fly Formation and the Mesozoic granitic rocks of the Sierra Nevada batholith near Emigrant Gap. To the east of the Sierra Nevada, geologically recent movements have occurred within the Basin and Range Province between Truckee and the California–Nevada state line. Within the Sierra Nevada the observed elevation changes have not been associated with significant seismic activity and are thus attributed mainly to aseismic deformation. Near the eastern front of the Sierra Nevada, however, the observed differences are probably related to Quaternary faulting and the more pronounced seismic activity that has occurred in this region since 1900 (figure 3).

Significantly, the sense of movement indicated by the leveling surveys has not been consistent; indeed, distinct reversals have occurred which suggest that periodic adjustments between major structural units may be the "normal" regimen of movement. The time elapsed between successive surveys spans too many years to determine whether the differences in elevation have accumulated during periods of more or less steady state deformation, whether they are the result of short–term episodic events, or are a combination of these. The observed elevation changes represent the condition at the time of the survey, and may not be the maximum changes that have occurred between surveys.

Aseismic and possibly episodic crustal movement evidenced by these and similar geodetic data elsewhere in California suggests that deformation of this nature may be common, and that our limited awareness of this behavior may reflect the lack of comparative geodetic data. The recently reported uplift near Palmdale in southern California (Castle and others, 1976) may in fact be a similar expression of "normal" processes of crustal adjustment. Most of the uplift near Palmdale developed over a brief period during the early 1960s without any unusual seismic activity. Castle and others (1976) also report that near the turn of the century, uplift possibly amounting to as much as 0.5 meter was indicated by leveling surveys in the Transverse Ranges and that subsequent releveling indicated this uplift had largely dissipated without significant seismic activity. Episodic vertical movement of a similar nature also occurred near Long Beach between 1928 and 1931 (Leypoldt, 1937), which may or may not have been related to the 1933 Long Beach earthquake (magnitude = 6.3).

Thus, while the long–term trend of vertical movement in the northern part of the Sierra Nevada and other tectonically active areas of California may be one of gradual uplift, this consequence may derive from countless varied and predominantly aseismic adjustments between major individual structural units. Perhaps it is only when these adjustments can not be accommodated either by fault creep or plastic deformation that brittle failure accompanied by seismic activity occurs along zones of weakness.

GENERAL GEOLOGY

The Sierra Nevada is a strongly asymmetric mountain range, fault bounded on the east by a high steep escarpment and with a broad gentle slope on the west. A 30–60 kilometer (km) wide zone of fault–bounded Paleozoic and Mesozoic metamorphic rocks occupies the western foothill region, extending some 320 km from Mariposa northward to Chico. This zone lies between the granitic rocks of the Sierra Nevada batholith on the east and is overlapped by unmetamorphosed volcanic and sedimentary Tertiary strata on the west.

Structurally, the metamorphic belt is not well understood but can be generalized in terms of four structural blocks separated by reverse faults, dipping steeply eastward, along which progressively younger metamorphosed sediments have been thrust beneath older metamorphosed sediments (Clark, 1976; figure 2). Direct evidence of the amount of vertical and horizontal movement and age of these major fault zones is lacking. However, most of the deformation in this region is older than the Sierra Nevada batholith (± 125 million years) indicating that this has been a major structural zone of deformation since pre–Jurassic time.

The highly deformed Paleozoic and Mesozoic metamorphic rocks of the western Sierra Nevada belt are covered, in part, by extensive westward dipping deposits of Tertiary volcanic tuffs and breccias that form an acute angular unconformity on a Tertiary erosion surface preserved in the underlying foliated metamorphic rocks. Little or no evidence of fault offset has been reported in these Tertiary units where they overlie any of the fault zones that bound the major structural blocks of metamorphic rocks. However, relative elevation changes described in the present paper are confined to or closely associated with these fault zones.

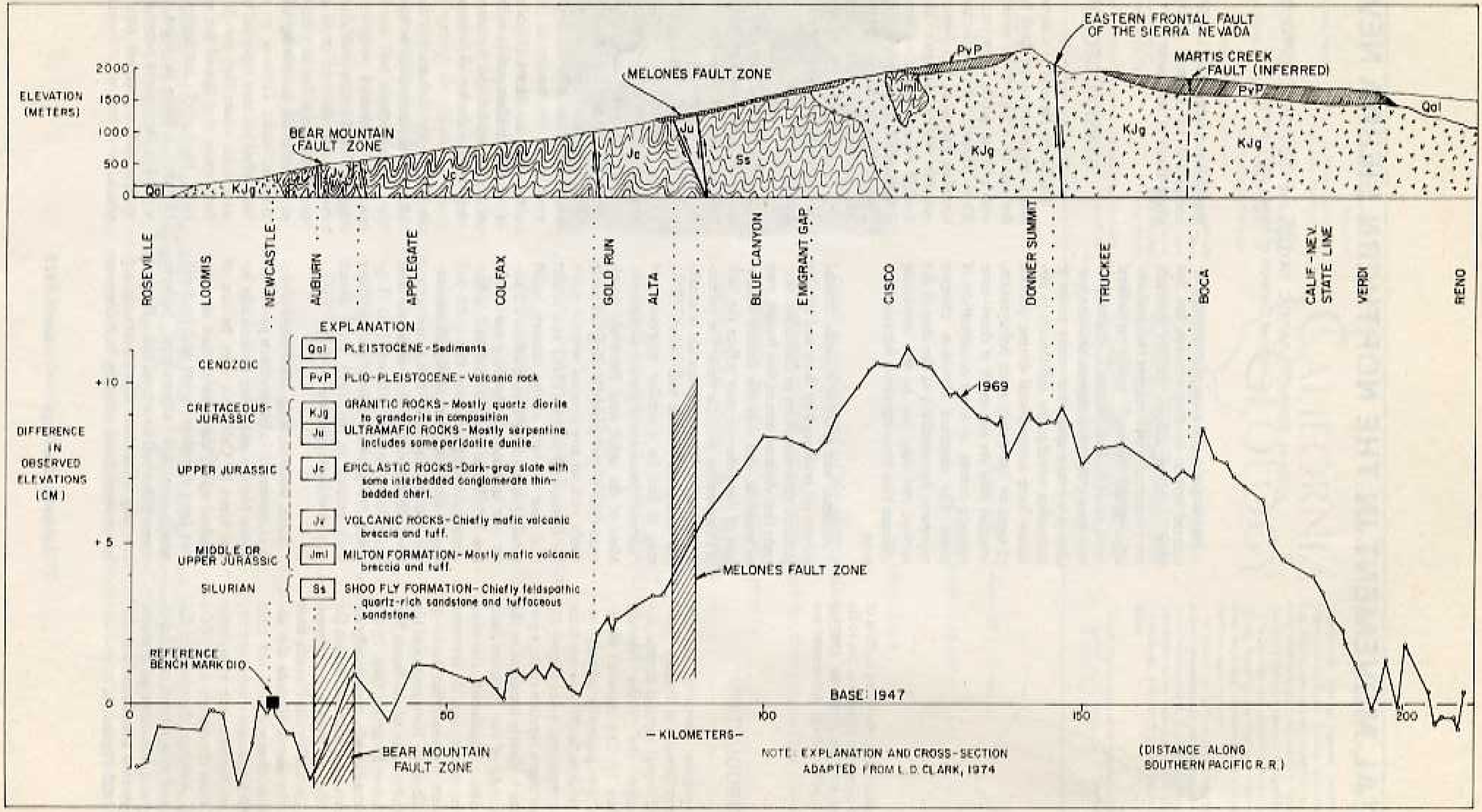
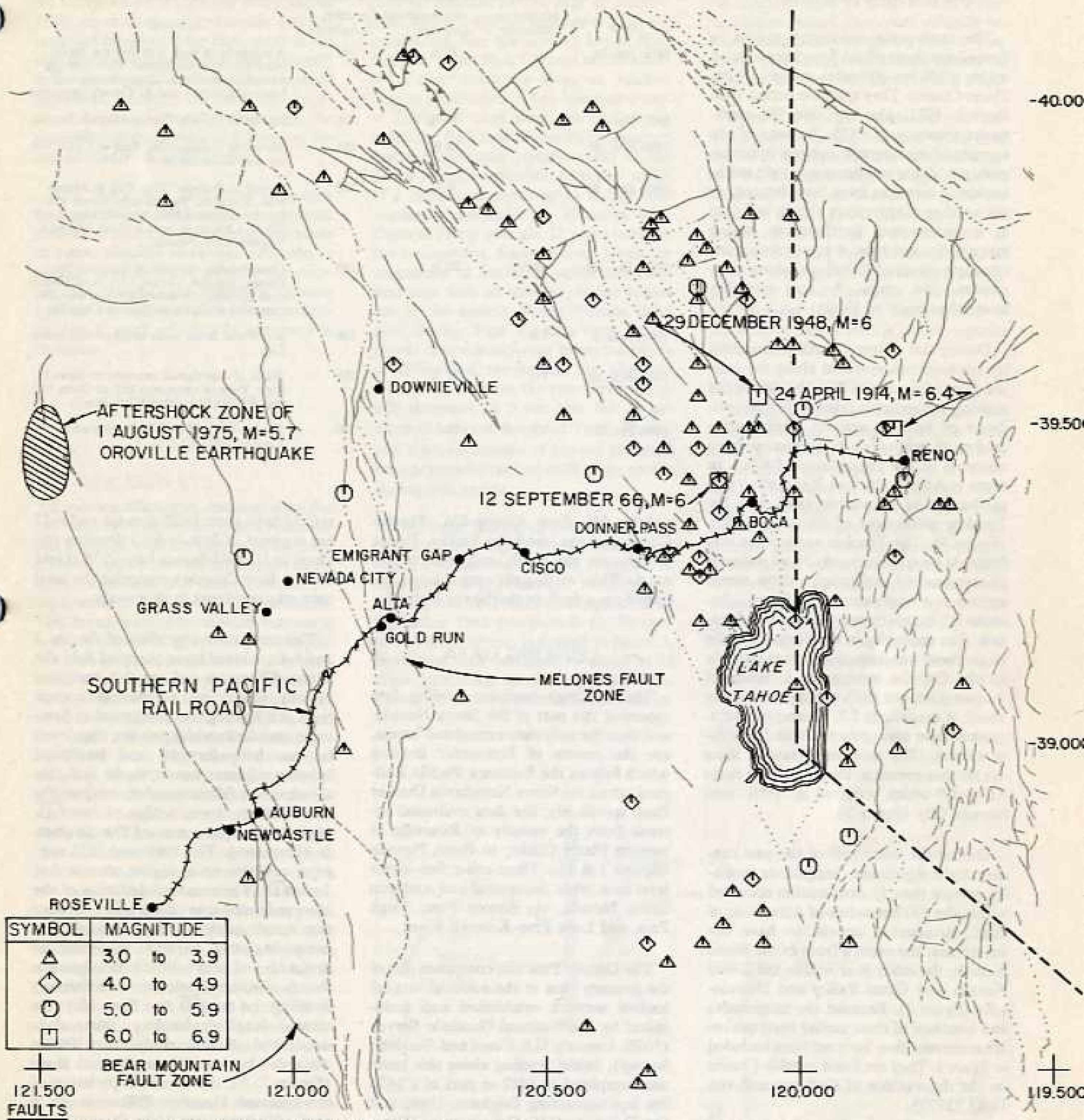


Figure 2. Profiles from Roseville, California, to Reno, Nevada showing topography, generalized geology, and differences in elevations observed between leveling surveys in 1947 and 1969. Differences in elevation are based on an assumed constant elevation of bench mark D10 near Newcastle.



SYMBOL	MAGNITUDE
△	3.0 to 3.9
◇	4.0 to 4.9
⊙	5.0 to 5.9
□	6.0 to 6.9

FAULTS

FAULT TRACES ARE INDICATED BY SOLID LINES WHERE WELL LOCATED, BY DASHED LINES WHERE APPROXIMATELY LOCATED OR INFERRED, AND BY DOTTED LINES WHERE CONCEALED BY YOUNGER ROCKS OR BY LAKES OR BAYS. FAULT ALONG WHICH HISTORIC (LAST 200 YEARS) DISPLACEMENT HAS OCCURRED SHOWN BY HEAVY LINE.

Figure 3. Earthquake epicenters located within a 100 kilometer radius of Alta, California from 1900 through 1971, plus the 1975 Oroville earthquake sequence.

REGIONAL SEISMICITY

The earthquake epicenters shown in figure 3 are those which have been located within a 100 km (60 mile) radius of Alta, Placer County. They span the period 1900 through 1971, plus the Oroville earthquake sequence of 1975. Because of the scarcity of seismograph stations in the region, not all the smaller magnitude earthquakes in this area have been located, so the number of epicenters shown in figure 3, is incomplete. Earthquakes having magnitudes less than 4 are probably incomplete prior to 1950; those having magnitudes less than 5 are probably incomplete prior to 1930.

During this century, earthquake activity has been concentrated along the eastern front of the Sierra Nevada, where the striking topographic relief is further evidence of tectonic activity. Three earthquakes of magnitude 6 or greater have occurred in the region since 1900: an event in April 1914 near Reno, the Verdi earthquake of December 1948, and the Truckee earthquake of September 1966 (figure 3). The Truckee earthquake was followed by approximately 50 aftershocks of magnitude 3 and greater; these events appear as a single symbol in figure 3 because of their common epicentral location. The seismicity in the Sierra foothills to the west was dominated most recently by the Oroville earthquake sequence of August–October 1975 which had a main shock of magnitude 5.7. Damaging earthquakes have also occurred within the Sierra block. The most important of these are the two events in the magnitude range 5.0 to 5.9 which occurred in 1909 near Nevada City (figure 3).

During the latter half of the past century, eight significant (magnitude probably greater than 5) earthquakes occurred within the 100 km radius of Alta. Four of these earthquakes appear to have occurred near the eastern front of the Sierra Nevada; the other four within the Sierra Nevada near Grass Valley and Downieville (figure 3). Because the magnitudes and locations of these earlier earthquakes are uncertain, they have not been included in figure 3. They are listed in table 1 based on the descriptions of Coffman and von Hake (1973).

A significant earthquake outside the area considered occurred on 10 April 1881 in the Stockton–Modesto area. Coffman and von Hake (1973) assigned an approximate location at latitude 38° N and longitude 121° W. The shock was widely felt from Greenville, Plumas County, on the north, to Visalia, Tulare County, on the south, and west to the coast. This earthquake may have occurred on a fault in the Sierra foothills.

Table 1. Pre-1900 Earthquakes Within 100 Kilometer Radius of Alta, Placer County

Date	*Maximum Intensity*	*Approximate Location Latitude*	*Longitude*	*Remarks*
1855, Jan. 24		39 ½	121	A pinnacle of rock was thrown down from Downieville Buttes. Felt strongly from Gibsonville to Georgetown and Nashville, Sierra and El Dorado counties.
1867, Dec. 1		39 ½	121	Strong at Nevada City, no details known.
1869, Dec. 20		39 ½	121	Severe at Downieville. Felt at Grass Valley and Sacramento.
1869, Dec. 26		39 ½	120	Strong at Railroad Flat. Felt at Marysville, Stockton, Sacramento, Grass Valley, Mokelumne Hill, Nevada City, and Chico, California, and at Gold Hill and Virginia City, Nevada.
1869, Dec. 27	VI–VII	39 ½	120	Considerable damage at Virginia City, Genoa, Dayton, Carson City, and Steamboat Springs, Nevada. Damage was also reported at Downieville and Oroville.
1887, June 3	VII	39	120	Stone and brick walls cracked in Carson City.
1888, Apr. 28	VII	39 ½	121	Walls of courthouse cracked at Nevada City. Tops of chimneys fell at Grass Valley. Felt as far as San Francisco.
1896, Jan. 27	VI	39	120	Plaster fell and buildings cracked in Carson City.

LEVELING DATA

The only high–precision leveling data spanning this part of the Sierra Nevada, and thus the only data considered herein, are the results of first–order leveling which follows the Southern Pacific Railroad across the Sierra Nevada via Donner Pass; specifically, the data evaluated extends from the vicinity of Roseville in western Placer County to Reno, Nevada (figures 1 & 3). Three other first–order level lines cross the central and southern Sierra Nevada, via Sonora Pass, Tioga Pass, and Lone Pine–Kaweah River .

The Donner Pass line comprises one of the primary lines in the national vertical control network established and maintained by the National Geodetic Survey (NGS, formerly U.S. Coast and Geodetic Survey). Initial leveling along this route was completed in 1912 as part of a 1434 km line connecting Brigham, Utah, and San Francisco (U.S. Department of Commerce, 1914). Subsequent releveling across the Sierra Nevada via this route was completed in 1947 and 1969. Portions of the line were releveled by the NGS in 1938 (Roseville to Gold Run) and 1953 (Emigrant Gap to Cisco). The data resulting from these NGS surveys and a 17 km segment of first–order releveling initiated by CDMG during June 1976 (Gold Run to Blue Canyon) comprise the total data set considered in this study.

The comparative profiles of figures 2 and 4–6 are based upon observed field elevation differences and are thus unbiased by any subsequent adjustment corrections. All leveling was performed to first–order standards which require that levels be run both forward and backward between adjacent bench marks and that the elevation differences derived from the two levelings agree within 4 mm$\sqrt{D}$ (4mm x the square root of the distance, in kilometers). The 1969 and 1976 surveys conform to a higher standard of 3 mm$\sqrt{D}$. The standard deviation of the observed elevation difference between two bench marks is about 1mm$\sqrt{D}$; in comparing two surveys the standard deviation of the difference between the two observed elevation differences is about 1.4 mm$\sqrt{D}$. Thus, for the most lengthy leveling comparison considered in this study, the 200 km distance – between Roseville and Reno (figures 2, 3), the standard deviation of the observed elevation difference for a particular survey would be about 15mm; for the difference between two surveys, about 20mm.

Evidence of systematic errors in precise leveling are often most readily detected by comparing observed elevation changes with the corresponding topographic profile as shown on figure 2. With the possible exception of the partial releveling of 1938, no evidence of systematic error is apparent in any of these data; most of the significant changes occur within relatively limited horizontal sections. The required agreement between forward and backward levelings virtually eliminates the possibility of these vertical differences being attributed to gross error.

This study was concerned primarily with evidence of differential movement within the Sierra, so no attempt was made to assess absolute elevations (relative to sea level datum). For each of the comparative profiles, the elevation changes between surveys are relative to a particular bench mark selected as invariant in elevation.

COMPARATIVE ELEVATION CHANGES

1947–1969 SURVEYS

Elevation differences resulting from the 1947 and 1969 surveys between Roseville and Reno, Nevada are compared in figure 2. Elevations for the two surveys are based upon bench mark D10 near Newcastle being arbitrarily held invariant in elevation. This bench mark was selected because it is one of the few original 1912 marks that has been preserved and included in each of the subsequent surveys, and because of its apparent relative stability with respect to several adjacent bench marks. In fact, one of the most significant conclusions to be drawn from the comparative data shown in figure 2 is the virtual absence of *any* relative elevation change over the entire 70 km distance from Roseville to near Gold Run. Except for the area of slight depression centered near Auburn, there is no more than 1 centimeter ± of relative elevation difference between the two surveys over this entire segment during this 22–year period. Although the magnitude of the elevation differences are very small, the segment within which several marks are depressed near Auburn coincides remarkably well with foliated metavolcanic rocks which apparently comprise the northern extension of the Bear Mountain fault zone (figure 3).

Just west of Gold Run, however, and in the immediate vicinity of the fault contact between rocks of Mesozoic age and the Paleozoic Calaveras Formation, relative uplift if indicated by the 1969 survey (figure 2). About 3 cm of positive elevation change accrues over the 10 km distance from this contact to the community of Alta at the western boundary of the Melones fault zone. Easterly of the fault an obvious increase in the rate of relative uplift occurs, with an additional 5 cm accumulating over the next 15 km to Blue Canyon. From Blue Canyon northeasterly to near Emigrant Gap, no relative change is indicated. A few kilometers east of Emigrant Gap near the contact between the Paleozoic Shoo–fly Formation and the Mesozoic granitic rocks of the Sierra Nevada batholith, a further uplift of 3 cm occurs resulting in a total and maximum difference in elevation near Cisco of 11 cm over the 22 years between the two surveys. Easterly from Cisco the magnitude of indicated uplift gradually decreases with no obvious change apparent at the eastern Sierra Nevada front near Donner Pass. Easterly from an apparent discontinuity near Boca, indicative of differential movement, the observed differences between the two surveys rapidly decreases by 9 cm over the 25 km distance between Boca and Verdi. The result is a total absence of any *net* elevation change between the two ends of the profile during this period.

Two large damaging earthquakes occurred in this region during the period between these two surveys: The Verdi earthquake of 29 December 1948 (magnitude 6), and the Truckee earthquake of 12 September 1966 (magnitude 6). Epicenters of these events, indicated in figure 3, show that both earthquakes occurred in close proximity to this leveling line. Therefore, it seems reasonable that the indicated movement near Boca–Verdi could be attributed to strain release accompanying either or both of these events. From the seismic record, there was virtually no major seismic activity during this 22–year period which might account for the movement on the western Sierra Nevada slope.

There is a similarity between the relative uplift occurring between Gold Run and Blue Canyon on the western slope and the corresponding changes between Boca and Verdi near the eastern end of the level line (figure 2). At both locations, the magnitude of change is on the order of 8–9 cm occurring over a distance of 20–25 km. A corresponding symmetry is suggested in the comparison of the 1912–1947 surveys (figure 4), but the sense of the relative movements is in the opposite direction.

1969–1976 SURVEYS

Noting the apparent change in the rate of indicated uplift occurring in the vicinity of the Melones fault zone near Alta, as evidenced by the data in figure 2, the Division of Mines and Geology initiated releveling of the segment between Gold Run and Blue Canyon during June 1976 to determine whether any additional evidence of movement was indicated since the 1969 survey. The data resulting from this most recent survey are shown in figure 5 together with an enlarged plot of the 1947–1969 comparative data in this area. For purposes of this comparison, bench mark D569 near Gold Run was assumed to have remained at constant elevation.

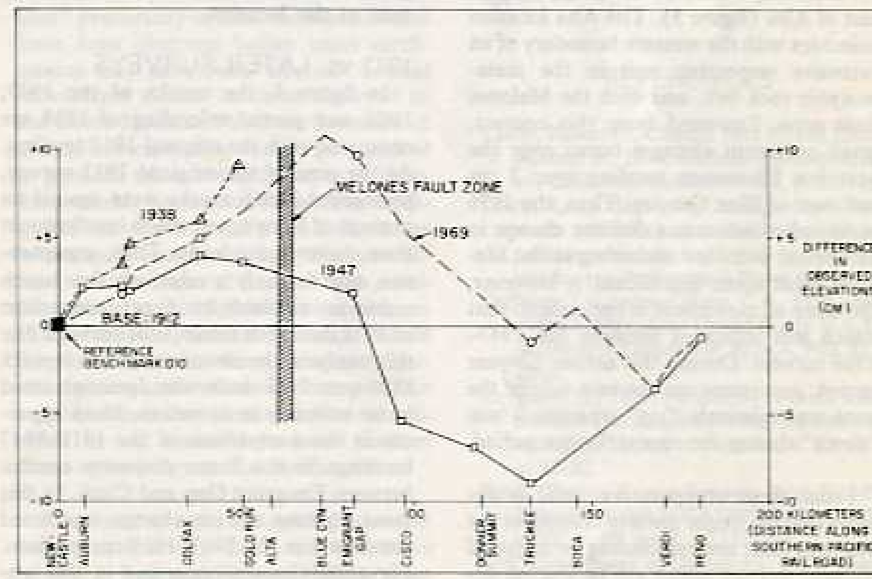


Figure 4. Comparative leveling profiles indicating differences between observed elevations from Newcastle to Reno, Nevada, derived from levelings surveys in 1912, 1938, 1947, and 1969. Elevation differences are relative to bench mark D10 near Newcastle.

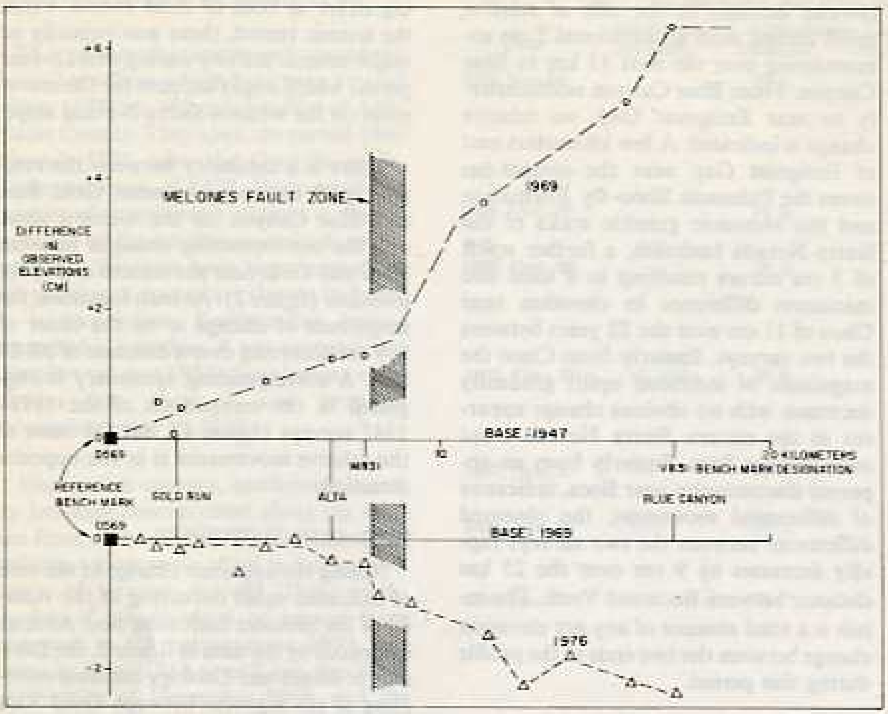


Figure 5. Differences in observed elevations in the vicinity of the Melones fault zone near Alta, California, derived from leveling surveys in 1947, 1969, and 1976. Elevation differences are relative to bench mark D569 near Gold Run.

were in the 1947–1969 comparison) in the Basin and Range Province between Truckee and the state line. As in the 1947–1969 period, significant *net* differential change between the two ends of the profile is absent.

Only a few bench marks common to the 1912 and 1947 surveys had survived by 1969 to provide a direct comparison of the 1912 and 1969 surveys. However, by taking the differences between the 1947 and 1969 surveys at a few selected locations, the general configuration of the 1912–1969 survey comparison is constructed as shown in figure 4. Again, relative change between the west end of the profile at Newcastle and the state line is nil, while additional evidence of deformation or tilting is indicated within the Sierra Nevada.

The significance of the data from the partial 1938 survey is uncertain. Taken at face value, this survey suggests approximately 9 cm of gradual uplift or tilting of the block between Newcastle and Gold Run over the period 1912–1938, but the possibility of systematic error in the 1938 data cannot be precluded.

The most significant change indicated in the 1912–1947 comparison is the dramatic change of 7 cm evidenced between Emigrant Gap and Cisco (figure 4). The NGS releveled this relatively short (14 km) segment in 1953 to confirm this obvious difference between the 1912 and 1947 leveling. The results of the 1947, 1953, and 1969 surveys within this section are compared in figure 6. Elevation differences are based upon an assumed constant elevation of bench mark 010 at Emigrant Gap. Significantly, the 1953 releveling revealed differences of up to 3 cm compared with the leveling of 1947 just 6 years previous, with the sense of movement *opposite* to the 7 cm change that was indicated during the earlier 1912–1947 period. During the ensuing 16 years, between the 1953 and 1969 surveys, no appreciable change is indicated. Thus, the 3 cm change between Emigrant Gap and Cisco from 1947 to 1969 (figure 4) evidently occurred during the 6-year period 1947–1953.

On 29 December 1948, during the period between these two surveys, (1947–1953), the previously noted magnitude 6 earthquake occurred near Verdi. This event was preceded by several foreshocks, the strongest of which was reported two days earlier, on December 27. This foreshock was recorded as follows: "Felt with greatest intensity at Emigrant Gap (Lake Spaulding) where there was visible sway-

The June 1976 releveling produced no evidence of relative elevation change (in excess of a few millimeters) over the westerly 8 km from bench mark D569 northeasterly to bench mark M831 just east of Alta (figure 5). The Alta location coincides with the western boundary of an extensive serpentine unit in the metamorphic rock belt, and with the Melones fault zone. Eastward from this contact, small persistent changes occur over the next few kilometers totaling over 2 cm just west of Blue Canyon. Thus, the 1976 survey also indicates a definite change in movement behavior occurring at the Melones fault zone. Significantly, however, the sense of movement is opposite to that which was indicated between the 1947–1969 surveys. During this earlier 22-year period, movement on the east side of the zone was relatively "up" whereas it was "down" during the recent 7-year period.

From these comparative data, it appears that the major units in contact at the Melones fault are responding to imposed regional stresses which are producing deformation (strain), or tilting, about an axis coincident with this major zone of weakness. These limited data do not clearly indicate, but neither do they preclude, the possibility of a component of vertical offset occurring within this broad fault zone. To establish a more detailed base for future releveling measurements, additional, closer-spaced, bench marks are planned across the entire Melones fault zone at this location.

1912 vs. LATER SURVEYS

In figure 4, the results of the 1947, 1969, and partial releveling of 1938 are compared with the original 1912 leveling. At the time of the original 1912 survey, permanent bench marks were spaced an average of 8 km apart, much less frequent than current standards. Thus, comparative data for only a relatively few bench marks are available for direct comparison of 1912 data with subsequent surveys. For this analysis, the elevation of bench mark D10 near Newcastle was again assumed to be invariant in elevation. Most apparent in the comparison of the 1912–1947 levelings is the 7 cm disparity evident between Emigrant Gap and Cisco. In this same segment a 3 cm change was noted previously in the 1947–1969 comparison. Elevation changes occurring in this segment are discussed later in greater detail. Although the location is not well defined, elevation differences of magnitude corresponding to those occurring near Emigrant Gap are again indicated (as they ing of buildings and trees, floor lamps, Christmas trees, pictures on walls, and doors. Distant roaring subterranean sounds heard at time of shock." (U.S. Department of Commerce, 1948). Although this foreshock was assigned the same epicentral location as the subsequent main shock, the greatest intensity was reported at Emigrant Gap nearly 60 km to the southwest. It is uncertain whether there was sympathetic movement or some other relation between the seismic activity in the Truckee–Verdi area and the vertical movements in the Melones–Emigrant Gap area.

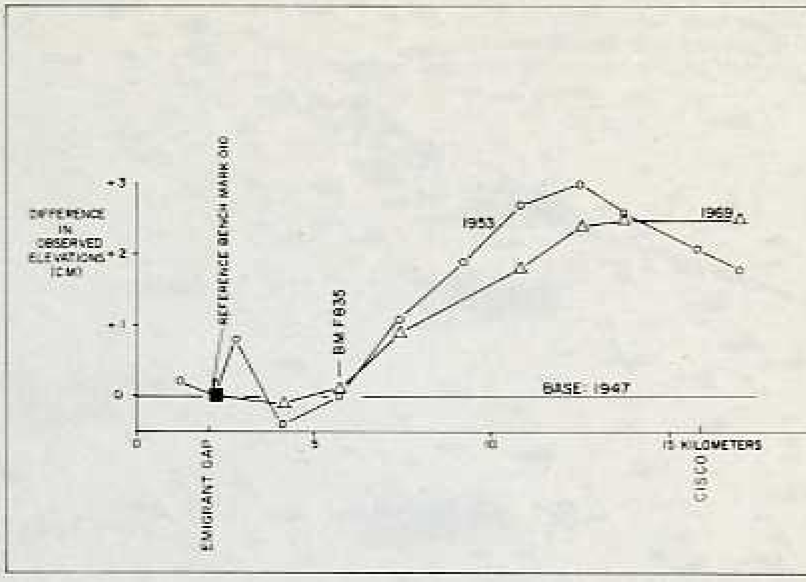


Figure 6. Comparative profiles indicating differences in observed elevations resulting from releveling between Emigrant Gap and Cisco, California, derived from leveling surveys in 1947, 1953, and 1969. Differences in elevation are relative to bench mark 010 at Emigrant Gap.

Bench marks added during the 1947 survey enable the location and configuration of the apparent deformation near Emigrant Gap to be examined. Although no surficial evidence of a major fault contact has been noted at this location, a contact between metamorphic and intrusive rocks exists. The leveling data suggest a possible vertical offset or axis of flexure similar to that indicated at the Melones fault occurring near bench mark F835 (figure 6). The proximity of this location to the contact between metamorphic rocks of the Paleozoic Shoo-fly Formation and the Cretaceous granitic rocks strongly suggests a possible correlation.

CONCLUSIONS

Relative elevation changes having a variable sense of movement are closely assoicated with the Melones fault zone and other known faults or structural contacts in the northern Sierra Nevada. Whereas elevation changes near the eastern front of the Sierra Nevada are probably related to the occurrence of frequent local earthquakes, similar changes within the Sierra block are not clearly related to seismic activity.

These movements imply strain accumulation and strain release; when the imposed stresses are not released by aseismic deformation and when they exceed the strength of the crust, the weakest zones will rupture by faulting to relieve the accumulated strain. Therefore, wherever current crustal movement is observed to be associated with known faults, those faults should be regarded as potentially active even though seismic activity or surficial geological evidence may be lacking.

Whether these changes within the Sierra Nevada have occurred as distinct episodic strain events or whether they reflect more gradual variations in the regional strain field is uncertain. Whatever the exact nature of the movement and whatever the causative forces may be, crustal movements of significant magnitude may be normal in tectonically active areas and may not necessarily precede earthquakes.

The knowledge that aseismic crustal movements occur in California bears upon current efforts to develop effective earthquake predictions. The "anomalous" precursory crustal movements that have been observed before some earthquakes may have been "normal" crustal movements similar to those observed in the Sierra Nevada. The mere detection of crustal movements by various geophysical or geodetic measurements may not, therefore, reliably portend an impending earthquake but may only suffice to define areas where more intensive geophysical surveillance will be required to detect the *possible* onset of crustal failure which produces the earthquake. Greater attention should be given to understanding those geophysical "anomalies" which do not produce earthquakes and are written off as inexplicable or are assumed to have resulted from some instrumental malfunction.

The recently reported uplift (Palmdale bulge) in Southern California (Castle *et al.*, 1976; Real and Bennett, 1976), most of which appears to have occurred during relatively brief episodes, affords an opportunity to assess the ultimate consequences of a very significant crustal upheaval. To date, this uplift has produced no unusual seismic activity other than, possibly, the magnitude 6.4 San Fernando earthquake of 1971 which relieved accumulated strain over only a small fraction of the entire uplift region (Thatcher, 1976). Should the nature of the movements exhibited in the northern Sierra Nevada be characteristic of crustal movements in southern California, the Palmdale uplift may one day subside as unobtrusively as it appeared.

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