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# THE SANTA RITA FAULT ZONE: EVIDENCE FOR LARGE MAGNITUDE EARTHQUAKES WITH VERY LONG RECURRENCE INTERVALS, BASIN AND RANGE PROVINCE OF SOUTHEASTERN ARIZONA

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## ABSTRACT

**A discontinuous zone of subdued, west-facing fault scarps offset Quaternary alluvium along 58 km of the western piedmont of the Santa Rita Mountains, south of Tucson, Arizona. Scarps trend NE to N-S and are 1 to 6 km basinward from the deeply embayed mountain front. Scarp heights range from 1 to 7 m, and maximum scarp slope angles range from 3° to 9.5°. A 6-m-deep trench excavated in middle Pleistocene and younger deposits exposed a high-angle fault zone with about 3.5 m of total displacement.**

**Estimated ages of faulted and unfaulted surfaces, extent of degradation of piedmont scarps, and stratigraphic relations exposed in the trench suggest an age of about 100 ka for the most recent surface-rupture event. Units having well-developed relict soils of late Pleistocene age and older are faulted, whereas units having weakly to moderately developed soils, of latest Pleistocene and Holocene age, are not offset. Morphologic fault scarp analyses suggest an age of 60 to 100 ka. Earthquake magnitude estimates derived using minimum and maximum seismic source moment calculations range from 6.4 to 7.3.**

**One or more earlier surface-rupture events are implied by significantly higher scarp heights on mid-Pleistocene than on late Pleistocene surfaces. Scarp heights on middle and early (?) Pleistocene surfaces are similar, restricting faulting to post-middle Pleistocene time (<200 to 300 ka). Stratigraphic relationships observed in the trench also suggest two fault-displacement events. Tectonic landform analysis of the mountain front-piedmont area implies several m.y. of inactivity along the range-bounding fault system prior to these late Quaternary displacements. Extremely long recurrent intervals between displacement events and reactivation of faulting after an interval of tectonic quiescence are typical of late Quaternary fault behavior in southeastern Arizona.**


## INTRODUCTION

Detailed geomorphic field studies have defined the timing, frequency, and possible magnitudes of late Quaternary surface ruptures on the western piedmont of the Santa Rita Mountains, 30 km south of Tucson, Arizona. This work has implications for the nature of Quaternary faulting in the Basin and Range province of southeastern Arizona and adjacent parts of New Mexico and Sonora, Mexico, where recent studies have delineated widely scattered piedmont fault scarps (Drewes, 1971; Drewes and Thorman, 1980; Morrison *et al.*, 1981; Menges and Pearthree, 1983; Machette *et al.*, 1986). This analysis of the Santa Rita fault zone is useful because it details individual fault behavior in a region where one major historic earthquake has occurred (the Great Sonoran Earthquake of 1887), but where background seismicity is very low (DuBois *et al.*, 1982), and little has been known about recurrence of fault movements.

Fault scarps of the Santa Rita fault zone trend from N-S to NE along about 60

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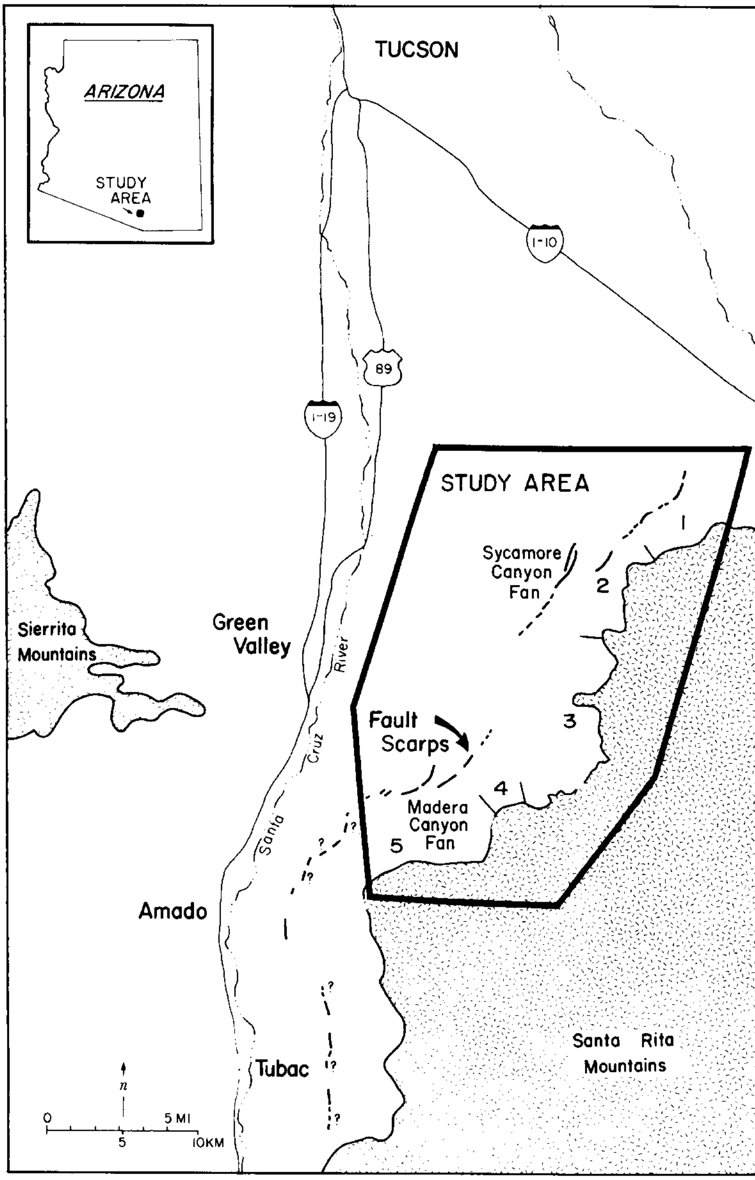


FIG. 1. Location of fault scarps and study area. Numbers indicate portions of the mountain front for which sinuosity values ($S$) (Table 6) were calculated.

km of the southeastern margin of the fault-bounded, north-trending Tucson basin. The scarps are located 1 to 6 km basinward from the topographic mountain front (Figures 1 and 2), range in height from 1 to 7 m, and have maximum slope angles of 3° to 9.5°. Scarps occur only on surfaces of late Pleistocene age and older.

Tectonic geomorphic analysis, including examination of surficial soils, alluvial stratigraphy, fault scarps, and the topographic mountain front, was used to assess the history of Quaternary surface-rupture faulting events on the Santa Rita piedmont. A soils chronosequence was delineated, and individual surface ages were estimated by comparison with a chronosequence of soils in the southern Rio Grande valley, New Mexico (Gile *et al.*, 1981). Estimates of the age of most recent faulting are constrained by the age of the oldest surface not offset by faulting and the youngest surface cut by faulting. Greater vertical offset of adjacent older surfaces provides evidence of previous surface faulting. Morphologic scarp-age estimates were made by comparison of the regression line of maximum scarp slope versus log scarp height from the Santa Rita scarps with dated scarps from central Utah (Bucknam and Anderson, 1979). Scarp age was also estimated using a diffusion model of scarp degradation (Nash, 1980; Mayer, 1984). Analysis of a 6-m deep, 37-m-long bulldozer trench crossing the fault provided detailed information on fault zone geometries and evidence for the age of most recent faulting. Field investigations were supplemented by evaluation of the sinuosity and erosional characteristics of the mountain front, parameters which can indicate the relative rate of uplift of the mountain block (Bull and McFadden, 1977).

A zone enveloping the loci of historical seismicity in Arizona extends southeastward from the southern end of the Intermountain seismic belt in northwestern Arizona and may continue through Arizona's southeastern corner to include the epicenter of the 1887 Sonoran earthquake (Sumner, 1976). This event, estimated at magnitude 7.2 to 7.4 (Natali and Sbar, 1982; Herd and McMasters, 1982), produced a 75-km-long (Herd and McMasters, 1982) 0.5 to 4-m-high fault scarp. Northwestern Arizona is the most active part of the zone, with numerous fault scarps cutting Quaternary alluvium and basalt flows, and evidence for extensive late Quaternary offset along some structures (Huntoon, 1977; Hamblin *et al.*, 1981; Menges and Pearthree, 1983). It is not clear, however, if the proposed seismic belt is indeed continuous through the state, as historical seismicity is diffuse (DuBois *et al.*, 1982) and late Quaternary fault scarps uncommon (Menges and Pearthree, 1983) in central Arizona.

## CHRONOSEQUENCE OF ALLUVIAL GEOMORPHIC SURFACES

Faulted and unfaulted alluvial units deposited on the Santa Rita piedmont provide a means to analyze the Quaternary history of movement on the Santa Rita fault zone. Alluvial units of different ages were defined based on elevation above modern stream channels, degree of surface dissection, surface color, and especially soil-profile development. Ages of units were estimated on the basis of soil-profile development as compared with a dated sequence of soils from the Desert Project of the southern Rio Grande valley of New Mexico (Gile *et al.*, 1981).

*Soil development—Basis for estimating absolute surface ages.* Theoretically, any soil property that increases with age can be used to date a sequence of soils. In order to absolutely date a soils chronosequence, independent absolute age dates are preferable. Unfortunately, we were unable to constrain the absolute ages of surfaces in this area. An alternative and much less precise method for estimating absolute soil ages is to select those soil properties that vary systematically with age in an area and compare them with a dated chronosequence of soils developed from similar parent materials under similar climatic conditions (including the rate of eolian dust fall). Soil properties found to vary consistently with age include redness, maximum amount of clay and iron, and calcic horizon development (see Gile *et al.*, 1966; Bachman and Machette, 1977). These properties were compared with those of a chronosequence of soils defined on the piedmont slopes near Las Cruces, New Mexico (Gile and Grossman, 1979) to estimate ages of surfaces on the Santa Rita piedmont (Tables 1 and 2).

## TRENCH STRUCTURE AND STRATIGRAPHY

A 6 m × 37 m bulldozer trench excavated across the Santa Rita fault zone about ½ km northeast of the Madera Canyon fan (see Figure 2) provided a detailed exposure of the shear zone in the Quaternary alluvium. The late Pleistocene Q2c surface is offset 2 to 3 m in this area, although no scarp exists at the surface of the trench site because it was dug in a small arroyo for practical and environmental reasons.

Mapping of the trench walls (Figure 5) revealed a sequence of seven thin Pleistocene alluvial deposits and two buried soils, and a thin, discontinuous late (?) Holocene deposit. All but the youngest two deposits were offset across a zone of steeply dipping normal faults during one or two faulting events. The sediments, ranging from poorly sorted conglomerate to massive silt, are characteristic of fluvial deposition on the piedmont in response to climatic variations that changed the discharge of water and sediment from the hillslopes of the Santa Rita Mountains (see Table 4 for description of units). Two depositional hiatuses in the sequence are indicated by buried paleosols developed on units I and II. A surficial soil has formed across the faulted and subsequently beveled alluvial sequence.

*Structure.* The 3.3 to 3.5 m total offset measured on units I to IV is distributed across a 3.5-m-wide zone of 70° to 90° westward-dipping normal faults. Thinning, passive folding, tilting, general disruption of bedding, and some drag structures are associated with the faulting. In plan view, the faults anastomose along strike. The 2-m-wide step in the trench excavation provided an excellent exposure of their pattern. The main fault plane branches out across the step to include five faults spread across 90 cm of very disrupted sediments.

*Age of the most recent faulting event.* Stratigraphic evidence in the trench suggests the most recent fault rupture occurred ~100 ka, in fair agreement with morphologic scarp-age estimates of 60 to 100 ka. The oldest unfaulted unit exposed in the trench (unit VII) provides a minimum age for the latest fault movement. Characteristics of the soil developed on unit VII (Table 5) correlate fairly well with those of the Q2d piedmont unit (Table 1), estimated to be 10 to 20 ka. At least part of the deposition of unit VII appears to be directly related to faulting, however, and predates the climatically caused deposition of the Q2d unit elsewhere on the piedmont. The lower part of the deposit at the main fault trace contains crude cobble layers and abundant gravel, which probably represent debris deposited at the base of the scarp. Unfortunately, any additional scarp-related features at the top of the trench section were eroded along with the scarp.

The absence of the late Pleistocene Q2c soil in the downthrown block of the exposure, even though the faulted Q2c geomorphic surface occurs adjacent to the trench site, suggests that the latest faulting event occurred shortly after stabilization of the Q2c surface, before substantial soil-profile development had occurred. In the trench, unit VI is tentatively correlated with Q2c because it is the youngest faulted unit; however, unit VI displays very little evidence of soil development. Substantial erosion of unit VI does not appear to have taken place, as units VI to VII contact is quite subtle. It appears, therefore, that faulting occurred shortly after deposition of the Q2c unit, about 100 ka.

*Evidence for an earlier faulting event.* Several lines of evidence suggest that two faulting events are recorded in the trench stratigrapy. Units I through IV are all vertically offset about 3.4 m, and their thicknesses do not increase on the downthrown side of the fault, indicating all faulting postdates deposition of unit IV. The

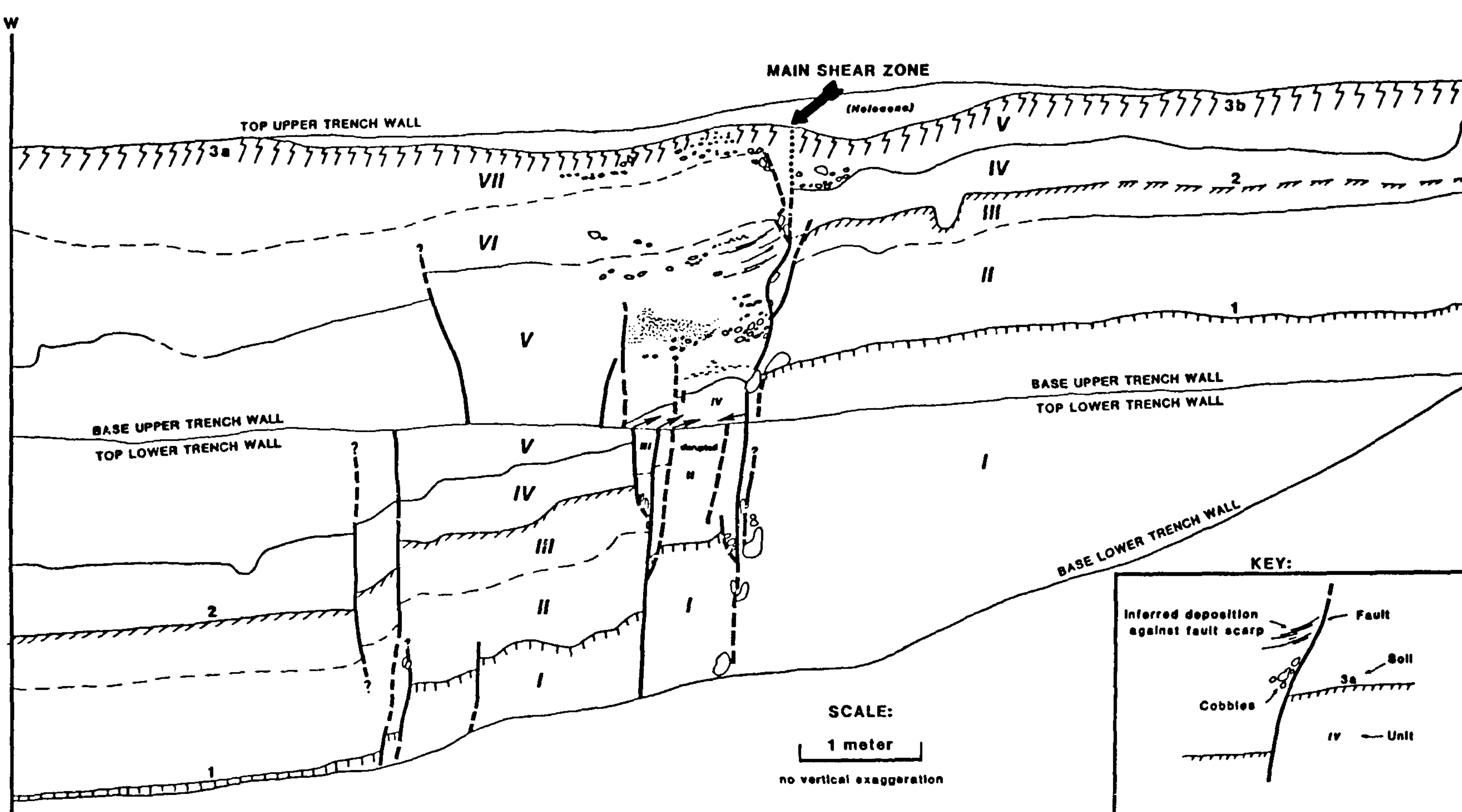


FIG. 5. Interpretation on trench excavated across the Santa Rita fault zone just north of Madera Canyon fan. Upper trench wall is set back from lower wall along 2.5- to 3-m step. Main shear zone in upper wall splays across the step to include five shear planes in lower wall, as indicated by arrows. See Table 5 for stratigraphic descriptions.

TABLE 4
DESCRIPTION OF ALLUVIAL UNITS MAPPED IN THE TRENCH EXPOSURE*

| Unit | Thickness (cm) | Description |
|---|---|---|
| | | Paleosol 3 |
| VII | 70–100 | Silty sand and gravel. Massive, moderately sorted, slightly hard, lower boundary clear to gradual. |
| VI | 70–100 | Silty sand and gravel. Massive, moderately sorted, hard, lower boundary gradual to diffuse. |
| V | 80(?)–180 | Cobbly fluvial gravel. Moderately well bedded, with sandy beds and cobbly beds, cut and fill structures. Locally well-developed cross-bedding in sandy layers, moderately well to poorly sorted, fairly loose to slightly hard; near main shear zone the inclined sandy gravel layers 4- to 5-cm-thick have well-developed red (2.5 yr 4/8) 1- to 2-cm-thick B-bands; lower boundary abrupt, wavy, locally eroded into or through unit IV. |
| IV | 0–64 | Silt. Massive, well sorted, very hard, vesicular, occasional slightly gravelly crude layers 2- to 3-cm-thick, lower boundary abrupt, wavy, locally eroded into unit III. |
| | | Paleosol 2 |
| III | 45 | Gravelly silty sand. Moderately well sorted, slightly hard to hard, some cross-bedding, lower boundary gradual to diffuse. |
| II | 85–115 | Cobbly gravel and silty sand. Moderately well-sorted, loose to slightly hard, weak imbrication, discontinuous slightly hard silt layers 10- to 20-cm-thick, basal slightly hard silty sand layers 10- to 15-cm-thick, lower boundary abrupt and straight. |
| | | Paleosol 1 |
| I | 280+ | Very cobbly boulder gravel. Massive, very poorly sorted, moderately well-to-well consolidated, lower boundary not exposed. |

* See Table 5 for Paleosol descriptions.

thickness of unit V measured on the downthrown block increases from 1.2 to 1.8 m downslope away from the main shear zone. Projection of the top of unit V from the eastern end of the trench suggests it was about 0.8-m-thick immediately upslope from the fault zone, although the original thickness of unit V may not be preserved in the upthrown block. The fact that unit V thickens across the fault zone implies that it was deposited over preexisting topography, probably a fault scarp.

Deposition of unit V shortly after a faulting event would explain the complex and disrupted sedimentary structures in unit V, located within $1\frac{1}{2}$ m downslope from the main fault shear. These may be debris deposited at the base of a low scarp that was subsequently faulted during the most recent displacement. Additionally, several of the faults west of the main shear zone offset units I to IV but not unit V. These relations suggest that offset during an earlier event involving units I to IV was distributed across a 3.5-m-wide zone of faults, while almost all offset during the most recent event occurred on the main shear zone. Vertical displacement attributable to the most recent faulting event is about 2.2 m, assuming the reconstructed top of unit V was originally uninterrupted across the fault zone.

Comparison of offset of trench units with surface offset calculated from scarp profiles on Q2c and Q2b surfaces near the trench supports the hypothesis that two surface ruptures have occurred. The average surface offset of the Q2c unit (2.3 m) is about the same as that postulated for the most recent event in the trench. Q2b-1 surface offset of about 3.2 m on the Madera Canyon fan, 0.5 km to the south, is very similar to total offset determined in the trench. These relations suggest that both the trench section and the mid-Pleistocene Q2b-1 surface record two faulting events, and that the late Pleistocene Q2c surface records only the most recent event.

## Estimated Magnitude of Paleoseismic Event(s)

Correlation between seismic source moment ($M_0$) and earthquake magnitude ($M$) allows estimation of earthquake sizes associated with the scarp-producing events. $M_0$ is the product of average fault dislocation ($\langle u \rangle$), the shear modulus ($\mu$), and fault plane area ($A$)

$$M_0 = \langle u \rangle \mu A \qquad (2)$$

(Brune, 1968). Vertical surface offset and length of scarps can be measured, but the amount of offset may be uncertain if a scarp actually represents multiple events, and total length of a prehistoric fault may be obscured by subsequent erosion or deposition across various scarp segments. Segments of the fault might rupture separately, although within the limits of the timing data we did not find evidence of this. Also, estimated average surface displacement is only a proxy for average fault dislocation, which is not determinable for prehistoric earthquakes. The value used for the shear modulus is $3.3 \times 10^{11}$ dyne/cm$^2$ (Brune, 1968; Hanks and Kanamori, 1979). Total depth of brittle failure is probably 10 to 15 km, as microearthquakes detected during a study of the Pitaycachi fault (Natali and Sbar, 1982) were no deeper than 16 km. Dip angles of 60° to 70° have been observed for range-bounding and bedrock normal faults in the southern Basin and Range province (Menges, 1981, unpublished data; Natali and Sbar, 1982). Fault geometries at depth are not constrained; if faults flatten at depth, fault plane area would be greater than assumed here. The calculated value of $M_0$ is used to estimate paleoearthquake magnitude through a moment-magnitude scale (Hanks and Kanamori, 1979)

$$M = \tfrac{2}{3} \log M_0 - 10.7. \qquad (3)$$

TABLE 5

SELECTED SOIL CHARACTERISTICS, SURFICIAL AND BURIED SOILS IN TRENCH SECTION

| Parent Material (Alluvial Units) | Maximum Redness | Thickness (cm) Zone of Clay Accumulation | Wet Consistence B22t Horizon | Texture B22t Horizon | Depth to Carbonate Accumulation (cm) | Maximum Stage $CaCO_3$ Development (Bachman and Machette, 1977) | Correlative Piedmont Surficial Soil |
|---|---|---|---|---|---|---|---|
| 3a VI, VII, surface, down-thrown block | 5 yr 4/6 | 91 | Sticky, plastic | Gravelly, silty clay loam | 76 | I–II | Q2d |
| 3b V–II, surface, up-thrown block | 5 yr 4/6 | 78 | Sticky, plastic | Very gravelly, sandy clay loam | 85 | I–II | Q2c or Q2d |
| 2 III, II, buried, down-block | 5 yr 4/8 | 52 | Sticky, slightly plastic | Very gravelly, sandy clay loam | None | — | — |
| 1 I, buried, upthrown block | 2.5 yr 4/8 | 280+ | Very sticky, very plastic | Cobbly, clay | 43 | II | Q2b-1 |

Combining regional structural characteristics with specific offset and fault length data collected from the Santa Rita fault scarps, a range of possible paleoearthquake magnitudes was calculated for the fault system. A minimum value of $M = 6.4$ is derived using 1.2 m average offset, 10 km length (total length of the northernmost scarp segment), and a fault plane dipping 70° extending to 10 km depth. The maximum value of $M = 7.3$ is derived with 3.5 m average offset on a fault plane dipping 60°, extending to 15 km depth, along the entire 58 km length from the scarps. A more realistic value might be $M = 6.9$, which could be generated by an average of 2 m offset along the 35 km of the fault north from the Madera Fan area.

## Plio-Quaternary Activity on the Santa Rita Fault Zone

The Santa Rita Mountain front was analyzed using landscape parameters which can indicate relative rates of vertical tectonic activity at mountain fronts (Bull and McFadden, 1977). Soil, stratigraphic, and scarp morphology studies restrict times of Quaternary faulting on the Santa Rita piedmont to late mid- and late Pleistocene. Analysis of the tectonic landforms of the mountain front, which extends our analysis of the faulting history back probably through the Pliocene, suggests that relative tectonic inactivity along the range front began at least 3 to 5 m.y. ago.

Calculation of landscape parameters allows quantification of the relative rates of base-level processes. Mountain-front sinuosity ($S$) and valley floor width-valley height ratios ($Vf$) compare the rate of uplift along the range-bounding structures and rates of fluvial erosion. Sinuosity ($S$) is defined as the ratio of the length along the actual bedrock/alluvium contact to the overall length of the mountain front, both measured from topographic maps. High $S$ values indicate the mountain front has been erosionally embayed from its originally more linear, fault-bounded configuration. $Vf$ ratios for drainages along the mountain front can be used as an index of whether streams are actively downcutting or primarily eroding laterally. $Vf$ is the ratio of valley floor width to the average elevation of the left and right divides above the stream channel. Large $Vf$ ratios, indicating lateral stream planation, is dominant relative to downcutting, a situation that occurs when uplift rates are low or nonexistent along range-front structures.

The mountain front was divided into five lithologically distinct parts (Figure 1) for which sinuosity and representative $Vf$ ratios were calculated from 1:24,000 scale topographic maps. $Vf$ ratios were determined at one-tenth (0.1) the distance of basin length up from the mountain front for moderate-sized drainage basins. The valley floor was defined as the gently sloping surface between steep hillslope walls.

Resulting values of $S$ and $Vf$ (Table 6) are characteristic of tectonically inactive fronts (Bull and McFadden, 1977). Variations in the values of $S$ and $Vf$ for the Santa Rita Mountains are related to differing resistance to erosion of the lithologic types and relative sizes drainage basins present along each mountain-front segment. Tectonic inactivity along the western Santa Rita front is also suggested by the presence of inselbergs and a broad pediment mantled by thin alluvial fan deposits. A regional depth-to-bedrock survey (Oppenheimer and Sumner, 1980) indicates that shallowly buried ($\leqslant$120 m) bedrock benches occur between the outer inselbergs and mountain front.

The length of time elapsed since substantial faulting has occurred along the Santa Rita Mountains can be estimated by the time required to develop the observed bedrock pediment. Mayer (1979) estimated that the Mogollon Rim in east central

TABLE 6
LANDSCAPE PARAMETERS CALCULATED FOR THE WESTERN SANTA RITA MOUNTAIN FRONT (AFTER BULL AND MCFADDEN, 1977)

| Mountain-Front Segment | Lithology | S | Basin Length* (km) | Vf |
|---|---|---|---|---|
| 1 | K quartz monzonite | 3.9 | 5.5 | 57.5 |
| | | | 1.6 | 58.3 |
| 2 | Paleozoic and K sediments | 3.5 | 3.2 | 22.7 |
| | | | 6.4 | 72.4 |
| 3 | p€ granodiorite | 3.6 | 4.2 | 19.2 |
| | | | 2.4 | 40.0 |
| | | | 3.1 | 30.0 |
| 4 | Tertiary volcanics; K sediments; p€ schist; complex faults | 3.1 | 5.0 | 3.5 |
| | | | 5.5 | 26.3 |
| 5 | mid-K granodiorite; quartz monzonite; quartz veins | 2.4 | 5.5 | 5.3 |

* Long drainage basins (≥5.0 km) also tend to be very wide. Thus, their area is proportionately much larger than shorter basins.

Arizona has retreated at a rate of 0.35 to 0.9 km/m.y. during the late Cenozoic. Denudation rates of ~1 km/m.y. have been suggested for coarse-grained plutonic rocks of north-central Nevada and the White Mountains of California (Marchand, 1971; Wallace, 1978). Pediment width in the study area can only be estimated as it is mantled with alluvium. A minimum estimate of 2 to 3.8 km is obtained from the distance between the outermost bedrock exposures and the mountain-front escarpment. The measured distance of the fault scarps from the mountain front (2 to 6 km; mean of ~4 km) was used as a maximum pediment width. Using maximum and minimum pedimentation rates, these data imply a 2 to 10 m.y. interval since uplift rates exceeded rates of mountain-front retreat.

## REGIONAL NEOTECTONIC IMPLICATIONS

Regional evidence is consistent with the late Cenozoic period of quiescence along the Santa Rita front. Menges and McFadden (1981) concluded that major faulting of the Basin-Range disturbance in southeastern Arizona occurred between 13 to 10 Ma (Scarborough and Peirce, 1978; Shafiqullah *et al.*, 1978) and 3 to 6 Ma. Their conclusion was based on paleomagnetic stratigraphy in upper basin-fill deposits of Sonoita Creek basin (east of the Santa Rita Mountains) and the presence of dissected bedrock pediments 2- to 7-km wide, overlain by thin Quaternary deposits, in several basins of southeastern Arizona.

Field studies have been conducted on other late Quaternary fault scarps in southeastern Arizona and adjacent New Mexico and Sonora, Mexico (Menges and Pearthree, 1983; Machette *et al.*, 1986). These studies have demonstrated that late Quaternary faulting in this region has been concentrated in a belt near the Arizona-New Mexico border. Several fault scarps, including the Santa Rita scarps, occur peripheral to this belt. Recurrence intervals between movements on individual faults, where they can be inferred, are consistently on the order of $10^5$ yr. Pediments