Seismic Hazard Posed by the Sugarloaf Fault, Central Arizona

by

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Summary

This report presents an assessment of the seismic hazard associated with the Sugarloaf fault, which crosses State Route (SR) 87 near Mesquite Wash in central Arizona. The Sugarloaf fault is a 20 km (12 mile) long, northwest- to north-trending normal fault with displacement down to the east. We conducted a multi-faceted investigation in order to evaluate the late Quaternary behavior of the Sugarloaf fault and assess the seismic hazard associated with it. The results of our investigations are summarized below.

(1) **Late Quaternary alluvial chronology and surficial geologic mapping.** We mapped the surficial geology and developed a chronologic sequence of the deposits along the Sugarloaf fault in order to investigate the late Quaternary rupture history of the fault. Map units identified in this study are late Holocene alluvium (stream deposits), the upper portions of which locally contain Hohokam artifacts (about 1,000 years old); late Holocene colluvium (hillslope deposits), which grades laterally into late Holocene alluvium; late Pleistocene alluvium (estimated age 50,000 to 100,000 years based on soil development and geomorphology), dissected Tertiary basin-fill deposits; Tertiary basalt; and Precambrian granite. Other late Quaternary deposits that were found only in the backhoe trenches and stream exposures are latest Pleistocene colluvium and alluvium (estimated age 10,000-20,000 years based on soil development); and late (?) Pleistocene colluvium and alluvium (estimated age about 50,000 years based on soil development). Mapping and stratigraphic exposures reveal that late Holocene alluvium and colluvium are not faulted. Latest Pleistocene and older colluvium and alluvium are faulted. The documented fault displacement of late and latest Pleistocene deposits is about 0.7 m.

(2) **Age estimate for the youngest fault rupture.** Detailed surficial mapping confirms that fault scarps formed in late Quaternary alluvium are rare along the Sugarloaf fault. Surficial alluvium found along the fault typically is very old (Tertiary basin-fill deposits) and faulted or very young (late Holocene alluvium) and not faulted. Alluvial deposits of late to middle Pleistocene age, which likely would be faulted, generally are not exposed along the fault. Trench and gully exposures reveal, however, that deposits as young as 10,000 to 20,000 years have been faulted. Thus, the fault has ruptured in the past 20,000 years, and possibly in the past 10,000 years. A minimum constraint on the age of faulting is provided by unfaulted late Holocene alluvium, which contains Hohokam artifacts and was evidently deposited in the past few thousand years.

(3) **Magnitude of surface-rupturing earthquakes generated by the Sugarloaf fault.** We estimate magnitudes of surface-rupturing earthquakes on the Sugarloaf fault ranging from 5.8 to 6.7 using regressions of rupture length and maximum displacement developed from historical earthquakes. The range of potential fault rupture lengths varies from about 4 to 20 km (2 to 12 miles). The central 4.3 km (2.7 miles) of the fault has the sharpest geomorphic expression and is the section of the fault where there is clear evidence of late Quaternary movement. This is the minimum length of the youngest fault rupture. The southeastern 4 km (2.5 miles) of the fault is associated with a prominent bedrock scarp that diminishes to the southeast. Possible evidence of late Quaternary movement has been discovered on this section, and the height and steepness of the bedrock escarpment suggests that this section has experienced Quaternary movement. The northern 12 km (7.5 miles) of the Sugarloaf fault separate Precambrian granite from Tertiary

basalt and sediment. Several discontinuous lineaments and short topographic escarpments exist along this portion of the fault, but we found no definitive evidence of late Quaternary movement. The earthquake magnitude estimated from the minimum fault length of 4 km is about 5.8; if the whole 20 km of the fault ruptured in one earthquake, the estimated magnitude is about 6.6.

The surface displacement associated with the youngest fault rupture is estimated from displacement of late and latest Pleistocene deposits in the gully and trench exposures. Vertical displacement of late Pleistocene colluvium in the south trench is about 0.5 m (1.6 ft); latest Pleistocene colluvium is displaced about 0.7 m (2.3 ft) in the gully exposure. We consider 1 m (3.3 ft) of vertical displacement to be a fairly conservative maximum. Earthquake magnitudes estimated from these displacements of 0.5 to 1 m range from 6.3 to 6.7.

(4) **Rate of reocurrence of surface-rupturing earthquakes on the Sugarloaf fault.** The rate of recurrent movement on the Sugarloaf fault is the least well constrained parameter. Evidence cited above indicates that late and latest Pleistocene deposits are displaced about the same amount, less than 1 m. This evidence implies that all of the late Pleistocene and younger displacement occurred in one latest Pleistocene to early Holocene faulting event, and only one surface rupture has occurred on the Sugarloaf fault in the past 50,000 to 100,000 years. We could not estimate the vertical fault displacement of any older alluvial units. Other late Quaternary faults in southern and central Arizona that have been studied in detail have surface rupture reocurrence intervals on the order of 100,000 years or more.

(5) Probabilistic acceleration values. We developed 50-year and 250-year, 90 percent non-exceedance acceleration maps for the Sugarloaf fault using SEISRISK III (Bender and Perkins, 1987) and assessed their impact on the regional acceleration maps produced for ADOT by Euge et al (1992). The Sugarloaf fault is well within the Arizona Mountain seismic source zone. It was not treated as a discrete source by Euge et al (1992), and evidently was not used directly in the development of the regional magnitude-frequency relationship. We therefore added the probabilistic acceleration values developed for the Sugarloaf fault to the background acceleration.

We used the SEISRISK III program to assess the 50-year and 250-year, 90 percent non-exceedance acceleration fields around the Sugarloaf fault. There is substantial uncertainty in our estimates of the magnitude of surface-rupturing earthquakes on the fault and the frequency of surface ruptures on the fault, so we used six combinations of maximum magnitude and reocurrence interval. The most conservative assumption, with a maximum magnitude of 6.7 and a reocurrence of 50,000 years, yields an increase in the 50-year horizontal acceleration as large as 0.05g around the fault. Adding this probabilistic acceleration value to the background level of 0.045g from Euge et al (1992), the resultant 50-year acceleration for the location of the proposed Mesquite Wash bridge is slightly less than 0.1g. All other scenarios produce smaller 50-year accelerations. Using the most conservative scenario, calculated 250-year probabilistic horizontal acceleration associated with the Sugarloaf fault is as high as 0.11g. Adding these to the background acceleration of 0.125g from Euge et al (1992) results in a 250-year acceleration of about 0.24g. Thus, faults with fairly long re-occurrence intervals may pose a significant seismic hazard to structures with long projected lifetimes.

Introduction

The Sugarloaf fault is a 20 km (12 mile) long Quaternary fault that crosses State Route 87 near the confluence of Sycamore Creek, Mesquite Wash, and Rock Creek, midway between Phoenix and Payson in central Arizona (figure 1). The Sugarloaf fault is a slightly arcuate, east-dipping, northwest- to north-trending normal fault. It forms the western boundary of a small late Cenozoic sedimentary basin informally named the Mesquite basin (Anderson et al, 1986), which is nestled on the western flank of the Mazatzal Mountains. The central and southern sections of the fault have a sharp geomorphic expression suggestive of relatively recent fault activity. Previous reconnaissance studies of this fault indicated that it has been the source of at least one magnitude 6 or greater earthquake during the late Quaternary (the past 250,000 years or so), and possibly during the Holocene (the past 10,000 years) (Pearthree et al, 1983; Anderson et al, 1986). Questions remained regarding the recency of fault rupture and the frequency of fault rupture, however. These unresolved questions became important to the Arizona Department of Transportation (ADOT) as it planned new bridges in this area as part of the upgrade of SR 87 to a four-lane highway. This report summarizes the results of our detailed assessment of the seismic hazard associated with the Sugarloaf fault.

Physiographic and Seismotectonic Setting

The Sugarloaf fault is located within the rugged Transition Zone of central Arizona. The Transition Zone (generally equivalent to the Arizona Mountain physiographic province) is so named because its substantial local topographic relief and extremely rugged physiography is transitional between the broad basins and low ranges of southwestern Arizona and the higher, smoother Colorado Plateau of northeastern Arizona. The Transition Zone is also a structural transition between the highly faulted and extended Basin and Range province and the relatively intact Colorado Plateau. The Transition Zone has many normal faults and some large extensional sedimentary basins, but has undergone much less Cenozoic extension than the Basin and Range (Menges and Pearthree, 1989). The major streams of the Transition Zone have downcut deeply during the Quaternary (about the past 2 million years), which has resulted in the dissection of most of the sedimentary basins in this region. This stream downcutting may have been caused by broad regional uplift (Pewe, 1978; Menges and Pearthree, 1989).

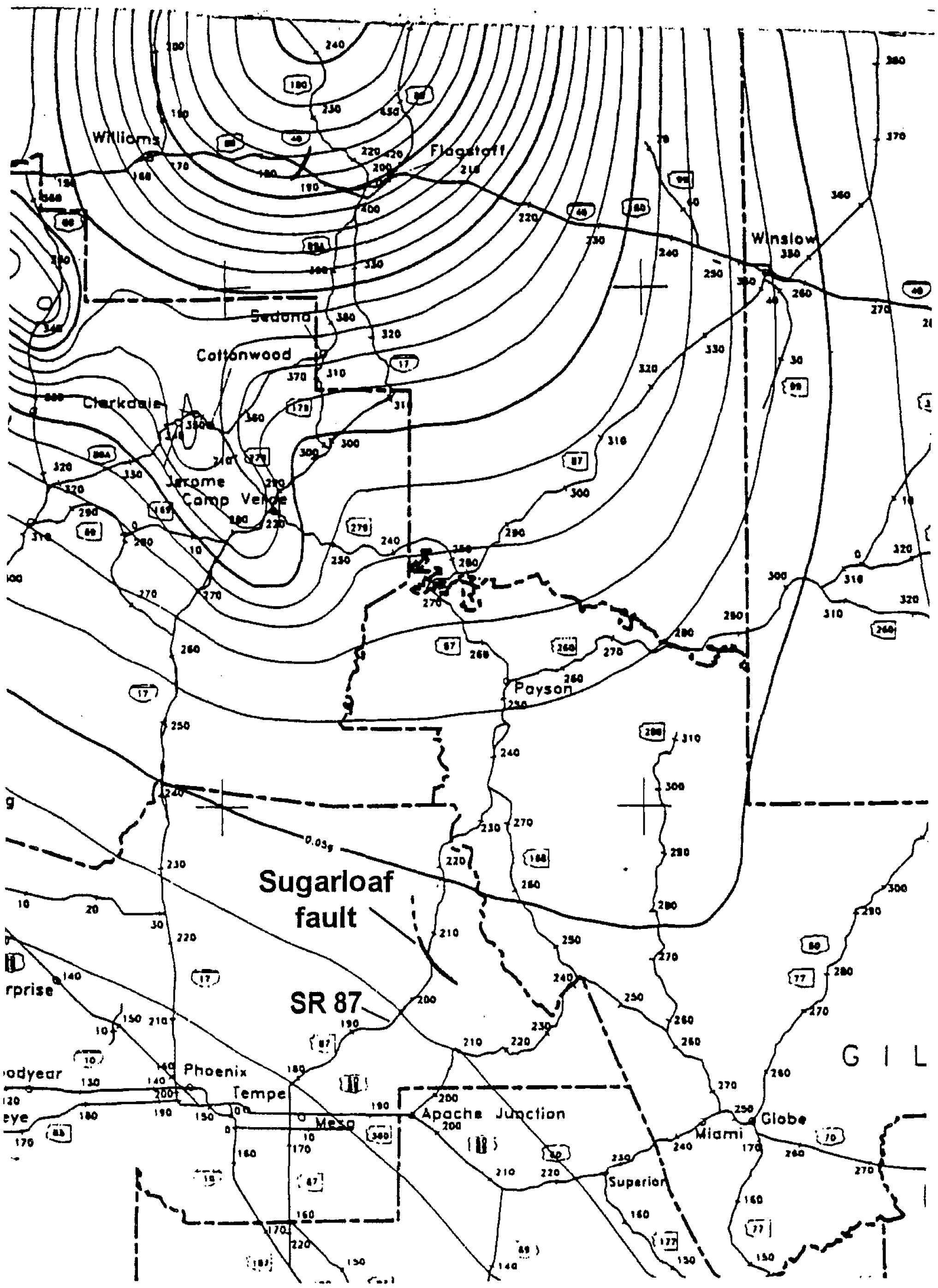

Figure 1. Location of the Sugarloaf fault in central Arizona. Base map is from Euge et al (1992). Contours are 50-year, 90 percent non-exceedance horizontal acceleration values; contour interval is 0.01g.

Neotectonic activity, including both the number of Quaternary faults and the level of historical seismicity, is somewhat higher in the Transition Zone of central Arizona than in either the Basin and Range of southwestern Arizona or the interior of the Colorado Plateau in northeastern Arizona. Sumner (1976) suggested that historical seismic activity in Arizona has been concentrated in a belt stretching from northwest to southeast across Arizona. This belt is anchored by abundant moderate seismicity in northwestern Arizona and the magnitude 7 1/4 Sonoran earthquake of 1887, which occurred about 50 km (30 miles) southeast of Douglas, Arizona. Seismicity in the Transition Zone of central Arizona has been quite modest compared with more seismically active portions of the western United States, however, with no earthquakes larger than about magnitude 5 (DuBois et al, 1982).

The Sugarloaf fault is one of a several late Quaternary faults in a belt that stretches from northwestern Arizona into central Arizona (Menges and Pearthree, 1983; Pearthree and Scarborough, 1984; Menges and Pearthree, 1989; Euge et al, 1992). Regional reconnaissance studies (Pearthree et al, 1983; Euge et al, 1992) concluded that the few late Quaternary faults in central Arizona probably have long reocurrence intervals between ruptures, so the regional rate of occurrence of large earthquakes is quite low. The only other detailed study of a late Quaternary fault in central Arizona was conducted on the Horseshoe fault, located approximately 25 km (15 miles) northwest of the Sugarloaf fault (Piety and Anderson, 1991). They found evidence for two or possibly three surface ruptures in the past 300,000 years, and concluded that the average reocurrence interval between surface ruptures is 50,000 to 100,000 years.

Surficial Geology of the Fault Zone

One of the objectives of this study was to re-evaluate and map the surficial geology along the Sugarloaf fault in order to develop constraints on the late Quaternary rupture history of the fault. We mapped generalized bedrock geologic units, alluvium (stream deposits) of different ages, and colluvium (hillslope deposits) along the central portion of the fault to determine which units have been faulted and which units have not. Criteria used to differentiate Cenozoic deposits include topographic relationships, surface dissection, drainage development, surface color, and soil development.

Quaternary (0 to 1.6 Ma)	Holocene (0 to 10 ka)	late Holocene (0 to 5 ka) early Holocene (5 to 10 ka)
	Pleistocene (10 ka to 1.6 Ma)	latest Pleistocene (10 to 20 ka) late Pleistocene (10 to 250 ka) late Quaternary (0 to 250 ka) middle Pleistocene (250 to 750 ka) early Pleistocene (750 ka to 1.6 Ma)
Tertiary (1.6 to 65 Ma)	Pliocene (1.6 to 5.5 Ma)	late Pliocene (1.6 to 3.5 Ma) early Pliocene (3.5 to 5.5 Ma)
	Miocene (5.5 to 22 Ma)	late Miocene (5.5 to 15 Ma)
	Oligocene (22 to 38 Ma)	

Table 1. Time intervals as used in this report. Periods and epochs listed in the first and second columns are formal divisions. Intervals listed in the third column are not formally defined. "Thousands of years before present" is abbreviated as **ka**. "Millions of years before present" is abbreviated as **Ma**.

Surficial deposits of several different ages and sources were identified in this study. The youngest units are of late Holocene age, a few thousand years old or less. They are (1) late Holocene piedmont alluvium that was deposited by the many small tributary drainages that cross the fault; this unit includes modern channels, which typically are steep-walled arroyos, and adjacent young fans and terraces; Hohokam artifacts (about 1,000 years old) were found in the uppermost 1.5 m (5 ft) of the fan and terrace deposits; (2) age-equivalent late Holocene hillslope colluvium on the fault scarp that merges smoothly into late Holocene alluvium; at least the uppermost colluvium is involved in active hillslope processes and is essentially modern in age; and (3) historical channels and low, young terraces of Sycamore Creek and Mesquite Wash. Limited late Pleistocene piedmont alluvium (estimated age 50,000 to 250,000 years based on surface characteristics and topographic relationships with adjacent Holocene alluvium) was mapped downslope from the fault scarp. Middle to early Pleistocene terrace remnants associated with

Mesquite Wash and Sycamore Creek are preserved in a few places, but they are not extensive or continuous enough to be useful in evaluating Quaternary movement on the fault. Much older, moderately to deeply dissected Tertiary basin-fill deposits cover much of the Mesquite basin; the age of these deposits is probably middle to late Miocene, based on regional relations (Skotnicki, 1992). Miocene basalts, which are probably correlative with the Hickey basalts of central Arizona (11 to 16 million years old; Skotnicki, 1992), are exposed at several localities along the fault. The oldest geologic unit exposed along the fault is Precambrian granite, which composes nearly all of the footwall along the fault. Other late Quaternary deposits that were found only in the backhoe trenches and stream exposures are described in the next section.

Detailed surficial mapping along the Sugarloaf fault provides only modest constraints on the age of youngest rupture and very little information regarding the long-term frequency of fault rupture. Fault scarps formed in late Quaternary alluvium are rare along the Sugarloaf fault (see Plate 1). Alluvium found along the fault typically is very old (Miocene basin-fill deposits) and faulted or very young (late Holocene alluvium) and not faulted. Surficial alluvial deposits of Pleistocene age, which probably would be faulted, do not cross the fault. Late to middle Pleistocene fan remnants are preserved locally on the downthrown (east) side the fault south of SR 87 (Plate 1). These deposits probably are in fault contact with adjacent bedrock, but the total displacement of the fan surfaces cannot be determined because correlative deposits are not found on the upthrown side of the fault.

Interpretations of Trenches and Gully Exposures Across the Fault

Backhoe trenches, hand-dug trenches, and natural exposures were interpreted and logged in an attempt to better constrain the age of youngest fault rupture and to estimate the long-term frequency of fault rupture. The U.S. Forest Service granted permission to excavate two backhoe trenches just north of SR 87, within the boundaries of an existing Environmental Impact Assessment. These trenches were excavated in December 1994 by an ADOT crew. These trenches provided valuable information regarding the recency of fault rupture. We were able to gain more information about the fault by cleaning off and interpreting several natural gully exposures in this same general area. In addition, we excavated by shovel two smaller trenches across the possible fault scarp near Sycamore Creek that was identified in earlier studies. All trenches were backfilled when our interpretations were complete. We summarize our findings from each of these stratigraphic exposures below.

North Trench. The northern trench revealed several faults and possible shear zones and several Quaternary depositional units, but the relationships between the faults and Quaternary units was not abundantly clear. The upper end of the north trench is about half way up the several-meter-high bedrock fault scarp (figure 2). The trench was excavated down the scarp and out onto a young alluvial fan that emanates from a small drainage south of the trench. The total length of the trench was about 35 m (120 ft) (the trench log in figure 2 does not include the lower 10 m or so of the trench; no faults were detected there).

The stratigraphy of the north trench is fairly complex and interesting. Because we found no material that provides numerical age constraints for any of the units in this trench, we estimate the ages of the trench units based on correlations with other units described along the fault. Late Quaternary deposits thicken gradually downslope from a very thin veneer of hillslope colluvium to a 3+ m (10+ ft) thick sequence of alluvium, as the bedrock surface drops away more rapidly than the ground surface. The two colluvial units we recognized in the trench stratigraphy are distinguished from alluvial units by their lack of bedding, poor sorting, and the angular character of the gravel clasts within them (see table 2). The younger colluvium (unit Ic) thickens from a few centimeters at the upper end of the trench to about 0.75 m (2.5 ft) near the 8 m mark. This colluvium grades laterally into the youngest alluvial unit (unit Ia, described below). There may be a wedge of older, latest(?) Pleistocene colluvium (unit IIc) between 8 and 12 m, although the contact between younger and older unit is quite subtle. The lateral relationship between latest(?) Pleistocene colluvium and latest(?) Pleistocene alluvium (unit IIa) is complicated by the presence of a probable fault zone. We interpreted four alluvial units in the downslope (eastern) portion of the trench. The stratigraphically lowest and oldest unit is relatively clay-rich, reddened, poorly bedded middle to late Pleistocene alluvium (unit IIIa2). This unit dives below the bottom of the trench at 2 m; it pinches out against bedrock at 8 m. The next younger unit, moderately clay-rich, reddened, fairly well-bedded late Pleistocene alluvium (unit IIIa1), is the lowest unit exposed in the east end of the trench. It onlaps the middle to late Pleistocene alluvium described above, and is

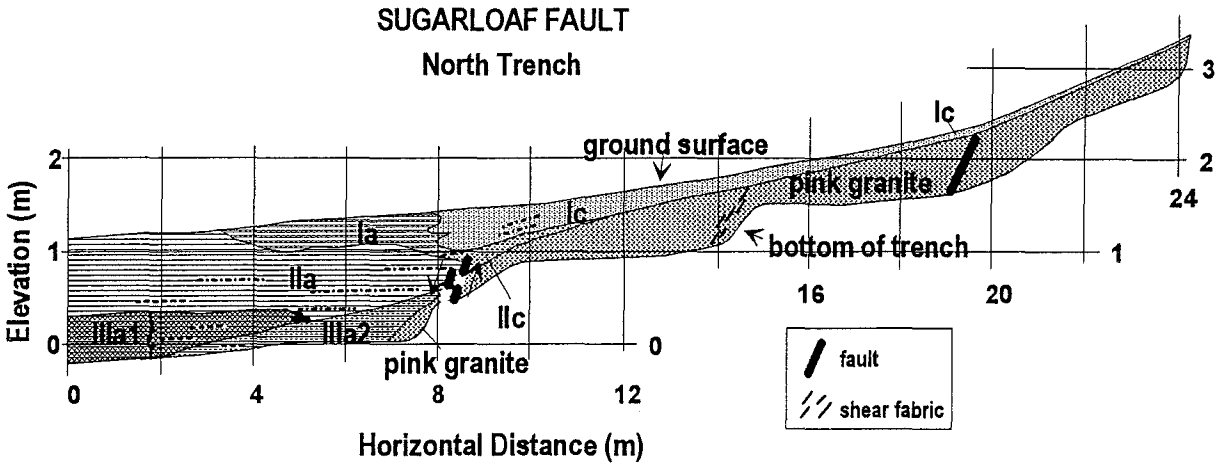

Figure 2. Log of the south trench. Stratigraphic units and relationships are described in table 2 and the text. View is from the north, horizontal distance is from east to west.

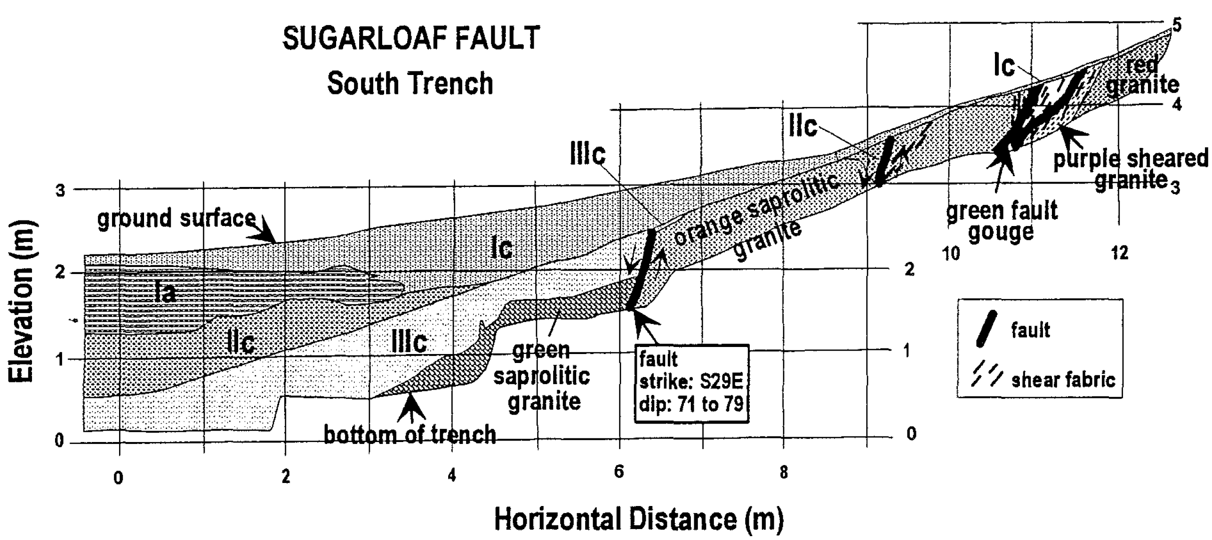

Figure 3. Log of the south trench. Stratigraphic units and relationships are described in table 2 and in the text. View is from the north, horizontal distance is from east to west.

Table 2. Descriptions of alluvial and colluvial deposits found in stratigraphic exposures.

Unit and Location	Description
Ia1 gully	White, well-stratified alluvium; sandy, with fine pebbles in relict channels; delicate bedding is preserved; deposits are less than 0.5 m (1.5 ft) thick where exposed; this is the youngest deposit that predates arroyo development, and may be less than 100 years old.
Ia2 gully	Yellowish, slightly oxidized alluvium; sandy with fine pebbles; bedding is well preserved; deposits are less than 0.5 m (1.5 ft) thick where exposed; deposited on erosion surface cut into late Holocene colluvium (Ic) and was eroded prior to deposition of unit Ia1.
Ia3, Ia gully, both trenches	Brown, variably stratified alluvium; gravelly to very gravelly loamy sand to sand, with some cobbles; well-stratified in north and south trenches and gully, weakly stratified in hand-dug trenches; minimal soil development; deposits are about 1 to 2 m (3 to 6 ft) thick where exposed, and fill channels or small valleys; artifacts found in this deposit indicate that deposition was occurring during the Hohokam period about 700 to 1500 years ago.
Ic gully, both trenches	Brown, non-stratified to very weakly stratified colluvium derived from bedrock hillslopes; poorly sorted, very gravelly loamy sand to sandy loam, noncalcareous, minimal soil development; grades laterally into late Holocene alluvium; represents aggradation at toes of hillslopes in response to late Holocene aggradation on valley floors.
IIc gully, both trenches	Brown, non-stratified colluvium; poorly sorted, very gravelly loam, slightly calcareous, but little visible carbonate accumulation; moderate soil structure; onlaps bedrock and older colluvium, grades downslope into latest Pleistocene alluvium in north trench, and possibly ar lower ends of gully and south trench as well; colluvium probably accumulated at toes of hillslopes in response to latest Pleistocene aggradation on valley floors, represented by unit IIa.
IIa north trench	Brown to weak reddish brown, well-stratified alluvium; sandy to loamy sand, with some pebble and cobble layers or lenses; weak to moderate soil development; onlaps and fills channels cut into older alluvium, grades upslope into latest Pleistocene colluvium; probably represents latest Pleistocene aggradation in the valley bottoms.

Unit and Location	Description
IIIc gully,south trench	Dull orange to brown non-stratified colluvium; very poorly sorted, extremely gravelly sandy loam; slightly calcareous, but not immediately adjacent to fault zones, little visible carbonate; light color near faults may be due to enhanced leaching; onlaps bedrock erosion surfaces; may grade downslope into alluvium in gully exposure.
IIIa1 north trench	Brown to reddish brown, well-stratified alluvium; very gravelly sand to loam, with coarse cobble lenses and layers; grades laterally into late Pleistocene colluvium (unit IIIc), onlaps older late Pleistocene alluvium (unit IIIa2); probably represents late Pleistocene valley aggradation.
IIIa2 north trench	Reddish brown, well-stratified alluvium; very gravelly sand to loam, with coarse cobble lenses and layers; onlaps bedrock erosion surface, may actually be colluvium there.

Table 2 (continued).

truncated by a small buried channel filled with the next younger unit at 5 m. This younger unit, brown, moderately well-bedded latest(?) Pleistocene alluvium (unit IIa) , is exposed at the surface at the eastern end of the trench. It onlaps the previous two units, grades into a colluvial unit, and apparently abuts a fault zone between 8 and 9 m. Late Holocene, well-bedded, brown alluvium (unit Ia) fills a small channel that ran along the base of the fault scarp. This unit grades into unit Ic.

The trench exposed two bedrock fault zones, one of which probably cuts late Quaternary alluvium and colluvium. The most obvious bedrock fault zone is near the base of the bedrock fault scarp (between 19 and 20 m on figure 2). This fault zone does not cut the thin layer of colluvium, which is very young, but there are essentially no constraints on how recently this fault zone may have ruptured. A pair of probable faults cutting bedrock and alluvium near the interface of hillslope colluvium and stream alluvium (between 8 and 9 m) provide somewhat more information about the recency of fault rupture. The stratigraphy in this area is fairly complex. The oldest alluvial unit pinches out at the fault zone. It is probably faulted, but the amount of fault displacement cannot be determined because this unit either did not exist or has been removed by erosion on the upthrown side of the fault zone. Latest(?) Pleistocene alluvium may be faulted, as it may be displaced and clearly abuts bedrock and possibly colluvium across the fault. Late Holocene alluvium and colluvium were deposited on an erosion surface that developed after the most recent fault rupture.

South Trench. The south trench provides somewhat more information regarding recency of fault rupture and the amount of displacement during the youngest fault rupture. The trench was excavated from fairly low on the bedrock fault scarp out onto the toeslope of scarp colluvium and an alluvial fan deposited by a drainage to the south (figure 3). This trench is within a few meters of the gully exposure described in the next section, so we are able to correlate a number of units from the trench and the gully. The total length of this trench was about 13 m (45 ft).

The stratigraphy revealed in the trench shares some similarities with the north trench, but colluvium is more abundant. The stratigraphically lowest and oldest colluvial unit is in the lower (eastern) half of the trench. This late(?) Pleistocene colluvium (unit IIIc) is poorly sorted and bedded, and somewhat reddened and clay-rich. This unit may subtly grade into alluvium in the eastern part of the trench. It onlaps weathered bedrock and abuts an obvious fault. A brown, slightly clay-rich, weakly calcareous colluvial unit that we estimate to be of latest Pleistocene age (unit IIc) onlaps the erosion surface cut on the oldest colluvial unit. It too may grade into alluvium in the eastern part of the trench, but the evidence for this is not conclusive. The main package of this latest Pleistocene colluvium pinches out downslope from the fault. However, a pocket of colluvium that we tentatively correlate with latest Pleistocene colluvium found farther downslope exists adjacent to the middle fault, between 9 and 9.5 m in the trench log. The surficial colluvial unit (unit Ic), which has minimal soil development, increases from a few centimeters thick on the scarp to about 1 m (3 ft) thick at the base of the scarp. This brown, poorly sorted and unbedded unit is probably of late Holocene to modern age. It onlaps an erosion surface cut on older colluvium and bedrock, and is not faulted. The only clear alluvial unit exposed in the trench is brown, moderately well-bedded and moderately sorted Holocene alluvium (unit Ia). This unit was deposited on an erosion surface cut into latest Pleistocene colluvium, and it grades laterally into

Age	Map Unit	Gully Exposure	South Trench	North Trench	Hohokam Trenches
late Holocene 0-5 ka	Qya, Qyc	Ia1 Ia2 Ia3, Ic	Ia, Ic	Ia, Ic	stratified alluvium unstratified alluvium
latest Pleistocene 10-20 ka		IIc	IIc	IIc, IIa	
late Pleistocene 50-250 ka	Qma	IIIc	IIIc	IIIa1 IIIa2	

Table 3. Correlation chart and estimated ages for piedmont alluvial and colluvial deposits. Units in the same line are approximately the same age. Older units within a given time interval are placed lower in the sequence.

late Holocene colluvium. In addition, the uppermost colluvium onlaps the Holocene alluvium, indicating that the youngest portion of the colluvium is younger than the alluvium.

Late Quaternary deposits have reasonably clear relationships to the three fault zones exposed in this trench. The westernmost fault zone (figure 3, at 11 m in the section) juxtaposes red, weathered granite and orange, highly weathered granite across a meter-wide, highly sheared zone of fault gouge. No faulted deposits were found adjacent to this fault zone. The odd pocket of possible latest Pleistocene colluvium adjacent to the middle fault zone (at about 9 m) suggests that this fault ruptured in the latest Pleistocene. This pocket of older colluvium may have been preserved because it was downfaulted, although the bedrock configuration and surface slope does require any young vertical displacement. Perhaps more likely, it may have been preserved because it was deposited in a fissure or cavity on the hillslope that developed without significant vertical displacement in the youngest fault rupture. Youngest movement on the eastern fault zone clearly post-dates deposition of late Pleistocene colluvium and pre-dates deposition of late Holocene colluvium. The contact between late Pleistocene colluvium and bedrock slopes about 75°. The bedrock there is highly weathered, erodible granite which would not sustain such a steep scarp under subaerial exposure. The most plausible explanation for this feature is fault displacement of the colluvium down against the bedrock. A sliver of the Pleistocene colluvium is preserved on top of bedrock on the upthrown side, which permits us to estimate about 0.7 m (2 ft) of vertical displacement of the colluvium - bedrock contact across this fault. Late Holocene colluvium and its underlying erosion surface are not displaced and must post-date the youngest fault rupture.

Gully Exposures. Exposures in the banks of the first gully along the Sugarloaf fault north of SR 87 provided some very useful information regarding the age of the youngest fault rupture. The gully is very near the south trench, so the extensive exposures in this area allowed us to reconstruct the recent geologic history of this area and track various strands of the Sugarloaf fault. The gully or arroyo is typical of many of the small drainages that cross the fault. The steep sides of the gully suggest that it has formed quite recently, possibly during the past century, as it entrenched itself into late Holocene alluvium and older deposits. This particular gully is especially interesting because it makes several sharp bends within the fault zone, thus giving a three-dimensional view of several strands of the fault (figure 4). We cleaned off and evaluated several

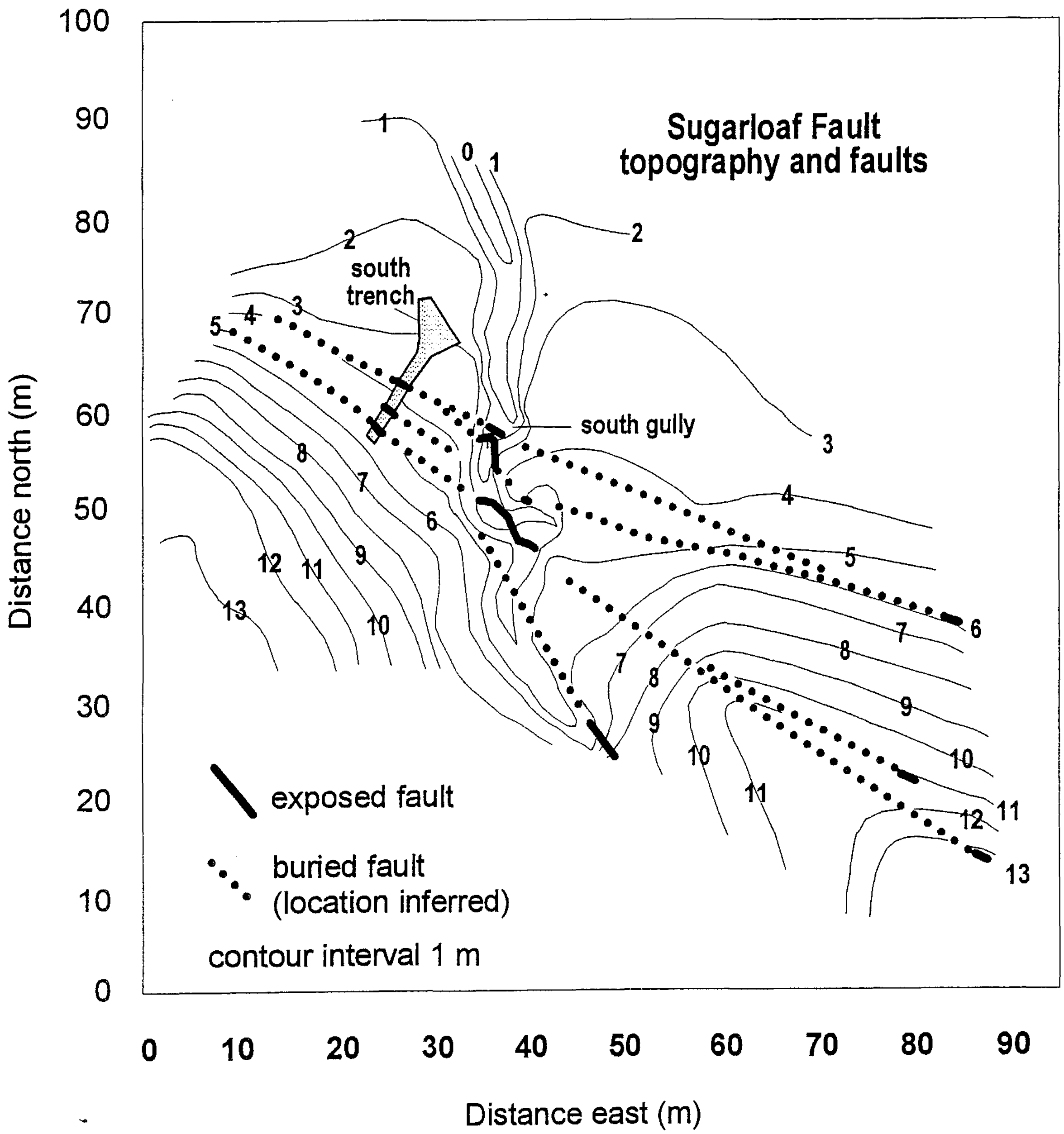

Figure 4. Detailed topographic map of the Sugarloaf fault just north of SR 87. Location of gully esposures and the south trench are shown.

gully walls. We logged and interpreted in detail a 12 m (40 ft) long, 2 to 3 m (6 to 10 ft) high gully wall that exposed several Quaternary units and fault zones (figure 5). Finally, we surveyed the area including the gully and the south trench in order to examine the spatial relationships between the various exposed fault zones.

The Quaternary stratigraphy exposed in the gully walls is illustrative of the oscillations between erosion and deposition that have occurred along this drainage in the late Quaternary. A surprising amount of the gully exposure is composed of colluvium. The oldest deposits exposed are late Pleistocene colluvium (unit IIIc). This unit is poorly sorted and bedding is not apparent. It is very light colored near the fault zone (between 2.5 and 4.5 m, in figure 5), and slightly indurated, but it is not calcareous. This light color may have been caused by accentuated leaching downslope from the fault zone. This late Pleistocene colluvium originally may have been deposited on a subaerially exposed resistant bedrock fault zone (labeled fault breccia, between 3.5 and 5 m), but now it abuts several fault strands. The upper surface of this colluvial unit is an erosion surface that is mantled by latest Pleistocene colluvium. The overlying colluvium (unit IIc) is brown, slightly clay-rich, and slightly calcareous. It grades into alluvium near the eastern end of the trench. Latest Pleistocene colluvium onlapped older colluvium and bedrock (fault breccia unit). Material that looks like unit IIc also fills two odd pockets that exist adjacent to a possible fault (labeled fissure fill (?), between 3 and 4 m). The upper contact with the next younger colluvial unit is visually subtle. The younger unit (unit Ic) is brown, massive, and is distinguished from the underlying latest Pleistocene colluvium primarily by the absence of soil calcium carbonate. The upper unit is probably correlative with late Holocene colluvium exposed in the trenches. It grades laterally into brown, well-bedded Holocene alluvium (unit Ia3) near 1 m in the section. The lower portion of the Holocene alluvium fills a one meter (3 ft) deep channel cut into latest Pleistocene colluvium. In another exposure along this gully, we discovered a Hohokam potsherd (about 1,000 years old) 0.5 m (2 ft) below the top of a deposit that we correlate with this brown Holocene alluvium. Several thin, very young alluvial deposits (units Ia2 and Ia1) found near the top of the gully truncate all older units. These deposits probably represent the youngest stream deposition prior to the recent phase of erosion and entrenchment.

The gully wall and trench exposures reveal much about the dynamic behavior of streams and hillslopes during the late Quaternary in this area. Evidently, there have been several periods of

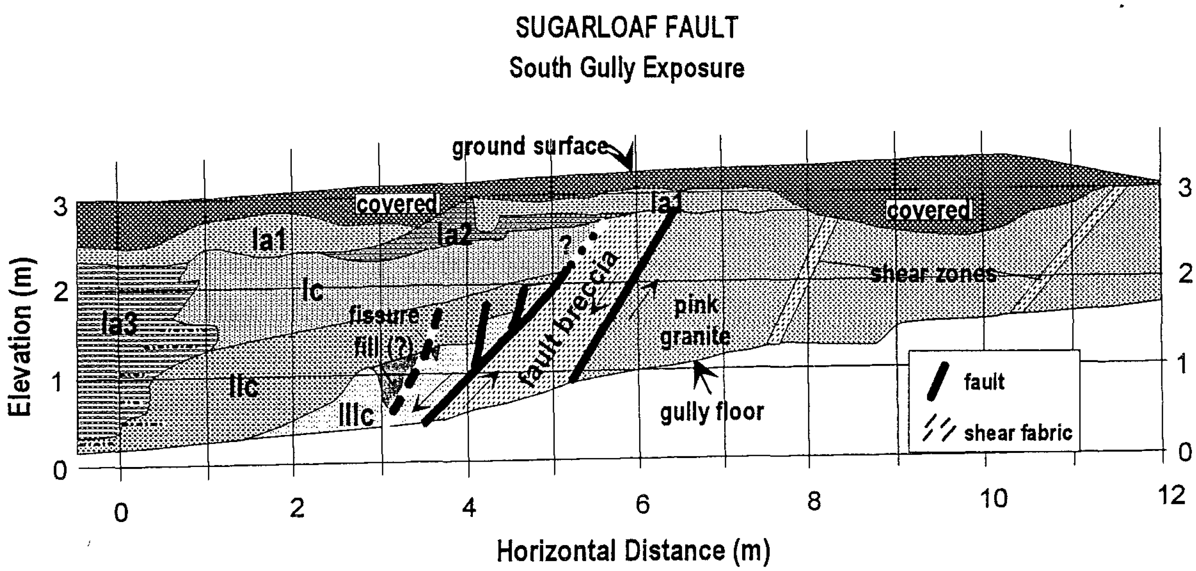

Figure 5. Log of the gully exposure near SR 87. Stratigraphic units and relationships are described in table 2 and in the text. View is from the north, horizontal distance is from east to west.

aggradation in the stream valleys and on adjacent hillslopes. Periods of stream downcutting and erosion of valley fill and hillslope colluvium occurred between these periods of aggradation. The youngest cycle of aggradation and downcutting, which is best exposed and preserved, may serve as a model for past oscillations between deposition and erosion. The relatively thick package of young colluvium exposed in the gully and the south trench accumulated near the base of the bedrock hillslope to the north; it grades laterally into young alluvial deposits. The young alluvial deposits clearly filled a channel or small valley cut into Pleistocene deposits. We believe that late Holocene aggradation of the stream valley caused a base-level rise at the toe of the scarp, which resulted in the accumulation of the thick package of colluvium there. This aggradational period ended abruptly with the stream downcutting the formed the modern gully. Tiny tributary gullies of the arroyo are only now beginning to erode the colluvium at the base of the fault scarp, but in time substantial amounts of colluvium will be removed. Latest and late Pleistocene colluvial units may well represent earlier periods of stream and hillslope aggradation. The latest Pleistocene colluvium exposed in the gully grades laterally into alluvial deposits, which are not very well preserved in the gully wall because they were truncated by erosion prior to late Holocene aggradation. These latest Pleistocene deposits onlap an erosion surface cut on late Pleistocene colluvium. Thus, we see evidence for at least three major periods of hillslope aggradation during and since the late Pleistocene, punctuated by three periods of downcutting and erosion.

Several fault zones are clearly exposed in the gully walls. The westernmost faults have fairly clear relationships with late Quaternary deposits, and thus can be fit into the chronology described above. It is apparent from the trench log that late Pleistocene colluvium exposed in the gully is faulted. The total vertical displacement of the top of unit is 0.5 to 0.7 m (1.5 to 2 ft). The overlying latest Pleistocene colluvium is likely faulted as well. The very steep contacts between these two units were probably formed by faulting and never exposed at the surface, so latest Pleistocene colluvium most likely mantled the late Pleistocene colluvium prior to faulting. The upper contact of the latest Pleistocene colluvium is smooth and shows no clear evidence of faulting; evidence for fault displacement within the latest Pleistocene colluvial unit becomes more tenuous higher in the unit. The gentle slope on this upper contact may be a subtle fault scarp that was seriously degraded prior to burial by late Holocene aggradation. In this case, the upper part of the colluvial unit was subject to erosion above the fault and deposition below it, and one would not expect to find evidence of faulting all the way to the top of the unit. In this scenario, faulting occurred during or shortly after deposition of the latest Pleistocene colluvium, and well before late Holocene aggradation commenced.

The numerous fault exposures in the relatively small area between SR 87 and the south trench allow us to consider some of the characteristics and complexities of the Sugarloaf fault (figure 4). Exposed fault zones are of limited extent; most of the fault trace is buried by late Holocene alluvium or colluvium. This is typical of the fault. The Sugarloaf fault is composed of multiple fault strands throughout this small area. Three fault zones are exposed in the south trench (figure 3). As many as four separate fault or shear zones cross the gully, and at least three distinct faults are exposed in roadcuts along SR 87. The heavy dotted lines in figure 4 show some possible fault connections, but the actual situation may be even more complex. It is our impression that multiple fault strands are common along the fault. This area may be especially complex, however, because it is at the northern end of a right bend in the general trace of the Sugarloaf fault (plate 1).

Hohokam Trenches. We excavated two trenches across the enigmatic scarp found on a young alluvial fan near Sycamore Creek. This 20 m (75 ft) long scarp was considered a probable fault scarp by Pearthree and Scarborough (1984) and Anderson et al (1986). However, it is the only scarp cutting a Holocene alluvial landform along the Sugarloaf fault. The scarp is located on a slightly entrenched alluvial fan emanating from a small drainage that heads west of the fault. It is in a mesquite thicket near a known Hohokam site, so excavation of a backhoe trench across the scarp was not permitted. Because we felt it was critical to determine whether this feature is actually a fault scarp, we excavated a 7 m (25 ft) long, 1.5 m (5 ft) trench with shovels, beginning near the top of the scarp and continuing for several meters beyond the toe of the scarp. In order to verify our interpretation of the first trench, we excavated a second, smaller trench across the scarp near the first trench.

Inspection of the larger trench revealed a sequence of late Holocene alluvial units but no clear fault zone (figure 6). Several stratified and fairly well sorted sandy or gravelly units exist in the upper portion of the western end of the trench. These units slope gently to the east and end at the scarp. There is also a curious silty fine sand layer up to 30 cm (1 ft) thick beneath the scarp and a zone where depositional stratigraphy may have been disrupted by biological activity. Downslope

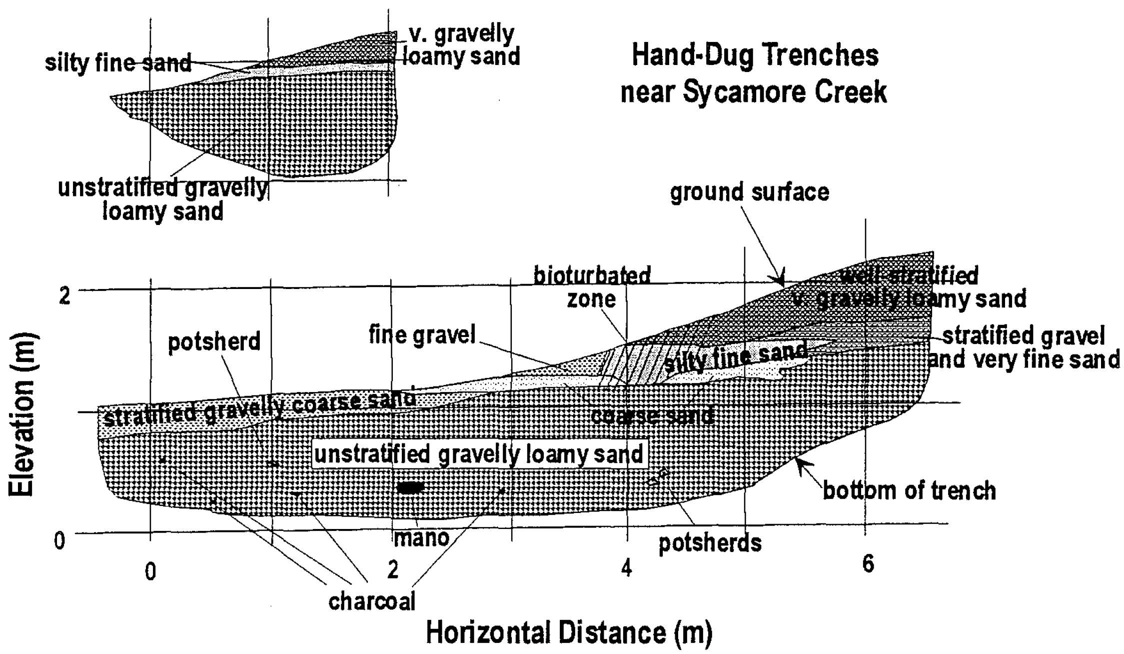

Figure 6. Logs of the Hohokam trenches. Stratigraphic units and relationships are discussed in the text. All of the stratigraphic units found in these trenches are of late Holocene age, and correlate with unit Ia shown in other logs. View is from the north, horizontal distance is from east to west.

from the scarp, a gravelly coarse sand deposit that is about 20 cm thick at the eastern end of the trench and pinches out at the base of the scarp. Underlying all of these units is a massive, very weakly stratified, poorly sorted deposit that contains a number of Hohokam artifacts and considerable small pieces of charcoal. The artifacts consist of four potsherds and a small, well-rounded basalt mano (grinding stone), found at depths ranging from about 0.5 to 1 m (1.5 to 3 ft) below the top of this unit. The presence of artifacts within this unit indicate that deposition of the lower unit occurred during Hohokam occupation of this area, between about 600 and 1,700 years ago. This lower unit appears to be continuous beneath the surface scarp, with no evidence of a fault zone or fault displacement. The lower massive unit and some stratified deposits overlying it were exposed in the second trench as well. Again, we found no evidence in the second trench indicating that this lower unit has been faulted.

This scarp cutting across a late Holocene alluvial fan is evidently not a fault scarp, but it remains an enigmatic feature. The general stratigraphy exposed in the trenches is a bioturbated, unstratified unit containing archeological artifacts and overlying, well-stratified stream deposits. The scarp is entirely within the overlying deposits. Lateral erosion by streams can form scarps, but this scarp is oriented virtually perpendicular to the local drainage. The channel of the next drainage to the south does roughly parallel the scarp, but it is at least 10 m downslope from it at present and the stratigraphy exposed in the trenches does not indicate the presence of a significant channel at the base of the scarp. Debris flow lobes or flow fronts may end in steep scarps, but debris-flow deposits are typically very poorly sorted and weakly stratified. Thus, there are no obvious geologic explanations for the formation of this scarp.

We propose that this scarp is the remnant of a feature constructed for agricultural purposes by prehistoric Indians (either late Hohokam or post-Hohokam people). We hypothesize that these people constructed a a leaky check dam or "trenchera"out of mesquite or other brush in order to trap water and sediment during flows on this alluvial fan. Water trapped in pore spaces in the alluvial-fan deposit facilitated dry-land farming above the check dam. After the agricultural plot was abandoned, the wood composing the dam was consumed by termites or was removed by natural processes, leaving a low, young scarp. The microstratigraphy within the upper stratified depositional unit, including the bioturbated zone in the scarp face where the dam may have existed, are consistent with this model.

Sediment was sampled for pollen analysis to evaluate our explanation for the formation of the scarp (see Appendix 1 for description of samples and analyses). Two samples were taken from the upper, stratified deposits (depth) and one from the lower, unstratified deposits (80 to 100 cm depth). The pollen signature for the deepest sample is indicative of intense prehistoric human disturbance, which is consistent with the numerous artifacts found in those deposits. In addition, pollen from the unstratified deposits is more abundant and better preserved than from the overlying deposits. This is consistent with a fairly high sedimentation rate and rapid burial of the pollen. Pollen from the uppermost sample pre-dates European settlement, and thus was emplaced at least 100 years ago. Based on the morphology of the scarp, it is probably a few centuries old (Hanks, in press). None of the samples contain pollen that is diagnostic of prehistoric agriculture (i.e., corn, beans, squash, cotton), but the preservation potential for agave, a common dry-land crop, is very low.

The pollen analyses do not provide definitive evidence of farming associated with the proposed check dam, nor do they rule out the possibility that dry-land farming was conducted above a dam. Two professionals with expertise in Arizona archeology who visited this site, Greg Woodall (Archeological Consulting Services) and Gary Huckleberry (AZGS), concluded that this scarp did not look like any archeological features they had seen. However, in the absence of an obvious natural mechanism for the formation of this scarp, we conclude that it is likely that it formed in association with some type of check dam.

Late Quaternary Rupture History

Our interpretations of trench and gully exposures across the fault indicate that the Sugarloaf fault ruptured most recently in the latest Pleistocene. Trench and gully exposures both reveal that the Sugarloaf fault is commonly composed of several fault strands. Some of these faults involve only Precambrian bedrock, and thus they may or may not have ruptured during the Quaternary. Other faults clearly have ruptured late Quaternary deposits. Colluvial deposits as young as latest Pleistocene (10,000 to 20,000 years old) are faulted. Vertical displacement in this youngest faulting event probably was about 0.5 to 1 m (2 to 3 ft). Subsequent to the this latest Pleistocene faulting event, streams crossing the Sugarloaf fault downcut and adjacent hillslopes were eroded. Substantial aggradation occurred in this area during the past few thousand years, resulting in accumulation of several meters of alluvium in the drainages and lesser amounts of colluvium on the hillslopes. Hohokam artifacts found in the upper 1.5 m (5 ft) of these deposits indicates that deposition was occurring around 1,000 years ago. The period of erosion followed by substantial aggradation evidently obliterated or buried the low fault scarps that existed after the youngest fault rupture.

Our interpretations of the trench and gully exposures provide only limited information on the long-term rate of recurrent surface ruptures. Late Pleistocene units exposed at the fault are not displaced any more than latest Pleistocene units. This indicates that only one surface rupture has occurred on the fault in the past 50,000 to 100,000 years. Since the youngest fault rupture occurred about 10,000 years ago, the interval between the two most recent fault ruptures is at 50,000 to 100,000 years. We discovered no other evidence to constrain the frequency of fault ruptures. Other late Quaternary faults that have been studied in southern and central Arizona apparently have similarly long reocurrence intervals (Menges and Pearthree, 1989; Piety and Anderson, 1991).

Seismic Hazard Implications

We used the geologic information gained from our field studies to assess the magnitude of surface-rupturing earthquakes on the Sugarloaf fault and the long-term frequency of such large earthquakes on the fault. These data were then incorporated into a probabilistic assessment of the seismic hazard posed by the Sugarloaf using the SEISRISK III program (Bender and Perkins, 1987).

Paleoearthquake Magnitude Estimates. Estimates of the length of fault rupture and surface displacement can be used to estimate the size of paleoearthquakes using empirical relationships developed from historical earthquakes (Wells and Coppersmith, 1994). The range of potential fault rupture lengths varies from about 4 to 20 km (2 to 12 miles). The central 4.3 km (2.7 miles) of the fault has the sharpest geomorphic expression and is the section of the fault where there is clear evidence of late Quaternary movement. This is the minimum length of the youngest fault rupture. The southeastern 4 km (2.5 miles) of the fault is associated with a prominent bedrock scarp that diminishes to the southeast. Possible evidence of late Quaternary movement has been

Length-based estimates

Section	Length (km)	Total rupture length (km)	Estimated magnitude (all faults)	Estimated magnitude (normal faults)
central	4.3	4.3	5.78	5.82
southeast	4	8.3	6.12	6.15
northern	12	20.3	6.59	6.59

Displacement-based estimates

Maximum Displacement (m)	Estimated Magnitude (all faults)	Estimated Magnitude (normal faults)
0.5	6.45	6.44
1	6.69	6.63

Table 4. Sugarloaf fault maximum magnitude estimates for surface-rupturing earthquakes.

discovered on this section, and the height and steepness of the bedrock escarpment suggests that this section has experienced Quaternary movement. The northern 12 km (7.5 miles) of the Sugarloaf fault separate Precambrian granite from Tertiary basalt and sediment. Several discontinuous lineaments and short topographic escarpments exist along this portion of the fault, but we found no definitive displacement of late Quaternary deposits. The earthquake magnitude estimated from the minimum fault length of 4 km is about 5.8; if the southeastern and central sections ruptured together (8 km), the estimated magnitude is 6.15; if the whole 20 km of the fault ruptured in one earthquake, the estimated magnitude is about 6.6 (table 4). The surface displacement associated with the youngest fault rupture is estimated from displacement of late and latest Pleistocene deposits in the gully and trench exposures. Vertical displacement of late

Pleistocene colluvium in the south trench is about 0.5 m (1.6 ft); latest Pleistocene colluvium is displaced about 0.7 m (2.3 ft) in the gully exposure. We consider 1 m (3.3 ft) of vertical displacement to be a conservative maximum. Earthquake magnitudes estimated from displacements of 0.5 to 1 m range from 6.3 to 6.7.

There is substantial uncertainty in our estimates of the magnitude of surface-rupturing earthquakes on the fault and the frequency of surface ruptures on the fault. The Sugarloaf fault ruptured about 10,000 years ago, and this was the only surface rupture in the past 50,000 to 100,000 years. The minimum interval between the past two surface ruptures thus is about 50,000 to 100,000 years, although the actual reocurrence interval could be longer. This range for the surface-rupture reocurrence interval is consistent with values determined from studies of other faults in this region (for example, Piety and Anderson, 1991).

Probabilistic Acceleration Analyses. We used various estimates of maximum earthquake magnitude combined with estimates of the frequency of surface ruptures on the fault in the SEISRISK III program to develop probabilistic accelerations for the area around the Sugarloaf fault. The SEISRISK III program was used to develop seismic acceleration maps for Arizona for ADOT (Euge et al, 1992). It can incorporate seismic source zones (regions with similar seismic characteristics) and discrete seismic sources (fault zones). The Sugarloaf fault is well within the Arizona Mountain seismic source zone of Euge et al (1992). It was not treated as a discrete source in their analysis, and evidently was not used directly in the development of the regional magnitude-frequency relationship. In this analysis, therefore, we treat the Sugarloaf fault as a discrete seismic source and add the probabilistic acceleration values developed for it to the background acceleration.

We ran the SEISRISK III program to generate probabilistic acceleration values for the area around the Sugarloaf fault. A 90 percent non-exceedance horizontal acceleration means that there is a 10 percent chance that this acceleration will be exceeded in a specified interval. The use of 50- and 250-year intervals is consistent with the study conducted for ADOT by Euge et al (1992). Also consistent with the earlier study for ADOT, we assume that the earthquake magnitude - frequency relationship for the Sugarloaf fault has a **b**-value of -1. This assumption implies that the fault will generate ten times as many earthquakes for each unit decrease in magnitude. The

A) 6.7 M, 50 years, 50,000 year RI

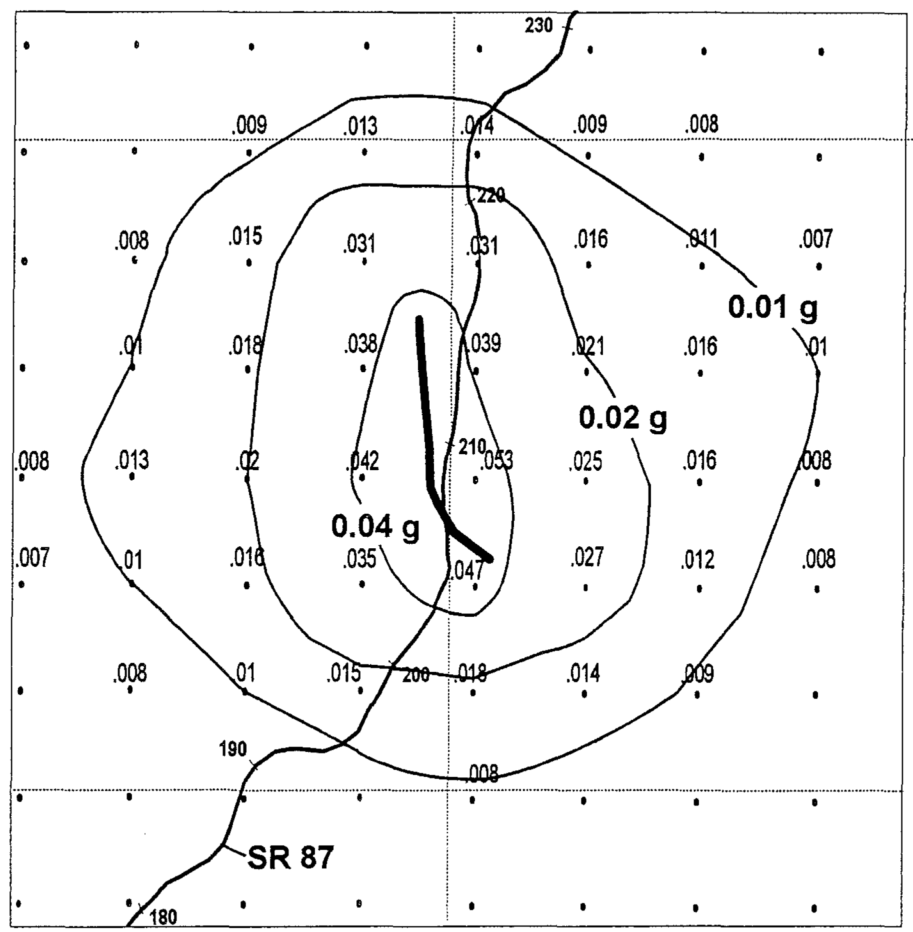

Figure 7. Examples of probabilistic horizontal acceleration maps for the Sugarloaf fault. Sugarloaf fault is the bold, north to northwest-trending line. Calculated accelerations as a fraction of 1 g are shown for grid points in normal font. Contour intervals vary. Ten-mile mileposts on SR 87 are labeled. A conservatively large maximum earthquake magnitude of 6.7 is assumed for each scenario; interval for which 90 percent non-exceedance accelerations were calculated and assumed re-occurrence intervals between maximum earthquakes at the top of each scenario.

B) 6.7 M, 50 years, 100,000 year RI

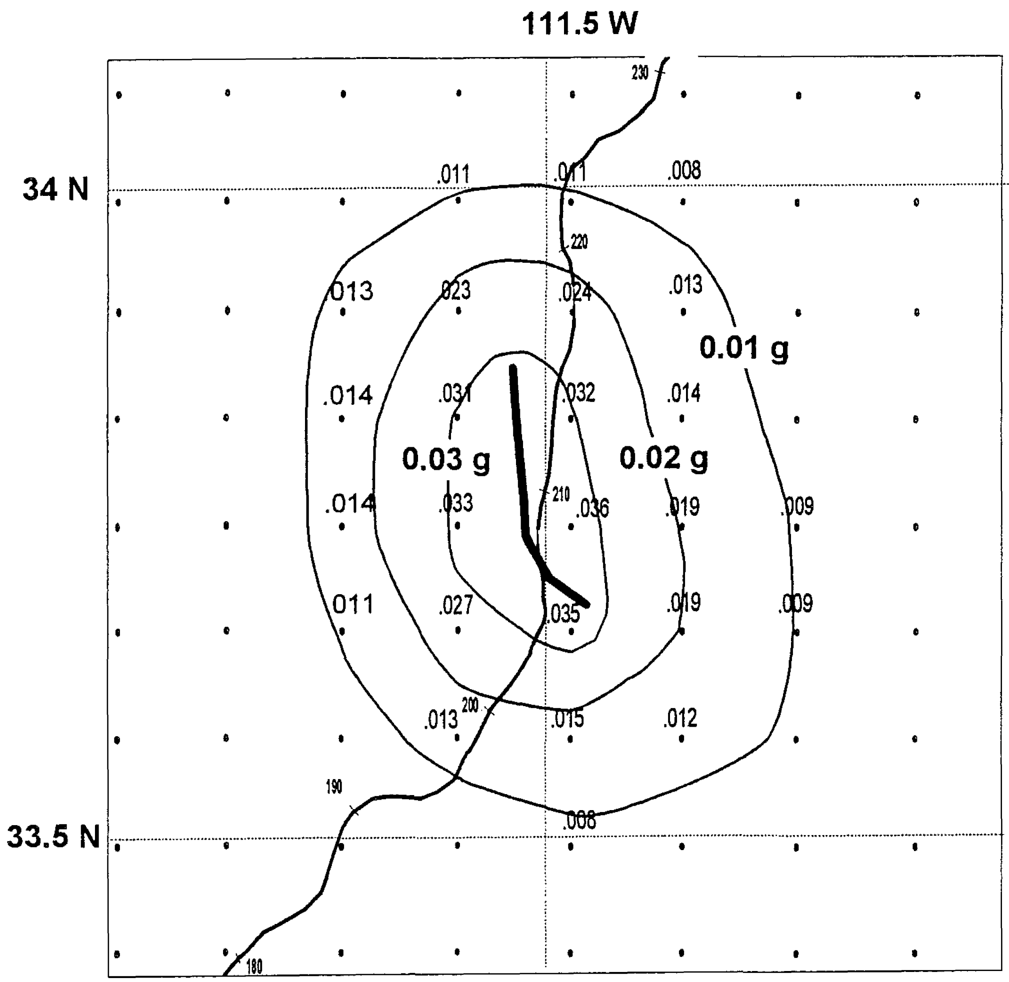

Figure 7 B..

C) 6.7 M, 250 years, 50,000 year RI

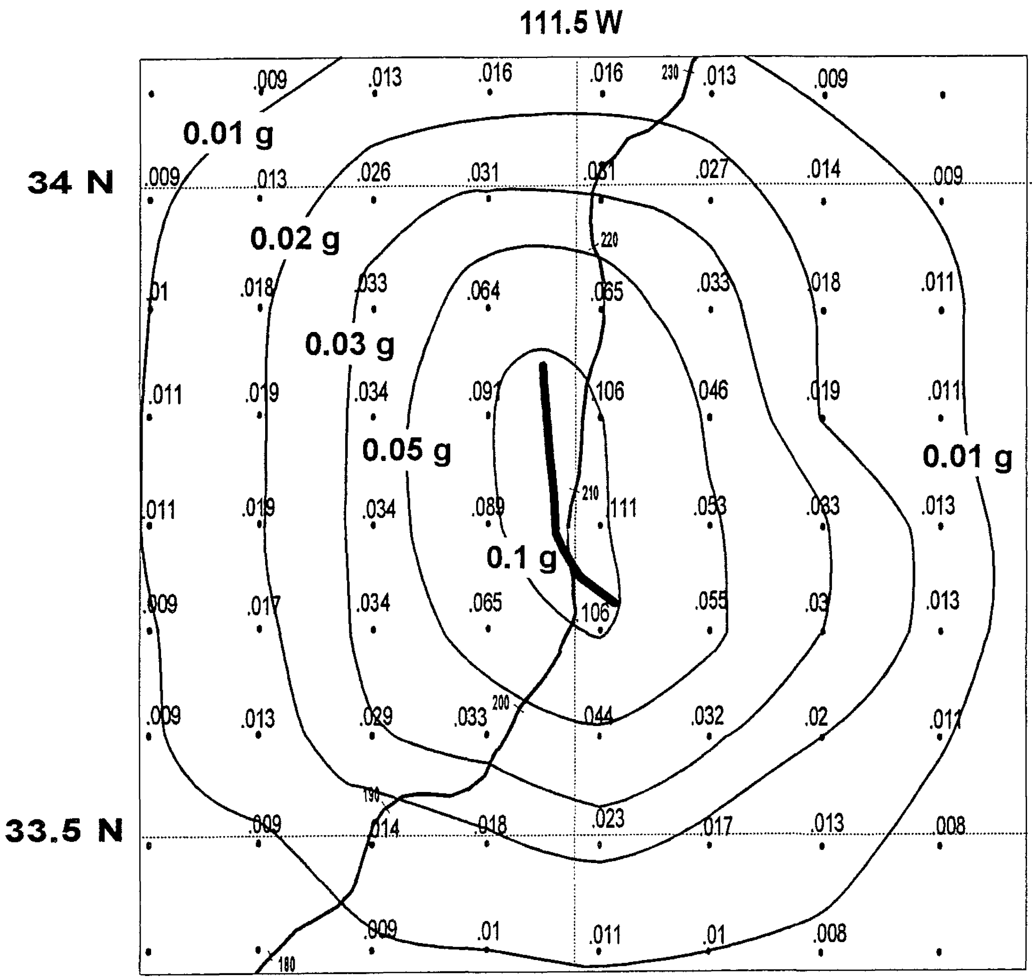

Figure 7 C.

D) 6.7 M, 250 years, 100,000 year RI

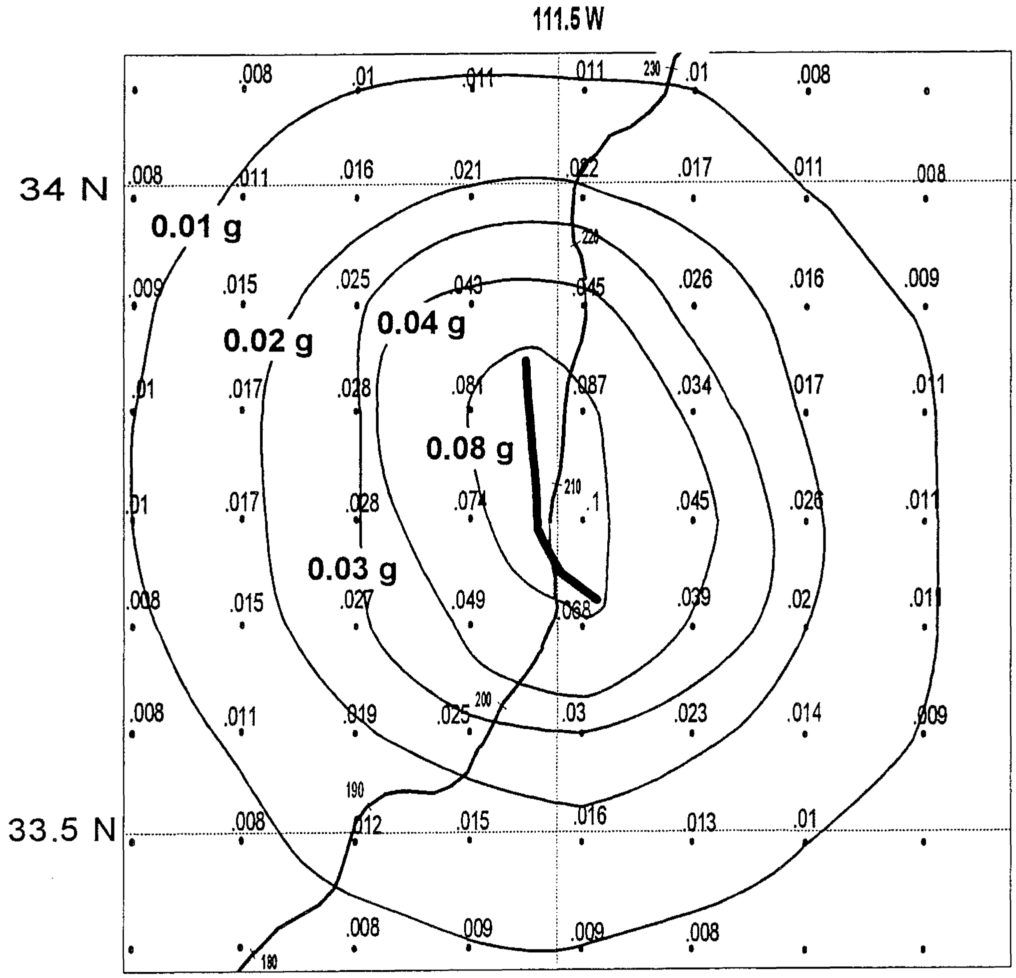

Figure 7 D.

Magnitude estimate	a value @ M=0	Maximum Probabilistic Accelerations Near the Fault			
		Sugarloaf fault only		Net Value	
		50-year	250-year	50-year	250-year
Current map				**0.045g**	**0.13g**
Re-occurrence interval 50,000 years					
6.15	1.45	0.041g	0.071g	**0.086g**	**0.20g**
6.7	2.00	0.053g	0.11g	**0.098g**	**0.24g**
Re-occurrence interval 100,000 years					
6.15	1.15	0.033g	0.062g	**0.078g**	**0.19g**
6.7	1.70	0.036g	0.1g	**0.081g**	**0.23g**

Table 5. Frequency relationships and the largest probabilistic horizontal accelerations near the Sugarloaf fault. Various magnitude - reocurrence relationships are shown to reflect the uncertainties in the data.

SEISRISK III program calculates probabilistic values for a series of grid points. We used a grid spacing of 0.09° for this is a specific study.

We used several combinations of maximum magnitude and re-occurrence interval to assess probabilistic accelerations (table 5). Assuming a re-occurrence interval of 100,000 years and a maximum earthquake magnitude of 6.7 for the fault results in increases in 50-year acceleration as large as 0.036g adjacent to the fault. We believe that a 100,000 year re-occurrence interval for surface ruptures on this fault is most likely. Making the more conservative assumption of a re-occurrence interval of 50,000 years for the maximum earthquake results in increases in 50-year acceleration of up to 0.053g. Superimposing these increases on the background acceleration value of 0.045g at the Sugarloaf fault, we find that even the most conservative set of assumptions (6.7 magnitude, 50,000 year reocurrence interval) yields a 50-year acceleration value of less than 0.1g. The impact of the Sugarloaf fault on regional acceleration values falls off rapidly with distance from the fault. At a distance of about 40 km (25 miles) the Sugarloaf fault adds less than 0.01 g to the 50-year acceleration field.

The significance of individual fault zones increases when considering probabilistic accelerations over longer periods. The background 250-year, 90-percent non-exceedance acceleration value for this area is about 0.125g. Accelerations calculated for the Sugarloaf fault using the same combinations of magnitude and frequency discussed above range from 0.06g to 0.11g, increasing the net acceleration for this area to 0.19g to 0.24g. Thus, there is a reasonable chance that structures near the Sugarloaf fault with very long design lives could be subject to substantial seismic shaking.

Conclusions

We conducted a paleoseismologic investigation of the Sugarloaf fault for ADOT in order to assess the seismic hazard associated with this fault. We conducted a field reconnaissance of most of the fault, mapped the central section of the fault in detail, and interpreted several trench and gully exposures across the fault. Our field investigations indicate that the fault ruptured most recently in the latest Pleistocene. Holocene alluvial fan and terrace deposits, which are found along most of the tributary drainages that cross the fault, are not faulted. Latest Pleistocene colluvium exposed in trenches and gullies is faulted. Late Pleistocene alluvium and colluvium is not obviously displaced more than latest Pleistocene deposits, implying that only one fault rupture has occurred in the past 50,000 to 100,000 years. We were not able to measure the fault displacement of any deposits older than late Pleistocene. The maximum surface displacement in the youngest rupture probably was less than 1 m (3 ft), and the length of the surface rupture was probably between 4 and 8 km (2.5 to 5 miles). Estimates of paleoearthquake magnitudes of surface ruptures on the Sugarloaf range from about 6 to 6.7, depending on the displacement and rupture length assumed. Using several reasonable magnitude - reocurrencence interval scenarios, we assessed the 50-year, 90 percent non-exceedance horizontal acceleration field around the Sugarloaf using the SEISRISK III program. Even the most conservative scenario of a magnitude 6.7 earthquake every 50,000 years results in an increase in acceleration values of 0.05 g, for a net 50-year acceleration value of less than 0.1g. Horizontal accelerations determined for the 250-year interval are more than twice as large as the 50-year values.

Acknowledgements

This project would not have been funded and this research would not have occurred without the interest and support of Nick Priznar and Doug Alexander of the ADOT Materials Section. Gary Huckleberry and Kyle House of the AZGS provided field assistance and valuable feedback on our trenches. Steve Skotniki of the AZGS helped us understand the late Cenozoic tectonics and stratigraphy of this area. Larry Anderson of the U.S. Bureau of Reclamation graciously volunteered to come to Arizona to review our work and help with trench interpretations. The U.S. Forest Service permitted excavation of trenches on the Tonto National Forest.

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APPENDIX 1:

POLLEN ANALYSIS OF THE HOHOKAM (?) SEDIMENTS SUGARLOAF FAULT PROJECT

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June 28, 1995

SUMMARY: Routine pollen analysis was performed for 3 sediment samples from the Sugarloaf Fault Project site, Pinal County, Arizona. Pollen concentration is low, but the pollen preservation is good. The better preservation and higher concentration of the sample from 80-100 cm is probably due to rapid burial. No pollen grains of exotic plants were recovered, and the abundance of historic invaders is lower than in surface sediments from nearby sites: juniper (Cupressaceae), mesquite (*Prosopis*), and *Sporormiella* (a dung fungus). Therefore the 3 samples are probably of pre-settlement age, without obvious contamination by mixing. The indications of prehistoric human disturbance are greatest in the deepest (80-100 cm) sample and decrease upward. These prehistoric indications of disturbance (weeds) are saltsage (Chenopodiaceae-*Amaranthus),* spiderling *(Boerhaavia*), buckwheat (*Eriogonum*), globe mallow (*Sphaeralcea*), and puncture vine (*Tribulus*). Charcoal also decreases in abundance upward, due to decreasing disturbance. In contrast, spiderling *(Euphorbia* [another weed]) pollen is most abundant in the uppermost sample (20-40 cm). None of the samples contain cultigens (corn, beans, squash, cotton) or other indications of agriculture. However, the predominance of prehistoric weeds, particularly the abundance (50 %) of Chenopodiaceae-*Amaranthus* pollen indicates extensive human modification of the prehistoric vegetation.

INTRODUCTION

Pollen analysis of sediments from above an alluvial scarp near the Sugarloaf fault was undertaken at the to determine whether prehistoric agriculture had been practiced behind the scarp. The scarp may have been a brush dam built to retard erosion and increase soil moisture for agricultural purposes. The presence of the pollen of corn (*Zea*) or other cultivate plants (beans, squash, cotton) in the sediments would support the hypothesized origin of the feature as a check-dam.

The Sugarloaf fault forms a steep scarp above an alluvial fan feeding into Sycamore Creek, about 50 km northeast of Phoenix, Arizona. Vegetation on the fan is transitional from Sonoran desertscrub to semidesert grassland (Brown and Lowe, 1980). Mesquite (*Prosopis*) trees are a prominent feature of the local vegetation.

Previous Studies

Pollen analysis of central Arizona sites has demonstrated the effects of prehistoric and historic human activities. The historic increase in the abundance of upland shrubs, particularly juniper (*Juniperus*) and mesquite has been documented by Davis and Turner (1987). The coincidence of this increase with decreased charcoal abundance supports a role of decreased fire frequency in the historic spread of these shrubs. The historic increase in shrubs is accompanied by the arrival of various exotic weeds such as filariae (*Erodium cicutarium*) and the increased abundance of the dung fungus *Sporormiella* (Davis and Turner, 1987).

The pollen of weeds is common in samples from Southwestern archeological sites, particularly members of the Chenopodiaceae-*Amaranthus* group. In terrace check-dams on Tumamoc Hill and Los Morteros, near Tucson, Arizona, sediments dated to late Archaic and Hohokam occupation contain 15-50% Chenopodiaceae-*Amaranthus* pollen; whereas modern sediments contain only about 5% of that type. Other abundant weed types in these check-dam's prehistoric sediments include *Tidestroemia Boerhaavia, Sphaeralcea*, and *Kallstroemia.* Corn pollen is present at both sites in low (1-2%) amounts (Fish, 1985).

METHODS

The three Sugarloaf samples were processed to maximize the likelihood of recovering the large (>60 m) pollen grains of cultivated plants (cf. Gish, 1995). Pollen was analyzed for the 840 - 20 µm size-fraction of the sediment (Table 1). One *Lycopodium* spore tablet was added to 20 cm^3 samples to permit calculation of the pollen concentration. An important aspect of this treatment was the disaggregation of the samples with detergent as a first step. This appears to improve recovery by freeing grains from adhering inorganic particles, and by dispersing clay particles (Davis, unpublished).

Quantification

Two - three hundred grains of the pollen of upland plants were counted per sample, including deteriorated (unidentifiable) pollen. This sum is the divisor for all pollen and spore percentages (Figure 1, Table 2). Pollen of aquatic plants and spores are not included in the sum.

RESULTS AND INTERPRETATION

The pollen concentration of the Sugarloaf samples is similar to that of archeological samples of the Southwest, but much lower than for Southwestern cienegas or lakes (20,000 - 100,000 gr/cc) or the surface sample from near Kearney, Arizona (Fig. 1). The pollen preservation, however, is better than for most archeological samples. The pollen percentages are typical for the desertscrub to semidesert grassland of central Arizona.

The pollen stratigraphy of the Sugarloaf site provides an interesting contrast to the typical pattern observed in open archeological sites. Usually, pollen concentration decreases and deterioration increases with depth (Davis, 1995). The upward-decreasing concentration in the Sugarloaf samples could result from 3 factors: decreasing pollen production, worsening pollen preservation, or increasing sedimentation rate. If the basal sediment was deposited more slowly than the upper 2 samples, it could contain more pollen per volume. Alternatively, if the disturbed vegetation associated with the lowermost sample produced more pollen, then the same volume of sediment should contain more pollen.

The somewhat lower percentages of background pollen types (*Pinus, Quercus,* and *Ambrosia*) indicates greater local pollen production (or better preservation) in the lowermost sample (Fig. 1, Table 2). The preservation of the lowest sample (7% vs 32% deteriorated) is dramatically better than the upper samples. This trend is unique for open sites in the American Southwest (Davis, 1995). A likely explanation for the better preservation and higher concentration of the sample from 80-100 cm is rapid burial beneath the overlying stratified sediment.

All 3 Sugarloaf samples are probably of pre-settlement age, because no pollen grains of exotic plants were recovered, and the abundance of historic invaders is lower than in samples from the modern vegetation (Fig. 1). A modern sample from nearby Kearney, Arizona (Fig. 1), contains the exotic filariae *(Erodium cicutarium)* and higher percentages of juniper (Cupressaceae), mesquite (*Prosopis*), and *Sporormiella* (a dung fungus). These differences are consistent with studies of the effects of historic vegetation change on the pollen stratigraphy of Pecks Lake, Yavapai Co., Arizona (Davis and Turner, 1987).

The Sugarloaf locality experienced intense prehistoric human activity. The indications of prehistoric human disturbance are greatest in the deepest (80-100 cm) sample and decrease upward. These prehistoric indications of disturbance (weeds) are saltsage (Chenopodiaceae-*Amaranthus),* spiderling (*Boerhaavia*), buckwheat (*Eriogonum*), globe mallow (*Sphaeralcea*), and puncture vine (*Tribulus*). These types are typically associated with prehistoric vegetation disturbance in the central Arizona (Fish, 1985). The upward decreases in Charcoal percentages (Table 2, Fig. 1) also is likely due to decreasing disturbance.

In contrast, spiderling *(Euphorbia* [another weed]) pollen is most abundant in the uppermost sample (20-40 cm). Spiderling pollen is also common in the modern sample from nearby Kearney, Arizona (Fig. 1), so the 20-40 cm sample may be young (100-200 yrs).

None of the Sugarloaf samples contain cultigens (corn, beans, squash, cotton) or other indications of prehistoric agriculture. Therefore, the pollen provides no direct evidence for the construction of a check-dam for agricultural irrigation. However, if the Sugarloaf scarp originated as a brush check-dam, the pollen percentages (the upward decreasing pollen concentration and increasing deterioration) suggests that it was abandoned soon after construction.

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TABLE 1. Extraction Procedure.

a. screen (20 mesh 840 µm) to remove coarse material
b. screen over 20 µm mesh to remove fine material
c. add 20 cm^3 sample to ca. 50 ml water with detergent, agitate 10 min.
d. swirl solution and screen (180 µm mesh, stainless steel) into 50 ml test tubes
e. add 1 *Lycopodium* tablet (batch # 710961, 13,911 grains/tablet)
f. add 10 ml conc. HCl, mix, add 30 ml H_2O, mix
    centrifuge, decant, water rinse
g. add 40 ml HF overnight or 1 hr in boiling water bath
    transfer to 15 ml centrifuge tubes
h. Acetolysis*
    centrifuge, decant, water rinse
i. add 10 ml 10% KOH 2 min. boiling water bath
    rinse with hot water until clear
j. stain with safranin "O"
k. transfer to labeled 1 dram shell vials
l. add a few drops of glycerin

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*ACETOLYSIS
a. 5 ml glacial acetic acid centrifuge and decant
b. stir sample, add 5 ml acetic anhydride (volumetric dispenser)
c. add 0.55 ml H_2SO_4 to acetic anhydride solution (volumetric pipet), mix, centrifuge, decant into glacial acetic acid
d. 5 ml glacial acetic acid centrifuge and decant

TABLE 2. Pollen Percentages, Sugarloaf Fault Project

SAMPLE DEPTH (cm)	20-40	50-70	80-100
POLLEN SUM	201	244	306
TRACERS	55	70	37
CONC. gr/cc	2542	2424	5752
DETERIORATED	31.8	20.1	6.9
saguaro - *Cereus*	0.0	0.8	0.0
juniper - Cupressaceae	0.5	0.0	0.0
pine - *Pinus*	1.5	0.8	0.3
oak - *Quercus*	5.0	6.1	2.0
humming bird plant - Acanthaceae	0.0	0.4	0.0
saltsage - Chenopodiaceae-*Amaranthus*	10.9	29.5	50.3
jointfir - *Ephedra*	0.0	0.4	0.3
ocotillo - *Fouquieria*	0.0	0.8	0.0
creosote - *Larrea*	4.0	1.2	2.3
pricklypear - *Cylindropuntia*	1.5	4.5	1.3
cholla - *Platyopuntia*	1.0	0.4	0.0
Rubiaceae	1.0	0.0	0.0
jojoba - *Simmondsia*	0.0	0.8	0.3
spiderling - *Boerhaavia*	0.0	7.0	7.2
pink family - Caryophyllaceae	0.5	0.0	0.0
buckwheat - *Eriogonum*	0.5	0.4	4.9
spurge - *Euphorbia*	13.4	2.9	0.7
grass - Gramineae	10.9	7.0	2.3
(Sunflower family)			
ragweed - *Ambrosia*	2.0	3.7	1.6
sagebrush - *Artemisia*	0.5	0.0	0.0
Liguliflorae	0.0	0.4	0.3
Other Compositae	14.9	11.1	18.0
bindweed - *Polygonum*	0.0	0.0	0.3
globe mallow - *Sphaeralcea*	0.0	0.8	0.3
puncture vine - *Tribulus*	0.0	0.8	0.7
Fern Spores	0.0	0.4	0.7
Fungal Spores	254.7	258.2	189.5
Selaginella	4.5	2.9	2.3
Sporormiella	0.5	0.8	0.0
Typha-Sparganium	0.0	0.0	0.3
Arthropod Feces	18.4	13.5	3.6
Charcoal	60.2	52.5	110.8

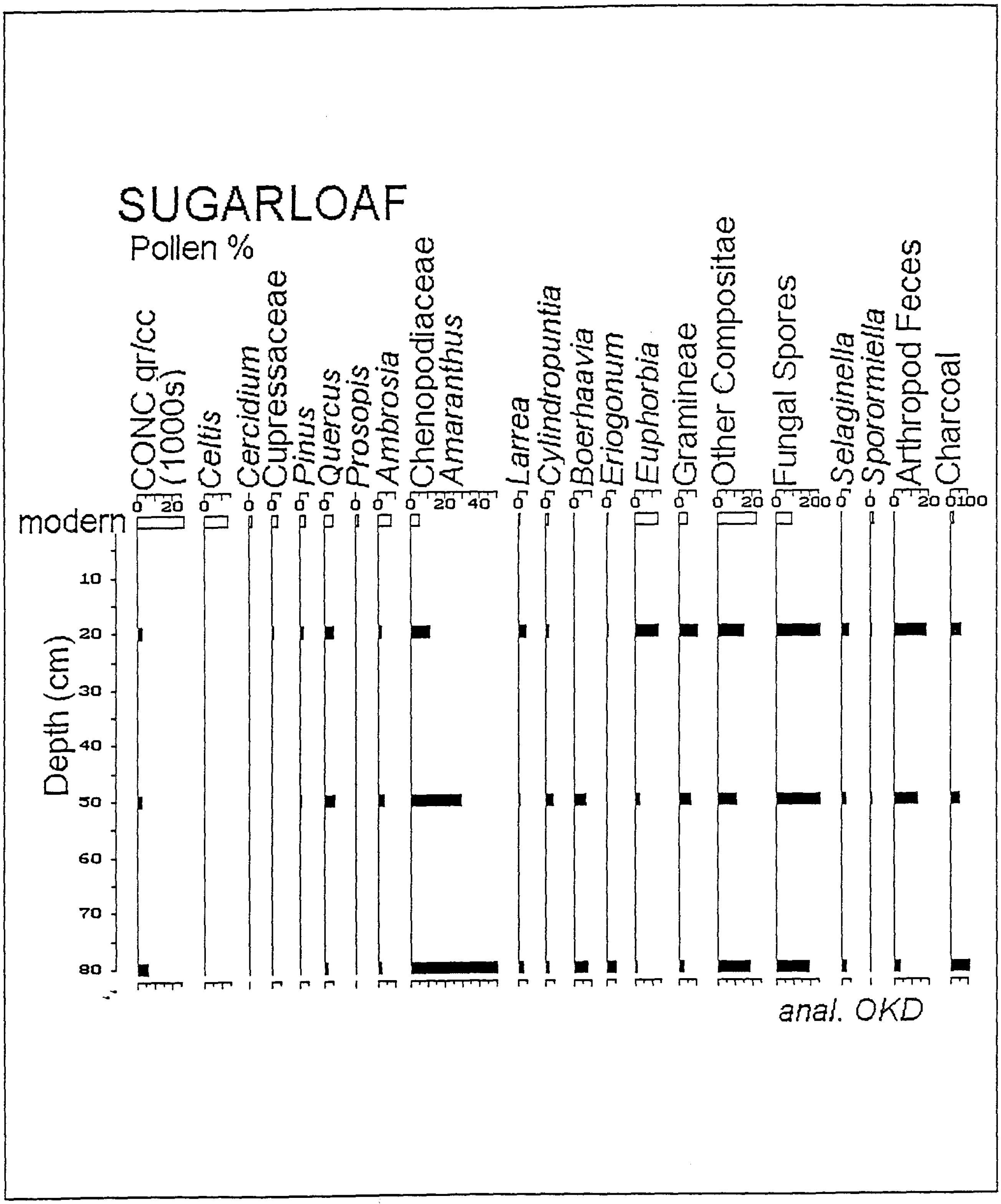

FIGURE 1. Pollen diagram showing the most abundant pollen and spore types for the three Sugarloaf "fault" samples. The fourth, uppermost sample (open boxes) is a modern surface sample from near Kearney, Arizona, included for comparison.