LATE QUATERNARY FAULTING AND SEISMIC HAZARD IN SOUTHEASTERN ARIZONA AND ADJACENT PORTIONS OF NEW MEXICO AND SONORA, MEXICO

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ABSTRACT

Geomorphic and Quaternary geologic studies provide data with which to assess seismic hazard in southeastern Arizona and adjacent New Mexico and Sonora, Mexico, where one large (M ~ 7 1/4) historic earthquake has occurred against a background of very low seismicity. Conclusions regarding the distribution and timing of late Quaternary faulting are based on (1) estimated ages of soils based on correlation with soils near Las Cruces in southern New Mexico; (2) use of surface age-fault offset relationships to constrain the age of most-recent fault movement and to estimate the frequency of movement along individual faults; and (3) morphologic analyses of fault scarps to estimate their ages. Individual late Quaternary faults in the region have surface rupture recurrence intervals on the order of 10^5 years. However, the major earthquake that occurred in 1887 in northeastern Sonora is evidently part of a series of 5 or 6 surface-rupturing earthquakes that have occurred since 20 ka in a N-S-trending zone straddling the Arizona-New Mexico border. Surface ruptures during the late Pleistocene (about 20-120 ka) occurred from near Tucson east to the border area, but the rate of surface rupture occurrence was evidently 4-25 times lower than during the past 20 ky. The rate of Holocene-latest Pleistocene surface-rupturing, while much lower than some portions of the northern Basin and Range province, evidently represents a burst of activity relative to the average long-term rate of faulting in southern Arizona.

INTRODUCTION

The potential for large earthquakes in southeastern Arizona and adjacent portions of New Mexico and Sonora, Mexico (abbreviated as SEAZ hereafter) was demonstrated by the Great Sonoran earthquake of 1887 ($M \sim 7\ 1/4$). Historical seismicity since 1887 has been very low, however (Dubois and others, 1982). Detailed studies of late Quaternary fault scarps in the region indicate that individual faults have very long recurrence intervals between surface ruptures, on the order of 10^5 years (Pearthree and Calvo, 1987; Bull and Pearthree, in press). This article investigates spatial and temporal patterns of faulting on a regional basis, and provides a geologic basis for estimating the rate of occurrence of large, surface-rupturing earthquakes.

Quaternary geologic and geomorphic studies of fault scarps are the best means for assessing the long-term behavior of individual faults and regional patterns of faulting in SEAZ. Geologic studies provide a chronologic framework into which surface-rupturing earthquakes can be placed. Surfaces of Holocene through mid-Pleistocene age provide a long record of surface displacement, and hence the evidence needed to estimate long-term rates of fault movement and recurrence of surface rupture. Analysis of fault-scarp morphology is another approach used to estimate ages of late Quaternary surface ruptures. We combine these methods to (1) define locations and estimate ages of Holocene and late Pleistocene surface-displacement faulting events; (2) assess regional seismic hazard; and (3) evaluate temporal and spatial patterns of late Quaternary faulting.

CORRELATIONS AND AGE ESTIMATES OF PIEDMONT GEOMORPHIC SURFACES

The piedmont landforms of the physiographic basins of SEAZ consist of flights of stream terraces, alluvial fans, and pediments; the oldest surfaces are typically highest and younger surfaces are inset or stair-stepped below them. These geomorphic surfaces are time planes that can be used to constrain the timing and rates of late Quaternary faulting.

Soil profile development was the principal tool used to estimate ages of surfaces in SEAZ. Detailed studies have been conducted on soil development vs. surface age in the Rio Grande valley in southern New Mexico, where absolute surface ages are constrained with variable precision by radiocarbon dates, dated volcanic material, and vertebrate paleontology (Gile and Grossman, 1979; Gile and others, 1981). The soils of the upper piedmont slopes of the Rio Grande valley correlate well with soils of SEAZ, because both areas have semiarid climates with about 60% of the annual precipitation falling during July, August, and September. Although soil parent material varies locally, several soil parameters, including maximum redness, clay content, and calcic-horizon develpment, increase fairly systematically with surface age (table 1).

Maximum clay content and redness vary most systematically with age in SEAZ and therefore were the main parameters used in age correlations. Age estimates based on soils correlation certainly incorporate substantial uncertainty, and great precision is not implied. Maximum stage of calcic-horizon development is quite variable for Pleistocene soils. During glacial climates leaching was sufficiently effective in some portions of SEAZ that available $CaCO_3$ was completely leached through soil profiles.

Soils of similar character found in a number of basis in southern New Mexico and Arizona suggest that depositional intervals are fairly synchronous regionally, if not completely synchronous in detail (see Waters, 1985). This suggests a causal mechanism external to the individual basins. A likely candidate is regional climatic change, which through interaction of a chain of drainage basin variables can change the amount of sediment supplied to streams and the ability of streams to transport sediment. Major depositional episodes may occur at glacial to inter-glacial climatic transitions, when vegetative density on hillslopes decreases (Bull, 1986).

DISTRIBUTION AND CHARACTERISTICS OF LATE QUATERNARY FAULT SCARPS

Late Quaternary fault scarps occur throughout SEAZ, but are most common in the valleys straddling the Arizona-New Mexico border (fig. 1). General orientations of fault scarps range from NE to NW, and they vary in length from about 2 to 75 km. Scarps typically cut gravelly to bouldery alluvium, well basinward from topographic mountain fronts, and principal offset is relatively down toward basins. Rare exposures of fault zones reveal normal offset along high-angle (50°-90°) faults.

AGES AND RATES OF RECURRENCE OF FAULTING

Ages of fault movement were estimated by morphologic scarp analysis and from relationships between scarps and alluvial geomorphic surfaces of different ages. The age of the most recent surface displacement along a given fault is bracketed by the ages of the youngest surface offset and the oldest surface not offset by faulting. Increases in scarp height with increasing surface age are evidence for recurrent fault movements, and estimates of ages of previous movements can be constrained by surface-age estimates.

Two morphologic age estimation techniques were used to estimate ages of late Quaternary scarp-forming earthquakes. Regression lines of maximum scarp-slope-angle v. log scarp height were determined and compared with those from

5 ka[1] scarps from New Mexico (Machette, 1986) and 15 ka scarps from central Utah (Bucknam and Anderson, 1979) (see fig. 2 for example). The second dating method uses a solution to the diffusion equation to obtain an age-range estimate for each topographic scarp profile (Nash, 1980; Mayer, 1984). Age-range estimates for a fault scarp are accumulated in a histogram, from which a modal age and a sense of the scatter can be obtained (fig. 3).

The above procedures provide general estimates of ages of prehistoric surface ruptures. Calibration for the methods comes from other portions of the Basin and Range province, since there are no precisely dated scarps or piedmont surfaces in SEAZ. The fact that Holocene scarp degradation rates on fan deposits apparently are similar in Utah, Nevada, and New Mexico (Hanks and others, 1984; Hanks and Wallace, 1985; Machette, 1986) lends credibility to Holocene age estimates determined for some scarps in SEAZ. The uncertainty in all dating methods increases with age, so ages of scarps >20 ka are estimated only in very broad terms.

Studies of individual faults in SEAZ consistently indicate exceptionally long surface rupture recurrence intervals. Most of the late Quaternary fault scarps in the region locally displace mid-Pleistocene surfaces, often with higher scarps indicating recurrent fault movement. However, no faults displace mid-Pleistocene surfaces more than 12 m vertically (table 2). Along Holocene-latest Pleistocene surface ruptures where relatively good age control exists for the age of the next prior event (Pitaycachi, Safford), late Pleistocene surfaces are displaced only by the most recent event. Composite fault scarps cutting probable early Pleistocene surfaces along faults active

[1]In this paper, the abbreviation ky is used for 1,000 years, and ka is used for thousands of years before present.

during the late Quaternary record less than 20 m of cumulative vertical displacement. Long-term displacement rates on faults in SEAZ are thus extremely low.

Regional recurrence intervals between surface-rupturing earthquakes in SEAZ since 20 ka have been much shorter. There have been 5 or possibly 6 surface rupture faulting events in the valleys straddling the Arizona-New Mexico border since 20 ka (table 2; fig. 1). Estimated magnitudes of these earthquakes range from about 6 3/4 to 7 1/4 (table 3), using surface displacement and fault length to estimate seismic moment (Hanks and Kanamori, 1979). Available evidence of fault rupture length and displacement suggests that the moment of the Pitaycachi event was at least twice as large as any other Holocene-latest Pleistocene event, due primairly to its long rupture length.

Intervals between surface ruptures in SEAZ since 20 ka have not been uniform. One or two events occurred between 10-20 ka. The Safford fault most likely was active during this period, but the Cotton City event is probably older than 20 ka. Three surface ruptures apparently occurred between 3-10 ka. Within the resolution of the data they could be nearly synchronous or spaced several thousand years apart. Of the three events, morphologic scarp analysis suggests that the Peloncillo event was the most recent. The 1887 earthquake is the only recognized surface-rupturing event in the last 3 ky. The average recurrent interval between surface ruptures since 20 ka is 3-4 ky, but actual recurrent intervals have varied substantially.

The frequency of surface rupture in SEAZ apparently was much lower during the late Pleistocene. Between 1 and 6 fault scarps probably date to between about 20-120 ka. This apparent decrease in frequency of surface rupture may be in part a function of incomplete preservation of older fault scarps, but most piedmonts of SEAZ contain substantial areas of late Pleistocene and older surfaces, and those late Pleistocene scarps recognized are moderately well-preserved. We feel that the record of late Pleistocene faulting is reasonably complete, and the rate of surface-rupture occurrence has been 4-25 times greater since 20 ka than between about 20-120 ka (table 4).

REGIONAL PATTERNS OF FAULTING

Late Pleistocene surface ruptures were distributed across SEAZ (fig. 1), but timing data are insufficient to discern any spatial or temporal trends in faulting during this interval. Over the past 20 ky, surface faulting has been restricted to the border valleys. Beginning with displacement on the Safford fault between 10-20 ka, there has been a general southward progression of faulting in the border area. This pattern may be a long-term, low-rate analog to historic surface ruptures in the Great Basin, where almost all events have occurred in a N-S band extending from eastern California into central Nevada. Wallace (1981) has hypothesized that remaining gaps in the eastern California-central Nevada seismic belt are likely sites for future large earthquakes. If the analogy can be applied to SEAZ, then faults last active prior to 120 ka in the border region may be candidates for surface rupture sometime during the next several thousand years.

SEAZ presents a good opportunity to estimate geologic strain rates because the number of faults active is relatively small and their displacements are recorded rather well. Estimation of seismic moment released over an interval permits calculation of a regional strain rate (Anderson, 1979). Alternatively, the vertical displacement can be translated into horizontal strain by assuming an average fault plane dip, and an extensional strain rate can be roughly estimated. The highest rate of extension determined for SEAZ, for the border valleys over the last 20 ka, is about 40 times less than a Holocene extension rate estimated for the northern Great Basin (Greensfelder and others, 1980, table 5).

CONCLUSIONS

Southeastern Arizona and adjacent portions of New Mexico and Sonora provide a good record of late Quaternary faulting because of generally well-preserved suites of piedmont surfaces varying from Holocene to mid-Pleistocene and older in age. Faults active during the late Quaternary are characterized by extremely long recurrence intervals between surface ruptures ($>10^5$ years), indicating that faults active in the latest Pleistocene or Holocene are unlikely to be the sources of large earthquakes in the foreseeable future. Late Quaternary faults are found throughout the region, but are concentrated in valleys straddling the Arizona-New Mexico border. Average rates of occurrence of earthquakes of magnitude about 6 1/2 or greater have varied from about 1 event/4 ky since 20 ka to 1 event/15-100 ky between about 20-120 ka. Surface ruptures during the past 20 ky have been restricted to the border valleys, and define a general north-to-south progression of faulting. The 1887 Sonoran earthquake can thus be seen as part of a relative temporal and spatial concentration of surface ruptures within the broader region of southeastern Arizona where long-term rates of surface rupture are extremely low.

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FIGURE CAPTIONS

Figure 1. Location map with approximate limits of study area. Late Quaternary fault scarps discussed in text are labeled as follows: Pi, Pitaycachi; Pe, Peloncillo; G, Gillespie Mtn.; C, Chiricahua; S, Safford; CC, Cotton City; H, Huachuca; SR, Santa Rita; RR, Rim Rock; BV, Buena Vista; D, Duncan. Hachured lines enclose mountainous areas. Faults probably active during the last 20,000 years in SEAZ are identified by the dark solid pattern. Faults probably or possibly (queried) active during the late Pleistocene are identified by the lighter pattern. The most recent (and only) displacement on the Cotton City fault could have occurred between 10-20 ka, but more likely occurred prior to 20 ka.

Figure 2. An example of a maximum scarp slope-angle vs. log scarp height plot, Safford fault. Lines labeled 5K and 15K are regression lines from 5 ka fault scarps in New Mexico (Machette, 1982) and 15 ka Lake Bonneville shoreline scarps in Utah (Bucknam and Anderson, 1979). Dark solid line is the best fit regression line for the Safford fault scarps, which are interpreted to be early Holocene or latest Pleistocene (10-20 ka) in age.

Figure 3. An example of a histogram compilation of age range estimates derived from a diffusion equation analysis of scarp age (Nash, 1980; Mayer, 1984). The Chiricahua scarps are considered to have formed between 3-10 ka.

Estimated Age		Maximum Values % Clay	Redness (YR)	Stage of Calcic-Horizon Development
middle to late Holocene (< 8 ka)	a)	12-18	5-10	I-II
	b)	5-15	7.5	I-II
	c)	1-15	7.5	I
	d)	4-7	7.5	I-II
early Holcoene to latest Pleistocene (8-20 ka)	a)	16-28	5	I-III
	b)	17	5	I-II
	c)	5-15	5-7.5	I
	d)	6-11	5	I
late Pleistocene (~ 100 ka)	a)	28-32	2.5-5	III-IV
	b)	25-33	2.5-5	I-IV
	c)	15-25	5	I
	d)	22	5	I-III
middle Pleistocene (~ 200-500 ka)	a)	33-47	2.5-5	III-V
	b)	45-50	2.5	II-IV
	c)	30-40	2.5	II-III
	d)	30-45	2.5	II-IV
early middle to early Pleistocene (~ 500-2000 ka)	a)	15-74	2.5-10	IV-V
	b)	40-60	2.5	I-IV
	c)		n.d.	
	d)	67	2.5-10R	II-V

Table 1. Soil-age correlations, southern Arizona and New Mexico and northeastern Sonora. a) piedmont slopes, Las Cruces area, southern New Mexico (from Gile and Grossman, 1979, and Gile and others, 1981); b) lower San Bernardino Valley, northeastern Sonora (Bull and Pearthree, in press); c) eastern piedmont, Pinaleno Mountains, San Simon Valley, Arizona (Calvo and Pearthree, unpubl. data); d) western piedmont, Santa Rita Mountains, Santa Cruz Valley, Arizona (Pearthree and Calvo, 1987). Absolute age intervals given are approximate. Stages of calcic-horizon development are after Machette (1985).

Fault Name	Age of Most Recent Rupture: Scarp Morphology (10^3 yrs)	Age of Most Recent Rupture: Surface Control (see below)	Multiple Ruptures: Scarp Height (m)	Multiple Ruptures: Surface Age (see below)	Multiple Ruptures: Est. No. Quaternary Events
Pitaycachi	(1887)		1-4 4-7 14-16	h - lp mp ep	3-6
Peloncillo	1-7	<lp		evidence is ambiguous	
Gillespie Mtn.	2-13	>lh, <lp	3 12 17	lp mp? ep?	4-6
Chiricahua	1-12	>lh, <mp	2-3 6-7	mp ep?	2?
Safford	5-50	<lsp	2 6 10	h - lp mp ep?	3+
Cotton City	7-25	<lp		no evidence	1
Huachuca	12-35	>h		no evidence	1?
Santa Rita	60-120	>lsp, <lp	2 4	lp mp - ep	2
Rim Rock	~100	<lp	1-2 17	lp ep?	?
Buena Vista	~100	<mp		no evidence	
Duncan	n.d.	<mp?	10	mp?	?

Table 2. Estimated ages of late Quaternary surface ruptures and evidence for recurrent movement. Age of most recent movement along a given fault is estimated from scarp morphology and surface offset relations. Abbreviations indicate the following: l, late; ls, latest; m, middle; e, early; h, Holocene; p, Pleistocene. Symbol < indicates faulting is less than or equal to this age; symbol > indicates faulting is older than this age.

Fault	Length (km)	Average Vertical Surface Offset (m)	Moment (10^{26} dyne.cm)	Magnitude (M_w)
Pitaycachi	75	2-3	5.7-16.0	7.1-7.4
Peloncillo	15	1.5	1.1- 1.6	6.7-6.8
Gillespie Mtn.	15	2	1.1- 2.1	6.7-6.8
Chiricahua	5-30	1.5-2	0.3- 3.7	6.3-7.0
Safford	10-30	1-1.75	0.4- 3.6	6.4-7.0
Cotton City	15	1	0.6- 1.1	6.5-6.6
Santa Rita	20-60	1.5	1.1- 6.3	6.7-7.2

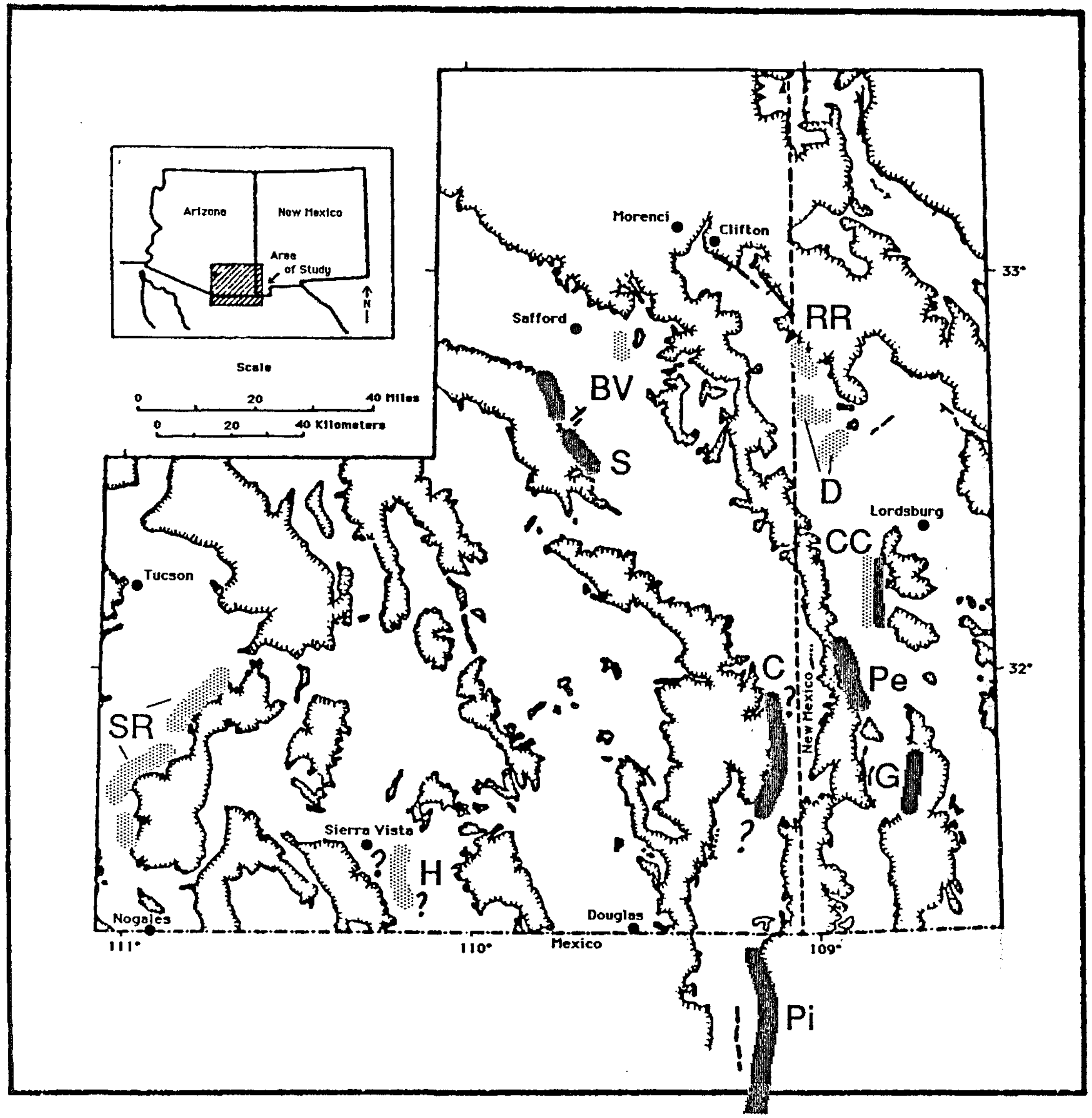
Table 3. Seismic moment release and magnitude estimates for Holocene and latest Pleistocene and selected late Pleistocene surface-rupturing earthquakes, SEAZ. Other possible late Pleistocene surface ruptures are not included because their lengths and average displacements are poorly constrained. Moment is calculated from the formula M_o = uDA, where u is the shear modulus, D is average displacement, and A is the fault plane area. For SEAZ, values of 3 x 10^{11} dynes/cm^2 for u, 10-15 km for total depth of faulting, and 45-60° for average fault plane dip are assumed. Magnitude is obtained using an empirical formula relating moment and magnitude, $M_w = 2/3 \log M_o - 10.7$ (Hanks and Kanamori, 1979). Because identical fault plane dips and maximum depths are assumed for all faults and surface displacements are similar, fault length is the most important variable accounting for variation in computed moments. Incomplete preservation of prehistoric ruptures or inaccurate knowledge of their lengths may contribute to the generally smaller moments computed for these events.

Interval (ka)	Number of Events	Average Recurrence Interval (ky)
0-20	5-6	3-4
20-120	1-6	17-100
0-120	7-11	11-17

Table 4. Average regional recurrence intervals between surface-rupturing earthquakes in SEAZ, estimated for various portions of the late Quaternary. Minimum and maximum numbers of events are our assessment of the uncertainty that (1) a scarp-forming earthquake actually occurred, and (2) it occurred during a given interval.

Region	Interval (10^3 yrs)	Moment (10^{26} dyne.cm)	Strain Rate/Yr
Entire SEAZ Region	0-20	13.9-29.2	a) $1\text{-}3 \times 10^{-10}$ b) 5×10^{-10}
	20-100	2.2-15.6	a) $0.5\text{-}4 \times 10^{-11}$
	0-100	15.6-37.9	a) $3\text{-}7 \times 10^{-11}$ b) $1\text{-}2 \times 10^{-11}$
Border Region Only	0-20	13.0-29.2	a) $3\text{-}6 \times 10^{-10}$ b) 1.2×10^{-9}
	20-100	0.9- 2.3	a) $0.4\text{-}1.5 \times 10^{-11}$
	0-100	13.9-31.5	a) $0.6\text{-}1 \times 10^{-10}$ b) 2.5×10^{-10}
Northern Great Basin	0-12		5×10^{-8}

Table 5. Calculated late Quaternary strain rates, SEAZ. Moments represent summations of individual earthquake moments (table 3), assuming in all cases a maximum depth of faulting of 15 km. Strain rates labeled a) are derived from the formula $e = kM_0/yr/2ul_1l_2l_3$, where k is the proportion of moment released in the direction of principal strain, assumed to be 0.75, $u = 3 \times 10^{11}$ dyne.cm, l_1 is the depth of brittle faulting, 15 km, and l_2 and l_3 are the horizontal dimensions of the region (Anderson, 1979). Strain rates labeled b) are obtained by assuming 2 m of horizontal extension in the border valleys over both the past 20 ky and the past 100 ky, and 2 m and 4 m of extension across SEAZ in the past 20 ky and 100 ky, respectively. These assumptions are reasonably consistent with the temporal and spatial patterns of faulting discussed in the text, and dip-slip movement on fault planes dipping 45°. Holocene strain rate for the northern Great Basin is from Greensfelder et al (1980).



LEGEND

Holocene - Latest Pleistocene (0 - 20 ka)

Late Pleistocene (20 - 120 ka)

Figure 1

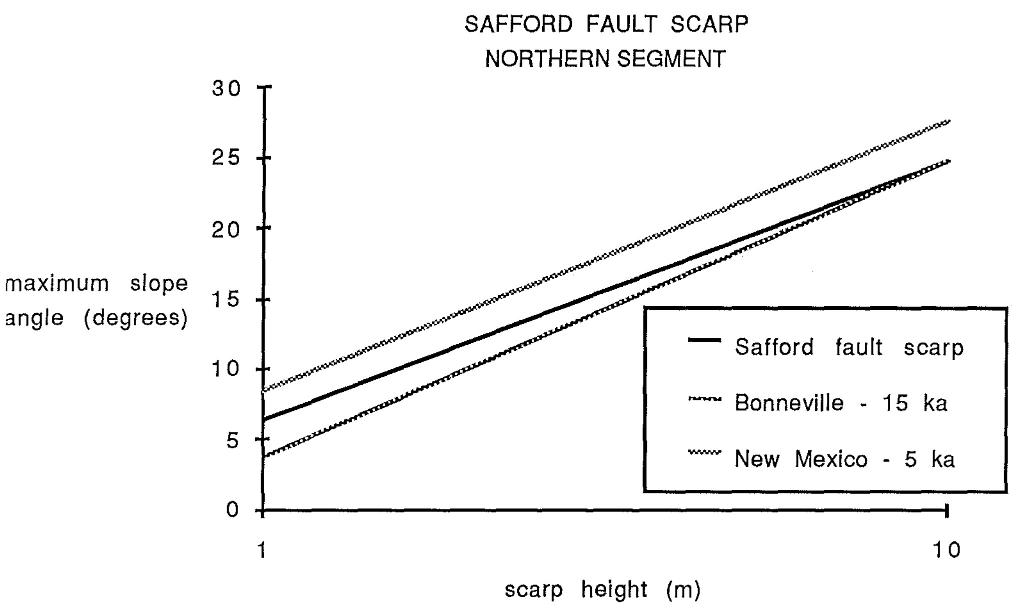

SAFFORD FAULT SCARP
NORTHERN SEGMENT
30
25
20
15
10
5
0
maximum slope angle (degrees)
1
10
scarp height (m)
Safford fault scarp
Bonneville - 15 ka
New Mexico - 5 ka

figure 2.

MORPHOLOGIC AGE BRACKETS
CHIRICAHUA FAULT SCARPS

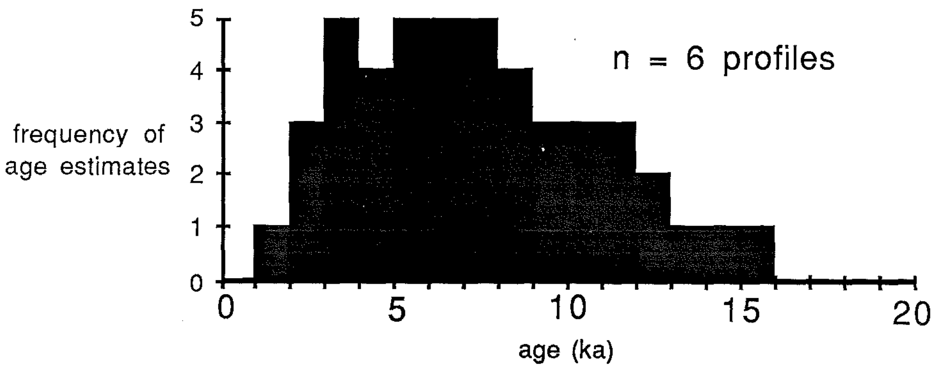


figure 3