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SEISMOTECTONIC INVESTIGATION FOR HORSESHOE AND BARTLETT DAMS-SALT RIVER PROJECT, ARIZONA

by

Lucille A. Piety
Larry W. Anderson

SEISMOTECTONIC REPORT 90-7

Seismotectonics and Geophysics Section
Geology Branch
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Prepared by:

Lucille A. Piety 8/8/90

Lucille A. Piety Date
Geologist

Prepared and reviewed by:

Larry W. Anderson 8/8/90

Larry W. Anderson Date
Lead Seismotectonic Geologist

Submitted by:

Hunter C. Harrell 8-8-90

Hunter C. Harrell Date
Head, Seismotectonics and
Geophysics Section

Approved:

Richard H. Throner 8-9-90

Richard H. Throner Date
Chief, Geology Branch

2. QUATERNARY FAULTING IN THE VICINITY OF HORSESHOE AND BARTLETT DAMS

Horseshoe and Bartlett Dams are located in the Transition Zone of central Arizona. Within this province, faults with evidence of Quaternary activity are widely scattered, and seismicity is low in comparison to other parts of the western United States. However, most of the known or suspected Quaternary faults and most of the historic seismicity in Arizona occur within or adjacent to the Transition Zone. Based on data gathered during this study for Horseshoe and Bartlett Dams and on the results of previous studies for Stewart Mountain and Theodore Roosevelt Dams (Anderson and others, 1986; 1987), two recurrent Quaternary faults have been identified in the immediate area of the subject dams (within approximately a 50-km radius). The two faults are the Horseshoe and Sugarloaf faults (fig. 1-1).

2.1. Horseshoe Fault

The Horseshoe fault, the name used in this report, is a recurrently active structure with evidence for late Quaternary activity. The fault consists of two segments, Hell Canyon and Horseshoe Reservoir, and has a total length of about 21 km. The Hell Canyon segment is 11 to 12 km long and bounds the steep, north-striking range-front west of Horseshoe Dam. The Horseshoe Reservoir segment is 9 to 10 km long, strikes west-northwest across the reservoir basin, and crosses the Verde River about 300 to 350 m upstream from the dam. Displacement on both fault segments is apparently normal, with the east or northeast side down.

The Hell Canyon segment is marked by strong topographic, tonal, and vegetational lineaments (fig. 2-1). This basin-bounding fault, the result of the Basin and Range disturbance (Shafiqullah and others, 1980), juxtaposes Precambrian granitic rocks (on the west) against Tertiary basin-fill deposits (plate 1). Down-to-the-east scarps preserved on alluvial fans near the range front have a maximum height of 7.5 m and a maximum angle of 27° (appendix A). These parameters suggest a latest Pleistocene to early Holocene age for the most-recent surface-faulting event on this segment.

The Horseshoe Reservoir segment is an intra-basin fault that juxtaposes Tertiary basin-fill deposits of different rock types and is expressed mainly as a linear topographic feature. Where this fault segment crosses the Verde River valley immediately upstream of Horseshoe Dam, a north-facing scarp is preserved on a Quaternary terrace (fig. 2-2). Stratigraphic units and associated soils exposed in two trenches excavated across the scarp indicate a minimum of two faulting events in about the last 300 ka, with about one meter of displacement per event. The most-recent event occurred before 10 ka to 20 ka based on the soil developed in unfaulted eolian sand that overlies the fault. A buried soil

Figure 2-1. View of the Hell Canyon segment looking north from Lime Creek (plate 1). The white beds in foreground are Tertiary sediments (Ts); mountains on left are Precambrian granite. The Verde River and the upper part of Horseshoe Reservoir are visible in the background.

Figure 2-2. View looking east-southeast of the arcuate scarp on terrace t6 produced by the Horseshoe Reservoir fault segment (plate 1). The scarp is well delineated by cocklebur plants, which prefer the downthrown side of the fault. The trenches excavated across the Horseshoe Reservoir segment are visible on the terrace. Trench 1 is in the middle ground; Trench 2 is in the foreground. The fault continues across the slope in the background, where a resistant basalt bed on the right is juxtaposed against erodible Tertiary sediments on the left. Left abutment of Horseshoe Dam is at far right.

developed in a unit that postdates the penultimate faulting event suggests that considerable time (50 000 to 100 000 years) elapsed between the earlier event and the most-recent faulting event. Although the uncertainties in the age estimates and lack of absolute age control make estimating the recurrence of surface-faulting events on the Horseshoe fault very difficult, the trench data appear to suggest that recurrence intervals of 100 000 years are possible. This would support the hypothesis, based on limited regional data, that active Quaternary faults in central and southern Arizona are generally characterized by recurrence intervals of 100 000 years or more.

2.2. Sugarloaf Fault

Geologic evidence noted during the seismotectonic investigation for Stewart Mountain Dam (Anderson and others, 1986) indicates that the Sugarloaf fault has experienced recurrent Quaternary activity. This 10-km-long, slightly arcuate, northwest-trending normal fault bounds the west side of a small unnamed late Cenozoic basin. The most-recent surface-faulting event ruptured the northern 4 km of the fault and produced 0.7 m of apparent vertical displacement. Scarp profiles suggest that this event occurred during the Holocene (Anderson and others, 1986). A detailed trenching investigation of the Sugarloaf fault has not been conducted.

2.3. Other Faults

Other major faults within the Transition Zone with evidence of Quaternary activity include the Chino, Verde, and Safford faults (Soule, 1978; Menges and Pearthree, 1983; Machette and others, 1986). Numerous additional faults and several late Cenozoic basins also have been suggested as possible sites for Quaternary activity (Fugro, 1981a; 1981b; Menges and Pearthree, 1983; Pearthree and Scarborough, 1984; Scarborough and Pearthree, 1987); however, these specific faults or basins either have been determined not to be Quaternary or they are at sufficiently great distances from the subject dams that they are not significant to this study. Several suspected faults and lineaments identified during previous investigations are within 15 km of Bartlett Dam (the approximate distance between the dam and the Sugarloaf and Horseshoe faults) but these features are not considered to be potential seismic sources (section 6.2).

3. HORSESHOE FAULT

Based primarily on the abrupt change in strike of the fault, the Horseshoe fault is subdivided into two segments: a north-striking segment along the range front west of Horseshoe Reservoir and a west-northwest-striking segment crossing the reservoir immediately upstream of Horseshoe Dam. The two segments have been informally named the Hell Canyon and Horseshoe Reservoir segments, respectively. The two fault segments, and the detailed studies of them, are discussed in the following sections.

3.1. Hell Canyon Segment

The Hell Canyon segment is the name given to the 11-to-12-km-long segment of the Horseshoe fault that extends from south of Lime Creek almost due north to near Tangle Creek (plate 1). The fault marks the western margin of a small, relatively unstudied basin, herein called the Horseshoe basin, that is the result of the late Tertiary Basin and Range disturbance (Shafiqullah and others, 1980). The fault separates Precambrian granitic rocks on the west from Tertiary basin-fill deposits on the east. The fault trace is marked for the most part by strong topographic, tonal, and vegetation lineaments; a very abrupt bedrock/basin-fill contact; and possible scarps on alluvial fans. The Hell Canyon portion of the fault and the above features were noted by earlier investigators (Ertec, 1981b; Menges and Pearthree, 1983; Pearthree and Scarborough, 1984).

The fault was originally identified by Stone and Webster (1979) as a potentially active fault. It was later mapped in a study for Reclamation by Ertec (1981b), who named it the Tangle Peak fault for a small peak about 10 km north of Horseshoe Dam (fig. 1-1; plate 1). Quaternary or "neotectonic" activity on this fault was also noted in subsequent studies by Menges and Pearthree (1983) and Pearthree and Scarborough (1984). Menges and Pearthree (1983) referred to the structure as the Horseshoe Dam fault, whereas Pearthree and Scarborough (1984) cited the feature as the Horseshoe fault. Geologic investigations carried out as part of our study identified several areas along the trace of the fault where scarps are present on late(?) Quaternary alluvial fans (plate 1).

3.1.1. Fault scarps

Fault scarps are preserved discontinuously along about 9 km of the Hell Canyon segment and occur in two sets with different trends. One set contains north-trending scarps that cross alluvial fans at the range front and that are aligned with the faulted contact between Tertiary basin fill and Precambrian granitic rocks (plate 1; fig. 3-1). The other set contains northwest-trending scarps that are preserved on alluvial fans about 1 km east of the range front and 2 km north of Lime Creek (plate 1).

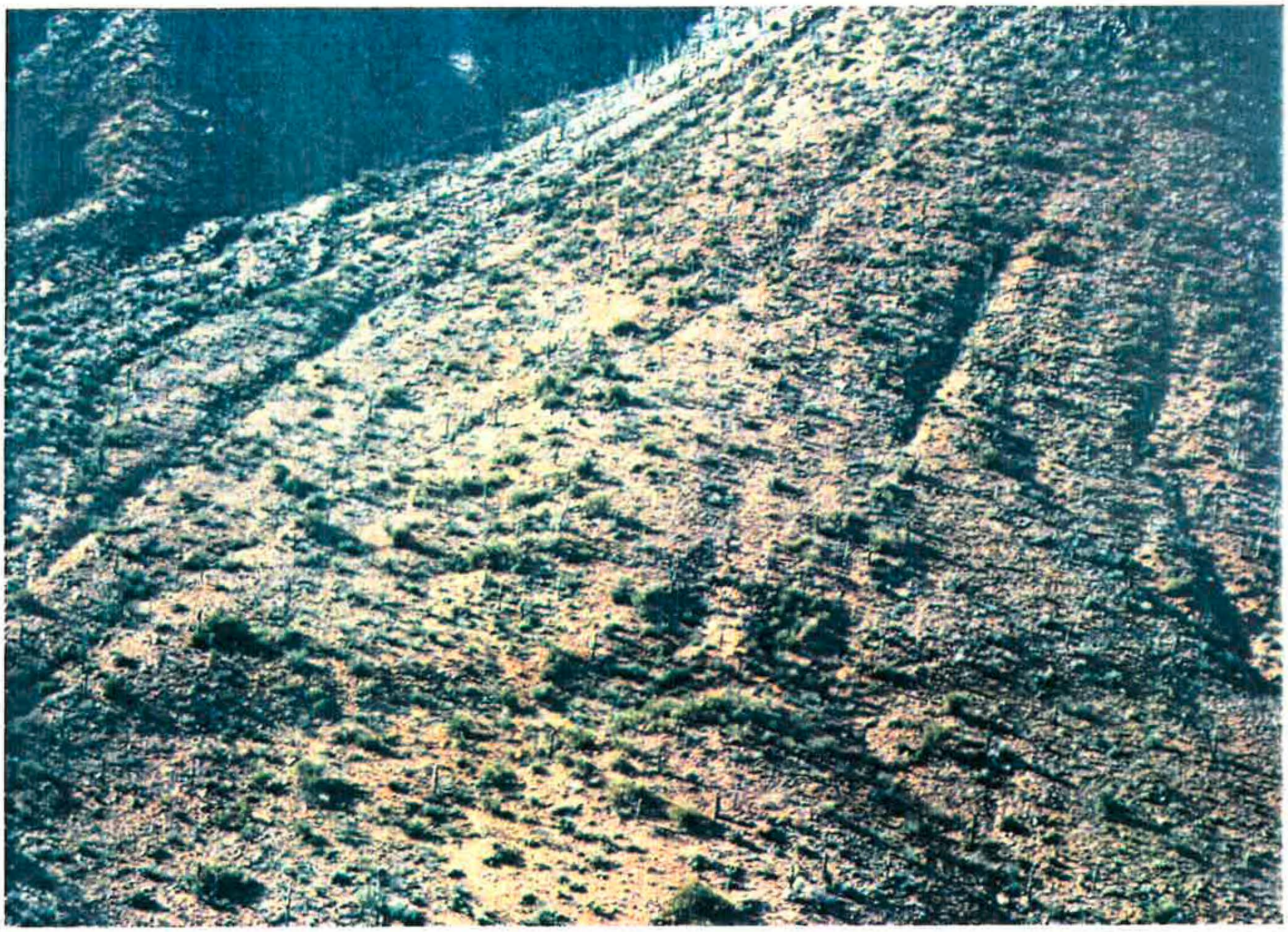


Figure 3-1. East-facing fault scarp at locality P3 along the Hell canyon segment (plate 1). At this locality between Lime Creek and Hell Canyon, the scarp height is 3.5 m, the vertical surface displacement is 2 m, and the maximum scarp angle is 27° (appendix A). The alluvial fan (f5) slopes about 10° to the east. View is to the west.

Topographic profiles (appendix A) indicate that the north-trending fault scarps have vertical displacements of 2 to 5 m, heights of 3.5 to 7.5 m, and maximum slope angles of 11° to 27°. Because of the range in scarp heights, their maximum heights, and bevels on the topographic profiles, the north-trending scarps are suspected of having formed during multiple surface ruptures. In contrast, the northwest-trending fault scarps have vertical surface displacements of 2 to 3 m, heights of 2 to 4.5 m, and maximum slope angles of 10° to 16°. Two of the three profiles measured across the northwest-trending scarps may exhibit facets, but these facets are not as obvious as those on the profiles across the north-trending scarps.

The ages of the scarps are not well constrained. Stratigraphic data that would allow an exact evaluation of the number of faulting events or their ages are not presently available. All scarps are on f5 alluvial fans (plate 1). Although this group of fans includes fans of several ages, these fans were not delineated during this study. Scarp morphology (e.g. scarp heights and maximum scarp-slope angles) is variable, but a majority of the scarps (5 of 8) have characteristics similar to those along the Lake Bonneville shoreline scarps (maximum angles of 12 to 24°) considered to have formed between 14 ka and 15 ka (Scott and others, 1983). In contrast, maximum angles of the scarps on the Hell Canyon segment (10-27°) are higher then those of scarps of similar height along the Santa Rita fault (5-27°) with an estimated age for its youngest rupture of 60 ka to 100 ka (Pearthree and Calvo, 1987). These comparisons suggest that the age of the youngest rupture on the Hell Canyon segment is probably close to 15 ka. Ages for the older surface ruptures could not be estimated. The small number of data points in our study, along with problems comparing scarp morphology and scarp degradation rates between regions with different geologic, climatic, and geomorphic conditions, limits our ability to estimate accurate ages for ruptures on the Hell Canyon segment.

3.2. Horseshoe Reservoir Segment

This previously unidentified segment of the Horseshoe fault extends in an east-southeast direction for about 9 to 10 km from just north of Lime Creek, across the Horseshoe basin immediately upstream of Horseshoe Dam, to an area about 2 km south of Davenport Wash (fig. 1-1; plate 1). The Horseshoe Reservoir segment is a high-angle, north-dipping fault that separates south- to southwest-dipping basalt, basaltic breccias, and tuffaceous sandstone on the south from nearly horizontal mudstones on the north. Where the fault trace crosses a terrace on the east side of the Verde River, a subdued north-facing scarp is present (fig. 2-2). The scarp is only visible at low reservoir water levels. Two trenches excavated across the suspected fault trace confirmed that the feature is indeed a fault scarp and revealed evidence of at least two surface-faulting events during the last 300 ka, with the most-recent event occurring prior to about 10 ka to 20 ka.

3.2.1. Geology of the Horseshoe Reservoir segment

Geomorphically, there is little to suggest that the Horseshoe Reservoir segment is a recurrently active late Quaternary fault. The fault, instead of bounding a major range front, trends diagonally across Horseshoe basin. In addition, the fault is oriented obliquely to the inferred extension direction for the region (Thompson and Zoback, 1979). It is unlikely that the fault would be identified as a potential late Quaternary fault were it not for the scarp on the Verde River terrace.

At high reservoir levels (maximum water surface elevation 2026 ft.), the Horseshoe Reservoir segment of the Horseshoe fault is an inconspicuous topographic lineament trending west-northwest across the axial part of the basin. Initial inspection of the lineament suggested that it was the result of differential erosion between resistant volcanic rocks to the south and less resistant mudstone to the north. Closer inspection of this lineament where it crosses Davenport Wash revealed a steeply dipping fault contact between southwest-dipping volcanic breccia and nearly flat-lying mudstone. Davenport Wash is the only known location outside of Horseshoe Reservoir where geologic relationships are well exposed and where a fault origin for the lineament is reasonably clear.

Northwest of Davenport Wash, a break-in-slope is present along the north side of the unnamed ridge between the wash and Horseshoe Dam. At first, the break-in-slope appears to be due to differential erosion between southwest-dipping basalt and nearly flat-lying mudstones. However, on trend with the fault exposed in Davenport Wash and with the topographic break-in-slope on the ridge are several vegetation lineaments and a distinct but subdued, arcuate, north-facing, topographic scarp that trends across a terrace of the Verde River immediately north of Horseshoe Dam (terrace t6, plate 1). These features are clearly visible on pre-construction aerial photographs taken in 1934, on U.S. Forest Service aerial photographs taken in 1979 (during low reservoir levels), and on various Reclamation oblique aerial photographs taken during times of low reservoir levels. The lineaments and north-facing scarp suggest possible recent fault activity.

Field inspection of the t6 terrace suggested that the terrace deposit could be faulted. The vegetation lineaments observed on the aerial photographs to cross the terrace form a complex zone that is up to 200 m wide and has the appearance of a graben. No subsurface exposures are present in this area, and deposition of eolian sand (dunes?) and reservoir silt, along with extensive gullying, has greatly modified the terrace surface. However, along the east margin of the terrace, at the location of the topographic scarp, an apparent displacement of 1.9 - 2.1 m in the terrace gravel was measured. The exposures are not very good, and the possibility existed that the apparent disruption of the gravel was due to depositional processes rather than faulting. Still, the limited evidence strongly suggested that the terrace is faulted.

Areas on the west side of Horseshoe Reservoir, along the projection of the suspected fault, were also inspected for evidence of recent faulting. A shear zone within volcanic breccia(?) is present above the area used as a boat ramp and beneath a t5 terrace (plate 1). Also, a fault relationship appears to exist between basaltic rocks and mudstone exposed on the north side of this terrace in the Lime Creek wash. Between these two fault exposures is a scarp between the terrace surface to the northeast and basaltic bedrock (mapped as Ts on plate 1) to the southwest. Visual inspection of the terrace surface suggests that the terrace could be rotated (sloped) toward the south, back toward the fault. No exposures were found from which it could be determined if the terrace is definitely faulted.

North of Lime Creek, a lineament that appears to correspond to the trace of the fault is present within basin-fill deposits (Ts). The lineament appears to separate different basin-fill units and can be traced to within 500 m of the range-bounding (Hell Canyon segment) fault (plate 1). Only small terrace remnants are preserved on the north side of Lime Creek along the southeastern projection of the lineament (plate 1). However, at one location, a slight topographic rise is present at the edge of one of the remnants. This feature could be fault related, but its location adjacent to a drainage raises some doubts regarding the exact origin of the feature. No obvious fault or shear zone was found in the underlying basin-fill deposits, but exposures are not good.

In summary, based on aerial photograph interpretation, aerial overflights, and ground reconnaissance geologic investigations, a fault was identified within basin-fill deposits. This fault extends from near the range front north of Lime Creek to at least 2 km southeast of Davenport Wash (plate 1). Vegetation lineaments, a subdued north-facing scarp, and possible faulted gravel on the terrace north of Horseshoe Dam indicate that the fault may have experienced late Quaternary activity. Trenching was considered necessary in order to verify this interpretation.

3.2.2. Trenches

Two bulldozer trenches were excavated across the north-facing scarp on the t6 terrace about 300 m upstream of Horseshoe Dam (plate 1). The surface of this fluvial terrace is about 18 m above the elevation of the Verde River's floodplain before the filling of Horseshoe Reservoir. This terrace is below the high-water level for the reservoir, so that the terrace surface is largely unvegetated and thinly (<15 cm) covered by reservoir silt and clay. The terrace surface is very irregular. Channels heading in two unnamed drainages to the east and on a slightly higher terrace surface to the north cut the terrace surface. Some of the irregular topography may also be created by eolian sand (dunes) deposited on the fluvial gravel. On the basis of its height above the Verde River and the soil developed in t6 alluvium at locality SP-1 downstream of Horseshoe Dam, the age of the terrace containing the scarp is estimated to be >250 ka, possibly 300 ka to 400 ka (section 5.3).

3.2.2.1. Trench 1

Trench 1, about 60 m long and 3.5 m deep, was excavated across the scarp at the highest part of the t6 terrace (plate 1). Trench 1 was initially oriented N5°E; however, the trench intersected the fault zone at an oblique angle near its change from an east-west orientation to a more southerly orientation. Consequently, the lower (northern) half of the trench, including the fault zone, was reoriented to N30°W to perpendicularly intersect the fault zone that was found to have a strike of about N60°E. The alluvial, colluvial, and eolian units exposed in the trench (plate 2) are interpreted as recording at least two surface-faulting events since deposition of the t6 terrace gravel about 300 000 to 400 000 years ago. The exact timing of the faulting events is not well constrained. The most-recent event occurred some time before about 10 ka to 20 ka, the estimated age of eolian sand that overlies the fault. A period of at least 50 ka to 100 ka probably elapsed between the two faulting events. This section and the accompanying figure 3-2 summarize the stratigraphy and faulting history inferred from Trench 1.

Stratigraphy

Stratigraphic units exposed in Trench 1 consist of alluvial, colluvial, and eolian deposits (plate 2). Gravelly alluvium associated with the t6 terrace (Unit 1) contains 50 to 60 percent rounded to well-rounded boulders and cobbles. The alluvium was probably deposited by the Verde River but could also have been deposited, at least in part, by tributaries from the east (plate 1). The fault zone in Trench 1 is readily visible as a zone of rotated and aligned cobbles and pebbles within the gravelly alluvium. The fault zone strikes N60°E and is about 3.5 m wide. Individual shear zones, expressed as aligned cobbles and pebbles, dip about 70°NW (fig. 3-3).

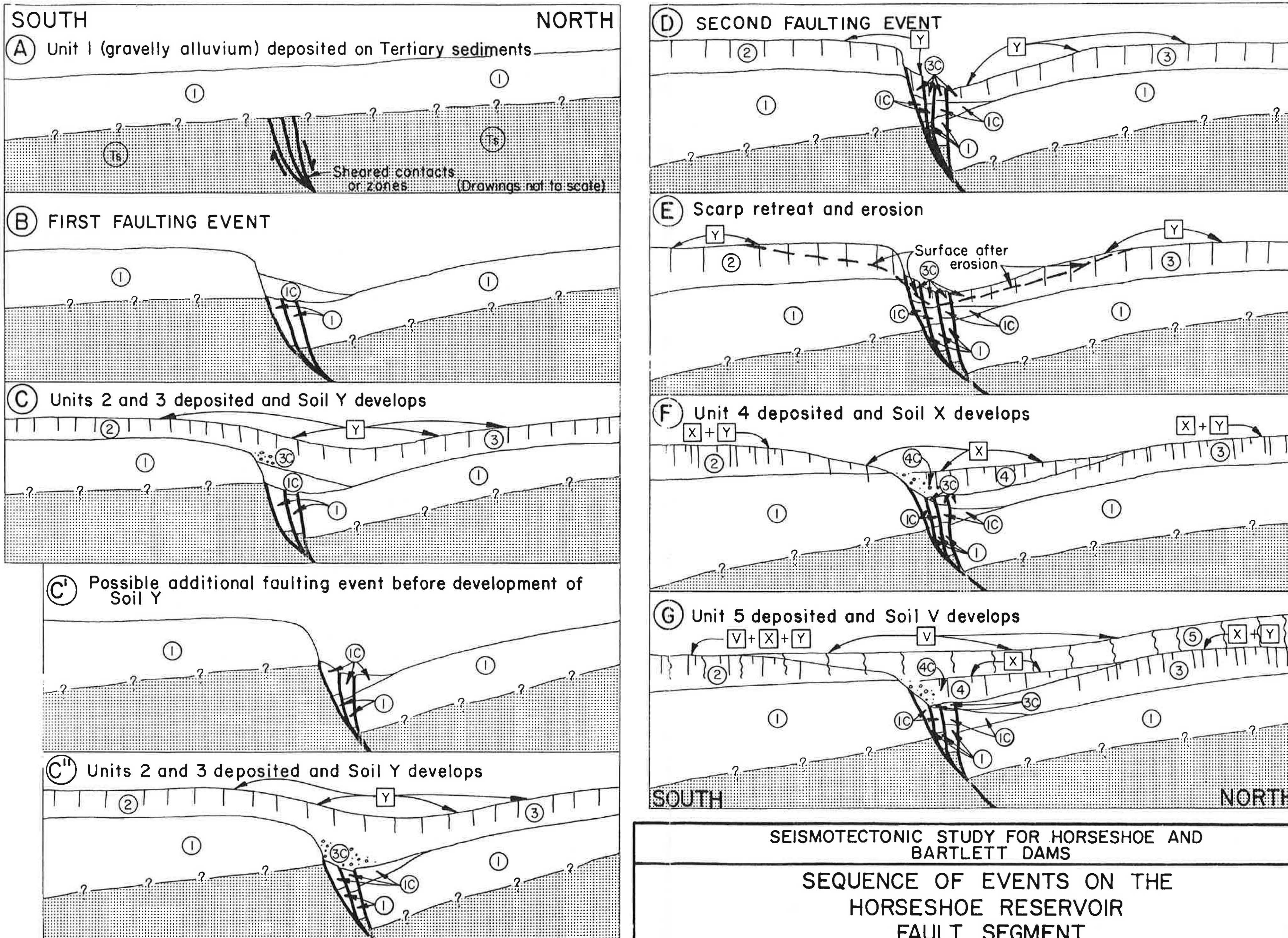
Unit 1 is overlain by three deposits (Units 2/3, 4, and 5) that are separated by buried soils. These three units, although chiefly eolian sand, include alluvium and colluvium. Unit 3 and Unit 4 near the fault zone include cobbles and pebbles that are interpreted to be colluvium shed from the exposed scarp (plate 2). Units 4 and 5 are eolian sand deposits that would be indistinguishable except for the weakly developed soil in Unit 4.

Units 2 and 3 are tentatively correlated and are sometimes referred to as one unit, Unit 2/3. Unit 2, delineated between stations 0 and 21, consists of slope colluvium and eolian sand. Unit 3 between stations 36 and 60 includes lenses of pebbles and cobbles that indicate that Unit 3 is, in part, alluvium (plate 2). Water moving downslope toward the south probably deposited these pebbles and cobbles while sand was blowing across the scarp. The upper part of Unit 3 between stations 36 and 60 also includes blocks of sand cemented by carbonate. These blocks were most likely eroded from

The following sequence of events is based on our interpretation of exposures in Trenches 1 and 2. Evidence for two ruptures during the last 300 000 years is clear; however, a third rupture could also be postulated. If this additional ruptu occurred, events **C′** and **C″** would replace event **C** in the sequence. Letters in circles indicate the events. Numbers in circles indicate depositional units exposed in Trench 1 (plate 2). Letters in boxes indicate soils described in Trench 1 (plate 2; appendix B).

Event	Description	Estimated time of event[1)] (ka)	Estimat time interva (10^3 yr
A	Deposition of gravelly alluvium (Unit 1) on top of Tertiary sedimentary rocks by the Verde River and(or) its tributaries. Initial slope of the alluvium (now terrace t6) was probably to the south.	300-400 (>250)	
B	**FIRST FAULTING EVENT:** North-facing scarp forms during rupture along the fault zone between stations 30 and 33 in Trench 1. Unit 1 is displaced about 0.5 m. Colluvium (Unit 1C) is deposited adjacent to the scarp from material eroded from the free face. Unit 1 on the downthrown side of the fault is rotated (backtilted) into the fault zone. Because Unit 1 lacks evidence for soil development, this rupture may have occurred shortly after Unit 1 was deposited. Alternately, a soil may have formed in Unit 1 that was eroded before this first rupture.	200-300 (60-300)	
C	Unit 3 (chiefly eolian sand) is deposited in the depression created by backtilting of Unit 1. Eolian sand mixed with slope colluvium (Unit 2) is deposited on the upthrown side of the fault at the same time that Unit 3 is deposited. Near the fault zone, pebbles and cobbles shed from the remaining free face are incorporated into the eolian sand (Unit 3C).	100-200 (60-250)	
	FORMATION OF SOIL Y: Soil Y develops in Units 2 and 3. The time over which this soil develops marks an interval lacking fault displacements or marked erosion and deposition on the terrace surface. The soil contains a strongly developed Bt horizon.		50-100
	Alternately, evidence in Trenches 1 and 2 could be interpreted such that an additional rupture occurred before Soil Y begins to develop:		
	C′ An additional event displaces Unit 1 and Unit 1C.		
	C″ Units 2 and 3 are deposited across the scarp. Near the fault zone, pebbles and cobbles shed from the free face are incorporated into Unit 3 (Unit 3C).		
D	**SECOND FAULTING EVENT:** Units 1, 1C, 3, and 3C are displaced about 1 m. Unit 3, as well as Unit 1, is backtilted into the fault zone.	10-50 (10-150)	
E	Retreat of the free face formed during the second faulting event. A stream flowing parallel to the scarp most likely erodes part of Unit 3, including Soil Y near the fault zone (plate 2), and colluvium shed from the free face.		
F	Eolian sand (Unit 4) is deposited in the depression created by backtilting of Units 1 and 3 and by erosion of these older units. Near the fault zone, pebbles and small cobbles erode from the remaining free face and are incorporated into Unit 4 (Unit 4C).		
	FORMATION OF SOIL X: Soil X develops in Unit 4, during a pause in deposition of eolian sand. This weakly developed soil is expressed by slightly harder consistence and slightly better structure than in the overlying Unit 5. Soils continue to developed in unburied portions of Units 2 and 3 away from the fault zone (Soil X+Y).		1-3?
G	Deposition of Unit 5 (chiefly eolian sand) against and across the scarp.	10-50 (10-150)	
	FORMATION OF SOIL V: Soil develops in Unit 5 after deposition ceases. This relatively weak soil is expressed as a leaching of carbonate to a depth of 22 to 37 cm and an accumulation of carbonate up to stage I+ morphology (appendix B). Soil continues to develop in Unit 2 where Unit 5 is not deposited (Soil V+X+Y).		10-20
	Flooding of the terrace surface following the completion of Horseshoe Dam in 1946. Silt and clay, Unit 7 (not shown here), is deposited in the reservoir (plates 2 and 3).		

1) Numbers on the first line show our best estimate of the ages. The numbers in parenthesis show the possible range in age based on the stratigraphy exposed in Trench 1.



SEISMOTECTONIC STUDY FOR HORSESHOE AND BARTLETT DAMS

SEQUENCE OF EVENTS ON THE HORSESHOE RESERVOIR FAULT SEGMENT

FIGURE 3 - 2

Figure 3-3. The Horseshoe Reservoir segment exposed in Trench 1 between stations 29 and 34 (plate 2). Note the rotated clasts that delineate the fault zone within the gravelly alluvium (Unit 1). Eolian and alluvial sand (Units 3, 4, and 5) overlie the gravelly alluvium. Pebbles are cobbles incorporated into the sandy units near the fault zone are interpreted as colluvium shed from the fault scarp.

a soil developed in a terrace older than the t6 terrace and transported by water to their present position when the upper part of Unit 3 was at the ground surface. Unit 2, on the upthrown side of the fault, contains blocks of cemented sand similar to those in Unit 3. The two units are tentatively correlated based on this similarity and on their similar stratigraphic positions overlying the eroded surface of Unit 1 and underlying Unit 5.

Soil development

Soils developed on four units exposed in or related to stratigraphic units in Trench 1 are important to interpreting the history of the Horseshoe Reservoir fault segment. The soils and their related units are, from oldest to youngest, Soil Z developed in the gravelly alluvium of the t6 terrace, Soil Y developed in Unit 3, Soil X developed in Unit 4, and Soil V developed in Unit 5 (plate 1; appendix B). All of these units were exposed in Trench 1. Because the t6 terrace deposit exposed in the trench (Unit 1) was probably buried shortly after its deposition, Soil Z was described on a correlative t6 terrace 15 m above the Verde River about 3 km downstream of Horseshoe Dam (locality SP-1, plate 1).

Soil Z, developed in the gravelly alluvium of the t6 terrace, has a clayey Bt horizon that is greater than 1 m thick, is very red, and has readily visible clay films (table 3-1; appendix B). Carbonate has been leached to a depth of greater than 155 cm. Because the gravelly alluvium of the t6 terrace has been buried and eroded near the fault (Unit 1), Soil Z most likely never developed on the t6 terrace at Trench 1 to the degree that it has on the stable surface of the t6 terrace remnant downstream of Horseshoe Dam (locality SP-1).

Soils Y, X, and V, developed in eolian, colluvial, and alluvial deposits, are not as well developed as Soil Z. Soil Y has a red Bt horizon, which is about 50 cm thick and contains about 10% more clay than the unweathered eolian sand (table 3-1; appendix B). This soil also has a Bk horizon (carbonate accumulation) with weak stage II carbonate morphology. Soil X is the weakest of the these soils. It lacks a Bw or Bt horizon, but a slightly stiffer consistence and a slightly better structure, perhaps the result of a slightly higher carbonate content, suggest a weakly developed buried soil at the base of the overlying Unit 5. Because Unit 4 and Unit 5 are chiefly eolian sand, the surface could have been intermittently active and stable for some time before the surface stabilized and Soil V began to develop. Soil V has a relatively thin (15-18 cm) Bw (cambic) horizon that is expressed as a color change where carbonate has been leached from the eolian sand. The carbonate accumulation is relatively weak (strong stage I) and is expressed chiefly as a few filaments and continuous to patchy coats on the bottoms and sides of pebbles within the unit. The development of Soil V does not appear to have been affected by submergence under Horseshoe Reservoir.

Table 3-1. Properties of soils described in Trench 1 and on Terrace t6[1]

Soil[2]	Time interval represented (10^3 yr)	Unit[3]	Parent material	Total profile thickness (cm)	Argillic/cambic horizon[4]: Reddest, brightest color	Max. clay content (%)	Strongest clay texture[5]	Clay increase from P.M.[6]	Max. clay films[7]	Horizon thickness (cm)	Carbonate horizon: Max. $CaCO_3$ content (%)	Max. stage $CaCO_3$ morph.[8]	$CaCO_3$ increase from P.M.[9]	Horizon thickness (cm)	Depth to $CaCO_3$ (cm)	Profile Development Index[10]
Soil V	>10-20	Unit 5	Eolian sand	99-185	5YR 5/4	13	SL	2	0	15-18	5-8	I+	3-6	23-123 ($\bar{x}$=84)	15-32 ($\bar{x}$=19)	11.6
Soil X	1-3?	Unit 4	Eolian sand	55						0	5	I	3	55	-11)	6.1
Soil V+X+Y	160-220	Unit 2	Eolian sand	78	5YR 5/4	22	SCL	11	0	55	10	I?	8	33	-11)	20.9
Soil Y	60-100	Unit 3	Eolian sand	126	5YR 4/6-4/8	22	SCL	11	v1n pf	50	14	II−	12	76	-11)	24.2
Soil Z	>250; 300-400	Terrace t6	Gravelly alluvium	155	2.5YR 4/6	23	L+	21	3mk-k pf	>135	0				>155	39.2

1) Properties shown have been summarized from detailed descriptions given in appendix B.
2) Soil designations are the same as those shown on figure 3-2 and on plate 2.
3) Unit numbers are from Trench 1 (fig. 3-2, plate 2). Terrace designation is from plate 1.
4) Soil X has no cambic or argillic horizon. Soil V has a cambic (Bw) horizon; other soils have clay-rich (Bt) horizons.
5) Abbreviations are L+=Clay-rich loam, SL=sandy loam, and SCL=sandy clay loam.
6) Clay increase from the parent material or C horizons. Clay content of eolian sand parent material is estimated to be 11%; clay content of gravelly alluvium parent material is estimated to be 2% (appendix B).
7) Abbreviations are v1n pf=very few, thin clay films; 3mk-k pf=many moderately thick to thick clay films (table B-3, appendix B; Soil Survey Staff, 1975; Birkeland, 1984).
8) Morphologic stages of carbonate accumulation are from Gile and others (1966) and Birkeland (1984).
9) Carbonate increase from the parent material or C horizons. Carbonate content of eolian sand and gravelly alluvium parent materials is estimated to be 2% (appendix B).
10) Index estimated using the methods described in Harden (1982) and in Harden and Taylor (1983) (appendix B).
11) These soils are buried, so that carbonate from overlying soils has been superimposed on these lower soils. Carbonate properties shown are for carbonate accumulations thought to be related to the overlying Bw or Bt horizon for that soil.

At the southern end of Trench 1, south of station 8, Unit 2 is not buried by Unit 5. The soil developed in Unit 2 at this location displays a 55-cm-thick Bt horizon with sandy clay loam texture and a maximum clay content of 22% (table 3-1). The soil also contains carbonate accumulation with as much as stage I morphology. This soil represents the time interval during which Soil Y (in Unit 3), Soil X (in Unit 4), and Soil V (in Unit 5) developed and is designated Soil V+X+Y. Soil Y (in Unit 3) ceased to develop after Unit 3 was buried by Unit 4 or Unit 5. Because Unit 2 was not buried and its soil has continued to develop, Soil V+X+Y is slightly better developed than Soil Y, although we tentatively correlate Unit 2 with Unit 3.

Soil Y (in Unit 3) was not buried simultaneously everywhere in the vicinity of the fault. Near the fault zone, Soil Y ceased to develop after Unit 4 was deposited. Away from the fault zone, Unit 3 was not buried by Unit 4, and Soil Y continued to develop as Soil X was developing in Unit 4. However, because the time over which Soil X developed was relatively short, properties of Soil Y and those of Soil X+Y cannot be differentiated. Thus, these two soils are both designated Soil Y.

Estimated ages

Ages for the t6 terrace and for the units exposed in Trench 1 are estimated based on the degree of soil development in these deposits compared to that in deposits elsewhere in Arizona and in New Mexico (Gile and others. 1981; Pearthree and Calvo, 1987). Climatic conditions at Horseshoe Reservoir, with an average annual precipitation (AAP) of 30 to 37 cm and a mean annual temperature (MAT) of 21^{o}C (appendix B), are similar to those in the Tonto basin (AAP of 36 cm; MAT of 20^{o}; Anderson and others, 1987) and along the Santa Rita Mountains (AAP of 31 to 34 cm; Pearthree and Calvo, 1987). Precipitation in all three areas peaks during summer and winter months (appendix B).

Soil Z. Soil Z is discussed in section 5.3.

Soil Y and Unit 3. - Soil Y, developed on Unit 3 (plate 2), is not as well developed as Soil Z on the t6 terrace (section 5.3) suggesting that the time interval during which Soil Y formed was shorter than the time interval during which Soil Z formed (300 000 to 400 000 years). In addition, the rate of soil formation in Unit 3, an eolian sand, may have been faster than that in Unit 1, a coarser gravelly alluvium. On the basis of soil development, we infer that the time interval represented by Soil Y is about 50 000 to 100 000 years. Considering the estimated age of the underlying gravelly alluvium of the t6 terrace (300 ka - 400 ka) and the inferred minimum age of the overlying Unit 5 (10 ka - 20 ka), Unit 3 could have been deposited any time between about 60 ka and 250 ka. Because ages based on soil development provide only a minimum age for the unit in which the soil is developed and because periods of erosion are indicated both before and after deposition of Unit 3 (plate 2), we estimate that Unit 3 was most likely deposited between about 100 ka and 200 ka.

Clay films of Soil Y are less developed than those of soils in the Group II deposits in the Tonto basin (Anderson and others, 1987). The Bt and Bk horizons of Soil Y are also thinner. These differences in development suggest that Soil Y formed in less than 200 000 years, the estimated minimum age of the Group II deposits in the Tonto basin (tables 3-1 and 5-1; appendix B). Although the Bt horizon of Soil Y has a higher clay content than Bt horizons developed in the Group III deposits in the Tonto basin, clay films and horizon thicknesses are similar (tables 3-1 and 5-1; appendix B). In addition, the color and maximum clay content in the Bt horizon and the carbonate content of the Bk horizon of Soil Y are similar to those of the soils in Q2c deposits along the Santa Rita Mountains (Pearthree and Calvo, 1987; tables 3-1 and 5-1). The estimated age of the Group III deposits is between 40 ka and 200 ka; the estimated age of the Q2c deposits is between 75 ka and 130 ka (Anderson and others, 1987; Pearthree and Calvo, 1987). These comparisons suggest that Soil Y developed over an interval of about 50 000 to 100 000 years.

This estimate takes into consideration that the rate of soil development in the eolian sand Unit 3 has probably been faster than the rate of soil development in the gravelly alluvium in the Tonto basin or along the Santa Rita Mountains. However, the development of Soil Y suggests only the time interval when the surface of Unit 3 was stable. Because Soil Y and Unit 3 are buried by younger eolian sand, the time interval over which Soil Y formed does not directly indicate the time when Unit 3 was deposited. Undulating contacts with the underlying Unit 1 and the overlying Unit 5 indicate periods of erosion both before and after deposition of Unit 3. This suggests that some time elapsed between deposition of Unit 3 and the units underlying and overlying it.

Soil X and Unit 4. - Soil X is weakly developed. It is expressed by a slightly stiffer consistency and a slightly better developed structure than at the base of Soil V in Unit 5. These properties are probably the result of a slightly higher carbonate content in Soil X than in the overlying Unit 5. Soil X lacks a Bw or Bt horizon. A comparison of Soil X with Soil Y and Soil V, also developed in chiefly eolian parent material, suggests that the time interval over with Soil X developed was very brief, perhaps 1000 to 3000 years.

Soil V and Unit 5. - A comparison of Soil V developed in Unit 5 (plate 2) with other soils exposed in Trench 1 and with soils developed in the Tonto basin (Anderson and others, 1987), along the Santa Rita Mountains (Pearthree and Calvo, 1987), and in the Desert Project area of southern New Mexico (Gile and others, 1981) suggests that the surface of Unit 5 has probably been stable over the last 10 000 to 20 000 years. The time when Unit 5 began to be deposited is not well constrained. Using the estimated age for the underlying Unit 3 (100 ka - 200 ka) and the estimated time interval represented by Soil Y developed in Unit 3 (50 ka - 100 ka) and by Soil X developed in Unit 4 (1 ka - 3 ka), we infer that deposition of Unit 5 could have begun any time between about 10 ka and about 150 ka. However, a faulting event between the deposition of Units 3 and 5 and erosion of the upper part of Unit 3 before deposition of Unit 5 suggest that some time elapsed after Soil Y had ceased to form and before deposition of Unit 5. Deposition of Unit 5 could have begun about 50 ka.

The color and thickness of the Bw horizon in Soil V are similar to those of soils developed on Group IV deposits in the Tonto basin (tables 3-1 and 5-1; appendix B; Anderson and others, 1987). In addition, the change in color and clay content from the parent material of Soil V is similar to that of soils developed on Q2d deposits along the Santa Rita Mountains (tables 3-1 and 5-1). The estimated age for the Group IV deposits is 15 ka to 40 ka (Anderson and others, 1987); the estimated age for the Q2d deposits is 8 ka to 20 ka (Pearthree and Calvo, 1987). Furthermore, the strong stage I carbonate development of Soil V is similar to that of latest Pleistocene (8 ka-15 ka) soils described in the Desert Project area of New Mexico (Gile and others, 1981; appendix B).

It is possible that Unit 5 is Holocene; however, the depth of carbonate leaching, the amount of carbonate accumulated, and the color of the Bw horizon in Soil V suggest that the surface of Unit 5 has been stable since about 10 ka and 20 ka. The time when deposition of Unit 5 began is not known, but is after 150 ka, the estimated age for the time when the underlying Soil Y was buried by Unit 4. However, erosion of Soil Y indicates that some time elapsed between the time when Soil Y formed and when Unit 4 was deposited. The length of this interval is not known.

Faulting history

Stratigraphic relationships exposed in Trench 1 suggest that at least two, but possibly three, surface ruptures have occurred on the Horseshoe Reservoir segment since deposition of gravelly alluvium of the t6 terrace (fig. 3-2). Three types of stratigraphic evidence indicate multiple surface ruptures: the number of deposits of possible fault colluvium, the evidence that colluvial deposits have been displaced subsequent to their deposition, and the different amounts of backtilting indicated by contacts and beds within units.

First, possible fault colluvium is present in Units 1, 3, and 4 (Units 1C, 3C, and 4C, plate 2). Soil Y, a relatively well developed soil in Unit 3, indicates that 50 000 to 100 000 years probably elapsed between deposition of Units 3/3C and Units 4/4C. Thus, the fault rupture after which the 4C colluvium was deposited occurred separately from ruptures after which the 1C and 3C colluvial units were deposited. In contrast, evidence in Trench 1 does not clearly indicate whether or not Units 1C and 3C were deposited after the same surface rupture. No soil is preserved between these two units. The lack of soil development in the fault colluvium within Unit 1 suggests (1) that the two colluvial units are related to a single fault rupture, (2) that the time between two events was not great, or (3) that the soil in the fault colluvium of Unit 1 was eroded before the fault colluvium of Unit 3 was deposited.

Second, whereas Unit 1C has definitely been faulted by a subsequent rupture, as indicated by rotated and aligned cobbles and pebbles within the colluvium (plate 2), evidence for subsequent displacement of Unit 3C is not as clear in the chiefly eolian sand of Unit 3. Displacement of Unit 1C and, possibly, displacement of Unit 3C could have occurred during the rupture after which Unit 4C was deposited. Alternately, Unit 1C could have been displaced by the rupture after which Unit 3C was deposited, and then both Unit 1C and, possibly, Unit 3C could have been displaced during the rupture that resulted in deposition of Unit 4C. These events cannot be easily separated because the timing of clast rotation within Unit 1C cannot be determined and because specific shears in Units 1 and 1C are difficult to trace into Units 3 and 3C.

Third, at least two ruptures are indicated because Unit 1 is rotated or backtilted into the fault zone more than the overlying Unit 3 (plate 2). Although both Unit 1 and Unit 3 have apparently been eroded, especially on the downthrown side immediately adjacent to the fault, projection of the upper surfaces of both of these deposits suggests backtilting of at least 1 m for Unit 1 and backtilting of about 0.5 m for Unit 3. Furthermore, stone lines within Unit 3 between stations 40 and 46 have flatter slopes than gravel beds within Unit 1 (plate 2). This also suggests less rotation of Unit 3 into the fault as compared to that of Unit 1. If only one surface rupture had occurred, then Unit 1 and Unit 3 should be tilted approximately equal amounts into the fault.

Amount of displacement

The initial slope of the surface of the gravelly alluvium (Unit 1) is assumed to have been toward the south, the downstream direction of the Verde River. Projection of the surface of Unit 1 into the fault zone from the ends of the trench away from the fault zone indicates that Unit 1 has a stratigraphic displacement of about 1.6 m (plate 2). This is probably a minimum value because the upper part of Unit 1 appears to have been eroded. In addition, Unit 1 appears to have been dragged upward into the fault zone (plate 2). Stratigraphic displacement of Unit 3 (the eolian sand overlying Unit 1) is about 1.1 m. This displacement was determined by projecting the surfaces of Units 2 and 3 (thought to be correlative units on the upthrown and downthrown sides of the fault) into the fault zone. These measurements imply that the displacement during the first surface rupture was about 0.5 m and that displacement during the second surface rupture was about 1 m.

Age of the youngest event

The age of the youngest rupture is bracketed by the estimated age of Unit 5, which overlies the fault, and by the estimated age of Unit 3, which is the youngest unit displaced by the most recent rupture. The age of Unit 5 is estimated from the soil (Soil V) developed in it. On the basis of relatively weak development, Soil V is estimated to have formed during the last 10 000 to 20 000 years. This gives a minimum age for Unit 5 because Soil V indicates the time when the surface of Unit 5 became stable. The length of time over which Unit 5 was deposited is not known. However, erosion of the upper part of Units 2 and 3 prior to deposition of Units 4 and 5, deposition of Unit 4, and development of Soil X suggest that Unit 5 was not deposited immediately following the youngest rupture; however, the length of this interval is not known. Thus, the minimum age for the youngest event is only constrained to >10 ka - 20 ka (fig. 3-2).

Using the estimated time intervals represented by soils exposed in Trench 1 and the estimated ages of the units in which these soils are developed, we infer that Unit 3 was most likely deposited between about 100 ka - 200 ka. Because the time interval represented by Soil Y, which is developed in Unit 3, is about 50 000 to 100 000 years, we estimate that the youngest rupture probably occurred after about 50 ka; however, the maximum age for the youngest event is about 150 ka (fig. 3-1).

Age of the older event(s)

The ages of the older rupture or ruptures are bracketed by the age of the gravelly alluvium of terrace t6 (300 ka - 400 ka) and by the cumulative time interval represented by all units overlying Unit 1 (60 000 to 125 000 years).

On the basis of the soil developed since deposition of the gravelly alluvium of the t6 terrace, Unit 1 is estimated to have been deposited by 300 ka to 400 ka. Because no soil is preserved in Unit 1, the time interval between deposition of Unit 1 and the oldest surface rupture recorded here is not known. The lack of soil development could indicate that the older rupture occurred shortly after Unit 1 was deposited. Alternately, a soil could have developed in Unit 1 and then been eroded. This would require that some time elapsed between the deposition of Unit 1 and the oldest rupture. We estimate that the maximum age of the older ruptures is about 300 ka (fig. 3-2).

The minimum age for the older ruptures is estimated from the combined time intervals represented by the soils formed in deposits overlying Unit 1 (Soils Y, X, and V). The cumulative time represented by these soils is about 60 000 to 125 000 years (fig. 3-2). Evidence for erosion of the upper portion of Unit 1 before deposition of Unit 3 suggests that the minimum age of the older events is greater than 60 ka to 125 ka. We estimate that the older ruptures occurred between 200 ka and 300 ka.

Time interval between events

It is clear from the previous discussion that the age estimates for the youngest rupture and for the one or two older ruptures are not well constrained. However, on the basis of the development of

Soil Y in Unit 3, we infer that the youngest rupture was separated from the older ones by an interval on the order of 50 000 to 100 000 years.

If two older ruptures are interpreted at this locality, the time interval between them can only be speculated. No soil is preserved on Unit 1C, which may suggest that the two older ruptures occurred relatively close together. Alternately, the undulating surface of Unit 1 and 1C suggests that these units, which may or may not have had a soil developed in them, were eroded before deposition of Unit 3 and that a few tens of thousand to as much as 100 000 years could separate the two older ruptures. Either scenario is possible given that the first rupture could be as old as about 200 ka to 300 ka, that the youngest rupture could be as young as about 10 ka to 20 ka, and that the interval between the older events and the youngest rupture is estimated to be 50 000 to 100 000 years.

3.2.2.2. Trench 2

Trench 2 was excavated on the t6 terrace about 120 m southwest of Trench 1 (plate 1). The trench was about 3.5 m deep and was located on the side slope of the terrace in an area where the gravelly alluvium is not covered by eolian sand. This trench was oriented N30°W, and the 17-m-long section that was mapped revealed gravelly alluvium similar to Unit 1 in Trench 1 (plate 3). In Trench 2, this alluvium is about 2 m thick and overlies Tertiary sediments consisting of siltstone, marl, and volcanic breccia (fig. 3-4; plate 3).

Because of the bouldery composition of the gravelly alluvium, the lack of fine-grained sediments, and the presence of a channel that has eroded part of the terrace surface, faulting history is more difficult to evaluate in this trench than it is in Trench 1. Displacement of a weathered zone in the upper part of the gravelly alluvium suggests that total displacement of the t6 alluvium is about 1.8 m, similar to the total displacement documented in Trench 1 (1.6 m). Evidence for more than one surface-rupturing event is not as clear in Trench 2. This section summarizes the stratigraphy and faulting history inferred from Trench 2.

Stratigraphy

Units exposed in Trench 2 consist of alluvial and colluvial deposits similar to those exposed in Trench 1 and basin-fill sediments that include siltstone, marl, and volcanic breccia. Gravelly alluvium associated with the t6 terrace (Unit 1) overlies the basin-fill sediments. Colluvium (Unit 3C) shed from the scarp is exposed near the fault zone. Colluvium (Unit 4), eroded from the slope of the t6 terrace, overlies the fault in Trench 2.