EXTENT AND OFFSET HISTORY OF THE BEN LOMOND FAULT SANTA CRUZ COUNTY, CALIFORNIA

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ABSTRACT

Detailed mapping of geology and Bouguer gravity has clarified both the location and history of the Ben Lomond fault in Santa Cruz county, California. The fault extends at least 10 km farther south than previously thought, passing through the city of Santa Cruz and probably offshore into Monterey Bay. The fault plane is vertical to steeply east-dipping and strikes generally north-south to N20°W. Vertical separation is down to the east; no evidence of horizontal separation has been observed.

Geology and gravity data show that a 10- to 12-m.y.-old nonconformity between Cretaceous granitic basement and the overlying Santa Margarita Sandstone is offset vertically about 200 m by the fault. However, a 5.9-m.y.-old vitric tuff in the Purisima Formation is offset vertically only about 3.3 m; we conclude, therefore, that most of the movement on the fault occurred prior to 5.9 m.y. ago. Most of the displacement on the Ben Lomond fault probably took place during deposition of the Santa Margarita Sandstone in the middle to late Miocene (9 to 12 m.y. ago), because isopachs of this sandstone are generally parallel to the fault and the sandstone thickens dramatically near the fault.

A very small offset of 3 cm in a Pleistocene marine terrace shows that the latest movement on the Ben Lomond fault occurred about 85,000 years ago. There is little evidence of earthquakes and no evidence of Holocene offset along the fault. Therefore, compared to the nearby San Andreas and San Gregorio-

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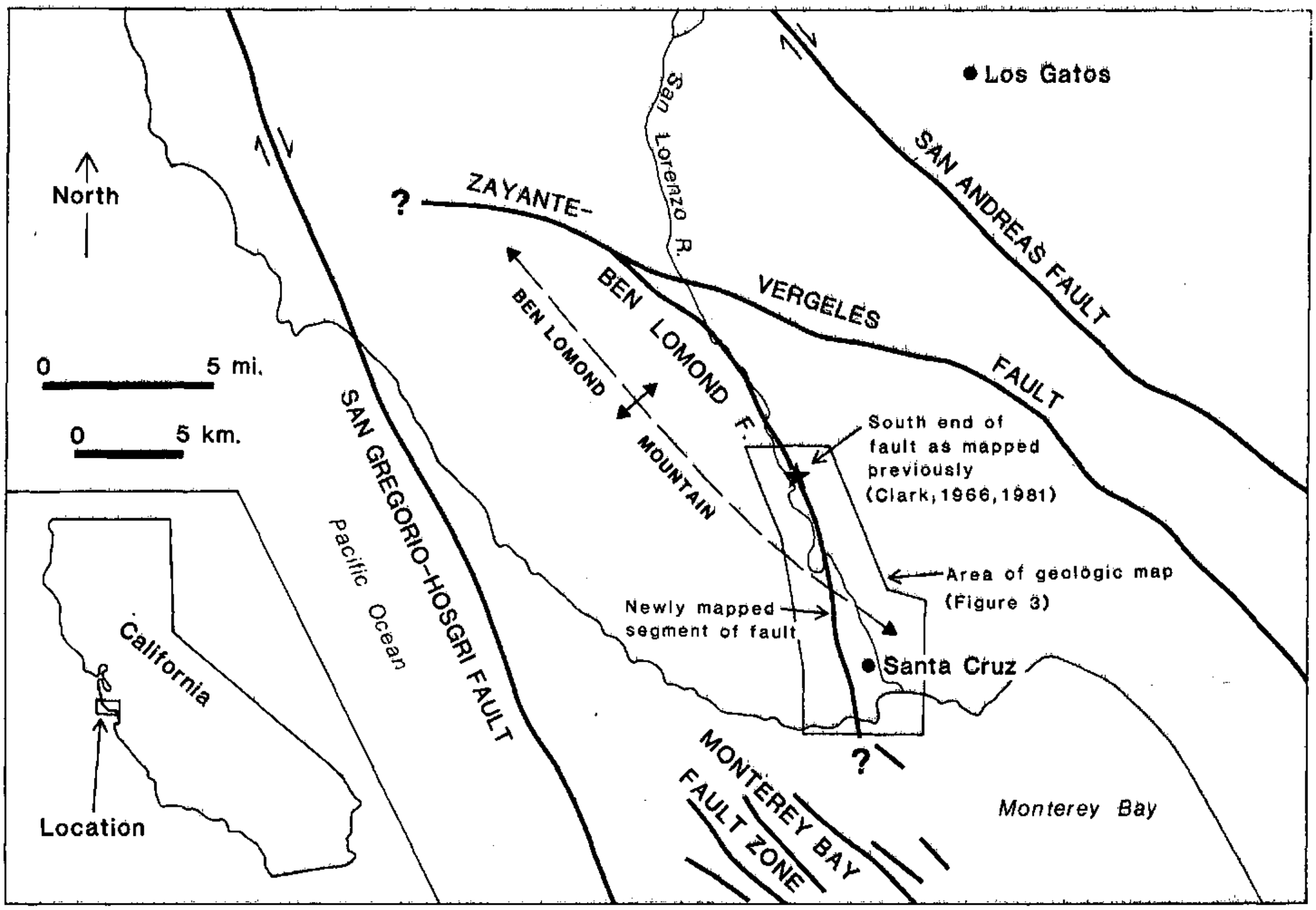

Figure 1. Location map, showing major regional geologic structures.

Hosgri faults, the Ben Lomond fault is inactive.

INTRODUCTION

The Ben Lomond fault is a subsidiary fracture within the San Andreas fault system and is located in the Santa Cruz Mountains of central California, about 90 km south of San Francisco (Fig. 1). From its junction with the Zayante-Vergeles fault, the Ben Lomond fault trends southeastward in a broad arc that coincides more or less with the deeply incised valley of the San Lorenzo River.

Current controversy regarding the Ben Lomond fault focuses on two points. The first concerns the lateral persistence of the fault along strike to the southeast and whether the fault extends as far as the city of Santa Cruz. The prevailing view, as reflected in most published geologic maps of the region (e.g., Jennings and Burnett, 1961; Clark, 1966, 1981) is that the fault dies out in an area of dense forest and poor outcrop about 10 to 15 km north of Santa Cruz (Fig. 2). However, alternative interpretations have been proposed by Leo (1967) and by Hall and others (1974), who suggested on the basis of air photo interpretation

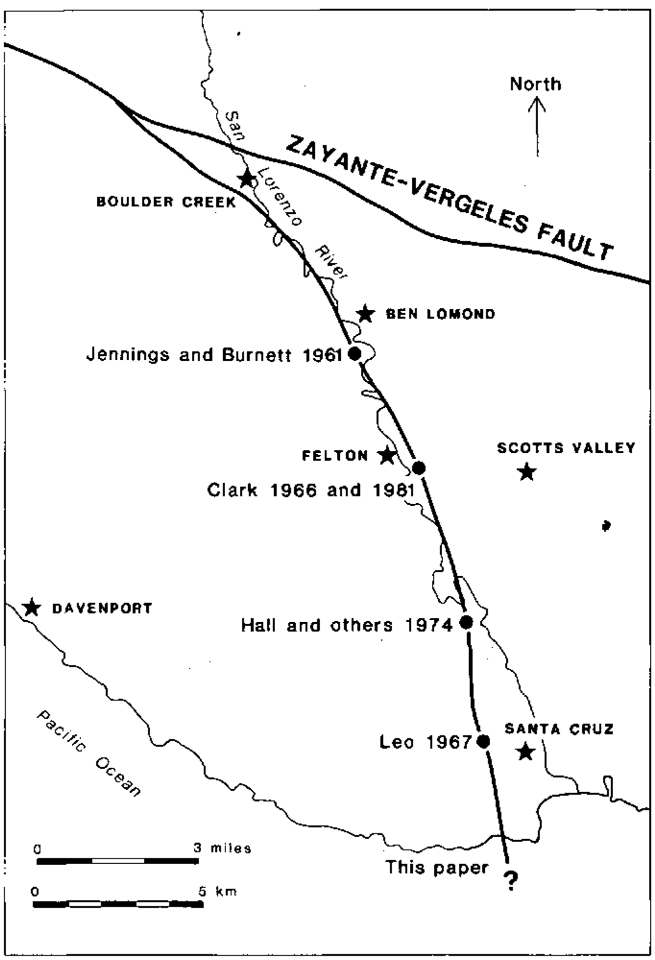

Figure 2. Locations of some previous interpretations of the southern end of the Ben Lomond fault, shown by filled circles. The southward extension of the fault proposed by us roughly doubles the length of the fault as mapped in the standard references on the geology of the area (Clark, 1966, 1981). The fault probably continues farther south into the offshore.

that the fault may extend at least a few kilometers farther south. Our studies support the latter view and indicate that the Ben Lomond fault continues south beneath the city of Santa Cruz and probably offshore into Monterey Bay.

The second point of controversy concerns the history of movement along the fault. Clark (1966, 1981) thought that the fault was active mainly during middle Miocene time, while others (e.g., Hall and others, 1974; Woodward-Clyde Consultants, 1981) have hypothesized that movement on the fault continued through the Pliocene and possibly into the Quaternary. New evidence, presented below, shows that major movement on the fault occurred prior to 5.9 m.y. ago, but that the most recent movement occurred about 85,000 years ago.

GEOLOGIC SETTING

The Santa Cruz Mountains consist mainly of Cenozoic sedimentary rocks that have been strongly folded and faulted by movements along the San Andreas fault system. In our study area (Fig. 3) the Cenozoic strata rest nonconformably on a crystalline basement of Cretaceous granitic rocks and pre-Cretaceous schist and marble. The Cenozoic strata include nine map units that range in age from Paleocene to Quaternary (Figs. 3, 4) and are described in detail by Clark (1981).

The geologic structure of the area is dominated by Ben Lomond Mountain, a basement-cored anticline plunging southeastward across the middle of the area (Fig. 1). The anticline is cut at an acute angle by the Ben Lomond fault, which trends from north-south to N20°W in our study area.

GEOLOGIC EVIDENCE

For most of its length the Ben Lomond fault is obscured by dense vegetation, Quaternary deposits, and urban development. However, the trace of the fault is marked by a number of linear topographic features observable on air photos and topographic maps. The most prominent of these features is a fault-line scarp about 5 km north of the coast (Fig. 3). The scarp is a linear eastward-sloping bluff, over 100 m high in places, that formed by differential erosion along the inferred fault contact between resistant basement rocks on the west and softer Miocene sedimentary rocks on the east. Farther north, about 10 km from the coast, another fault-line scarp occurs where steep slopes eroded in the Locatelli Formation adjoin the flat-lying alluvial deposits of the San Lorenzo River. Other geomorphic features that mark the trace of the fault include several small linear valleys, a notch in a ridge, and numerous springs and spring-related tufa deposits (Fig. 3). The nearly straight trace of the fault across ridges and canyons--including the 150-m-deep gorge of the San Lorenzo River--indicates that the fault plane is nearly vertical.

The Ben Lomond fault is rarely exposed in outcrop. One small exposure of the fault, located in a stream bank about 9 km north of the coast (Fig. 3), was created by erosion during unusually heavy rains on 4 January 1982. In this outcrop, the Ben Lomond fault is a vertical zone of fractures and gouge less than 50 cm wide separating sheared mudstone of the Locatelli Formation on the east from sheared granitic rocks on the west.

A second fault exposure that we infer to be the Ben Lomond fault occurs in the seacliff at the foot of

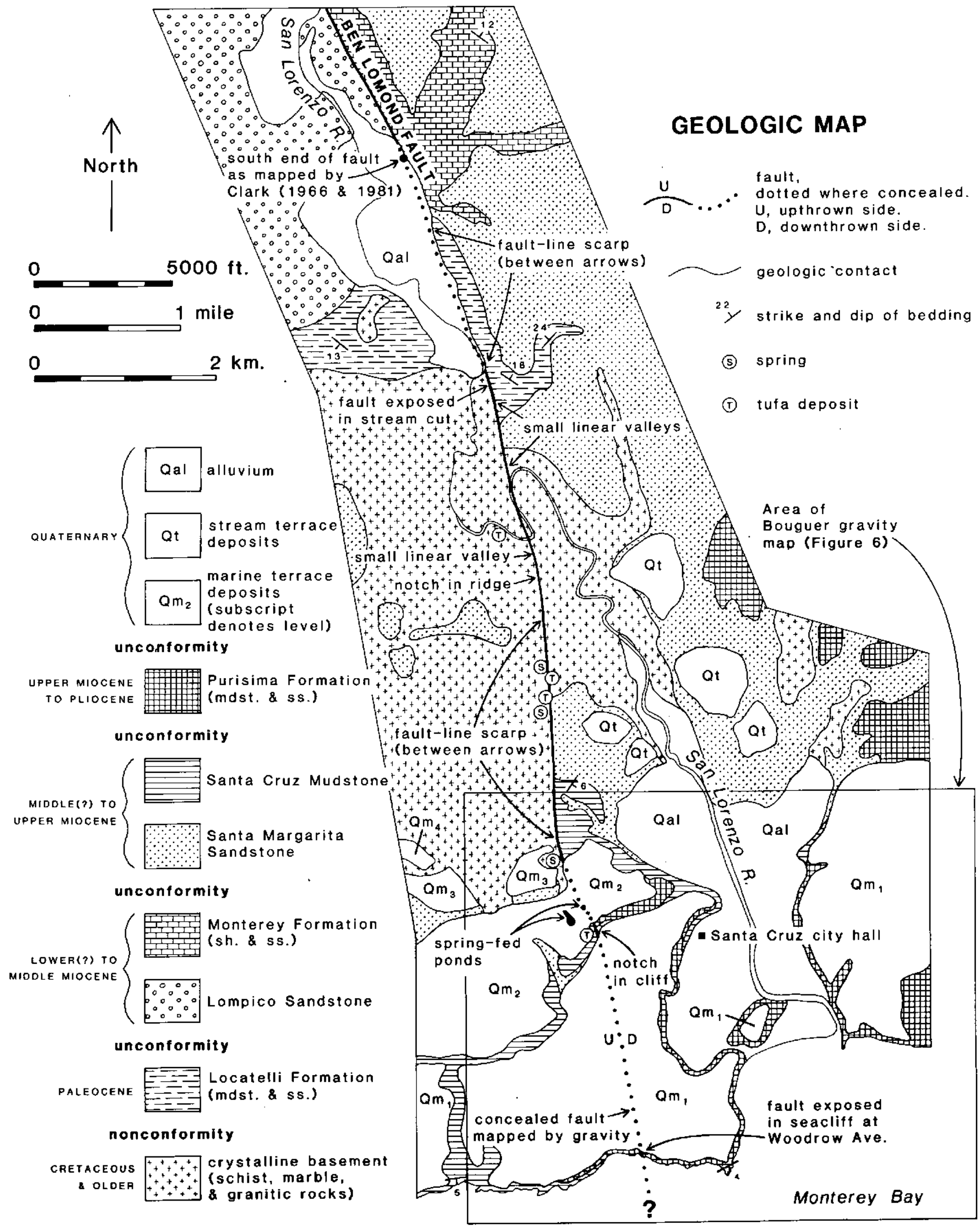

Figure 3. Generalized geology and fault-related geomorphology along the proposed southern extension of the Ben Lomond fault. Geology compiled and modified from Clark (1981) and Stanley (1982).

Woodrow Avenue in Santa Cruz (Figs. 3, 5). In this outcrop, the fault is a zone about 6 m wide of closely spaced fractures and gouge developed in mudstone of the Purisima Formation. The zone trends approximately north-south and consists of a series of fractures that are vertical to steeply east-dipping. Although several other small faults are visible in the seacliff nearby, we interpret this zone as part of the Ben Lomond fault because (1) it occurs nearly in the center of a gravity gradient, discussed below, that defines the trace of the Ben Lomond fault beneath Santa Cruz, and (2) it is the only exposed fault in the area of the gravity gradient that has the approximately north-south strike of the Ben Lomond fault (Fig. 5).

GRAVITY EVIDENCE

Within the city of Santa Cruz, we used a gravity survey to map the Ben Lomond fault beneath the cover of Quaternary deposits and urban development. More than 250 gravity measurements were made with a Lacoste-Romberg Model G gravimeter. As shown in Figure 6, most of the measurements were made in five traverses crossing the Ben Lomond fault, and the remainder were used to constrain the regional gravity field and complete the contours away from the detailed traverses. Station elevations were read from 1:1200-scale topographic maps obtained from the Public Works Department of the City of Santa Cruz. The contour interval on these maps is 2 ft (0.6 m), leading to a possible error in gravity of 0.2 mgal due to elevation. Relative errors along the five detailed traverses are much smaller (less than 0.1 mgal) because traverse elevations were obtained by hand-leveling. Simple Bouguer corrections were made using an infinite slab approximation and a reduction density of 2.0 g/cm^3, because this density is representative of the Cenozoic strata that lie between the gravity stations and the sea level datum over most of the area. Terrain corrections were not applied and are generally less than 0.3 mgal in the northwest part of the area (Fig. 6) and close to zero elsewhere. The total error in the gravity anomalies is at most 0.5 mgal, but generally it is less.

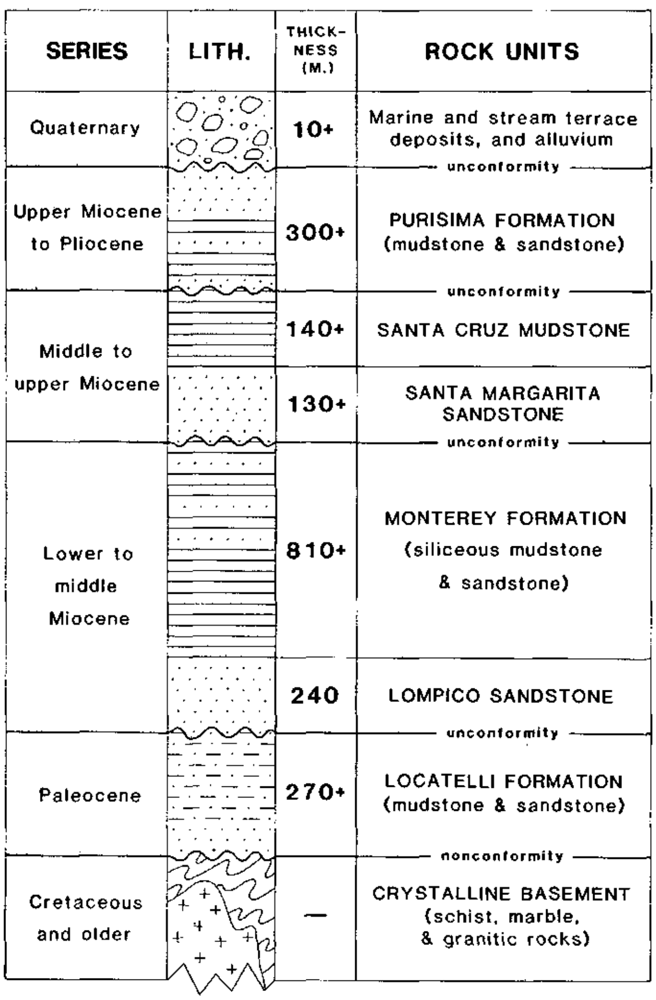

Figure 4. Generalized stratigraphic column for the area shown on the geologic map (Fig 3). Compiled and modified from Clark (1981) and Phillips (1981).

The Bouguer gravity map of western Santa Cruz (Fig. 6) is dominated by a regional field that decreases gently to the south and south-southeast, and is bisected by a much steeper gradient striking north-northwest. The northern end of this steep gradient coincides with a fault-line scarp, discussed earlier, along the Ben Lomond fault. We therefore interpret the steep north-northwest-trending gravity gradient as the effect of the Ben Lomond fault, and suggest that the fault extends southward beneath the city of Santa Cruz and probably offshore beneath Monterey Bay.

The vertical separation on the fault can be estimated from the shape of the gravity curve and knowledge of the density contrast between crystalline basement and the Cenozoic sedimentary strata. In a previous, less detailed study of the gravity of this region, Clark and Rietman (1973) suggested densities, based on surface sampling, of about 2.7 g/cm^3 for the basement and about 2.0 g/cm^3 for the Cenozoic strata. Using a density contrast of 0.7 g/cm^3 and a difference in gravity of 5 to 7 mgal across the fault, we calculate a vertical separation on the fault of 170 m to 240 m, or an average of about 200 m. This figure agrees with other estimates based on different data and discussed below. The overall shape of the gravity field (i.e., a southward decrease in the maximum gradient) suggests that the thickness of the Tertiary sedimentary section increases to the south, but the vertical separation on the fault remains constant, at least within the resolution of the gravity method (possibly a few tens of meters within our detailed traverses).

SUBSURFACE STRUCTURE

The geologic structure beneath Santa Cruz was further investigated by generating two-dimensional models constrained by gravity data and by geologic data derived from surface outcrops and a few wells. Because of limited geologic control and the non-uniqueness of the gravity method, we generated several models, using different density contrasts and structural interpretations. We assume a constant regional gravity contribution of 35 mgal, because this is the Bouguer anomaly in the northwest corner of our map where crystalline basement rocks crop out. Our preferred gravity models and geologic interpretations are shown in Figures 7 and 8.

The dominant structural feature in an east-west cross-section of the city of Santa Cruz (Fig. 7) is the Ben Lomond fault, which in this model has a vertical separation of 250 m. A short-wavelength trough in

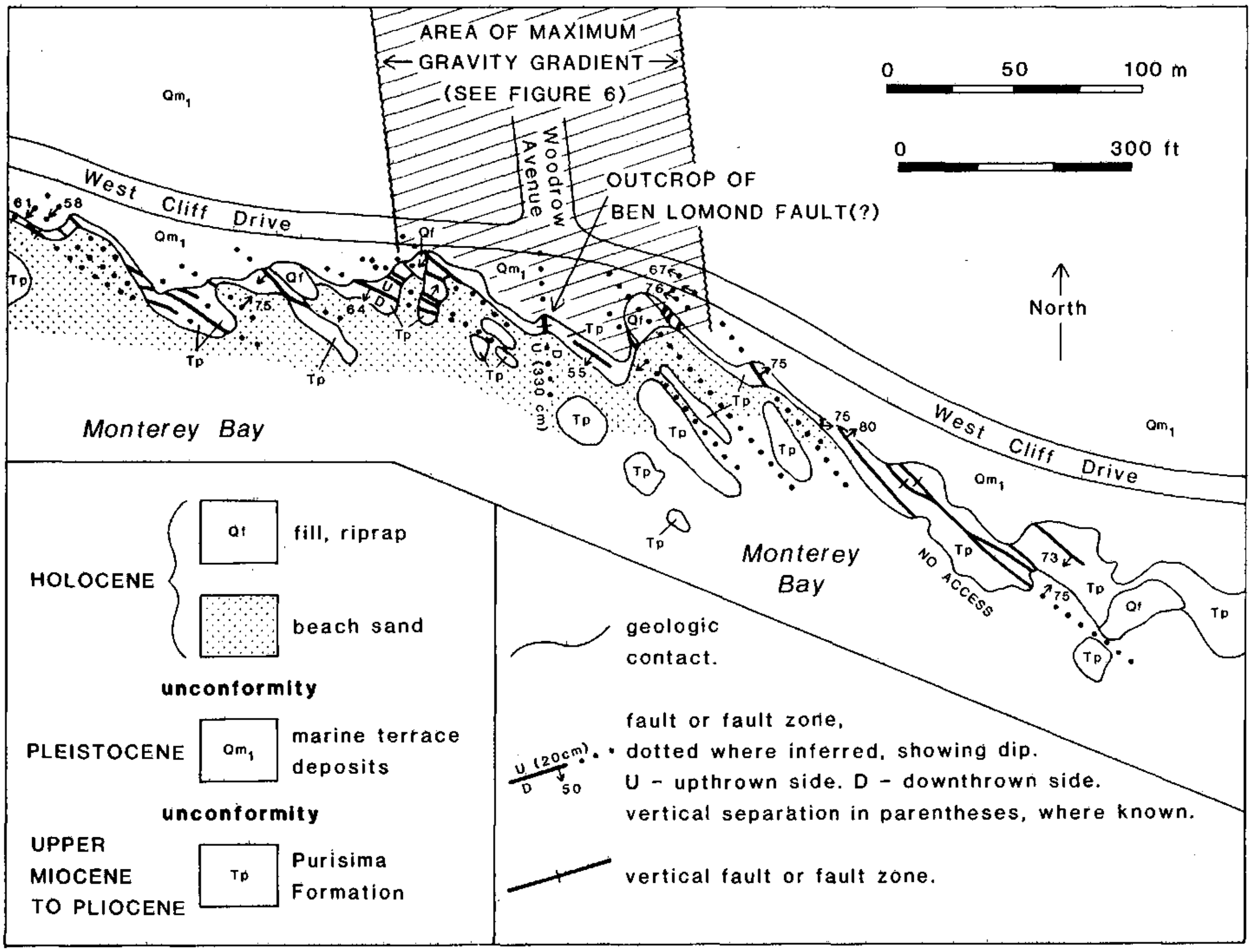

Figure 5. Geologic sketch map along the seacliff at the foot of Woodrow Avenue in the city of Santa Cruz. See text for discussion. Mapped in June 1982.

the observed gravity above the fault itself cannot be explained by structure on the basement surface. The gravity trough may be due to the presence of lower-density sheared rock adjacent to the fault.

Another gravity gradient occurs about 3 km east of the Ben Lomond fault. We interpret this eastern steep gradient as a second fault, tentatively named the "Water Street fault" in Figure 7. The lateral extent of the Water Street fault is unknown because the fault is entirely covered by Quaternary alluvial deposits of the San Lorenzo River. We suspect that it may connect with the Ben Lomond fault to the northwest, and a gravity investigation to test this hypothesis is underway.

Figure 8a shows our preferred model for the vegetation-covered contact between crystalline basement and Cenozoic strata along line B-B′ of the map in Figure 6. A recently published geologic map (Clark, 1981) implies that this contact is an eastward-dipping nonconformity; however, the gravity curves calculated for such a model (Fig. 8b) do not agree with the observed field. In contrast, a fault model (Fig. 8a) for the same contact is in much better agreement with the observed gravity field.

ESTIMATES OF OFFSET BASED ON GEOLOGIC DATA

Due to poor outcrop, estimates of offset on the Ben Lomond fault can be made in only a few places. These are summarized in a graph of time vs. displacement (Fig. 9) and discussed below.

Point A of Figure 9 is from the best exposure of the fault, in the seacliff at Woodrow Avenue. Here, the unconformable contact between the upper Miocene Purisima Formation and the upper Pleistocene marine terrace deposits is offset vertically about 3 cm, down to the west, by a single shear strand of the fault zone. The unconformity surface is about 85,000 years old, based on amino-acid dating of fossil rock-boring molluscs collected from an exposure of the same unconformity less than 1 km east of the fault (Lajoie and others, 1979). The overlying, well-laminated marine terrace sand--thought to be only slightly younger than the unconformity (Bradley and Griggs, 1976)--is <u>not</u> offset by the fault. These relations suggest that the most recent movement on this segment of the Ben Lomond fault occurred about 85,000 years ago. This is the youngest offset that has been documented along the fault, and the first report of unequivocal evidence of Quaternary displacement.

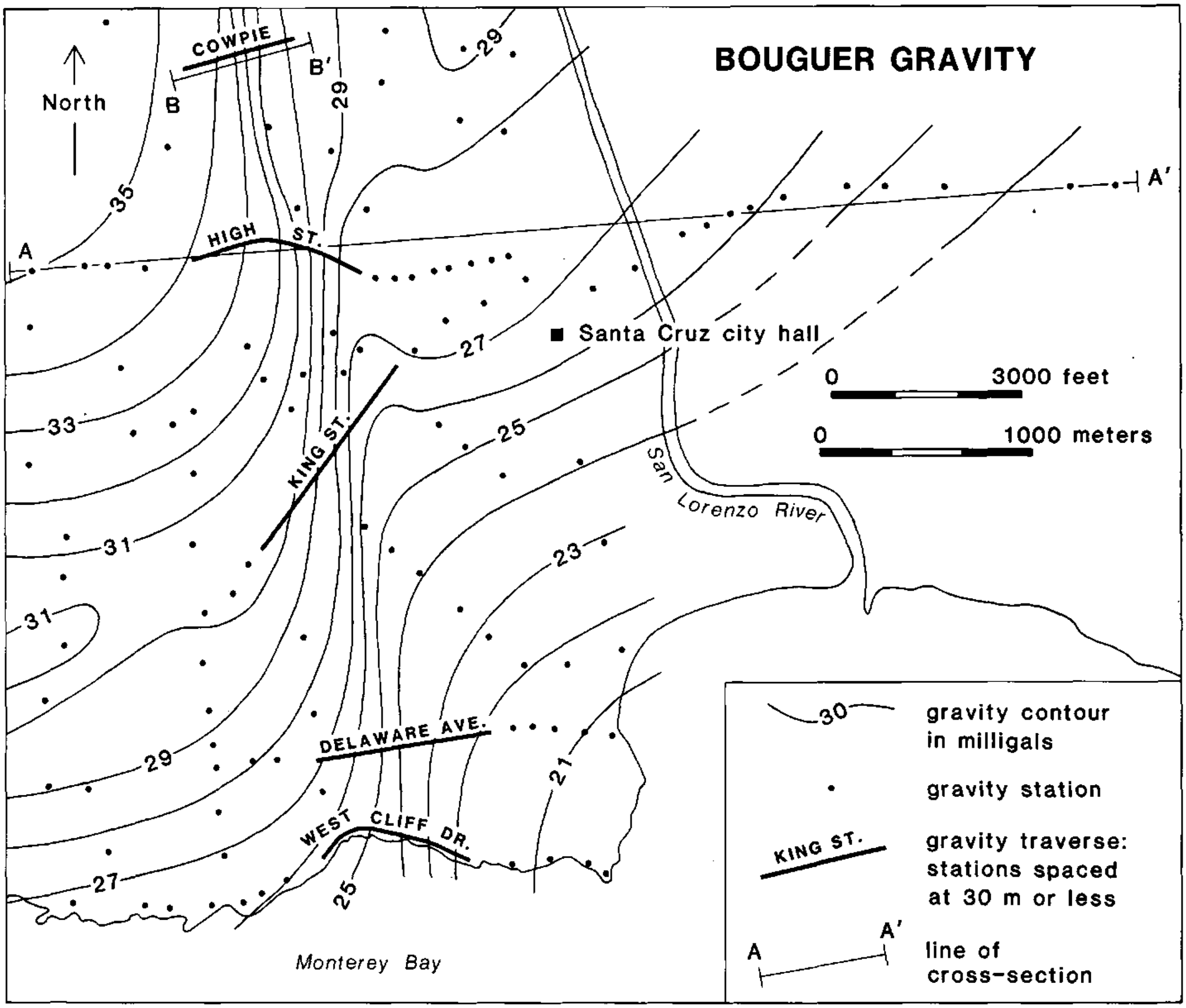

Figure 6. Bouguer gravity map of the western part of the city of Santa Cruz, based on Bouguer reduction density of 2.0 g/cm^3 and sea level datum. Contour interval is 1 mgal, dashed where approximate. The steep north-south trending gravity gradient on the left corresponds to our proposed extension of the Ben Lomond fault.

Point B in Figure 9, also from the seacliff outcrop, represents a vertical separation along the Ben Lomond fault of 3.3 m, down to the east, on an offset vitric tuff within the Purisima Formation. This tuff bed occurs about 30 m above the base of the Purisima Formation and is about 5.9 m.y. old, based on paleomagnetic and fossil evidence (R.M. Stuart, personal communication, 1982).

A number of estimates of offset of the nonconformity between the crystalline basement and the overlying Santa Margarita Sandstone are summarized by box C in Figure 9. The age of the nonconformity is 10 to 12 m.y., based on vertebrate and invertebrate fossil evidence (R.L. Phillips, 1981, and personal communication, 1982). A rough estimate of offset based on purely geologic evidence can be made about 5 km north of the coastline, where the nonconformity is at an elevation of about 270 m on the west side of the fault and about 120 m on the east side (Fig. 3). This relationship gives an estimate of 150 m of down-to-the-east vertical separation, which agrees reasonably well with the estimates of 170 to 240 m from our gravity data. These figures also agree with previously reported estimates of 150 to 350 m for the more northerly section of the fault (Clark, 1966, 1981).

Immediately north of our study area, the nonconformity between the crystalline basement and the overlying Lompico Sandstone is offset vertically about 230 m by the Ben Lomond fault (Clark, 1981, his cross-section C-C′). This offset is shown by box D in Figure 9. The nonconformity is not well dated; fossil evidence summarized by Clark (1981) suggests that the Lompico Sandstone correlates with the Relizian stage of Kleinpell (1938) which occurred about 17 to 18 m.y. ago (Poore and others, 1981).

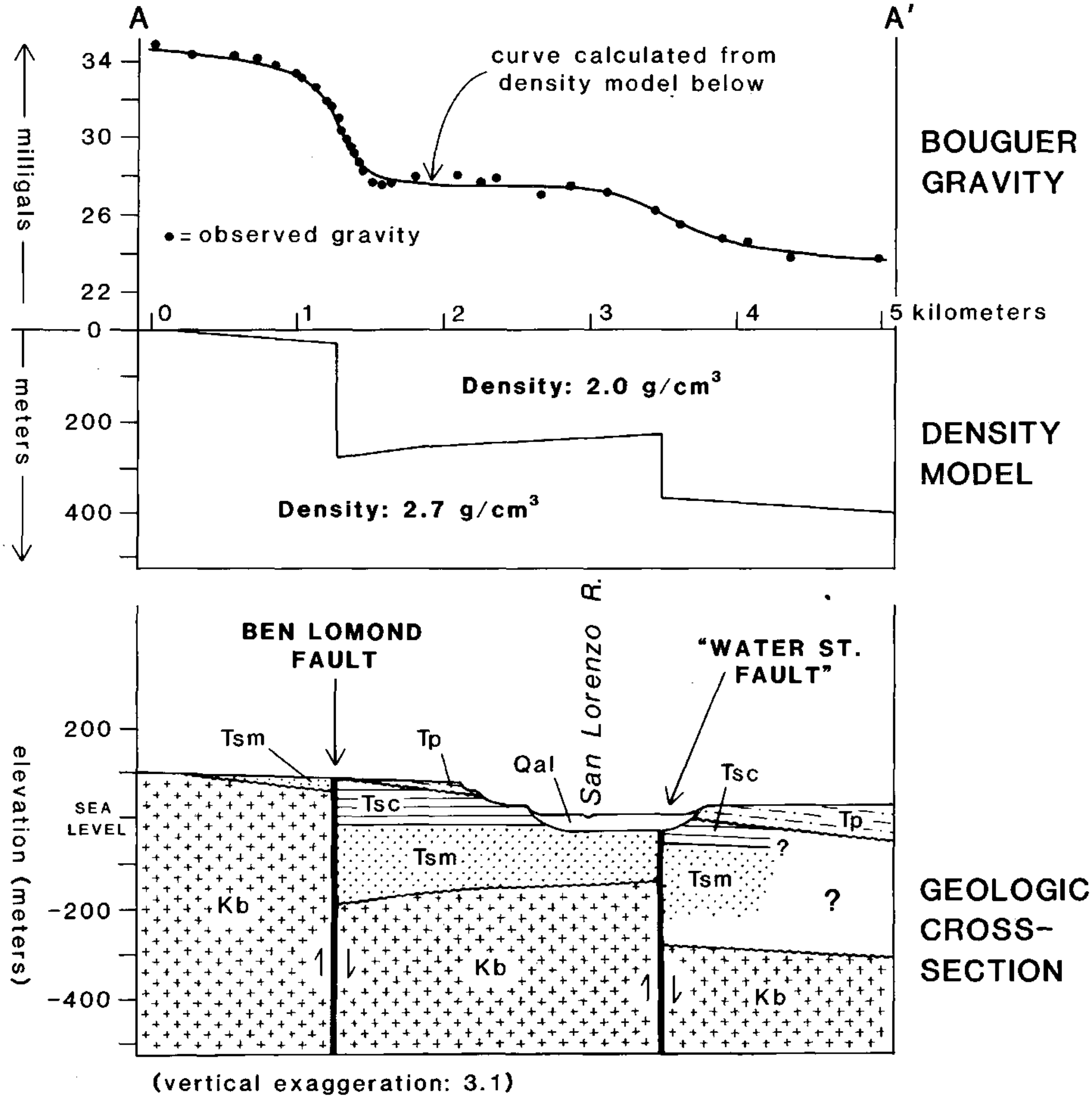

Figure 7. Bouguer gravity anomaly, density model, and interpretive geologic cross-section along line A-A′ of Figure 6. Symbols are as follows: Kb, crystalline basement rocks; Tsm, Santa Margarita Sandstone; Tsc, Santa Cruz Mudstone; Tp, Purisima Formation; Qal, Quaternary alluvium. Marine terrace and other Quaternary deposits less than 20 m thick are omitted for clarity.

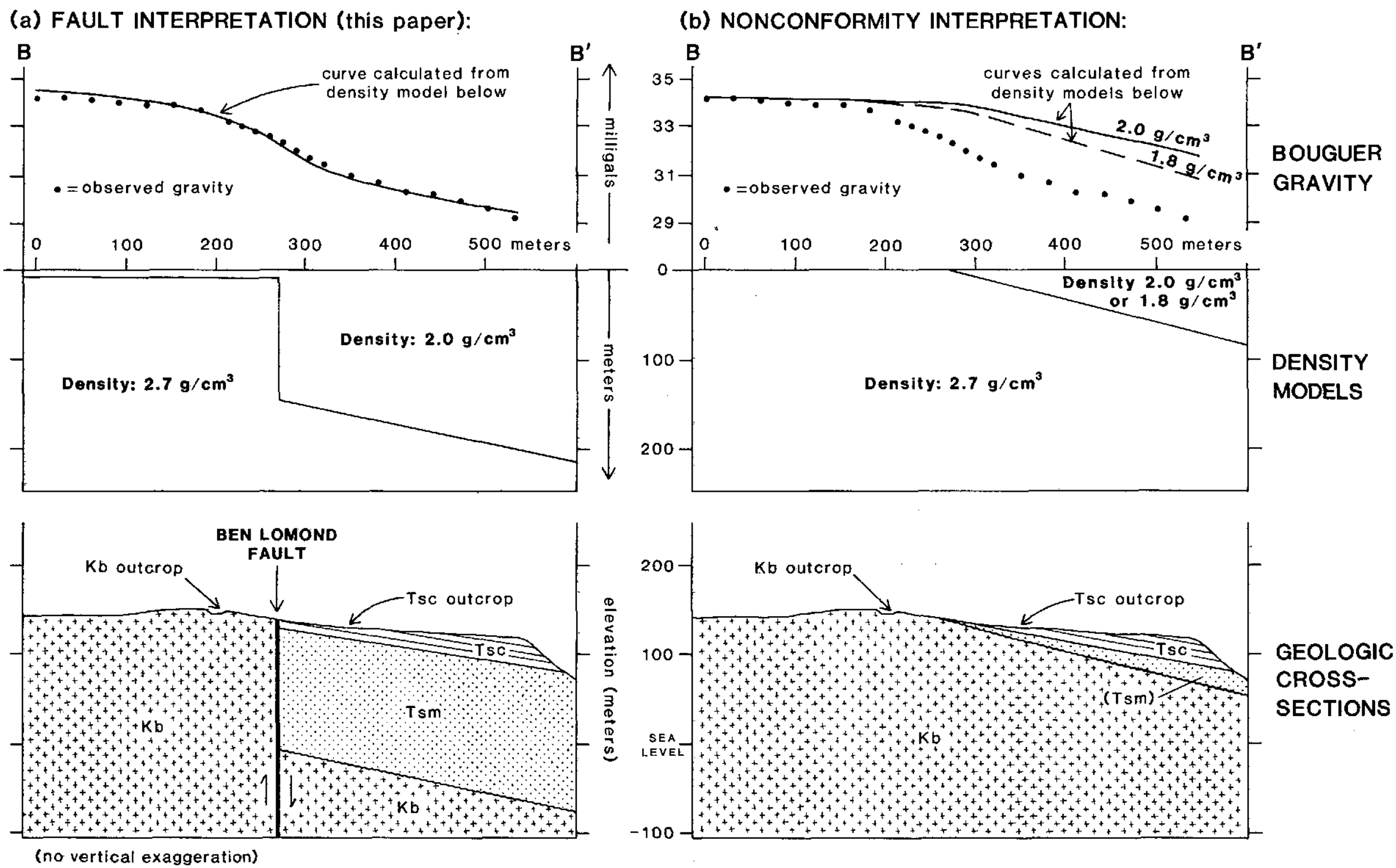

Figure 8. Two alternative interpretations of the contact between crystalline basement (Kb) and Cenozoic sedimentary rocks (Tsm and Tsc) along line B-B′ of the map in Figure 6. This contact is covered by vegetation and therefore not exposed at the surface, but must lie between the outcrops shown. The left-hand column, Figure 8a, shows the fault interpretation proposed in this paper; the right-hand column, Figure 8b, shows the unfaulted nonconformity implied by previously published maps (e.g., Clark, 1981). Figure 8b also shows the effect on gravity of assuming a lower density of 1.8 g/cm^3 for the Cenozoic sedimentary rocks in the nonconformity model. The gravity curve calculated from this very low density gives a slightly improved but still unsatisfactory fit to the observed gravity field.

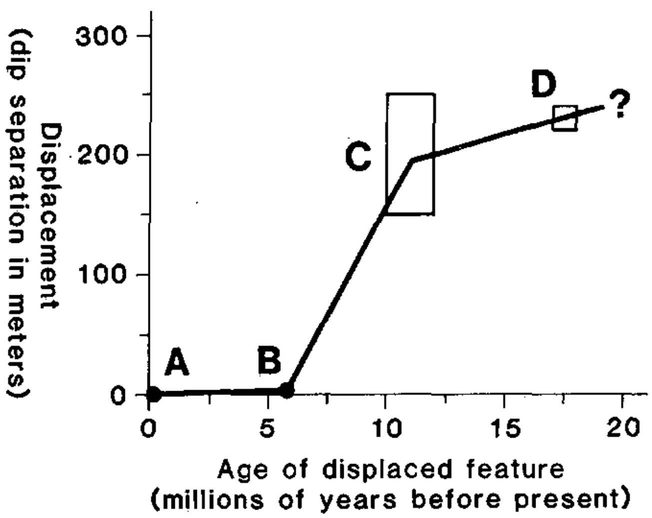

Figure 9. Time vs. displacement on the Ben Lomond fault. Sources of data are described in the text. Heavy line shows a tentative interpretation of the slip history of the fault.

FAULT HISTORY

The interpretation of the time vs. displacement curve (Fig. 9) is ambiguous because the slip direction on the Ben Lomond fault is unknown. No slip indicators--such as piercing points, drag folds, or slickensides--have been observed. The time vs. displacement curve is based on estimates of vertical separation only, and therefore the following interpretation of this curve in terms of slip history is tentative. The time vs. displacement curve (Fig. 9) suggests that most of the approximately 200 m of vertical offset on the Ben Lomond fault occurred prior to 5.9 m.y. ago, and that since that time the vertical offset on the fault has been only about 3.3 m. The precise timing of the period of maximum displacement is not clear because we lack detailed data on the offset of older Tertiary rock units. However, we speculate that much of the fault offset occurred during the late Miocene deposition of the Santa Margarita Sandstone, because an isopach map of that unit (Fig. 10) shows that the sandstone thickens dramatically toward the fault and that the isopachs are generally parallel to the fault.

FURTHER DISCUSSION

The southern end of the Ben Lomond fault has yet to be identified. The trace of the fault is not evident in seismic reflection profiles obtained offshore Santa Cruz (Harding-Lawson Associates, 1976; Greene,

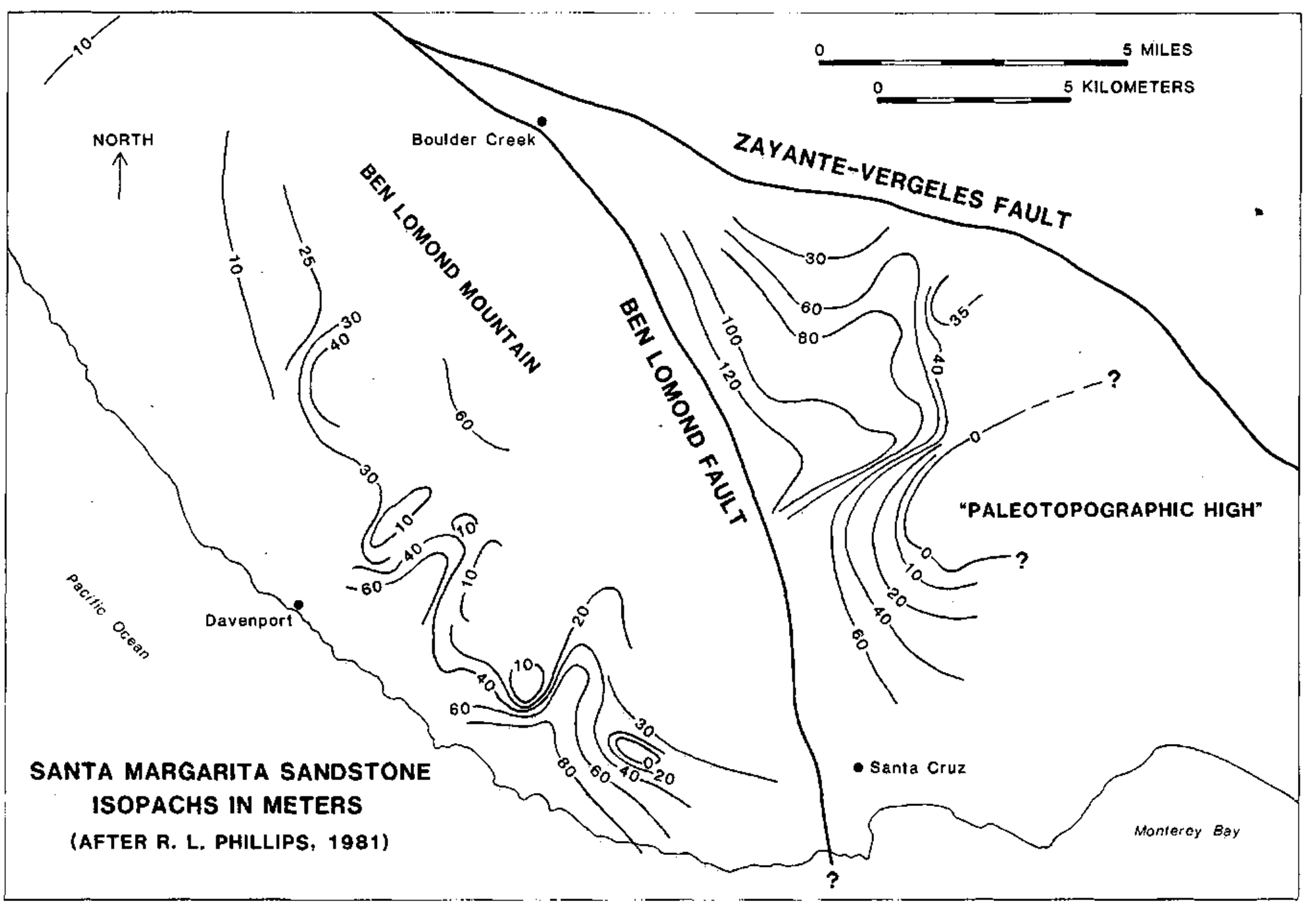

Figure 10. Isopach map of the middle to upper Miocene Santa Margarita Sandstone (modified from Phillips, 1981). Note that the sandstone thickens from east to west toward the Ben Lomond fault and that the isopach lines are roughly parallel to the fault.

1977; H.T. Mullins, R. McCaffrey, and R.G. Stanley, unpublished data, 1981). We attribute this to a rocky seafloor which inhibits penetration of seismic energy. Underwater gravity measurements in Monterey Bay by Cronyn (1973) and Spikes (1973) also do not reveal the Ben Lomond fault offshore, probably because their average station spacing (greater than 1800 m) was too large to resolve the narrow and steep gradient over the Ben Lomond fault. The fault may connect with or be offset by the Monterey Bay fault zone (Fig. 1); more data are needed to determine its location and extent beneath Monterey Bay.

Is the Ben Lomond fault active? The following elements appear in most definitions of active faults: (1) association with earthquakes or creep; (2) offset of Holocene deposits; and (3) the presence of ephemeral fault-related geomorphic features such as sag ponds, offset streams, and fault scarps (Wesson and others, 1975; Slemmons, 1977; Slemmons and McKinney, 1977). These elements are present along many faults in central California, including the San Andreas and San Gregorio-Hosgri faults, but are not present along the Ben Lomond fault. Recently published maps of earthquake epicenters show no seismic activity that may be confidently assigned to the Ben Lomond fault (Fig. 1; see also Real and others, 1978; Olson, 1980), although possible errors in the location of epicenters make this interpretation tentative. There is no record of creep or older historical earthquakes along the fault (Woodward-Clyde Consultants, 1981). No offsets of Holocene deposits and no obviously young fault-related geomorphic features have been observed. Our interpretation of the Woodrow Avenue seacliff outcrop suggests that no movement has occurred on that segment of the fault since 85,000 years ago. Thus, according to commonly accepted land-use planning criteria, the Ben Lomond fault is inactive.

The role of the Ben Lomond fault in the evolution of the San Andreas transform is unclear. Part of the problem is that we know nothing about horizontal offset on the fault; any such offset, however, is probably small, because stratigraphic sequences and sedimentary facies on either side of the fault are virtually identical. The north-south to N20°W strike of the Ben Lomond fault, when compared to a simple strain ellipse (e.g., Wilcox and others, 1973), suggests that the fault is a conjugate shear or tension fracture related to wrenching along the San Andreas. The small amount of post-Miocene vertical offset and the absence of Holocene activity suggest that the Ben Lomond fault is not an active strand in the modern San Andreas system, but formed during an older tectonic episode. The Ben Lomond fault may have been most active about 10 m.y. ago during a brief period of regional extension and basin formation that accompanied a change in relative motion between the Pacific and North American plates (Blake and others, 1978). Alternatively, the Ben Lomond fault may have formed in response to local extension as the locus of strike-slip motion between the Pacific and North American plates shifted landward during the Miocene from offshore faults to the San Andreas and other onshore faults (Graham, 1978).

SUMMARY

Detailed mapping of geology and Bouguer gravity shows that the Ben Lomond fault extends farther south than previously thought. The fault is present in the subsurface beneath the city of Santa Cruz and shows up as a sharp gradient in the Bouguer gravity field. It probably continues southward beneath Monterey Bay. Both geology and gravity suggest that the fault plane is vertical to steeply east-dipping, and that vertical separation on the fault is about 200 m and down to the east. Most of the displacement on the fault apparently occurred prior to 5.9 m.y. ago. Outcrop evidence shows that the latest discernible offset along the Ben Lomond fault occurred about 85,000 years ago. There is no evidence of Holocene offset and only very weak evidence for earthquakes along the fault. Therefore, in comparison with other central California faults such as the San Andreas and San Gregorio-Hosgri, the Ben Lomond fault is inactive.

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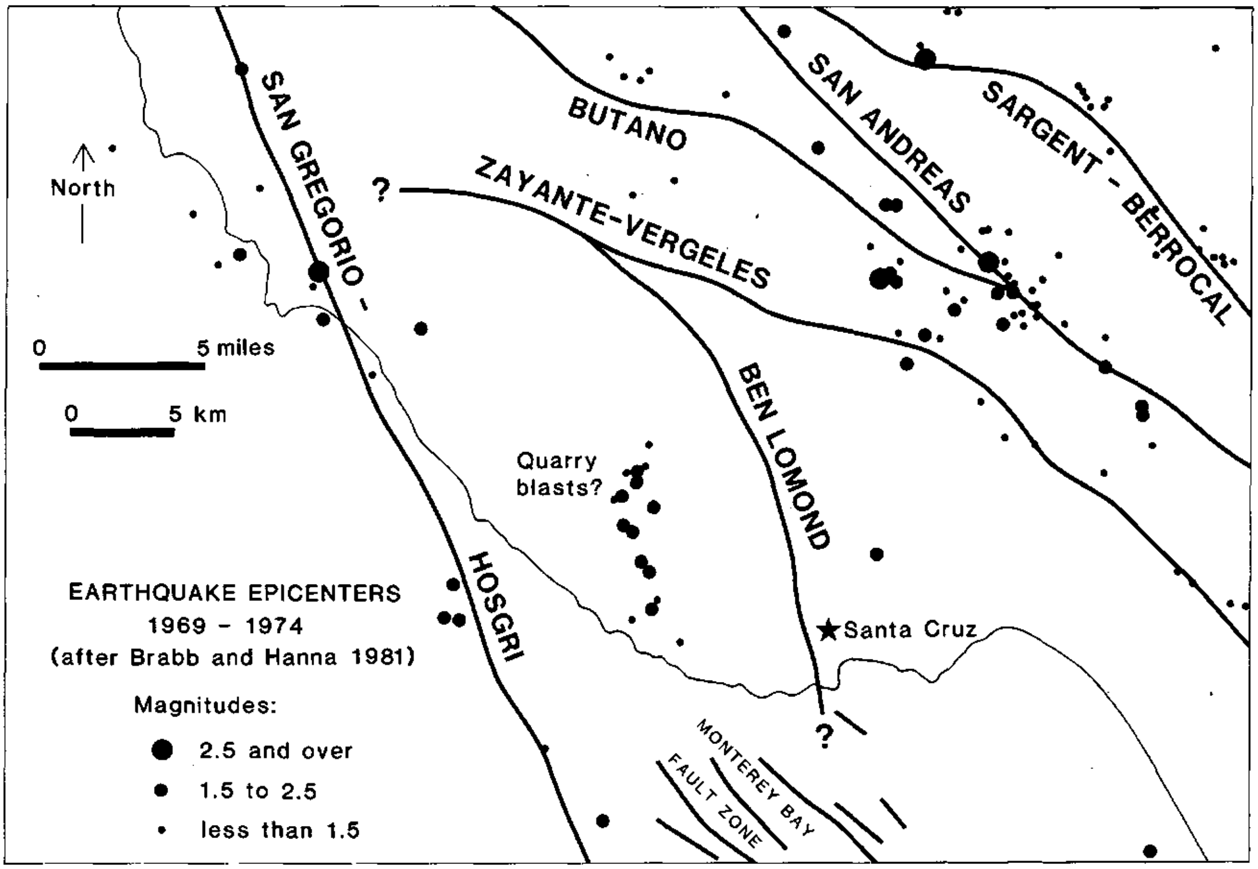

Figure 11. Earthquake epicenters for the period 1969-1974 in the area of the Ben Lomond fault (after Brabb and Hanna, 1981). Brabb and Hanna believe that the epicenters in the cluster about 5 km west of the fault may be quarry blasts.

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