DISTRIBUTION, RECURRENCE, AND POSSIBLE TECTONIC IMPLICATIONS OF LATE QUATERNARY FAULTING IN ARIZONA

by

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(data from Laboratory of Geophysics, Univ. of Arizona), are located between the dashed lines, with bar and ball indicating sense of displacement. Numerals are estimates of ages latest Pleistocene - Holocene surface ruptures.

Figure 9. Quaternary faulting in northwestern Arizona and southern Utah. Bold lines define boundaries of fault domains in Arizona, which are discussed in the text. Stipple pattern delineates approximate physiographic boundary of the Colorado Plateau. Faults labeled are Big Chino, BC; Camp Verde, CV; Grand Wash, GW; Mesquite, Me; northern and southern Hurricane, NH and SH; Paunsaugunt, P; Seligman, Se; Sevier, Sv; Toroweap, T; and Washington, W.

Figure 10. Regional neotectonic framework of Arizona, including domains of late Quaternary faulting in Arizona. Regional tectonic provinces defined by physiography, late Quaternary fault activity, or historic seismicity. Tectonic provinces bordering Arizona are the San Andreas transform system, SA; Great Basin or northern Basin and Range, GB; Rio Grande rift, RGR; Colorado Plateau, CP; Sierra Madre Occidental, SM. Area between the thick shaded lines in Arizona is a zone of possible Plio-Quaternary uplift.

TABLES

Table 1. Ages and rates of displacement on late Quaternary faults in Arizona. Alluvial geomorphic surfaces of late and mid-Pleistocene age or basalt flows between 100,000 and 1 million years old were used to estimate displacement rates. Surfaces listed as 500,000+ years old may be substantially older, and displacement rates obtained from these surfaces are maximum rates. Estimates of average total surface displacements and surface-age estimates are not precise, so displacement rates should be regarded as preliminary.

Table 2. Average regional surface-rupture recurrence intervals in Arizona during the last ~15,000 years. Regional recurrence intervals are most likely to be over-estimated in domains NW and SF due to the large number of faults in these areas that either have not been studied in the field or for which age of most-recent displacement is not well-constrained. Use of maximum and minimum numbers of events is mandated by uncertainties in determining the actual number of surface ruptures that have occurred during the last 15,000 years.

ABSTRACT

Probable Quaternary faults in Arizona have been mapped by systematic interpretation of aerial photographs, extensive geomorphic field studies, and compilation of previous work. Greatest concentrations of late Quaternary normal faults are found near the Colorado Plateau margin in northwestern and north-central Arizona, with lesser concentrations in central and southeastern Arizona and the Lake Mead area. Late Quaternary faults are rare in southwestern Arizona and none have been recognized in the interior of the Colorado Plateau province in northeastern Arizona.

Ages of most recent surface rupture, average recurrence intervals between surface ruptures, and vertical displacement rates were estimated for faults across the state, based on quantitative studies of fault scarp morphology combined with surface age-fault offset relationships. An average recurrence interval of 10^4 years and a vertical displacement rate of 30 m/10^5 years apparently typifies the northern Hurricane fault, which extends about 65 km south of the Arizona-Utah border. Recurrence intervals on individual faults increase to 10^4-10^5 years and displacement rates decrease to 3-15 m/10^5 years from the southern Hurricane fault southeastward along the Colorado Plateau margin to Big Chino valley, and on the Algodones fault near Yuma. Recurrence intervals of 10^5+ years and displacement rates of 3 m/10^5 years characterize faults studied in the rest of Arizona. Average regional recurrence intervals, computed from the number of surface ruptures that may have occurred in the last 15,000 years, are as short as 2000-3500 in northwestern and north-central Arizona. They increase to 3000-5000 years in southern and central Arizona and 3500-15,000 years in southwestern Arizona. Rates of surface-rupture occurrence per unit area during the last 15,000 years are at least 10 times higher in northwestern than in southwestern Arizona.

The predominance of non-tectonic landforms in the Basin and Range and Transition Zone provinces of Arizona indicates that major, widespread normal faulting ceased there during the late Miocene or early Pliocene. A few faults in these areas have been reactivated during the Quaternary or have had extremely low Plio-Quaternary vertical displacement rates, permitting bedrock pedimentation to proceed. Major Quaternary normal faulting in Arizona directly relatable to the Basin-Range disturbance is apparently restricted to the northern Hurricane and related faults, evidencing a late Cenozoic encroachment of normal faulting into the western Colorado Plateau region. Step-wise decreases in displacement rates on individual faults from the Utah border

to central Arizona suggest that late Quaternary regional extension diminishes gradually to the south. Faulting associated with the San Francisco volcanic field has also migrated northeastward onto the Colorado Plateau since the late Miocene, but apparently is not accomodating major, uniformly-directed extensional stress. The zone of Quaternary faults in southeastern Arizona and adjacent areas of New Mexico and Sonora, Mexico, is subparallel to the Rio Grande rift and may be related to it. Additionally, late Quaternary faulting and historical seismicity in Arizona are concentrated in a 200-300 km-wide zone of possible regional upwarping extending from southeastern to northwestern Arizona, between the interior Colorado Plateau and Sonoran regions. Thus, faulting and seismicity may be interrelated with upwarping localized between these adjacent more stable blocks.

INTRODUCTION

The nature and distribution of late Quaternary faulting and the resultant seismic hazard in Arizona were very poorly known prior to the last five years. Late Quaternary (less than about 500,000 years) faulting had previously escaped intensive study because of generally low levels of historical seismicity and an absence of population centers adjacent to obviously active faults. However, recent studies of fault scarp morphology, soil-stratigraphy, uplifted stream terraces, and offset dated basalts have demonstrated recurrent movement along faults across Arizona (Bull, 1974; Soule, 1978; Hamblin and others, 1981; Mayer, 1982; Pearthree and Calvo, in prep.; Bull and Pearthree, in prep.). These detailed studies have been integrated into a project to systematically map and conduct reconnaissance field studies on Quaternary faults throughout Arizona (Menges and Pearthree, in prep.). As a result of this work, the distribution of late Quaternary faults in Arizona is now fairly well-defined, and some characteristics of fault behavior are known in most portions of the state.

Proven, probable and possible Quaternary fault scarps in Arizona have been mapped through systematic interpretation of 1:125,000 scale black and white aerial photographs, extensive field studies, and compilation of previous work (Figure 2; Menges and Pearthree, in prep.). Offsets of stratigraphic units or shear zones were observed along some scarps; more commonly, however, geomorphic criteria, including non-parallelism of scarps with modern stream channels, non-uniform scarp altitude, and occurrence of the same alluvial geomorphic surface above and below the scarp were used to distinguish tectonic scarps from purely erosional features. Five detailed and about 40 reconnaissance field studies have been conducted on fault scarps across Arizona to estimate age of most recent fault movement, recurrence intervals between fault movements, and late Quaternary vertical displacement rates. Based on this data and studies by previous workers, the distribution of probable Quaternary faults and regional patterns of recurrent movement along individual faults during about the last 500,000 years can be characterized. In addition, preliminary estimates of regional recurrence intervals between surface-rupturing earthquakes averaged over the last approximate 15,000 years will be presented. Finally, the temporal relationship between late Quaternary faulting and major late Cenozoic block-faulting of the Basin-Range event and the tectonic significance of late Quaternary faulting in Arizona will be considered.

Physiographic, Geologic, and Seismic Setting

Arizona can be subdivided into three major physiographic regions (Figure 1). The Colorado Plateau province of northern and eastern Arizona is characterized by relatively high elevation and smooth topography interrupted only by broad monoclinal uplifts and the dramatic canyons of the Colorado River and its tributaries. Southern and western Arizona lie within the southern Basin and Range province (Fenneman, 1931), a region of discontinuous bedrock mountain ranges and alluviated valleys. Within this province, physiography varies from the broad valleys and subdued mountains of the Sonoran Desert subprovince of southwestern Arizona to the higher elevation, greater relief, and extensive valley dissection of the Mexican Highland and Mohave subprovinces. The Transition Zone, with rugged relief, dissected basins and small bedrock plateaus, straddles the boundary between the Colorado Plateau and Basin and Range provinces in central and eastern Arizona.

The Cenozoic histories of the Basin and Range and Colorado Plateau provinces in Arizona have been distinctly different. Regional compression during the Laramide orogeny (90-50 Ma) affected the entire state. It resulted in the formation of great monoclinal flexures on the Colorado Plateau (Davis, 1978), low-angle thrusts in much of southwestern Arizona (Reynolds, 1980), and possible large-scale, low-angle thrusts (Drewes, 1980), or basement-cored uplifts (Davis, 1979) in southeastern Arizona. Following the cessation of Laramide compression in the Eocene, a broad, north- to northeastward-sloping erosion surface is inferred to have existed in much of Arizona (Scarborough and Peirce, 1978). During the mid-Tertiary (38-15 Ma), much of the Basin and Range province was profoundly disrupted as arc or back-arc magmatism swept westward across southern and western Arizona (Coney and Reynolds, 1977; Elston and Bornhorst, 1979). This event was manifested as voluminous calc-alkaline volcanism, pervasive crustal shearing in metamorphic core complexes, and extensive supracrustal block rotation related to low-angle normal faulting and thin-skinned extension (Anderson, 1971; Anderson and others, 1972; Shafiqullah and others, 1978, 1980; Rehrig and Reynolds, 1980). Higher-angle normal faulting and predominantly basaltic volcanism of the Basin-Range event post-dates this interval, beginning between 15-10 Ma (Scarborough and Peirce, 1978; Shafiqullah and others, 1980; Menges, 1981; Lucchitta and Suneson, 1983). This high-angle faulting is primarily responsible for the mountain block-alluvial basin physiography typical of the Basin and Range province (Scarborough and Peirce, 1978; Scarborough, Menges and

Pearthree, in prep.). The timing of cessation of the Basin-Range event and its relationship to late Quaternary faulting in Arizona will be discussed in some detail later.

Much of the seismicity in the interior of the Cordillera of the western United States is concentrated in the Intermountain seismic belt (ISB) that extends along the Wasatch front in Utah (Smith and Sbar, 1974), continues into southwestern Utah and then probably turns west across southern Nevada (Smith, 1978). However, a secondary prong may extend southward into northwestern Arizona. Seismicity in Arizona is concentrated in a poorly-defined belt stretching from this possible extension of the ISB southeastward along the Colorado Plateau margin into the Basin and Range province in southeastern Arizona (Sumner, 1976; DuBois and others, 1982; see Figure 3). The largest instrumentally recorded earthquake in Arizona, a magnitude 5.5-5.75 event, was located west of the Kaibab Plateau in northwestern Arizona (DuBois and others, 1982). However, an estimated 7.2-7.4 magnitude event (Natali and Sbar, 1982; Herd and McMasters, 1982) occurred in 1887 on the Pitaycachi fault in northeasternmost Sonora, Mexico, at the southeastern end of this belt of historical seismicity.

THE NATURE AND DISTRIBUTION OF QUATERNARY FAULTING

All faults that offset Quaternary units in Arizona have steep (55° - 90°) near surface expression, although Hamblin (1965) found evidence that some fault plane dips in northwestern Arizona decrease with depth. Most exposed fault planes show normal separation and dip away from the adjacent fault escarpment or bedrock mountain block, with a few being nearly vertical or very high-angle reverse. Surface rupture patterns vary from relatively simple, arcuate scarps to very complex anastomosing and en echelon ruptures, and antithetic scarps or roll-back features are common on the downthrown block. Total Quaternary surface offset along individual faults ranges from as little as 1-2 m on the Sand Tank fault in southwestern Arizona to at least 310-470 m on the Hurricane fault in Utah (Anderson, 1980) slightly north of the Arizona border. Average vertical surface displacements during individual events, estimated from topographic scarp profiles, range from about 0.5-3 m. Documented surface rupture lengths vary from 2-3 km along several faults to 75 km along the Pitaycachi fault during the 1887 event (Herd and McMasters, 1982), although the potential for longer surface ruptures may exist along some major structures in northwestern Arizona. Earthquake magnitudes of surface-rupture events, estimated from geologic moment-magnitude calculations (see Brune, 1968; Hanks and Kanamori, 1979), range from slightly less than 6 to about 7½.

Quaternary faults have been recognized throughout much of Arizona, with the exception of the interior of the Colorado Plateau in northeastern Arizona. Faults are concentrated in a band stretching diagonally from northwest to southeast across the state, generally coinciding with areas of historical seismicity (compare Figure 2). The greatest number of faults are found near the margin of the Colorado Plateau in northwestern Arizona, where numerous subsidiary faults are associated with several major, continuous, N-S-trending faults. A second major locus of faults, with a wide variety of trends, clusters around the northern and eastern margins of the San Francisco volcanic field of north-central Arizona. Lesser concentrations of faults are located in the Lake Mead region, the basins of central Arizona, and in southeastern Arizona. Quaternary faults are rare in southwestern Arizona.

METHODS USED TO ESTIMATE AGE OF MOST RECENT SURFACE RUPTURE, DISPLACEMENT RATES, AND SURFACE-RUPTURE RECURRENCE INTERVALS ALONG FAULTS

Quantitative analyses of fault scarp morphology and offset alluvial geomorphic surfaces of different ages were the primary tools used to estimate ages of most recent surface rupture, surface-rupture recurrence intervals, and vertical displacement rates on faults studied in the field. Several methods were employed to estimate fault scarp age from scarp morphology. These estimates were then compared with constraints provided by offset or lack of offset of alluvial geomorphic surfaces, whose ages were estimated based on soil-profile development. Using these combined data, we estimated minimum and maximum ages for the most-recent surface ruptures along faults (Table 1). Average surface-rupture recurrence intervals and displacement rates on faults were estimated based on increasing offset with increasing surface age. Because of the uncertainty in estimating surface ages from soil-profile development, only order-of-magnitude estimates of recurrence intervals and rough estimates of displacement rates were attempted.

Wallace (1977) noted the decrease in maximum fault scarp slope with scarp age, and demonstrated how this could be used to roughly estimate scarp age. Subsequently, several more quantitative methods have been proposed to estimate ages of scarps probably formed during one surface-rupture event, and three of these were used in our studies. All the methods depend on the work of Bucknam and Anderson (1979) in central Utah, where the Bonneville shoreline provides a timeline to which fault scarps can be compared. The first approach, developed by Bucknam and Anderson (1979), involves comparing regression lines of maximum scarp-slope angle v. log of scarp height from undated scarps with regression lines from scarps with independently estimated ages. We used the 14,000-15,000 year old Lake Bonneville shoreline scarps (scarp data from Bucknam and Anderson, 1979; shoreline age from Scott and others, 1983) and two 4,000-5,000 year old scarps in New Mexico (Machette, 1982; see Figure 3) as reference lines.

The second scarp-dating method is derived from the diffusion equation model of hillslope scarp-degradation (Nash, 1980). Using this model, the age of a scarp can be estimated from the following equation:

$$t_u = t_d(H_u/H_d)^2 \qquad (1)$$

where t_u and t_d are the ages of the scarp one seeks to date and a reference scarp of known age, respectively, H_u is any representative height of the undated scarp, and H_d is the height of a dated scarp with the same maximum slope as the chosen undated scarp (Nash, 1980). Mayer (1982) modified this method to take into account some of the uncertainty inherent in the age estimation process. He used the combined maximum slope angle and height data from 5,000 year old Drum Mountains fault scarps (Hanks and others, in press) and 14,000-15,000 year old Bonneville shoreline scarps to define a regression line for a 10^4 year old scarp. Minimum and maximum values of H_d, defined by the 95% confidence interval around this regression line, provide maximum and minimum values of t_u for each topographic profile of the undated scarp (SCARP program, Mayer, 1982). The age range estimates are then compiled in histograms to determine a modal scarp age estimate (Figure 4a). The third dating approach uses a function designed to discriminate between scarps of Holocene and late

Pleistocene age, based again on maximum slope angle v. scarp height data (Mayer, 1982; Figure 4b).

Uncertainty inherent in morphologic scarp age estimates is substantial and increases with scarp age. The dated scarps, which provide the control for scarp age estimates, occur in unconsolidated alluvium under semi-arid climatic conditions (Bucknam and Anderson, 1979; Machette, 1982). Most of the fault scarps studied in Arizona occur in semi-arid or arid portions of the state, and we emphasized the topographic profiling of scarps formed in unconsolidated, cobbly alluvium. Some amount of error is introduced into scarp age estimates in any situation where lithologic and climatic conditions are not identical with those of the dated scarps, however. Machette (oral communication, 1983) has further suggested that the effects of regional climatic change on rates of scarp degradation are substantial. Also, there are no very precisely-dated scarps older than 15,000 years. For these reasons, we do not imply great precision in the age estimates based on scarp morphology given in Table 1, especially for those older than 15,000-20,000 years.

Amount of offset of alluvial geomorphic surfaces or lack thereof further constrains estimates of ages of faulting, and provides the primary evidence used to roughly define recurrence intervals and displacement rates. Several soil properties, including amount of pedogenic calcium carbonate and clay and maximum redness, have been found to increase with surface age in semi-arid and arid portions of the southwestern U. S. (Gile and others, 1966, 1981; Bachman and Machette, 1977; McFadden, 1978, 1982; Gile and Grossman, 1979; Shroba, 1982). Surface ages were estimated by describing soil properties and comparing their development with those of soils whose ages are known or fairly well constrained. Chronologies of stages of calcium carbonate accumulation have been defined in both arid and semi-arid portions of the southern Rio Grande valley in New Mexico (Gile and others, 1966, 1981; Gile and Grossman, 1979), and at other localities in the southwestern U. S. (Bachman and Machette, 1977). Increases in percent clay and redness in soil B horizons were also used to estimate surface ages by comparison with the soils of the southern Rio Grande Valley.

Soils in Arizona considered to be Holocene-latest Pleistocene in age ($\lesssim$15,000-20,000 years old) typically display minor increases in clay and redness and stage I or II calcic horizons. Late Pleistocene soils ($\lesssim$50,000-100,000 years old) typically have substantial increases in maximum clay content and redness and/or stage II-III calcic horizons. Mid-Pleistocene ($\sim$200,000-700,000 years old) soils exhibit further increases in clay and redness and stage III-V calcic horizons. Certainly, variations in parent material and climate introduce variation into rates of soil-profile development; thus the resultant surface age estimates incorporate substantial uncertainty.

Recurrence intervals between surface ruptures along individual faults and vertical displacement rates were estimated from observed increases in offset of older surfaces. Valid comparison of displacement rates between faults depends on averaging displacement rates over similar intervals. Realistically, surface age estimates are imprecise, ages of surfaces available for estimating displacement rates vary between faults, and relatively recent ruptures along faults with long recurrence intervals can give inflated displacement rates. Therefore, displacement rates given in

Table 1 and referred to later are based on offset of late and mid-Pleistocene surfaces, and in a few cases offset of dated Quaternary basalts between 0.1 and 1.0 Ma. Separate displacement rates were calculated wherever late and mid-Pleistocene surfaces are displaced by different amounts. Where possible, the average amount of displacement attributable to the most-recent surface rupture was estimated from topographic profiles of surfaces inferred to be offset only during that event, or from the steepest segments of composite scarp profiles. This increment was then used to obtain a preliminary estimate the total number of surface ruptures recorded by composite offsets of older surfaces or dated volcanic rocks. Average recurrence intervals on faults were obtained by dividing surface age by the estimated number of surface ruptures. Uncertainties in estimates of surface ages and the number of surface ruptures dictate that only order of magnitude estimates of recurrence intervals be attempted for most faults in Arizona.

RECURRENCE INTERVALS AND DISPLACEMENT RATES ON INDIVIDUAL FAULTS AND DOMAINS OF LATE QUATERNARY FAULTING

Recurrence intervals between surface ruptures and displacement rates on individual faults vary by at least an order of magnitude within Arizona (Table 1). This variation in fault behavior, combined with the spatial distribution and relative densities of faulting discussed earlier, allow us to define distinct domains of late Quaternary faulting in Arizona (Figure 5).

Faults with surface-rupture recurrence intervals on the order of 10^4 years and displacement rates as high as 30 m/10^5 years are restricted to a narrow zone in northwestern Arizona (domain NW1). The northern Hurricane fault has evidently been the most active structure in the state during the late Quaternary. A basalt flow dated at 2.9 (±0.09) x 10^5 years at the town of Hurricane, Utah, 20 km north of the Arizona border, has been displaced 87 m vertically along the Hurricane fault (Hamblin and others, 1981). If movement along the Hurricane fault has occurred as discrete events resulting in 2-3 m of surface offset, as is suggested by scarp profiling at one locality just south of the Arizona border, then the average late Quaternary recurrence interval between such events at Hurricane, Utah, is 6,000-10,000 years. If surface ruptures have occurred at different times along individual segments of the Hurricane fault, as has been the case along the Wasatch fault during the Holocene (Swan and others, 1980), then the average recurrence interval along the whole fault is much less.

Analysis of the geomorphology of the cliffs associated with the Hurricane fault, extrapolated from the area where the amount of late Quaternary displacement is known, indicates that these high displacement rates have extended about 65 km south of the Arizona-Utah border along the Hurricane fault. Similar fault escarpment morphologies suggest that the Washington fault zone along the southeastern margin of the St. George basin (domain NW1) and a short segment of the southern Toroweap fault (domain NW2) may have experienced similar high displacement rates during at least the latest Quaternary. Rates of displacement and recurrence intervals along the numerous smaller structures that offset the Shivwitz Plateau west of the Hurricane fault, as well as the structures associated with the Kaibab Plateau, are not well-constrained.

Recurrence intervals of between 10^4 and 10^5 years and displacement rates of 3-15 m/10^5 years are characteristic of faults in the region extending from the southern Hurricane and Toroweap faults southeastward to Big Chino valley (domain NW2). Basalt flows along the southern Hurricane fault estimated to be 100,000-200,000 years old (based on thermo-luminescene dating; Holmes and others, 1978; Holmes, 1979) have been offset 6-8 m probably during 2-3 events (see earlier discussion for methods used to estimate number of surface ruptures). Along both the Big Chino and Seligman faults, surfaces estimated to be 50,000-100,000 years old, based on soil-profile development, have been offset 6-7 m during about 3-4 events. Similar displacement rates have prevailed along the Algodones fault of southwesternmost Arizona (Bull, 1974).

Recurrence intervals between surface ruptures on faults increase to 10^5 years and displacement rates are less than 3m/10^5 years in southern Arizona and the Lake Mead region (domains SE, SW and LM), and probably in central Arizona as well (domain C). Uncertainty exists concerning recurrence intervals along some faults in the latter area, but 10^5 years recurrence intervals have been inferred for most faults. An example of this is found along the Camp Verde sement of the Verde fault, where a surface estimated to be 500,000+ years old has been offset 4-6 m during about 3 events. Recurrence intervals on the order of 10^5 years are ubiquitous along faults in domains SE, LM and SW. Mid-Pleistocene surfaces (200,000-500,000(?) years old) along the Pitaycachi, Santa Rita, and Safford faults in domain SE have been offset an average of 2.5-4.0 m probably during only two events. Early to mid-Pleistocene surfaces (500,000+ years old) have been offset 4-5 m during ~3 events along the

Needles fault in domain SW and <17 m during 4-8 events along the Mesquite fault in domain LM. Individual faults in domain SF have not been studied in sufficient detail to confidently estimate recurrence intervals.

The high density of late Quaternary faults and relatively high displacement rates across some faults imply that domain NW1 has the highest regional late Quaternary strain rate in Arizona. Average recurrence intervals estimated along the northern Hurricane fault are similar to those reported for other faults studied in the Great Basin (summarized in Wallace, 1981, Table 1). Fault densities remain fairly high, but displacement rates decrease, in domains NW2 and SF. Several moderate concentrations of late Quaternary faults occur in central, southeastern and northwesternmost Arizona, but very low regional strain rates are implied by recurrence intervals on the order of 10^5 years and displacement rates of ≤ 3 m/10^5 years on individual faults. Similar long recurrence intervals have been reported for faults in the Rio Grande rift (Machette, 1978; Machette and Colman, 1983; McAlpin, oral communication, 1983).

REGIONAL RECURRENCE INTERVALS AND SEISMIC HAZARD FROM LARGE EARTHQUAKES

Seismic hazard posed by large earthquakes in Arizona can be considered in the context of average regional recurrence intervals between surface-rupturing earthquakes. Analyzing recurrence on a regional basis within Arizona is mandated by the wide variations in numbers and recurrence histories of faults between regions. Further, long surface-rupture recurrence intervals on faults in much of the state imply that faults or fault segments most recently active are at least likely to be active again in the foreseeable future. Finally, low levels of historic seismicity make it an ineffective data source for predicting rates of large earthquakes.

Surface ruptures that may have occurred in about the last 15,000 years were used to compute average regional recurrence intervals (Table 2). Age control on faulting events older than about 15,000 years is imprecise, and the problem of erosional removal of evidence of faulting increases with age of faulting. In addition, only the ages of most recent movement have been estimated on the more active faults in the state; ages of earlier events are not well-constrained. Uncertainties inherent in the methods used to estimate ages of surface ruptures even during the last 15,000 years dictate that we 1) estimate average, not actual regional recurrence intervals; and 2) use maximum and minimum numbers of events that may actually have occurred during this interval.

Differences in regional recurrence intervals averaged over the last 15,000 years generally reflect relative concentrations of late Quaternary faulting. Northwestern and north-central Arizona (domains NW1, NW2 and SF) are the areas of greatest seismic hazard in the state, with estimated recurrence intervals as short as 2000 to 3500 years (Table 2). Furthermore, recurrence intervals are most likely to be over-estimated in these domains due to the large number of faults that either have not been studied in the field or lack relationships that permit definitive estimation of displacement ages. In the rest of the state, Holocene-latest Pleistocene has occurred in most areas where late Quaternary faulting has been recognized (Figure 6), but average regional recurrence intervals range from 3000 years to perhaps as much as 15,000 years or more. Actual regional recurrence intervals undoubtedly vary substantially, however, and the potential for moderately large to large earthquakes exists throughout much of Arizona.

Rates of surface rupture occurrence during the last ~15,000 years normalized for domain area further emphasize the variation in fault activity across Arizona (Table 2). The highest surface rupture rates observed, those of domains NW1 and SF, are apparently comparable to that of north-central Nevada (computed from Wallace, 1981). Rates decrease somewhat in domain NW2 and are much less in the rest of the state, even in areas of relatively concentrated faulting. It appears that the rate of surface rupture occurrence in southwestern Arizona has been a minimum of 10 times less than those of domains NW1 and SF.

Patterns of late Quaternary faulting in domain SE suggest the existence of long-term temporal variations in regional rates of surface rupture occurrence. Most basins in southeastern Arizona and adjacent New Mexico and Sonora have suites of well-preserved alluvial geomorphic surfaces of Holocene to at least mid-Pleistocene age, which provide a relatively good record of late Quaternary fault activity. There have been at least 4, and probably 5 surface ruptures in the last 15,000 years in a N-S-trending zone within domain SE (domain SE2; see Figure 8). In the entire area of domain SE, we have found evidence for no more than 7 surface-rupture events in the previous 100,000± years. Even if the late Pleistocene record is not absolutely complete, this evidence suggests that the Holocene-latest Pleistocene has been a period of substantially elevated (about 4 times higher) fault activity in domain SE. In addition, there appears to have been a general north-to-south migration of surface ruptures during this period (see Figure 8). Movement along the Safford fault is estimated to have occurred 10,000-20,000 years ago (see Table 1). Surface ruptures along the Animas, Gillespie Mtn., and Chiricahua faults are all considered to have occurred during the mid-Holocene (about 2,000-10,000 years ago), although the exact sequence of these events is not certain. The most recent surface rupture in domain SE2 occurred farther south along the Pitaycachi fault, in 1887.

RELATIONS BETWEEN LATE QUATERNARY FAULTING IN ARIZONA AND THE BASIN-RANGE DISTURBANCE

Late Quaternary displacement rates on individual faults, spatial concentrations of faults, and variations in the physiographic expression of faulting are critical to assessment of the temporal relationship of Quaternary faulting to the Basin-Range event and the tectonic implications of late Quaternary faulting in Arizona. The physiographic expression of faulting changes from bedrock escarpments on the western Colorado Plateau (see Figure 7A) to piedmont fault scarps in the Basin and Range province to the south and west (see Figure 7b); a transitional region in north-central Arizona includes both piedmont scarps and bedrock escarpments (domain NW2, Figure 5). This change coincides with at least an order of magnitude decrease in estimated late Quaternary displacement rates on faults. As the nature of Quaternary faulting is quite different in the western Colorado Plateau and Basin and Range provinces, faulting in the two areas will initially be discussed separately.

Basin and Range Province

The Basin and Range province of Arizona has been considered to be tectonically inactive, based primarily on physiographic comparisons with the Great Basin and to a lesser degree on low levels of historical seismicity (Eaton and others, 1978; Best and Hamblin, 1978). Extensive pedimentation of mountain blocks in the Sonoran Desert subprovince of southwestern Arizona in particular has indicated to previous workers that active block-faulting ceased there as much as 8-10 Ma (Eberly and Stanley, 1978; Shafiqullah and others, 1980). Some have suggested, however, that Basin-Range activity has continued to the present in portions of the topographically higher Mexican Highland subprovince of southeastern Arizona and the Transition Zone of central Arizona (Shafiqullah and others, 1978, 1980; Strand and others, 1982; see Figure 1 for province locations). Our studies confirm that late Quaternary faulting has been concentrated in this region relative to the Sonoran Desert subprovince. However, before this faulting is considered part of an on-going Basin-Range event, the implications of faulting of piedmonts basinward from topographic mountain fronts and very low displacement rates on faults should be evaluated.

The occurrence of late Quaternary piedmont fault scarps in the Basin and Range portion of Arizona can be inferred to represent either Quaternary reactivation of older structures after some interval of tectonic quiescence or very low Plio-Quaternary fault-displacement rates. Pedimented, embayed mountain fronts are nearly ubiquitous in the Basin and Range and Transition Zone provinces of Arizona. Bedrock pediments begin to form when the rate of relative uplift along a range-bounding fault is less than denudation rates at the mountain front, allowing stream valleys to widen and embay the mountain front and mountain front hillslopes to retreat from the structure (Bull, in prep.). Rates of bedrock pedimentation or escarpment retreat have been estimated at between 0.4-0.9 km/m.y. for the Mogollon Rim in east-central Arizona (Mayer, 1979) and 1 km/m.y. for the White Mountains of California (Marchand, 1971). Using these rates, the length of time since relative vertical uplift of the mountain block exceeded the rate of mountain front retreat can be estimated.

Relations between Quaternary fault scarps and mountain fronts have been studied in the most detail in domain SE, and evidence indicates that large-scale block-faulting ceased in this region a minimum of 3-6 Ma. Studies of the Canada del Oro and Sonoita basins near Tucson revealed that mountain fronts had retreated 2-7 km from major range-bounding structures prior to deposition of unfaulted units of latest Pliocene-early Pleistocene age (Menges and McFadden, 1981). In addition, magnetic-polarity stratigraphy developed in the Sonoita basin establishes an age range of 3.3-5.8 Ma for an undeformed upper basin-fill unit (Menges, 1981). From this evidence, they concluded that no significant displacement has occurred across the range-bounding for at least 3-6 million years. Pediment widths along the west side of the Santa Rita Mountains south of Tucson imply tectonic inactivity for at least 4 million years prior to minor late Quaternary faulting (Pearthree and Calvo, in prep.). Everywhere Quaternary faulting occurs in domain SE, mountain fronts have retreated from major structural boundaries inferred from gravity gradients. Further, the minor amounts of Quaternary displacement observed have occurred along only about 30% of the major structural basin boundaries (Figure 8), implying that far fewer faults have been active during the Quaternary than were active during the main late Miocene phase of the Basin-Range disturbance in Arizona (as defined by Scarborough and Peirce, 1978).

The main phase of Basin-Range activity apparently ceased during the late Miocene-early Pliocene in the rest of the Basin and Range and

Transition Zone provinces in Arizona as well. In almost all cases, mountain fronts are substantially pedimented, suggestive of an extensive interval of relative tectonic quiescene, even in areas where late Quaternary faulting has occurred. Major block-faulting in the Mohave portion of the Basin and Range province (Figure 1) evidently ceased at least 5-7 Ma. Lucchitta (1979) determined that substantial movement on the southern Grand Wash fault, the structural boundary of the Colorado Plateau in northwestern Arizona, ceased prior to 5-6 Ma although offset may have occurred along the Wheeler fault to the west since that time. High-angle faulting in the Bill Williams River area to the south had ceased by 7 Ma (Lucchitta and Suneson, 1983). Displacement across faults bounding the Black Mountains in domain LM probably ceased prior to about 6 Ma (Anderson and others, 1972). S. Reneau (written communication, U. S. Geological Survey, Menlo Park, 1982) analyzed a number of mountain fronts in domains LM and SW using topographic maps and photographs and concluded that the majority are certainly inactive. Several mountain fronts in domain C have characteristics suggestive of long-term tectonic activity. These linear mountain fronts may be the result of erosional removal of poorly-indurated late Cenozoic sediments and exhumation of range-bounding structures, or they may actually be indicative of Plio-Quaternary fault displacement. There is evidence for an interval of tectonic quiescence even in domain NW2, where late Quaternary displacement rates on faults have been higher than in central and southern Arizona. The mountain front associated with the Big Chino fault scarp in this domain has been tentatively classified as inactive (Soule, 1978), although the piedmont has been displaced over 20 m during the mid- to late Quaternary.

The predominance of non-tectonic landforms in most portions of Arizona affected by the Basin-Range event implies that major block-faulting ended at least during the Pliocene, and probably during the late Miocene in many areas. Relatively small-scale late Quaternary faulting observed in the Basin and Range and Transition Zone provinces represents minor reactivation of faulting after a period of tectonic quiescence and/or long-term vertical displacement rates sufficiently low that erosional retreat of mountain fronts has dominated over uplift.

Colorado Plateau Margin

The physiographic expression of Quaternary faulting, larger number of faults, and more active faults on the western Colorado Plateau in northwestern Arizona have important implications for its relationship to the Basin-Range disturbance. Best and Hamblin (1978) argued that normal faulting and basaltic volcanism of the latest phase of Basin-Range activity have migrated to the north and east in Arizona and Utah during the late Cenozoic. Consequences of this pattern would be the northward migration of both the initiation and cessation of block-faulting in the Basin and Range province and encroachment of normal faulting into the Colorado Plateau region. The timing of initiation of major normal faulting is now constrained in several areas of southwestern Utah and northwestern Arizona, permitting assessment of whether encroachment to the east has continued into the Quaternary. We will also consider whether late Quaternary faulting farther south in Arizona along the Colorado Plateau margin is consistent with a simple northward migration of normal faulting.

In northernmost Arizona and southern Utah, it does appear that major block-faulting of the Basin-Range event has encroached eastward into the Colorado Plateau province during the last 10 million years (refer to Figure 9 for locations). Deep, sediment-filled basins began to form in the Basin and Range province in southwestern Utah between 10 and 8 Ma (Anderson and Mehnert, 1979). Normal displacement along the northern Hurricane fault on the western Colorado Plateau, however, may be primarily of Quaternary age (Anderson and Mehnert, 1979). Anderson and Mehnert (1979) estimated major block displacement across the northern Hurricane fault at 600-850 m. Basalts in southwestern Utah, dated at about 1 Ma, have been displaced 300-450 m across the Hurricane fault (Anderson, 1980). Given this displacement rate for the last million years, most of the normal displacement on the Hurricane fault has probably occurred during the Quaternary, although movement may have begun during the Pliocene (Anderson and Mehnert, 1979).

Farther north in southwestern Utah, Rowley and others (1981) have documented progressive late Cenozoic encroachment of normal faulting eastward into the Colorado Plateau province. Evidently, major normal fault displacement migrated eastward from the Basin and Range province about 9 Ma to the Sevier fault on the Colorado Plateau between 7.6 and 5.4 Ma and the Paunsaugunt fault zone still farther east subsequent to 5 Ma (Rowley and others, 1981). Late Quaternary faulting has been reported at several locations near this E-W transect (Hoover, 1974; Clark, 1976; Anderson, 1980; Best and others, 1980), but it is not clear that late Quaternary displacement has been concentrated along one structure defining the eastern edge of normal faulting, as apparently was the case in this region when major displacement occurred along the Sevier fault zone between 7.6 and 5.4 Ma (Rowley and others, 1981). Therefore, while eastward encroachment of normal faulting onto the Colorado Plateau occurred in southwestern Utah during the late Cenozoic, it has been fairly complex in detail, and faulting may have been distributed over a fairly broad region during the Quaternary.

The Hurricane fault evidently has formed the eastern margin of major displacement on normal faults near the latitude of the Arizona-Utah border during the Quaternary. There is no evidence of substantial late Quaternary movement along the Toroweap fault directly east of th active northern Hurricane fault, as there is little or no topographic relief on the eastern (upthrown) side of the Toroweap fault. Farther east, Quaternary offset on the faults associated with the Kaibab Plateau is uncertain (Strahler, 1948; Mayer, unpubl. data), but significant microseismicity occurs in this region (Kruger-Knuepfer and others, 1983). The lesser faulting and microseismicity of domain NW3 may be precursory to eastward migration of major normal faulting.

High mid- and late Quaternary displacement rates, which indicate normal displacement on the northern Hurricane fault is predominantly of Quaternary age, appear to have continued only about 65 km south into Arizona (domain NW1, Figure 9). Data is not available to closely constrain the timing of initiation of normal displacement on faults farther south in domain NW2, but lower late Quaternary displacement rates in domains NW2 and LM are consistent with northward and eastward migration of faulting, leaving in its wake domains of reduced fault activity (Best and Hamblin, 1978). Alternatively, the evidence for reactivation of faulting in these domains discussed earlier argues that faulting may actually have increased during the late Quaternary. The presence of late Quaternary piedmont faults scarps out from the base of bedrock escarpments along portions of the southern Hurricane and Toroweap faults near the Colorado River may be the result of escarpment retreat during an interval of tectonic quiescence. although structural complexities could also be responsible. The fact that the transitional zone NW2 extends beyond the margin of the Colorado Plateau and includes a clearly reactivated structure such as the Big Chino fault, however, suggests the possibility that intermediate fault displacement rates have extended southeastward during the mid- and/or late Quaternary.

Faulting and volcanism of domain SF have migrated to the north and east since late Miocene time (Ulrich and others, 1979 ; Scarborough and others, in prep.), but the nature of faulting is distinctly different in domains SF and NW. Late Quaternary faulting has been concentrated around the northern and eastern margins of Quaternary volcanism, apparently slightly preceding the encroachment of volcanism north and east into the Colorado Plateau province. While there are several preferred orientations, faults in domain SF have a variety of contemporaneously active trends imply the absence of a regionally consistent horizontal extension direction, in contrast to northwestern Arizona and southwestern Utah.

POSSIBLE TECTONIC IMPLICATIONS OF LATE QUATERNARY FAULTING

Arizona lies between three tectonic provinces that have had major late Cenozoic activity, the San Andreas transform system, the northern Basin and Range, and the Rio Grande rift. Connections between patterns of late Quaternary faulting in Arizona and tectonic activity in adjacent areas are relatively obscure, however, and can only be speculated on.

Widespread, major fault deformation has not affected the Basin and Range and Transition Zone provinces of Arizona during Pliocene and Quaternary time. Faulting directly relatable to the San Andreas transform system is apparently restricted to the Algodones fault near Yuma. Immediately to the east, the Sonoran Desert subprovince is one of the least active areas in Arizona.

Only faulting in northwestern Arizona (domain NW1) can confidently be related directly to the Basin-Range disturbance, as high rates of faulting near the western Colorado Plateau margin extend semi-continuously from the northern Hurricane fault north to the Wasatch front (Hamblin and Best, 1980). Faulting in domains NW2, C, and SF may be related less directly to active Basin-Range extension. Faulting and volcanism of domain SF has mimicked the larger late Cenozoic north- and eastward migration of Basin-Range extension and volcanic activity into the Colorado Plateau region, but there is no evidence that faulting in domain SF is accomodating major regional extension. Abrupt decreases in displacement rates along faults from domains NW1 to NW2 and again from domains NW2 to C suggest that extension concentrated near the Colorado Plateau margin decreases in a step-wise manner from southern Utah to central Arizona. However, evidence for reactivation of many faults in domains NW2 and C indicates that the present regional pattern may have developed during the mid- and late Quaternary. The nature of the southward termination of major extension is even less clear prior to the mid-Quaternary.

Late Quaternary faulting in domain SE is concentrated in a N-S-trending zone (domain SE2) that bridges the area between the Colorado Plateau and the northern end of the Sierra Madre Occidental and is subparallel to the Rio Grande Rift 100 km to the east (Figure 10). This suggests that domain SE2 may be either a separate, weakly-developed rift-like feature, perhaps indirectly related to the Rio Grande rift (Seager and Morgan, 1979), or a portion of the diffuse southern rift (Machette and Colman, 1983). If the apparent absence of Quaternary faults along the Colorado Plateau margin between domains C and SE is real, then faulting in these domains may occur in response to separate regional tectonic stresses, even though displacement rates on individual faults are similar.

Alternatively, all of the faulting near the Colorado Plateau margin south of domain NW1, as well as the faulting in domain SE, may be interrelated with regional upwarping. Lucchitta (1979) asserted that the western Colorado Plateau margin and much of the lower Colorado River valley have been uplifted since early Pliocene time, with uplift not along discrete faults. It is further possible that a 200-300 km wide, arch-like zone, generally following the Transition Zone and the Colorado Plateau margin but trending N-S in southeastern Arizona, has been upwarped during the Pliocene and Quaternary (Figure 10). The hypothesis is based on locations of divergent stream terraces of major drainages, stream downcutting rates determined from dated basalt flows, and the distribution of dissected alluvial basins (Menges and Pearthree, in prep.). This zone coincides with concentrations of Quaternary faults and historical seismicity. It also coincides with a region of crustal thinning and anomalous upper mantle structure beneath the southern and western margins of the Colorado Plateau (Keller and others, 1979). Quaternary faults occur within but do not bound the proposed zone of regional uplift, suggesting that both types of deformations may be interrelated manifestations of some more fundamental crustal-scale, geodynamic process localized between the more stable interior Colorado Plateau and Sonoran Desert blocks.

CONCLUSIONS

Late Quaternary normal faulting has occurred in most portions of Arizona, although late Quaternary faults have not been recognized in the interior of the Colorado Plateau in northeastern Arizona and are rare in southwestern Arizona. Relative concentrations of faults have been found along the Colorado Plateau margin from central to northwestern Arizona, and in southeastern Arizona. Very long surface-rupture recurrence intervals, on the order of 10^5 years are typical of faults in almost all of the southern Basin and Range and Transition Zone physiographic provinces. Recurrence intervals decrease to 10^4-10^5 years in part of the Transition Zone in north-central and the Colorado Plateau province in northwestern Arizona (fault domain NW2, Figure 5), and are as short as 10^4 years along the northern Hurricane fault (domain NW1). Average regional recurrence intervals, based only on the number of possible surface ruptures in about the last 15,000 years, are also shortest in northwestern and north-central Arizona. Although average regional recurrence intervals are longer in the rest of the state, it nonetheless appears that there has been surface-ruptures in all portions of Arizona except the interior of the Colorado Plateau during the last 15,000-30,000 years.

High rates of late Quaternary vertical displacement on faults, probably related to active extension at the margin of the northern Basin and Range province, continue about 65 km south of the Arizona-Utah border along the Hurricane and associated faults (domain NW1). This fault activity is apparently part of a late Cenozoic eastward encroachment of Basin-Range tectonic patterns into the Colorado Plateau region. Displacement rates on faults decrease substantially in a transitional region to the south (domain NW2), and are lower still in central Arizona and the Lake Mead region (domains C and LM). Evidence for reactivation of some structures in domains NW2 and C after a period of tectonic quiescence suggests that the present pattern may have developed during the mid- or late Quaternary.

This southward-decreasing trend overlaps with a pattern of minor Quaternary reactivation and very low long-term Plio-Quaternary vertical displacement rates on faults in the Basin and Range and Transition Zone provinces of Arizona. The predominance of non-tectonic landforms in these areas indicates that the main phase of block-faulting of the Basin-Range event ended in most of Arizona by the early Pliocene. Subsequent to that time, movement probably ceased entirely along most range-bounding structures prior to Quaternary reactivation of a few faults. Some faults, however, may have been active sporadically ever since the main late Miocene phase of the Basin-Range event.

Relative concentrations of faults and variations in late Quaternary displacement rates suggest several possible explanations. The general southward decrease in both numbers of faults and late Quaternary displacement rates on faults along the Colorado Plateau margin from southern Utah to central Arizona suggests that active regional extension associated with the Basin-Range event in Utah dies out gradually to the south. The concentration of faulting in southeastern Arziona may be related to the Rio Grande Rift system of New Mexico and distinct from this pattern. Finally, late Quaternary faulting south of domain NW1 may also be related to a zone or corridor of Plio-Quaternary uplift localized between the more stable Sonoran Desert and interior Colorado Plateau provinces, each of which have experienced much less late Quaternary fault deformation.

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Table 1. Ages and rates of vertical displacement on some late Quaternary faults in Arizona.

FAULT (no. of scarp profiles)	AGE OF MOST-RECENT DISPLACEMENT					RECURRENT DISPLACEMENT AND VERTICAL DISPLACEMENT RATES		
	Diffusion[1] (10^3 yr.)	Scarp Morphology: Regression[2]	Scarp Morphology: Discriminant[3] Analysis (yr.)	Surface-Offset[4] Relations	Combined Estimate (10^3 yr.)	Interval[5] Recorded (10^3 yr.)	Average[6] Displacement (m)	Average Displacement Rate (m/10^5 yr.)
LAKE MEAD DOMAIN								
Southern Grand Wash (14)	5 - 30	late Pleist.	10^3 - 10^4	Holocene / mid-Pleist.	20 - 100	no unambiguous information available		
Mesquite (60)	20 - 60	late Pleist.	10^4	Holoc. / late Pleist.	20 - 50	50 - 100(?) 200 - 500(?)	2 - 3 5 - 8	2 - 6 1 - 4
Petroglyphs (3)	15 - 160	- -	10^4 - 10^5	mid-Holoc. / mid-Pleist.?	50 - 100	200 - 500(?)	3 - 4	0.6 - 2
Wheeler Graben (4)	50 - 500	- -	10^5	? / early Pleist.?	>100	500+	6 - 9	2
NWI DOMAIN								
Northern Hurricane								
Hurricane (2)	0.3 - 3.2	- -	10^3	mid- to late Holoc. / early? Holocene	3 - 10	290[7] 1000[7]	87[7] 300 - 470[7]	30 30 - 47
Merchant Tank	- -	- -	- -	mid- to late Holoc. / late Pleist.	20	no quantitative data available, but relatively high displacement rates implied by geomorphology of fault escarpment		
Washington								
Northern	- -	- -	- -	mid- to late Holoc. / ?	$\leq$10	ditto.		
Mokaac (1)	14 - 60	- -	10^4	early to mid-Holoc. / late Pleist.	>20	no data		

Table 1. Ages and rates of vertical displacement on some late Quaternary faults in Arizona.

FAULT (no. of scarp profiles)	AGE OF MOST-RECENT DISPLACEMENT					RECURRENT DISPLACEMENT AND VERTICAL DISPLACEMENT RATES		
	Scarp Morphology			Surface-Offset Relations[4]	Combined Estimate (10^3 yr.)	Interval Recorded[5] (10^3 yr.)	Average Displacement[6] (m)	Average Displacement Rate (m/10^5 yr.)
	Diffusion[1] (10^3 yr.)	Regression[2]	Discriminant Analysis[3] (yr.)					
NW2 DOMAIN								
Southern Hurricane								
Whitmore Wash (23)	2 - 20	early Holoc.	$10^3 - 10^4$	mid-Holoc. / ear.Hol.-latest Pl.	5 - 15	100 - 200[8]	6 - 7	3 - 7
Toroweap								
Losing Cyn. (1)	21 - 72	- -	10^4	early Holoc. / late Pleist.	20 - 70	no data		
Ranger Sta. (4)	3 - 20	- -	$10^3 - 10^4$	Holocene / late Pleist.	5 - 20	100 - 400	5 - 7	1 - 7
Straight	- -	- -	- -	late Holoc. / ?	<10	300[8]	13 - 20	4 - 7
Aubrey (11)	3 - 25	latest Pleist.	$10^3 - 10^4$	Holocene / late Pleist.	10 - 20	no data		
Big Chino (41)	2 - 12	early Holoc.	10^3	mid-Holoc. / latest Pleist.	5 - 12	50 - 100 500?	6 - 7 16 - 21	6 - 14 3 - 4.5
Seligman (3)	1 - 11	- -	10^3	late Holoc. / latest Pleist.?	1 - 12	50 - 100? 500?	5 - 7 15	5 - 14 3
CENTRAL DOMAIN								
Camp Verde (9)	1 - 9	mid-Holoc.	10^3	late Holoc. / latest Pleist.	3 - 10	200 - 400 500+	3.5 4 - 6	1 - 2 0.8 - 1.2
Cottonwood (7)	1 - 12	- -	10^3	Holocene / mid-Pleist.	1 - 12	500+	0.5	0.1
Sugarloaf	- -	- -	- -	late Holoc. / latest Pleist.	<15	recurrent movement likely, rates uncertain		

Table 1. Ages and rates of vertical displacement on some late Quaternary faults in Arizona.

FAULT (no. of scarp profiles)	AGE OF MOST-RECENT DISPLACEMENT: Diffusion[1] (10^3 yr.)	Scarp Morphology: Regression[2]	Discriminant[3] Analysis (yr.)	Surface-Offset[4] Relations	Combined Estimate (10^3 yr.)	RECURRENT DISPLACEMENT AND VERTICAL DISPLACEMENT RATES: Interval[5] Recorded (10^3 yr.)	Average[6] Displacement (m)	Average Displacement Rate (m/10^5 yr.)
SOUTHEASTERN DOMAIN								
Chiricahua (6)	2 - 12	mid-Holoc.	10^3	mid- to late Hol. mid- to late Plei.	4 - 12	200 - 400 500+	1.5 - 2 3 - 5	0.7 - 1.0 0.6 - 1.0
Cotton City (9)	7 - 25	late Pleist.	10^4	late Holoc. late Pleist.	10 - 50	50 - 100	1	1 - 2
Gillespie Mtn. (6)	2 - 13	mid-Holoc.	10^3	mid- to late Holoc. late Pleist.	4 - 12	50 - 100 500+	2 9 - 13	2 - 4 1.8 - 2.6
Peloncillo (13)	1 - 7	mid-Holoc.	10^3	late Holoc. latest Pleist.?	2 - 8	200 - 400?[10] 140 - 500	1.5 - 2 2.5 - 3	0.7 - 1.0 0.5 - 2.0
Pitaycachi	historic surface rupture in 1887					200 - 500	3.5	0.7 - 1.8
Safford (44)	5 - 50	early Hol.-late Pleist.	10^4	mid-Holoc. latest Pleist.	10 - 20	200 - 500	3 - 4	0.6 - 2
Santa Rita (61)	60 - 120	late Pleist.	10^5	late Pleist. mid- Pleist.	60 - 100	50 - 100 500+	1.5 - 2 2 - 3	1.5 - 4 0.4 - 0.6
SOUTHWESTERN DOMAIN								
Blythe Graben[11]	--	--	--	mid-Holoc. latest Pleist.	5 - 30	no recurrent movement reported		
Cargo Muchacho[12]	--	--	--	Holocene mid- or late Pleist.	15 - 200	no recurrent movement reported		
Needles (14)	1 - 20	early Holoc.-late Pleist.	10^3 - 10^4	latest Pleist.? late Pleist.	10 - 50	200 500+	1 - 1.5 3.5 - 5	0.5 - 0.8 0.6 - 1.0

TABLE 2. Average regional surface-rupture recurrence intervals, last ~15,000 years.

DOMAIN	NO. OF EVENTS MIN.	NO. OF EVENTS MAX.	ESTIMATED Mw RANGE	AVERAGE RECURRENCE INTERVAL	AREA (km^2)	NO. OF EVENTS / 10^3 KM/ 10^4 YRS.
NW1[1]	2	7	6.5-7.4	2000-7500	3.4×10^3	0.4 - 1.4
NW2	4	8	6.4-7.0	2000-3500	17.2×10^3	0.2 - 0.3
NW3	none documented					
LM	none documented					
SF	2	4	6.3-6.7	3500-7500	4.6×10^3	0.3 - 0.6
C	2	3	5.8-6.4	5000-7500	13.6×10^3	0.1 - 0.15
SE	4	5	6.6-7.2	3000-3500	48.7×10^3	0.05 - 0.07
(SE2)	4	5	same	same	26.2×10^3	0.11 - 0.13
SW[2]	0	4	6.0-6.6	3500-15,000+	112×10^3	0.0 - 0.025
NORTH-CENTRAL[3] NEVADA	10	12	7?	1000-1200	22.4×10^3	0.4 - 0.5

[1] Many faults in this region probably have been active during the late Quaternary, but control on age of latest rupture is poor. The northern Hurricane and Washington fault zones have been studied in more detail and probably have been active in the last ~15,000 years. However, it is unclear whether surface-ruptures have occurred along substantial lengths of these faults, or shorter segments, accounting for the maximum and minimum numbers of events.

[2] Algodones fault near Yuma is included in domain SW in this table only.

[3] Computed from Wallace, 1978, 1981; interval used is 12,000 years.

Table 1. Ages and rates of vertical displacement on some late Quaternary faults in Arizona.

FAULT (no. of scarp profiles)	AGE OF MOST-RECENT DISPLACEMENT: Scarp Morphology — Diffusion[1] (10^3 yr.)	Regression[2]	Discriminant Analysis[3] (yr.)	Surface-Offset Relations[4]	Combined Estimate (10^3 yr.)	RECURRENT DISPLACEMENT AND VERTICAL DISPLACEMENT RATES: Interval Recorded[5] (10^3 yr.)	Average Displacement[6] (m)	Average Displacement Rate (m/10^5 yr.)
Sand Tank (12)	2 - 20	early Holo.-late Pleist.	10^3 - 10^4	mid-Holoc. / late Pleist.	5 - 30	50 - 100 200 - 400	0.5 1 - 2	0.5 - 1 0.2 - 1
YUMA DOMAIN								
Algodones[12]	- -	- -	- -	early Holoc. / late Pleist.	≤ 15	100 - 200	~15	7 - 15

[1] Estimates based on compilation of age-range estimates from individual scarp profiles, using the SCARP program of Mayer (1982).

[2] Estimates made by comparison of regression lines of maximum fault scarp-slope-angle v. log of scarp height, with regression lines from 15,000 year old (Buckram and Anderson, 1979) and 5,000 year old (Machette, 1982) alluvial scarps.

[3] Estimates derived from a discriminant function developed by Mayer(1982). Scarps are considered Holocene (10^3 yrs.), Holocene-late Pleistocene (10^4 yrs.), or late Pleistocene (10^5 yrs.) in age.

[4] Oldest surface not offset by faulting appears over bar, youngest surface offset by faulting appears below bar.

[5] Rough estimates of surface ages. Only surface considered to be late Pleistocene or older (50,000-100,000 yrs. or more) were used to estimate displacement rates.

[6] Average surface displacements within recorded interval, as determined from topographic scarp profiling or reported values.

[7] From Hamblin, Damon, and Bull (1981), and Anderson (1980).

[8] From Holmes, Best, and Hamblin (1978).

[9] Cottonwood scarps may be part of the Verde fault system. Most-recent movement on Cottonwood segment could be part of the same event which ruptured the Camp Verde segment.

[10] Dates of 140,000 yrs.(Marvin et al, 1978) and 510,000 yrs. (Deal and others, 1978), uncertain which pertains to offset basalt flow.

[11] Purcell and Miller (1979)

[12] Bull (1974)

PHYSIOGRAPHIC SUBDIVISIONS OF ARIZONA
(Based on Regional Subenvelope Maps)

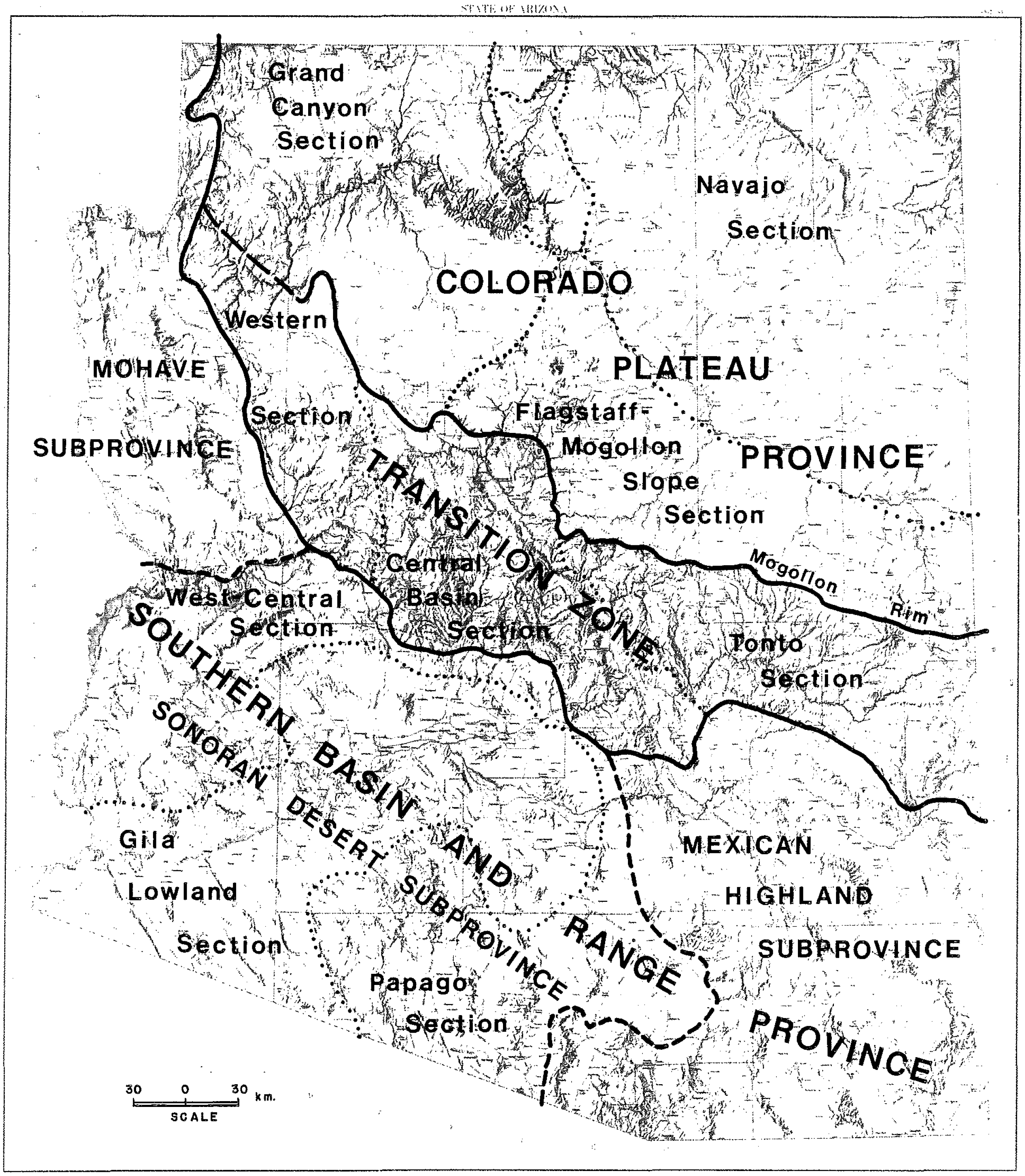

Figure 1. (Pearthree)

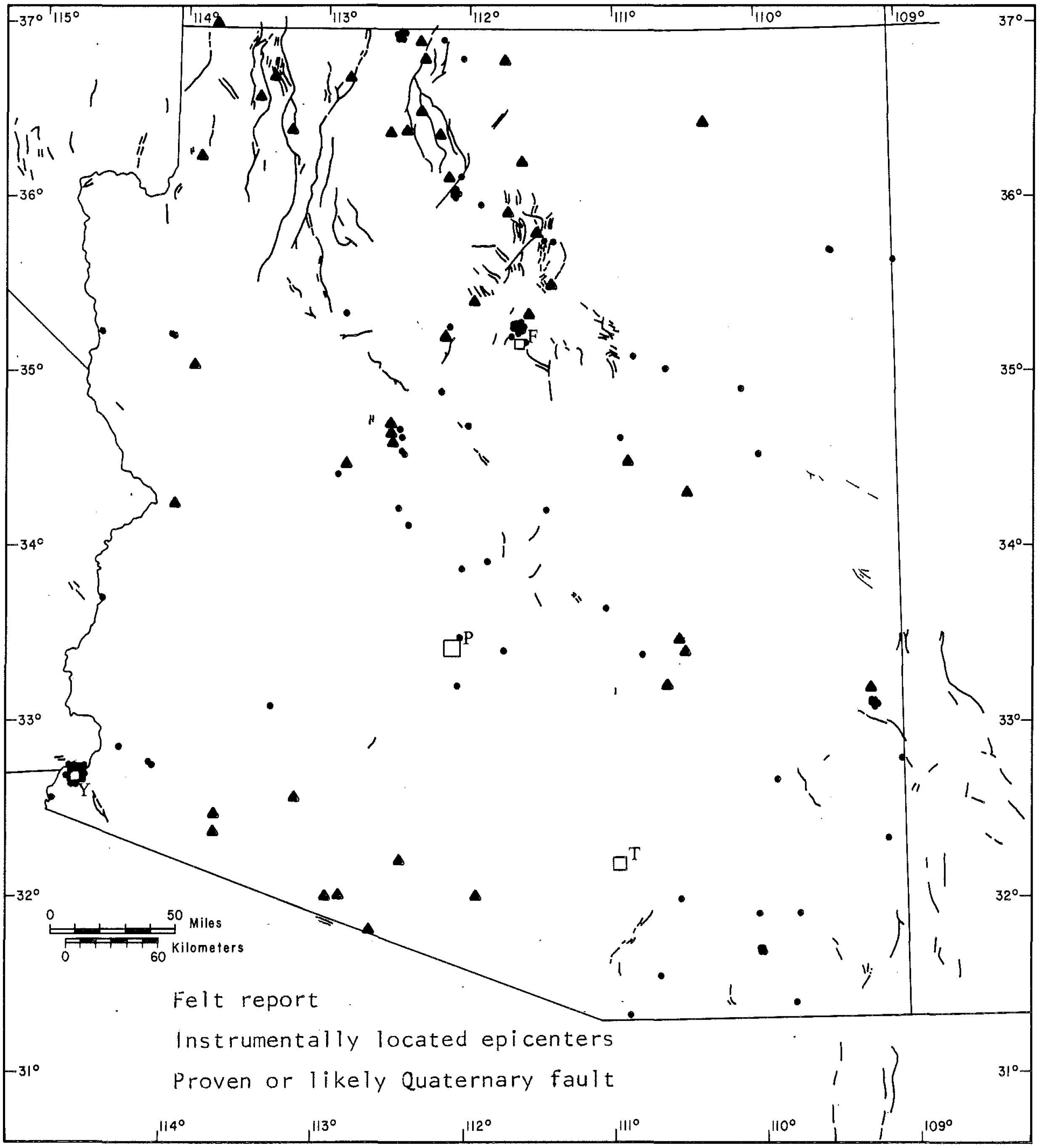

Figure 2. (Pearthree)

Animas Scarps (n=13)
Morphologic Age Bracket

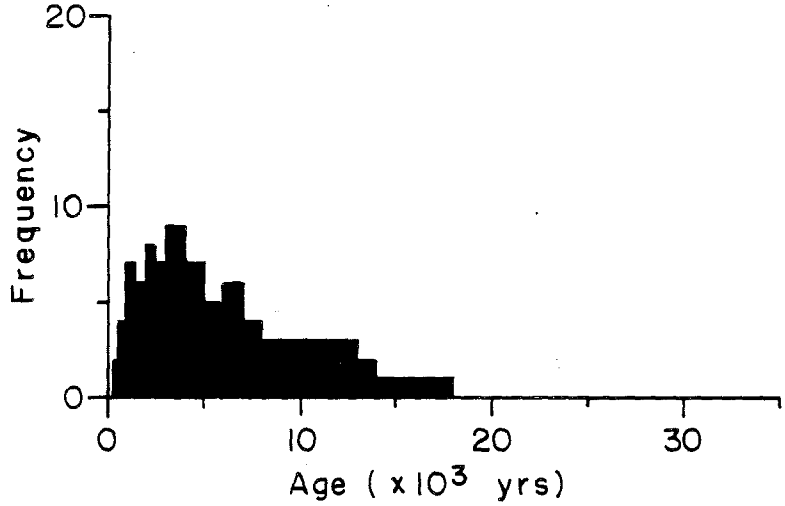

Figure 4a

Discriminant Function Scores

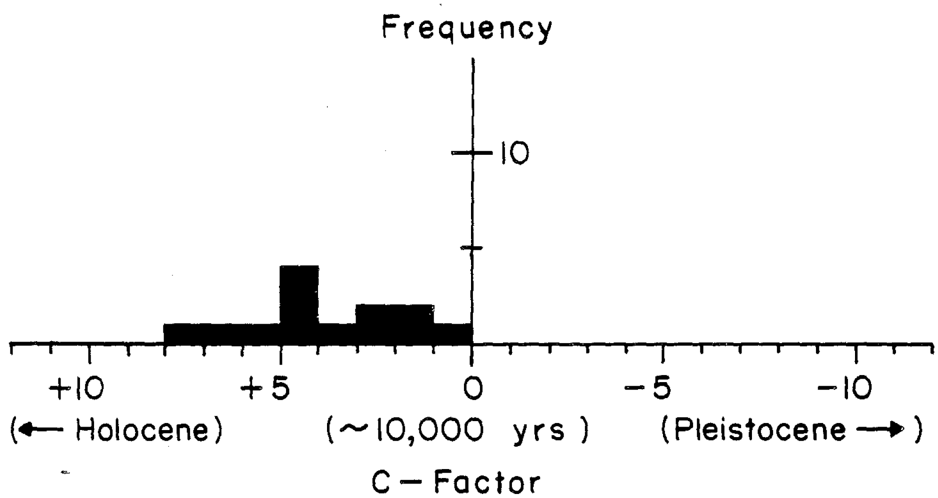

Figure 4b

DOMAINS OF LATE QUATERNARY FAULTING

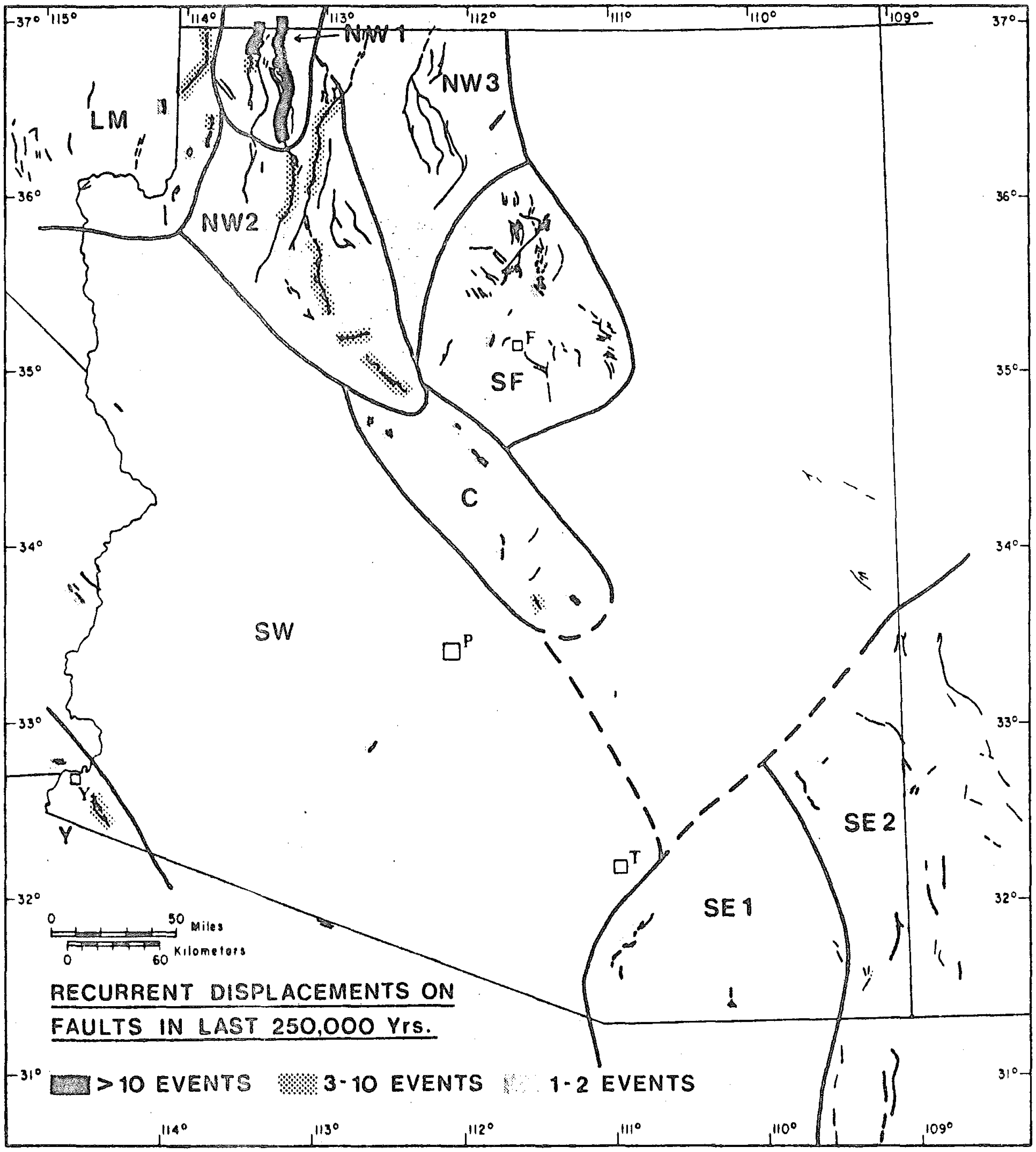

Figure 5.

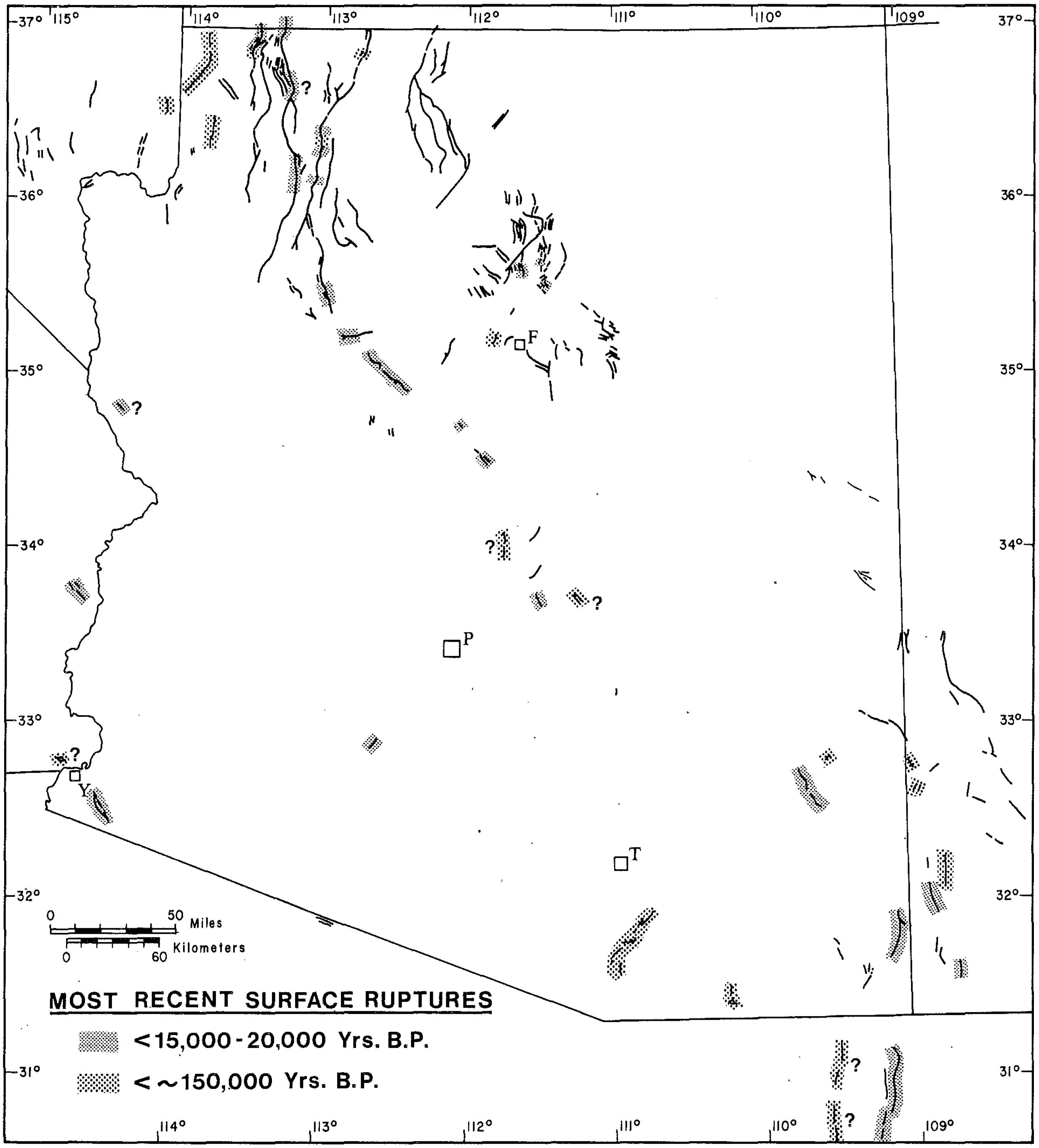

Figure 6. (Pearthree)

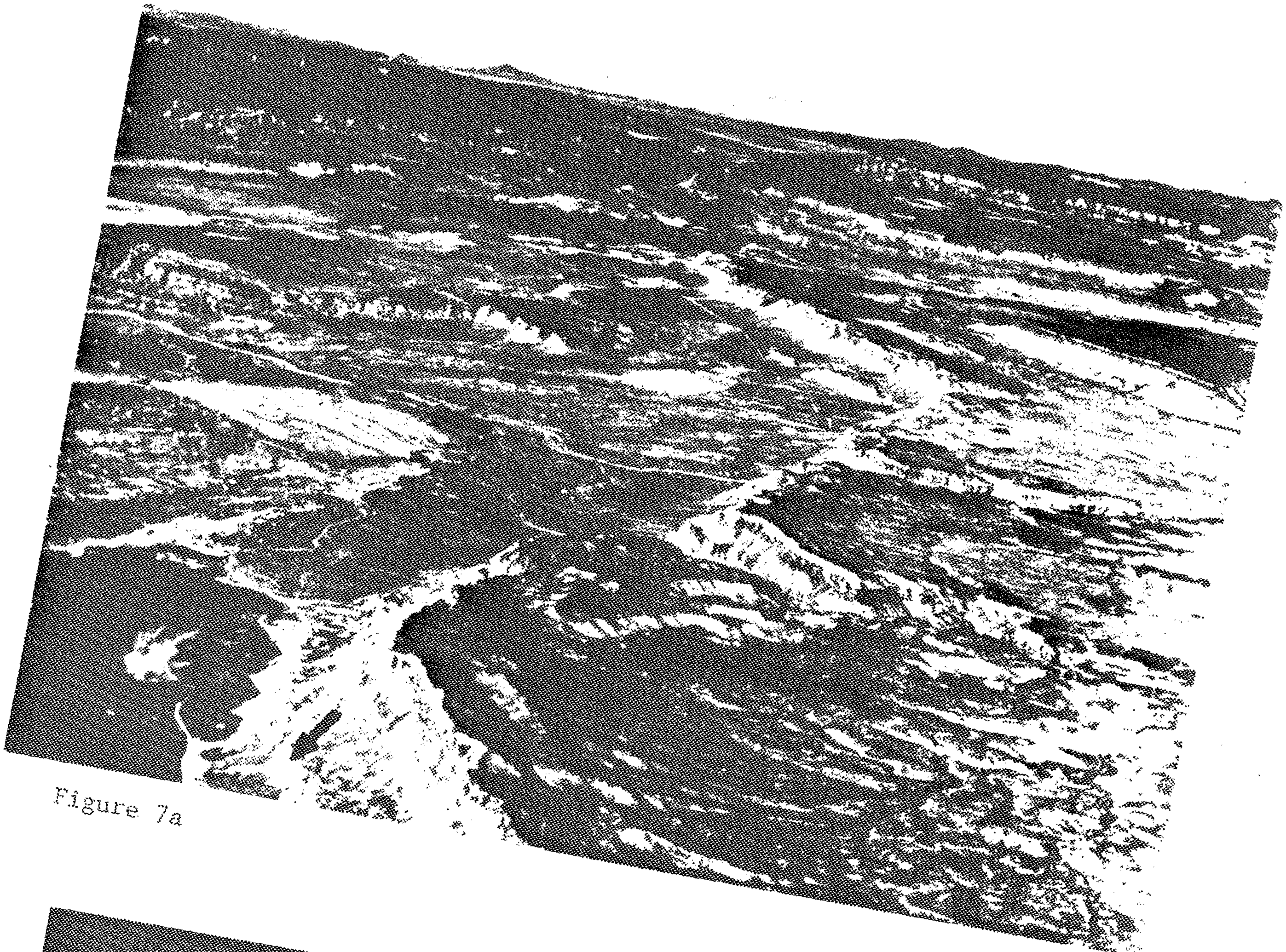

Figure 7a

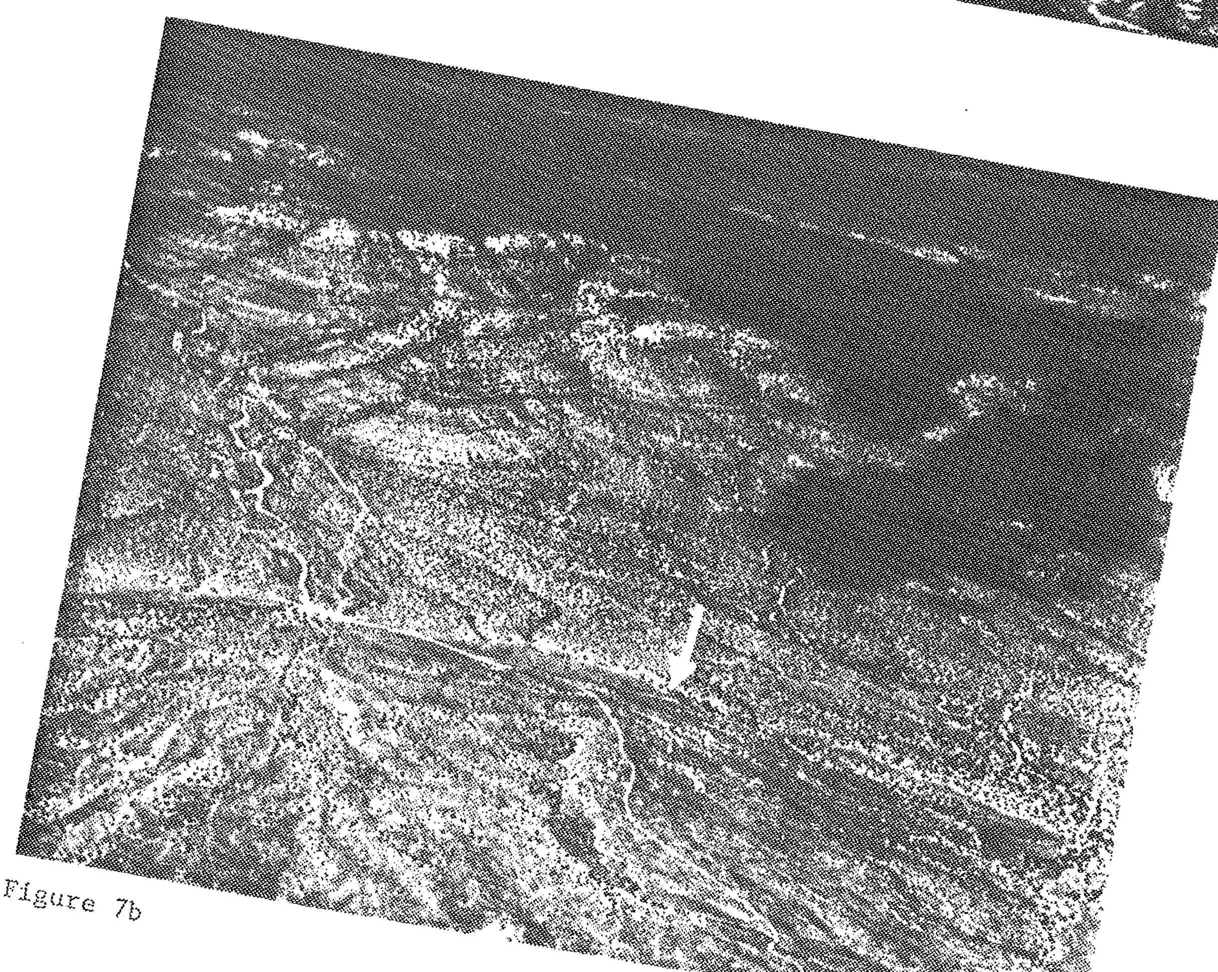

Figure 7b

Figure 7c. View looking southeast of the Pitaycachi Fault,
NE Sonora, Mexico.

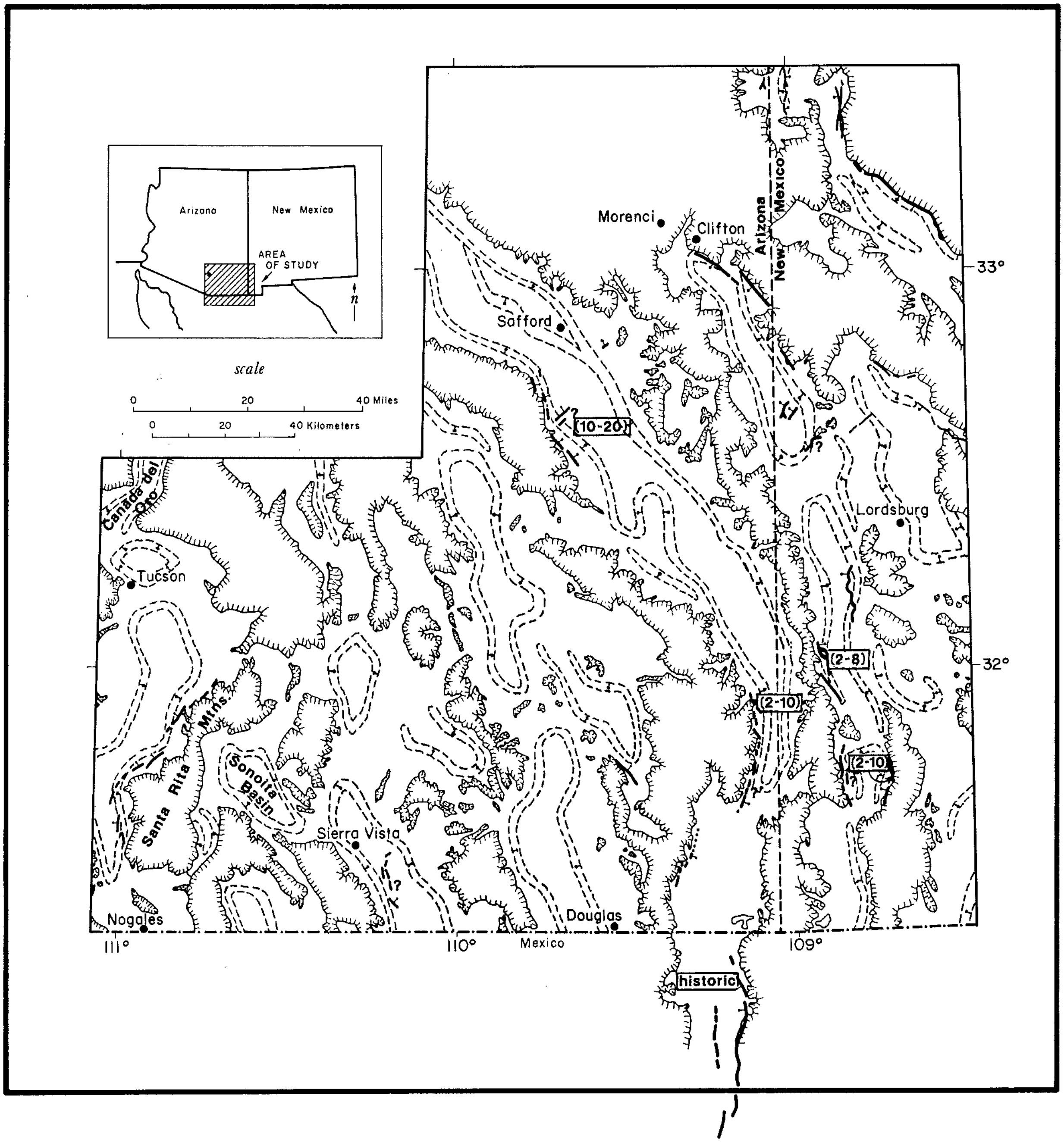
Arizona
New Mexico
AREA OF STUDY
n
scale
0
20
40 Miles
0
20
40 Kilometers
Morenci
Clifton
Safford
Arizona
New Mexico
33°
(10-20)
Lordsburg
Canada del Oro
Tucson
32°
(2-8)
(2-10)
(2-10)
Santa Rita Mtns.
Sonoita Basin
Sierra Vista
Nogales
Douglas
111°
110°
Mexico
109°
historic

Figure 8.

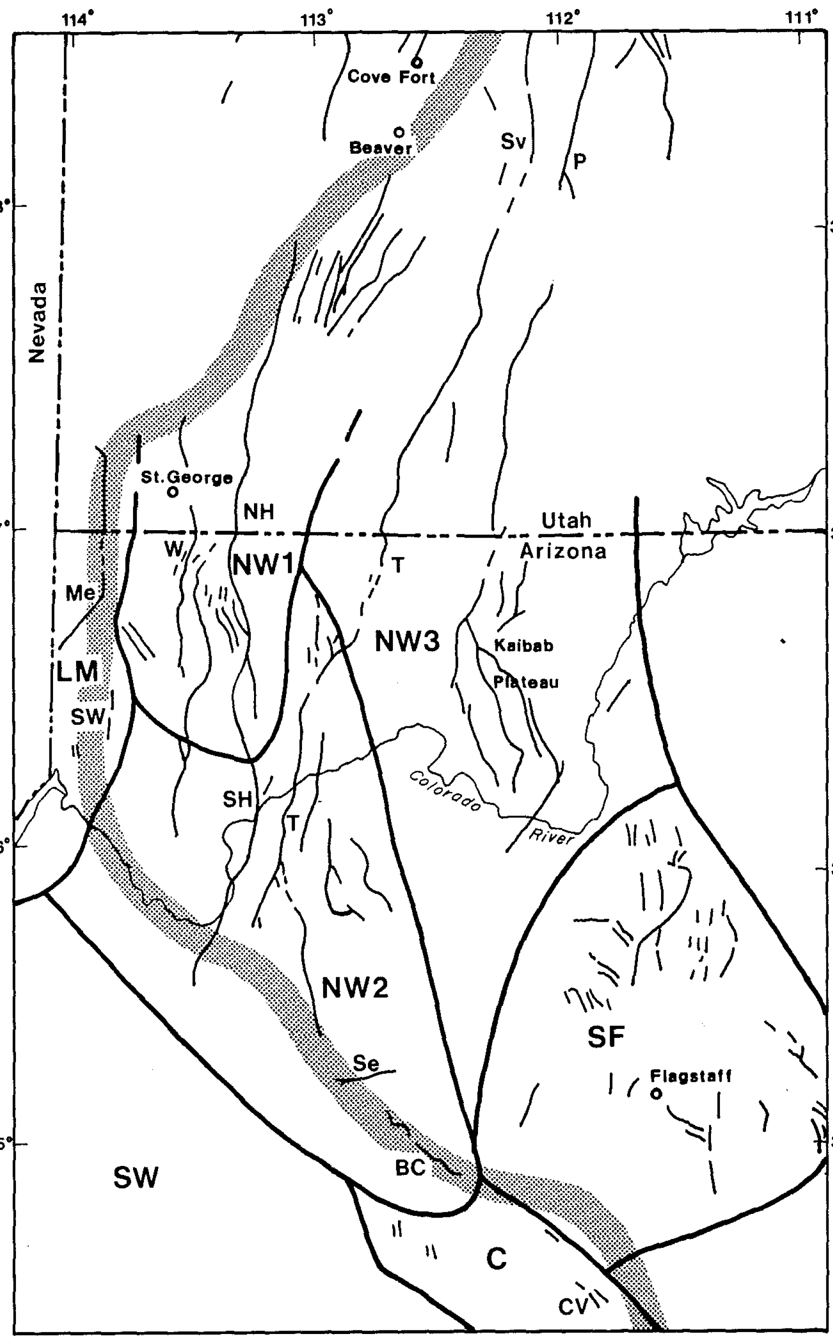
114°
113°
112°
111°
38°
37°
36°
35°
Cove Fort
Beaver
Sv
P
Nevada
St.George
NH
Utah
Arizona
W
NW1
T
Me
NW3
Kaibab
Plateau
LM
SW
SH
Colorado
River
T
NW2
SF
Se
Flagstaff
BC
SW
C
CV

Figure 9.

Regional Neotectonic Framework of Arizona

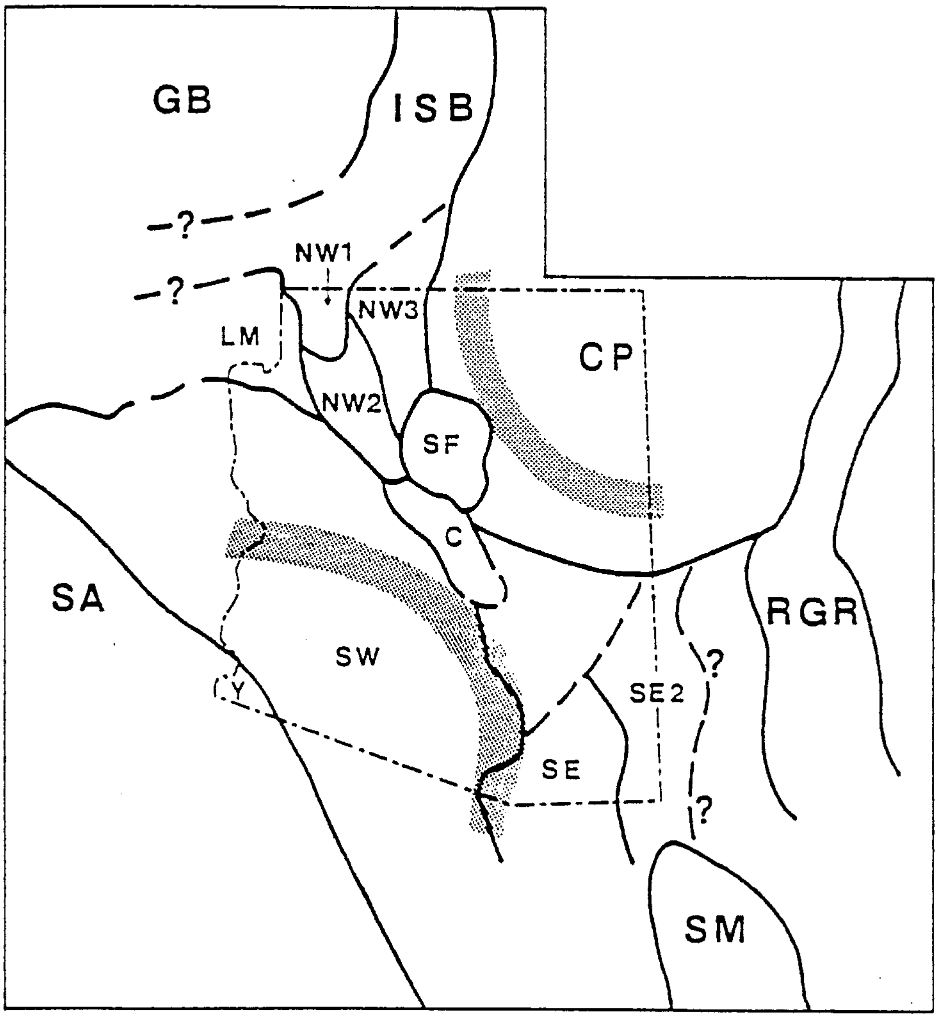

Figure 10.

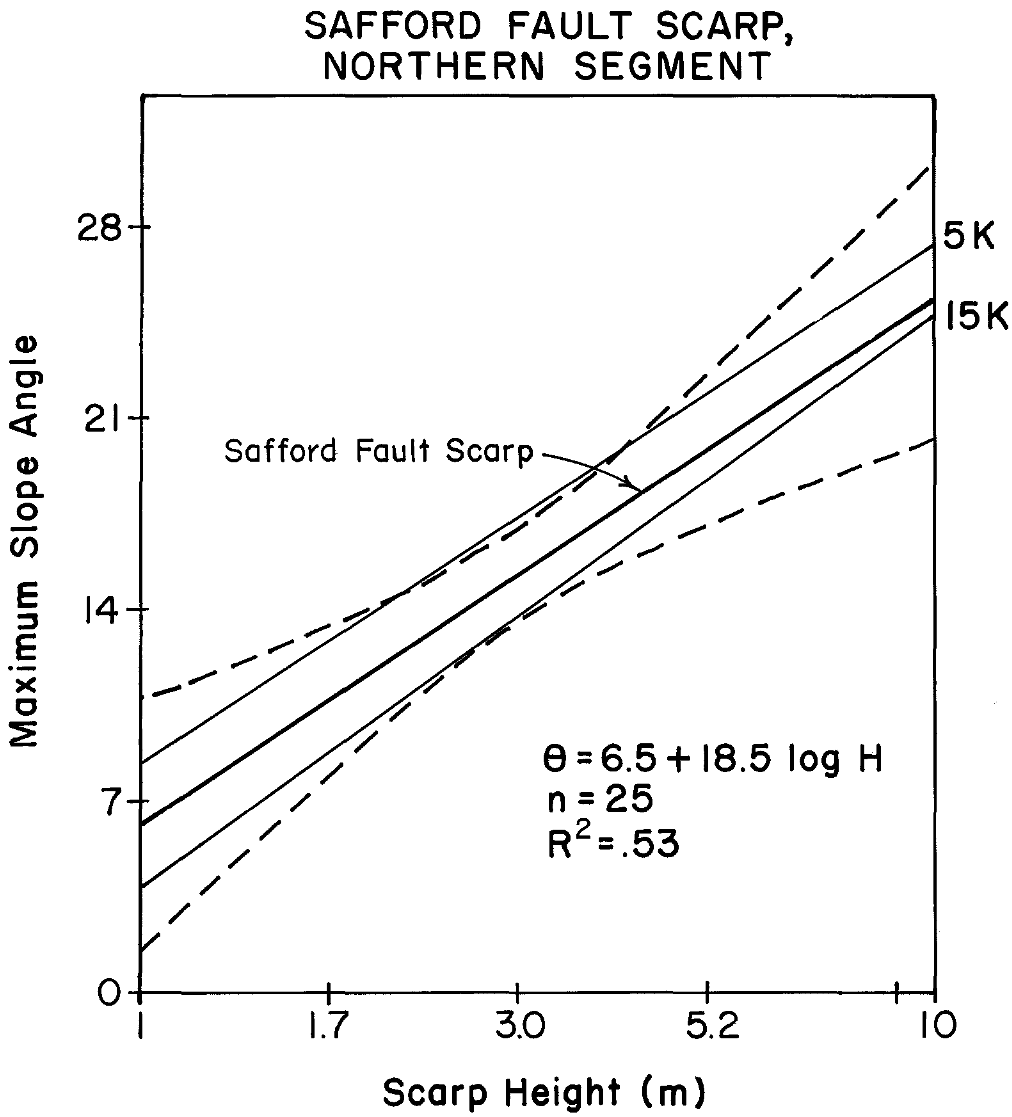
SAFFORD FAULT SCARP,
NORTHERN SEGMENT
Maximum Slope Angle
28
21
14
7
0
5K
15K
Safford Fault Scarp
θ = 6.5 + 18.5 log H
n = 25
R2 = .53
1
1.7
3.0
5.2
10
Scarp Height (m)

Figure .