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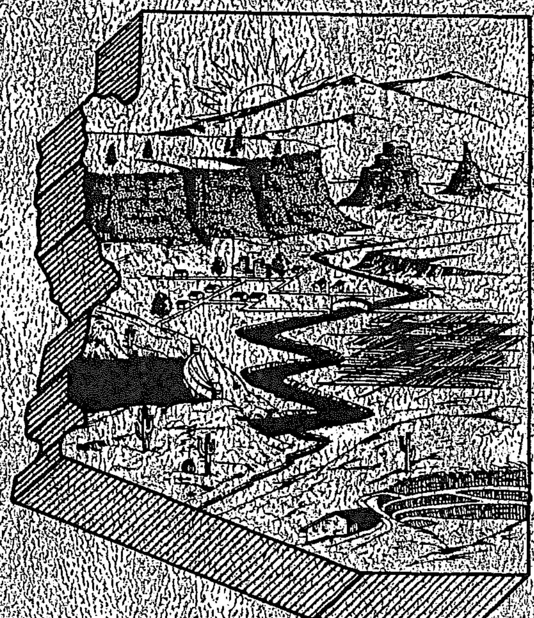

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RECONNAISSANCE ANALYSIS OF POSSIBLE QUATERNARY FAULTING IN CENTRAL ARIZONA

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INTRODUCTION

This report presents the results of a reconnaissance analysis of Quaternary faulting in central Arizona, conducted for the U. S. Bureau of Reclamation. The goal of this study has been to thoroughly delineate locations of possible Quaternary faulting in the area surrounding existing and potential dam sites in central Arizona. Analysis consisted of three phases: 1) systematic interpretation of color-infrared aerial photographs of central Arizona to locate possible Quaternary faults; 2) helicopter overflight of targets defined in part 1; and 3) brief field reconnaissance studies at sites of possible displacement of Quaternary deposits. As a result of these studies, features delineated in part 1 were classified as unlikely, possible, or probable Quaternary faults. Features considered most likely to warrant further investigation are discussed individually in this report, with recommendations for further study.

Previous Work

Potential earthquake hazard in central Arizona has been the subject of several previous reports. Historical seismicity in Arizona from about 1900 through 1980 was summarized in two reports by DuBois and others (1982a,b). Modified Mercalli intensity maps of the larger historic earthquakes in central Arizona (data from DuBois and others, 1982a; Sauck,1976; figure 1) show that the region has been subject to MM intensities of up to VI. In addition, Eberhart-Phillips and others (1981) and Sauck (1976) have published analyses of focal mechanisms of recent earthquakes in Chino Valley and the New River area, respectively.

Geologic studies of Quaternary faulting in Arizona include a state-wide reconnaissance analysis (Menges and Pearthree, 1983; Pearthree and others, 1983) and a report on Quaternary faults around several U.S. Bureau of Reclamation dam sites in central Arizona (Fugro, 1981). These studies provided a useful background from which to proceed with the present, more detailed analysis. The state-wide study of Menges and Pearthree (1983) consisted of interpretation of 1:125,000 scale, black and white aerial photographs of the entire state, compilation of previous field studies, and approximately eight weeks of field study. Three field days were spent in the area covered by this report, and several possible and demonstrable Quaternary faults were identified (figure 2). Other features were included as possible Quaternary faults based solely on photointerpretation. Possible Quaternary faults delineated in the statewide study, and Quaternary faults reported by Fugro (1981), were investigated in the present study where photo coverage allowed. If evidence suggestive of Quaternary faulting was observed, the features were further investigated in parts 2 and 3 of this study.

Seismotectonic Setting

Studies of Quaternary faulting (Menges and Pearthree, 1983; Pearthree and others, 1983) and historical seismicity (Dubois and others, 1982a,b) in Arizona have defined the general seismotectonic setting of central Arizona. Most of the region studied for this report was subjected to extensive late Tertiary normal faulting of the Basin-Range disturbance. This latest major extensional event in Arizona evidently began between 13-10 Ma in the southern Basin-Range and Transition Zone provinces, resulting in formation of most of the present structural basins in southern and central Arizona (Scarborough and Peirce, 1978; Shafiqullah and others, 1980). Landforms indicative of tectonic inactivity dominate this same region today, implying that major extension ceased in most areas during the late Miocene or Pliocene (Shafiqullah and others, 1980; Menges and McFadden, 1981). This conclusion is consistent with the rather low levels of historic seismicity and sparse evidence of late Quaternary faulting in southern and central Arizona.

The greatest concentration of possible or probable Quaternary faults in Arizona occurs from Big Chino valley and the San Francisco volcanic field northwest to the Utah border (see figure 2). Estimated average displacement rates on individual faults decrease from 0.3mm/yr. along the Hurricane fault in northwesternmost Arizona to 0.05-0.1 mm/yr. along the Big Chino fault in north-central Arizona. Quaternary faults in southern and central Arizona consistently show evidence of very long recurrence intervals, on the order of 10^5 years, and displacement rates <0.03mm/yr. (Pearthree and others, 1983). These data suggest that evidence of Quaternary faulting in the area of central Arizona studied for this report might be subtle because of low long-term displacement rates.

The largest historic earthquake in central Arizona, of magnitude 5, occurred in 1976 in Chino Valley. Portable seismograph nets operated in the Chino Valley area for 10 days each in 1978 and 1979 measured levels of microseismicity about 10 times less than the rate typical of the Intermountain seismic belt (Eberhart-Phillips and others, 1981). Other historic earthquakes in central Arizona have had Modified Mercalli intensities up to VI (DuBois and others, 1982a; see figure 1 for summary).

METHODOLOGY

Interpretation of Aerial Photography

Potential sites for field study were identified through interpretation of 1:58,000 scale color infrared aerial photographs of the region, available from the National High Altitude Photography (NHAP) program. These photographs were chosen because they provide uniform coverage of central Arizona at a scale more than twice as large as the black and white aerial photography available for an earlier reconnaissance study of Quaternary faulting in Arizona (Menges and Pearthree, 1983). Coverage is complete west of ~111° longitude (approximately the east end of Roosevelt Lake); the northern and southern limits of coverage were chosen to adequately cover the area around existing and proposed USBR dam sites in central Arizona (see figure 3 for coverage). Photograph quality is excellent, permitting substantial magnification without loss of image quality. Color IR photographs are quite sensitive to changes in vegetative density and type, which often serve to highlight topographic breaks or unusual sedimentation patterns possibly resulting from Quaternary faulting.

The aerial photographs were systematically reviewed for features that might be indicative of Quaternary faulting. In this process of defining targets for field and/or aerial observation, many features of uncertain origin were included in an effort to comprehensively examine all possible evidence of Quaternary faulting. Quaternary alluvial surfaces were examined in detail in an attempt to identify all topographic scarps cutting across them. These potential alluvial fault scarps were identified either by observable (probably >3-5 m) relief across them, or by changes in vegetation and/or surface particle size associated with them. Scarps paralleling adjacent drainages were considered likely to be risers between fluvial terraces rather than tectonic scarps, and were generally not investigated further. Linear bedrock mountain fronts and escarpments (possibly fault-generated) were closely examined for evidence that Quaternary alluvial surfaces are offset at or near the front. Other types of features that were noted include linear contacts between basin-fill sediments and bedrock, inferred to be basin-margin faults, and strong vegetation or lithologic lineaments in intrabedrock settings. These features were considered worthy of field reconnaissance if there is visible topographic relief across them.

Sedimentation patterns can also provide evidence for tectonic activity. Thick, extensive wedges of relatively young sediments occur adjacent to active fault-bounded mountain fronts (Bull, 1973). This type of sedimentation, indicative of relatively rapid uplift, was not observed in central Arizona. A different sedimentation pattern possibly indicative of young faulting was seen in several localities, including Brushy Hollow (61-78-2) and Kennedy Ranch (59-92). In these cases, streams flow through linear bedrock escarpments that face upstream, and sediments of unknown thickness have ponded upstream from the escarpment. This sedimentation may result simply from back-water effects during large flow events, due to abrupt decreases in channel width as the stream crosses the escarpment. It is possible, however, that relative uplift of the escarpment along a fault at its base has resulted in periodic ponding of sediment against the escarpment. If late Quaternary faulting has occurred, then trenching might reveal ponded sediments in fault contact with bedrock of the escarpment.

Field Procedures

Target sites identified through interpretation of the aerial photographs were subsequently investigated by ground reconnaissance studies and/or helicopter overflight. The purposes of these investigations were to 1) evaluate the likelihood that the target features are indeed Quaternary faults; 2) decide, based on this evaluation, which features may warrant further study; 3) provide recommendations for future Quaternary geologic studies of the individual features. All features labeled on figure 3, except those specifically noted, were observed during helicopter reconnaissance. Use of a helicopter for aerial reconnaissance permitted us to conduct brief ground investigations of sites where Quaternary faulting might be evidenced. More extensive ground reconnaissance evaluations were conducted on those features readily accessible by vehicle.

As field studies progressed, we decided to group the target features into three categories based on the likelihood that they represent Quaternary faulting. The highest category includes features considered demonstrable or probable Quaternary faults. Exposed fault zones associated with clear offset of Quaternary alluvial surfaces (fault scarps) are demonstrated Quaternary faults. Fault zones found in conjunction with probable offset of alluvial surfaces, or alluvial scarps unlikely to result from fluvial erosion but without exposed fault zones, comprise the probable Quaternary fault category.

Many more features were included in an intermediate category labeled "possible Quaternary faults". This category includes features possibly resulting from Quaternary faulting, but with an equal or greater likelihood that they are of non-tectonic origin. Many features in this category are demonstrable faults for which no certain evidence of displacement of Quaternary deposits was found. Others of these features are in settings where Quaternary alluvial surfaces are sparse or poorly preserved, so the potential record of Quaternary faulting would also be poor. Some of the features are intrabedrock faults associated with topographic escarpments. These features were included in this intermediate category if variable lithologic resistance to erosion was not the obvious cause of the topographic relief. Finally, alluvial scarps of likely purely fluvial origin, but with a reasonable possibility that they are fault scarps, were included in the intermediate category.

The third and lowest category is comprised of lineaments or geomorphic features for which no evidence of Quaternary faulting was discovered. This includes lineations on alluvial surfaces with no relief across them, bedrock escarpments and bedrock-alluvium contacts with no evidence of displacement of Quaternary alluvial surfaces that cross them, alluvial scarps created by stream erosion and terrace formation, and intrabedrock dikes where more resistant lithologies are responsible for scarp-like relief.

Limits of Resolution

Identification of Quaternary faults in this study depends primarily on three factors: 1) faulting must affect Quaternary alluvial surfaces; 2) evidence of faulting must be preserved; and 3) this evidence must be resolvable on the aerial photographs used for this study. Recognition of relatively small displacements of alluvial surfaces (<3-5m) depends on changes in surface texture or vegetative cover. In the absence of these changes, scarps <3-5m high are probably not generally discernable at 1:58,000 scale.

However, processes of scarp degradation tend to result in concentrations of coarse surface lag materials, which tend to highlight scarps. Vegetation changes are often associated with changes in surface particle size as well. Where this is the case, rather subtle scarps of 0.5 m height have been observed on the photographs. Helicopter overflights increased the resolution of topographic relief. Nonetheless, without vegetation change scarps <1 m high are generally not observable even during low level overflight. Low, extremely subtle scarps are detectable through ground reconnaissance studies. However, a decision to proceed with ground reconnaissance studies depended on recognition of features on aerial photographs or during helicopter overflight.

Preservation of Quaternary alluvial surfaces is critical in identifying Quaternary faults in much of central Arizona, where long-term regional base-level fall has resulted in extensive dissection of basin and bedrock areas. Within basins, the intensity of dissection and the particle-size of Quaternary deposits dictate whether well-preserved suites of terraces have formed, or ridge and ravine topography has developed with few planar surfaces preserved.

Suites of terraces of different ages provide excellent records of any Quaternary faulting post-dating the age of the oldest terrace. Terrace surfaces are relatively stable and therefore are conducive to the preservation of fault scarps. Several meter-high fault scarps are probably recognizable for 100,000-200,000 years after a displacement event on gently sloping terrace surfaces (Wallace, 1977; Pearthree and Calvo, 1982; Hanks and others, 1984). In contrast, dissected ridge and ravine terrain provides few stable surfaces to record and preserve fault scarps. The physiography of dissected areas indicates that all surfaces are undergoing relatively rapid dissection, and individual fault scarps are probably not recognizable for more than several tens of thousands of years at most. Faults in intrabedrock settings present a similar problem, i.e., absence of Quaternary alluvial surfaces. Quaternary activity on such faults would be recognizable only if it resulted in unusual sedimentation patterns or steep, linear bedrock escarpments.

The ability to recognize Quaternary faulting in central Arizona is extremely variable because of this variety of physiographic settings. Evidence of individual fault displacement events might be preserved from 10,000-20,000 yrs. to 100,000-200,000 yrs. depending on the local setting. Recognition of individual faulting events is therefore restricted to the last several hundred thousand years, and possibly much less. Higher scarps, possibly resulting from several displacement events, are preserved for longer periods because of their size (Hanks et. al., 1984). Relatively more active faults that generate high composite fault scarps are more easily identifiable, in general, and evidence of their activity is preserved for longer periods. In general, however, late Quaternary (<500-100 ka) fault activity is probably all that can be identified in central Arizona.

DISCUSSION OF INDIVIDUAL FEATURES

Carefree

The Carefree fault (63-78; Table 2, figures 3 and 4) is a sharp lineation at the contact between granitic rock and a ~0.25 km-wide zone of alluvium, within a large area of pedimented granitic rock north of the McDowell Mtns. The feature is particularly obvious where carbonate-rich white sediment is exposed on the downthrown side. Ground reconnaissance revealed 1-3 m of topographic relief between alluvium to the west and granitic rock to the east. A fault plane truncating exposed granitic rock was observed in the central portion of the feature (T5N., R5E., Sec. 3; near the left arrow in figure 4b), but the alluvium-granite contact is not exposed. Carbonate-cemented alluvium, probably part of a petrocalcic soil horizon, commonly litters scarp slopes and is occasionally found in place on the downthrown side. This material was never observed in place above the scarp, however, and some of the carbonate rubble could be eroded fault gouge. The petrocalcic horizon implies that the potentially faulted surface on the downthrown side is of substantial antiquity. At least two alluvial surfaces east of Browns Ranch (T5N., R5E., Sec. 15, NE 1/4; near figure 4a), considered to be younger based on surface morphology and absence of petrocalcic horizons, cross the trace of the fault without being displaced.

Thorough ground reconnaissance of the Carefree fault might reveal locations where the topographic scarp occurs solely in alluvium. An alluvial scarp would imply Quaternary movement, and might be amenable to morphologic fault scarp analysis. Careful geologic mapping using larger-scale aerial photographs, combined with soil description, could be used to constrain the age of most recent movement. Trenching in a favorable locality might confirm faulting of Quaternary alluvium, as well as providing information concerning recurrent fault movement.

Sugarloaf

Faulting at the base of a prominent N- to NW-trending, NE-facing bedrock escarpment near Sugarloaf Mountain (61-90, 477-82; figure 5a) apparently involves late Quaternary alluvium (Fugro, 1981; Pearthree and others, 1983). Several NE-dipping faults that juxtapose basalt and sediments are exposed in a roadcut along Arizona highway 87, and weakly consolidated sediments are faulted along the easternmost shear zone. Stream deposits of the first stream north of Arizona 87 along the Sugarloaf fault, of late Pleistocene or Holocene age, are probably faulted as well. Ground reconnaissance was conducted from the southern end of the Sugarloaf feature north to its intersection with Sycamore Creek. Although the large bedrock escarpment is well-defined throughout this length, a smaller (ca. 10m high), very linear bedrock scarp is best-defined between Arizona 87 and Sycamore Creek. The only potential fault scarp displacing late Quaternary Alluvium discovered during our reconnaissance (<1m high, about 50m long; figure 5b) is located in this segment, about

0.25 km south of Sycamore Creek. Many small Holocene(?) alluvial fans cross the fault without being displaced in this segment. Linear features north of Sycamore Creek were noted on the aerial photographs, but aerial reconnaissance did not reveal scarps in this area. This evidence suggests that the segment of the Sugarloaf fault between Arizona 87 and Sycamore Creek may have been active more recently than the rest of the fault.

Several natural exposures of the Sugarloaf fault could be mapped in detail to determine whether datable alluvium (probably datable through soil development) is faulted. Description of soils developed on faulted and unfaulted surfaces could provide a constraint on the age of most recent faulting. Examination of soil development on the possibly faulted fan south of Sycamore Creek may reveal whether it is older, and therefore records a fault movement that pre-dates deposition of the unfaulted fans.

Tonto Basin

Two features in the Tonto basin are considered of probable tectonic origin. Three other faults may possibly have had Quaternary movement. However, in each case no fault exposures involving Quaternary alluvium have been observed. The Punkin Center feature (59-292-2) is a physiographic graben that truncates a Pleistocene alluvial fan at the eastern Mazatzal mountain front (figure 6). The trend of this graben-like feature is generally perpendicular to local drainage. The scarp is formed in fine-grained deposits, overlain by a thin cap of coarse gravel.

The steepest segment of the scarp is near its base, suggesting possible recurrent movement. A fluvial origin for this feature is possible, but at present the stream flowing in the graben is small and does not flow near the base of the scarp. The feature can be traced for only about 0.5 km with confidence, although the Mazatzal mountain front is linear to the north and south, suggesting possible long-term faulting. Aerial photographs reveal another graben-like feature about 5 km to the north along the Mazatzal front.

Ground reconnaissance surveys to the north and south might reveal fault exposures or surface displacements not apparent from the air. Trenching may be necessary to confirm whether or not this feature is tectonic, however. Ground access requires a significant hike at present; it might be possible to excavate a shallow trench at the base of the mountainward scarp of the graben by hand, if necessary.

Low, subtle, scarp-like features cut across a Pleistocene alluvial surface north of Windy Hill, near Roosevelt Lake (59-86-3; figure 7). Fine-grained sedimentation has occurred at the base of a series of NW-trending, SW-facing cobble-mantled scarps. In plan view, these features are en echelon and some appear to splay. They are apparent only on one terrace, however, and older, higher terraces to the north and south are not obviously affected. Paleo-indian agricultural wall alignments and mounds were found in association with these features, raising the possibility that they are human-caused.

Further field reconnaissance might reveal subtle evidence that these features extend to adjacent alluvial surfaces. Natural exposures are poor at this site, however, so it is likely that trenching would be necessary to determine whether these features have formed as the result of structural deformation.

Three other features in the Tonto Basin adjacent to Roosevelt Lake are exposed faults for which there is no clear evidence for Quaternary movement. The El Oso (59-294) fault trends north across an extremely dissected granitic piedmont (possibly an uplifted former pediment) just northwest of Roosevelt Lake (figure 8). The fault trace is highlighted by a striking vegetation lineation and a subdued topographic scarp generally <10 m high. The steeply eastward-dipping fault has juxtaposed two different granitic lithologies. Well-preserved alluvial terraces are non-existent in this dissected setting, so the potential record of Quaternary faulting is poor. The topographic scarp associated with the fault may be the result of Quaternary faulting, but it might equally well reflect differing erodibility of the two types of granitic rock.

Two Bar Mtn. North and South (59-88; 59-90) are prominent linear fault contacts between basin fill deposits and Precambrian bedrock. Again, there is no clear evidence of involvement of Quaternary deposits in the faulting. The Two Bar Mtn. North fault was investigated where it crosses Cave Canyon, near the entrance to Tonto National Monument. Weakly to moderately indurated sediments are apparently faulted on NE-dipping normal faults exposed on the NW side of Cave Creek at this locality. However, several pre-Holocene terraces of Cave Creek are not displaced as they cross the fault trace. More precise estimation of the ages of these surfaces through soil description could provide a minimum constraint on the age of last movement on the Two Bar Mtn. North fault.

Two Bar Mtn. South fault (the northern portion of the west branch of the Gold Gulch fault, as defined by Fugro, 1981) is a strikingly linear contact between basin fill and bedrock. However, the fault contact does not define a strong break in topographic relief between the mountain block and the basin. Near the southern end of Two Bar Mtn. South, pre-Holocene terraces of Tule and Two Bar creeks cross the fault trace without any displacement apparent from aerial reconnaissance.

Horseshoe

The Horseshoe fault (53-72; 53-74; Tangle Peak fault of Fugro, 1981) is a very prominent, generally north-trending vegetation and lithologic lineation along the west side of the basin that contains Horseshoe Reservoir (figure 9). The lineament is usually located at the mountain-piedmont junction, but locally crosses the piedmont. The mountain front itself is quite steep and linear, suggesting that the mountain-bounding fault could be relatively active (see later discussion of tectonic landforms). Ground reconnaissance conducted along the southern portion of this feature for an earlier study (Menges and Pearthree, 1983) did not reveal unequivocal evidence of displacement of Quaternary surfaces. There is, however, a fairly consistent several-meter-high bedrock scarp in that area, and several possible ~2m-high alluvial fault scarps were discovered. Displaced Quaternary surfaces were not apparent during aerial overflight of the entire feature during this investigation, but a low bedrock scarp was observed at approximately the latitude of the northern end of Horseshoe Reservoir. The Horseshoe fault probably deserves a more thorough ground reconnaissance survey to determine if definitive evidence of Quaternary movement exists.

Verde Basin

The Cottonwood (63-214; figure 10) and Camp Verde (477-128, 63-60; figure 11) segments of the Verde fault zone have probably been active during the late Quaternary. Other segments have possibly been active during the late Quaternary (Wilbur Canyon, 63-216; Squaw Peak, 63-62). The Verde fault zone forms the southwestern structural margin of the late Cenozoic Verde basin. This basin evidently began to form 7-9 Ma and continued to fill with sediment into the early Pleistocene (Bressler and Butler, 1978). Subsequent to that time the basin has undergone substantial dissection, resulting in the formation of suites of alluvial terraces, some of which have been displaced by faulting.

Displacement of Quaternary surfaces down to the northeast is certain along about 6 km of the Verde fault zone near Camp Verde. A suite of terraces of ranging in age from latest Pleistocene to early mid-Pleistocene are displaced by increasing amounts (1.5-6m), with higher scarps displaying evidence of being produced by several displacement events (segmented, composite scarps; figure 11d). At site 63-60, a fault zone exposed in a ravine projects up to a fault scarp displacing a mid-Pleistocene terrace (figure 11c). The most recent movement probably occurred between 5-15 ka, based on scarp morphology and the age of the youngest terrace displaced (Pearthree and others, 1983).

Another series of probable tectonic scarps were observed 20 km to the northwest, just south of Cottonwood, Arizona. These are low (~0.5 m high), short, sinuous scarps that extend discontinuously for about 2 km across mid-Pleistocene terraces (figure 10). They trend perpendicular to local drainages and are not obviously stream-cut features. However, no fault zones nor evidence of recurrent movement were observed.

Several possible fault scarps were observed between the Cottonwood and Campe Verde segments and southeast of the Camp Verde segment. The subtlety of these possible scarps indicates that they have not been active as recently as the Camp Verde segment. This implies that the segments of the Verde fault zone have moved separately in the late Quaternary, and at least the most recent movement occurred along the 6 km long Camp Verde segment.

TECTONIC LANDFORM ANALYSES

Reconnaissance field studies were supplemented by tectonic landform analysis of several mountain fronts whose overall morphologies suggest that they might be associated with active faulting. Tectonic landform analysis involves quantitative study of various landscape parameters that reflect relative rates of base level fall, possibly caused by faulting. Calculated landscape parameters allow quantitative comparison of mountain front morphologies in central Arizona and with mountain fronts studied in other portions of the southwestern United States (Bull , 1978). When combined with evidence of late Quaternary faulting of the types discussed above, tectonic landform analysis can suggest which faults have been relatively active over the last 10^5-10^7 years. Limitations on the application of tectonic landform analysis to mountain fronts in central Arizona will be considered as well.

Calculation of landscape parameters allows quantification of the relative rates of base-level processes. Mountain front sinuosity (S) and valley floor width-valley height ratios (Vf) allow one to compare the rate of uplift along the range-bounding structures with rates of fluvial erosion. Sinuosity (S) is defined as the ratio of the length along the bedrock-alluvium contact to the sublinear approximation of mountain front length, both measured from aerial photographs. Mountain fronts were analyzed in segments where bedrock lithology and/or gross morphology are fairly uniform. High S values indicate the mountain front has been significantly modified by erosion from its original more linear configuration. Values approaching 1.0

suggest little erosional mountain front retreat from sublinear range-bounding faults, but linear mountain fronts can also reflect resistant bedrock lithologies or exhumation of contacts between lithologies with varying resistance to erosion.

Vf ratios quantify cross-valley morpholgies of streams that flow across mountain fronts. The ratios of valley-floor width to the average elevation above the stream channel (Vf) were measured at one-tenth the distance of the basin length up from the mountain front. Several Vf ratios were calculated for each mountain front segment, using the largest streams available. In an attempt to take regional dissection into account, average height to drainage divides was also measured at the same distance down from the mountain front and this value was subtracted from the drainage divide height to obtain an adjusted Vf value (see later discussion). Large Vf ratios indicate greater degrees of lateral stream planation relative to downcutting, a situation indicating minimal base-level fall. Small Vf ratios imply that stream downcutting, driven by base-level fall downstream, is dominant.

A third measure of relative rates of faulting is the development and extent of dissection of triangular facets at the mountain front. Analysis of triangular facet development permits one to consider three-dimensional mountain front morphology as it reflects relative rates of uplift at the mountain front. Triangular facet development along the fronts studied in central Arizona was described using a seven-part classification scheme (Bull , 1978; table 4) that reflects different rates of mountain front uplift.

Landscape parameters calculated for mountain fronts in central Arizona suggest that faults bounding a number of fronts may be relatively active (table 5), but several factors complicate this interpretation. Limitations on the application of these landscape parameters to central Arizona are imposed by the fact that most of central Arizona has been subjected to late Cenozoic dissection. Major trunk streams such as the Verde and Salt river systems have downcut extensively during the Quaternary, as evidenced by spectacular bedrock canyons, deeply dissected alluvial basins, and stair-stepped suites of stream terraces within basins. As a result of downcutting of the trunk streams, tributaries are eroding both downstream and upstream from mountain fronts.

In this erosive environment, it is not surprising that Vf ratios measured within the mountains indicate that streams are responding to base level fall by downcutting. How much of the downcutting is due to uplift at the mountain front is difficult to gage, however. An attempt was made to remove some of the effects of general basin dissection using adjusted Vf ratios (defined above), but even these adjusted values are similar to those of fairly tectonically active mountain fronts (Bull , 1978). Mountain front sinuosity (S) values are also consistent with active uplift, but again general basin dissection has undoubtedly contributed to mountain front linearity. With regional base level fall, weakly resistant basin fill is preferentially removed, and this can exhume basin-bounding contacts between basin fill and bedrock (often late Cenozoic normal faults). Also, the fact that streams have tended to downcut rather than erode laterally both down- and upstream from mountain fronts, has tended to keep the mountain fronts rather straight.

Triangular facet development is probably a better indicator of relative rates of faulting in central Arizona. In general, triangular facets are not well developed. The mountain fronts studied have facets indicating moderate to very low uplift rates. This conclusion is consistent with the rather sparse and subtle evidence for displacement of Quaternary alluvial surfaces along these mountain fronts. Tectonic landform analyses indicate that some mountain fronts in central Arizona might be sites of long-term faulting. Verification of this tentative conclusion, however, depends on finding faulted Quaternary deposits associated with these mountain fronts.

SUGGESTIONS FOR FURTHER STUDY

The objective of this study has been to define locations of possible Quaternary faulting in central Arizona. Features that were investigated were based on photointerpretation, and certainly a different operator might have chosen a somewhat different set of features. In addition, some fault-generated features might not be apparent at the scale and under the lighting conditions at the time the aerial photographs were taken. It might therefore be advantageous to obtain larger-scale, low-sun angle photographs of areas considered important or critical. For example, such photography might be acquired for areas adjacent to dam sites. Larger-scale photography could be of great use in Quaternary geologic studies of features delineated in the present study.

The following framework is suggested for field studies of features in the probable/demonstrable and possible categories that are determined to warrant further investigation: 1) Detailed reconnaissance helicopter overflights of features, with extensive ground reconnaissance studies where appropriate. This procedure would most certainly allow reclassification of some "possible" features into "unlikely" or "probable" categories. It might also indicate whether any further ground study of some features is likely to yield evidence of Quaternary faulting. 2) Detailed mapping of fault scarps and adjacent Quaternary alluvial surfaces. These studies can potentially bracket the age of most-recent fault movement and reveal evidence of recurrent fault movement. Soil-profile development will likely be the principal criteria used to estimate alluvial surface ages. In a few locations, topographic fault scarp profiling might provide evidence of the amount of fault displacement and recency of fault movement. 3) Finally, trenching would likely provide definitive evidence of fault displacement of Quaternary deposits, if the features are indeed Quaternary faults. Trenching might also document recurrent fault movement and amounts of displacement associated with individual faulting events. Relatively few probable and possible faults delineated in the present study will likely merit full investigation. Many possible faults will undoubtedly be eliminated in the first phase of any future study, and other features may be insufficiently close to dam sites to warrant further investigation.

CONCLUSIONS

This study has not involved detailed analyses of any late Quaternary faults in central Arizona. Nonetheless, evidence of Quaternary faulting observed during these reconnaissance studies permits some general conclusions to be reached. Evidence of faults offsetting Quaternary deposits in central Arizona is extremely subtle. This contrasts strongly with relatively active faults in Arizona, such as the Big Chino fault just northwest of the study area (figure 12). Big Chino fault is estimated to have a late Quaternary displacement rate of about 0.1 mm/yr., with an average surface-rupture recurrence interval of tens of thousands of years (Pearthree and others, 1983). Relatively active normal faults such as Big Chino generate relief across them, resulting in high, prominent fault scarps. The general absence of obvious fault scarps suggests that individual faults in central Arizona have very long recurrence intervals, on the order of 10^5 yrs. Such recurrence intervals are typical of faults in southern Arizona (Pearthree and others, 1983).

Assessment of the regional potential for surface-rupturing earthquakes in central Arizona will depend on 1) documentation of locations of late Quaternary faulting; and 2) analysis of histories of fault movement, especially ages of last movement. Documentation of locations of late Quaternary faulting will depend on more detailed field studies of the features discussed in this report. Detailed studies may involve mapping of fault scarps and adjacent Quaternary alluvial surfaces. Studies of soils developed beneath faulted and unfaulted surfaces likely will provide criteria with which to estimate surface ages, and thereby constrain estimates of age of most recent fault movement. Finally, trenching may provide definite evidence of faulting, if it exists, and permit further refinement of displacement histories. Once individual fault displacement histories have been studied, it should be possible to estimate average regional rates of surface-rupture occurrence and to consider regional patterns of late Quaternary faulting in considerably more detail than at present.

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TABLE 1. EARTHQUAKES FELT IN THE STUDY AREA

DATE	TOWN NEAREST THE EPICENTER	MODIFIED MERCALLI INTENSITY (Roman numerals) or MAGNITUDE (Arabic)
11 Mar 1870	Prescott	V
12 Aug 1870	Prescott	IV?
7 Feb 1871	Constellation	V
9 Mar 1875	Phoenix	III
** 3 May 1887	Batepito, NE Sonora	VI in Phoenix, IV in Prescott, at epicenter, XII, 7.25.
27 Jun 1915	Mesa	III
** 17 Jun 1922	Miami	VI
30 Sep 1923	Payson	IV
28 Jul 1931	Cottonwood	VI
8 Feb 1932	Perkinsville	II
28 Oct 1935	Phoenix	II
21 Jul 1937	Phoenix	V
** 11 Sep 1963	Globe	VI; 4.1
21 Oct 1963	Globe	3.5
20 Dec 1974	Cave Creek	VI; 2.5
** 24 Dec 1974	Cave Creek	V; 3.0
** 4 Feb 1976	Chino Valley	VI; 4.9-5.2
9 Feb 1976	Chino Valley	III; 4.6
23 Feb 1976	Chino Valley	VI; 3.5
4 May 1976	Chino Valley	II; 3.0
21 Oct 1977	Chino Valley	V; 2.5
11 Dec 1979	Roosevelt Lake	IV; 2.5

** These events are plotted on Figure 1

Data taken from: DuBois S.M., and others (1982)"Arizona Earthquakes, 1776-1980". Arizona Bureau of Geology and Mineral Technology Bulletin 193, 456 p.

Table 2. PROBABLE AND POSSIBLE QUATERNARY FAULTS DISCUSSED IN TEXT

Feature Name	Photo Number	Location
Carefree	63-78	T5N., R5E., Sec. 2,3,10,14,15, 23; T6N., R5E., Sec. 27,30 Wildcat Hill 7 1/2'
Sugarloaf	61-90 477-82	NEmost portion, Adams Mesa 7 1/2'; SE for 4 km from 42'30"N, 111o30'W, Mine Mtn. 7 1/2'
Tonto Basin NW	59-292-2	T6N., R10E, Sec. 16,17,21,28, Tonto Basin 7 1/2'
Windy Hill	59-86-3	T4N., R13E., Sec. 8,17, Windy Hill 7 1/2'
Tonto Basin Central	59-294-1	T5N., R11E., Sec. 18,19,30, Tonto Basin 7 1/2'
Two Bar Mtn. North	59-88-4	T4N., R12E., Sec. 27,34,35, Windy Hill 7 1/2'
Two Bar Mtn. S. (NW branch, Gold Gulch fault, Fugro, 1981)	59-88-1	NW 1/4, Two Bar Mtn. 7 1/2' NNW-trending feature, near Gila-Maricopa Co. line
Horseshoe	53-74-2 53-72-2	NWmost part, Horseshoe Dam 7 1/2'; SW edge, Chalk Mtn. 7 1/2'; NEmost part, Rover Peak 7 1/2'
Camp Verde	477-128-1,-2; 63-60	T14N., R4E., Sec. 35; T13N., R4E., Sec. 1,2,11,12, Middle Verde 7 1/2'; T13N., R5E., Sec. 18,19, Camp Verde 7 1/2'
Cottonwood	63-214-1	T15N., R.3E., Sec. 8,17,20, Cottonwood 7 1/2'
Wilbur Canyon	63-216-1	T14 1/2 N., R.3E., Sec. 34, Cottonwood 7 1/2'
Grief Hill	477-128-3	T14N, R4E., Sec. 26, Middle Verde 7 1/2'
Squaw Peak	63-62-1	T12N., R5E., Sec. 5 Horner Mtn. 7 1/2'

Table 3. POSSIBLE QUATERNARY FAULTS NOT DISCUSSED IN TEXT

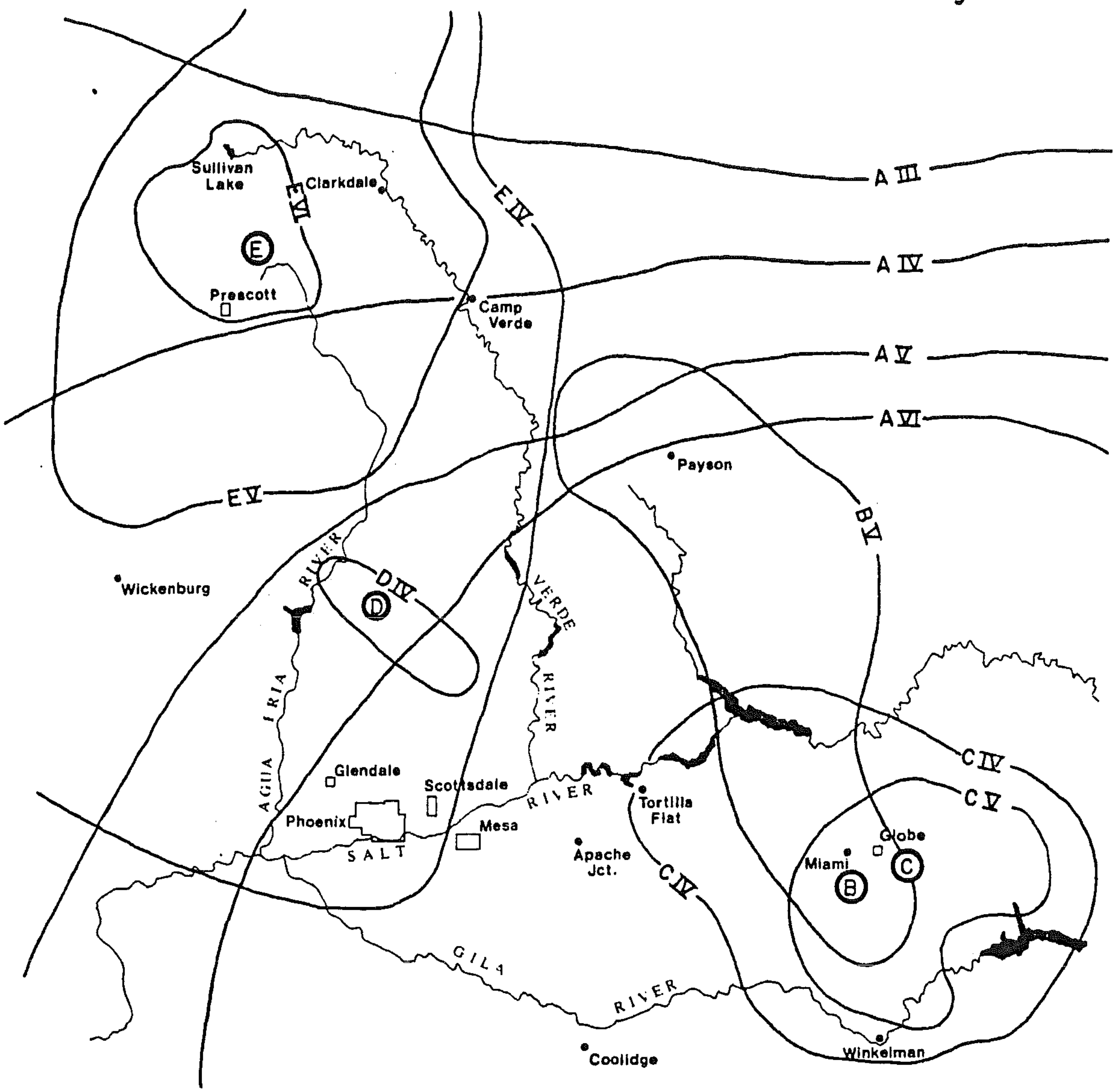
Feature Name	Location	Comments
Alder Creek 477-79	upper part, NE 1/4 Maverick Mtn. 7 1/2′	lineation and bedrock escarpment; no Quaternary fault scarps observed in aerial recon.
Apache Lake 477-32-2	NW 1/4 Pinyon Mtn. 7 1/2′, parallel to Apache Trail SE of Camp Waterdog	strong linear feature with topographic relief across it, completely intra-bedrock, no alluvium observed to be faulted; poor preservation of Quat. surfaces in general
Boulder Creek 61-86, 61-88	T6N, R9E, Sec. 26, 27,28,21,20, Boulder Mtn. 7 1/2′	Prominent lineation at base of bedrock escarpment, but no unequivocal scarps cutting Quat. alluvial surfaces observed in aerial recon.
Brushy Hollow 61-78-2	T10N, R8E, Sec. 1, 12,13(estimated) North Pk. 7 1/2′	E. Verde River sedimentation east of prominent bedrock; possible lower scarp cutting late Cenozoic basalt to the north; Quat. movement uncertain
East Verde 477-70	upper part, Cypress Butte 7 1/2′; SWmost 1/4, Cane Springs Mtn. 7 1/2′	strong vegetation lineation at base of major bedrock escarpment; no fault scarps observed in aerial recon.; in Mazatzal Wilderness Area
Granite Mtn. 477-82,-80	SW 1/4, Maverick Mtn 7 1/2′, extending ~10 km SE from Bartlett Res.	Moderate to strong lineation, almost entirely within bedrock; ill-defined NE-facing bedrock scarp near Bartlett Reservoir; lower, SW-facing bedrock scarps SW of Granite Mtn.
Kennedy Ranch 59-92-2	just E of Kennedy Ranch, Haunted Cyn. 7 1/2′	sedimentation along Pinto Cr. upstream from topographic scarp; substantial widening of stream valley floor suggests ponding; feature much less well defined to NW and SE
Rolls 61-92,477-84	SWmost part, Mine Mtn. 7 1/2′; SEmost part, Adams Mesa 7 1/2′	curious topographic-physiographic features suggest folding at surface; no scarps observed; longitudinal terrace profiling to determine if warped is possible strategy

Feature Name	Location	Comments
St.Clair Peak 53-68-1	SW 1/4, Horseshoe Dam 7 1/2', east of St. Clair Peak	well-exposed fault with relief across it in bedrock east of St. Clair Pk., continues S across weathered granitic piedmont as subdued, but 5+ m-high scarp
Snowstorm Mtn. 61-78-1	T10N, R9E, Sec. 12,14	Prominent vegetation lineation at base bedrock escarpment and cutting across Quaternary alluvial surfaces; scarps not apparent, however
V Mesa 59-292-4	T7N, R10E, Sec.33; T6N, R10E, Sec. 3,4; Kayler Butte 7 1/2'	Several meter-high scarp follows edge of mesa; probably purely erosional, as scarp occurs at break between coarse gravel cap and underlying fine beds

MOUNTAIN FRONT	LENGTH (km)	BEDROCK LITHOLOGY	MTN.FRONT SINUOSITY (S)	Vf RATIO	ADJUSTED Vf RATIO	FACET DISSECTION CLASS
Verde 1	7	mixed sediments	- -	visual inspection - topographic front ill-defined; substantial dissection		
Verde 2	5	pC granite, schist	1.7	12-16	20-80	5-6
Verde 3	13	Tertiary basalt, sediments	1.26	0.1-0.4	0.2-0.5	4-5
Verde 4	6	pC schist, granite, Paleozoic sediments	1.14	0.2	0.4	3-6
East Verde	11	pC metavolcanics	1.04	0.1-0.3	0.1-0.3	3-5
Horseshoe North	8	pC granite	1.15	0.2-0.3	0.2-0.7	4-6
Horseshoe South	7	pC granite	1.4	0.3-0.4	0.3-0.5	4-7
Mazatzal East	15	pC granite	1.48	0.1-0.5	0.2-0.6	4-5
Mazatzal SE	20	pC granite, sediments	- -	visual inspection - poorly defined mtn. front; Roosevelt Lake has submerged bedrock-alluvium contact in places		
Two Bar North	8	pC sediments	1.06	0.3	0.3-0.4	3-5
Two Bar East	8	pC granite	1.7	0.6-1.1	1.1-1.7	4-6

Table 5. Summary of tectonic landform analyses in central Arizona. Mountain front segments are labeled in figure 3. Methods for determining mountain front sinuosity (S), valley floor width/ valley height ratios (Vf), and adjusted Vf ratios are discussed in the text, p. 18-22. Facet dissection classes are summarized in table 4.

Figure I.



◯ Epicenters	A. 3 May 1887, Sonora, Mexico	Mag. 7.25 at epicenter, Int. VI in Phoenix.
-B V- Line of equal modified Mercalli Intensity.	B. 17 June 1922, Miami, Arizona	Int. VI.
	C. 11 Sept. 1963, Globe, Arizona	Int. VI, Mag. 4.1.
	D. 24 Dec. 1974, Cave Creek, Arizona	Int. V, ML 3.0.
	E. 4 Feb. 1976, Chino Valley, Arizona	Int. VI, Mb 4.9-5.2.

Contoured Modified Mercalli Intensity Maps of Selected Historic Earthquakes Felt in Central Arizona.

Data from Dubois and others (1982) and Sauck (1976).
This map drawn by Scarborough, 8/84.

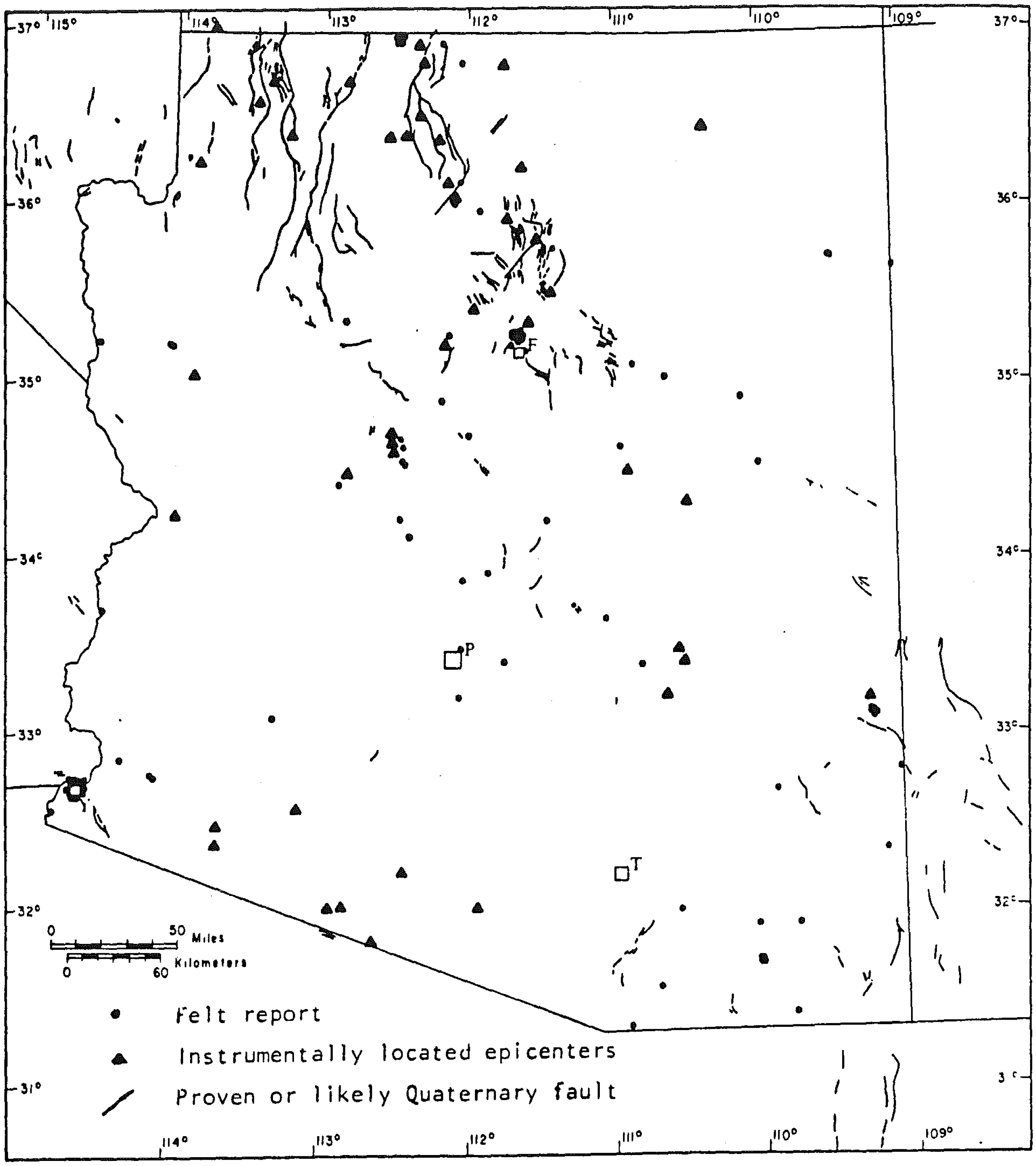


Figure 2. Probable and possible late Quaternary faults (Menges and Pearthree, 1983) and historical seismicity (DuBois et al, 1982) in Arizona. F-Flagstaff, P-Phoenix, T-Tucson, Y-Yuma.

Fig. 4a

Figure 4a

Carefree scarp (63-78), looking westerly. The 1-2m high, west facing scarp is highlighted by the vegetation lineation cutting diagonally across the photo. The 30-60m wide lighter colored band on the far side of the scarp is composed of fine-grained sedimentary fill deposited in a graben or half-graben, and overlain by a noncontinuous residual caliche cap. The pedimented terrane throughout the view consists of Precambrian granite overlain by Tertiary volcanics (light-streaked hill in upper left). The pediment meets granite bedrock knobs in the low foreground.

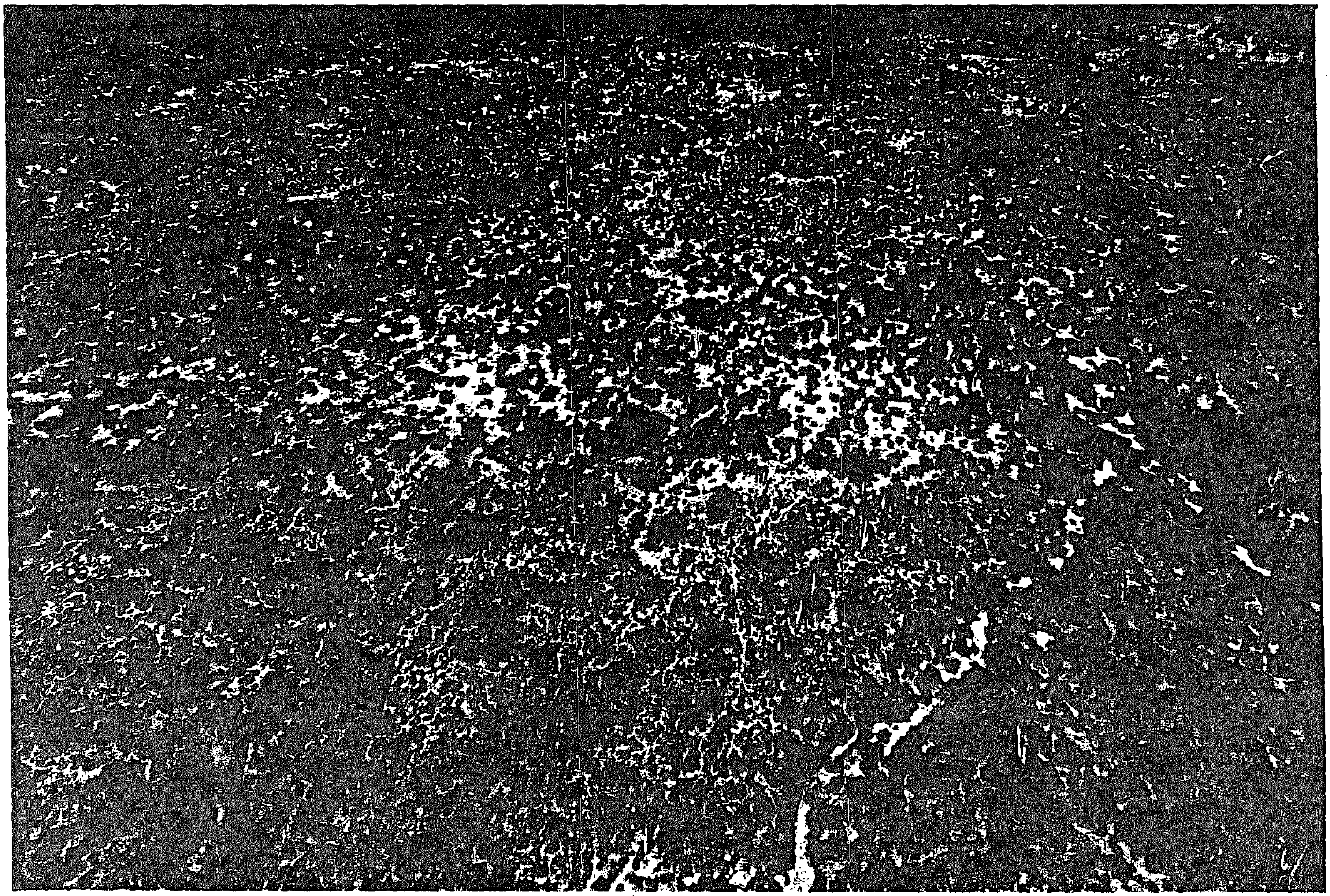


Fig. 4a (alternate view)

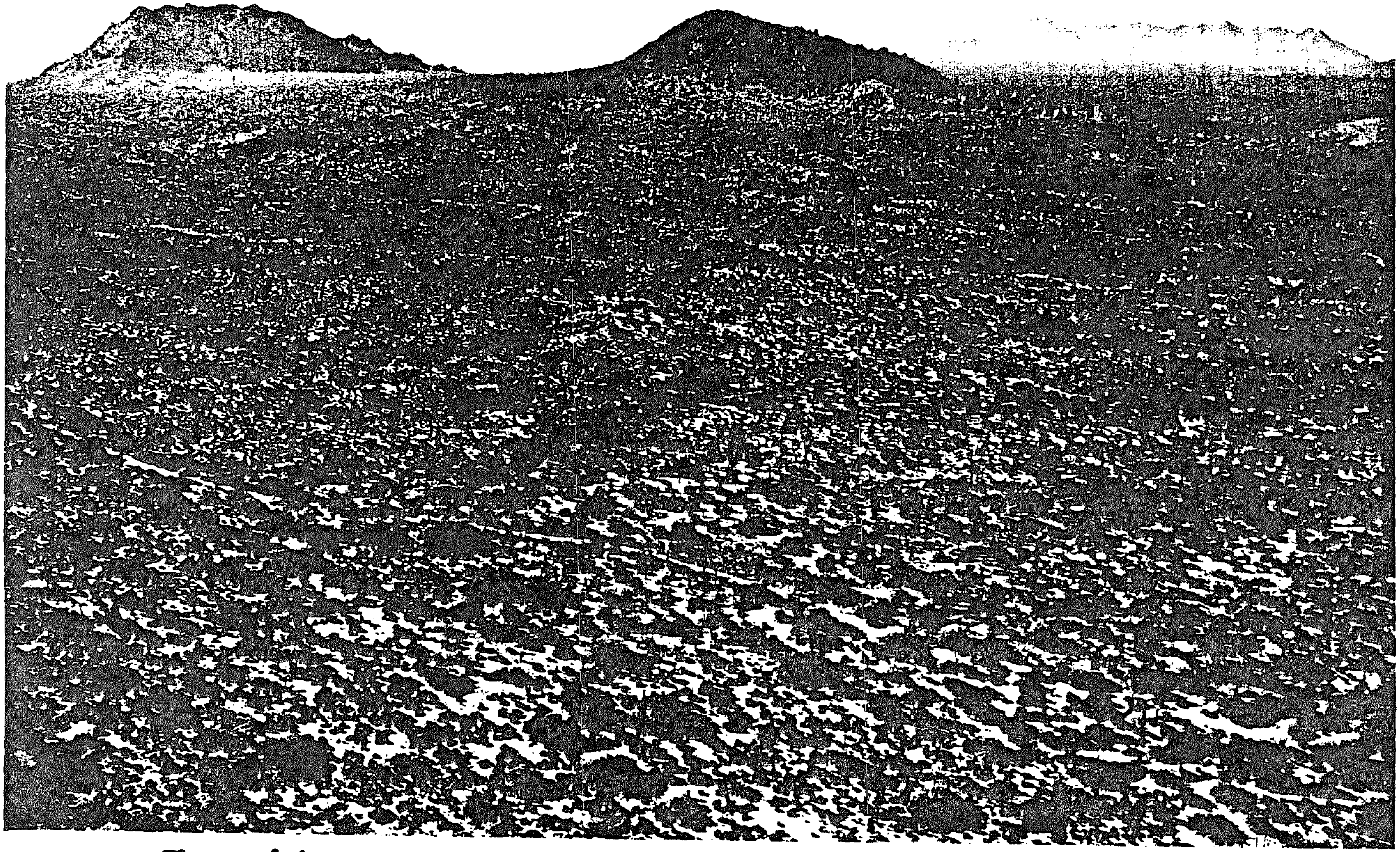


Fig. 4b

Figure 4b

Carefree scarp (63-78), looking southward. The scarp extends from the middle left foreground toward the right edge of the prominent inselberg in the near distance. Morning lighting makes the stripped granite pediment and the west-facing scarp stand out. The graben extends in the foreground from the scarp about half way to the right hand edge of the photo, as indicated by arrows.

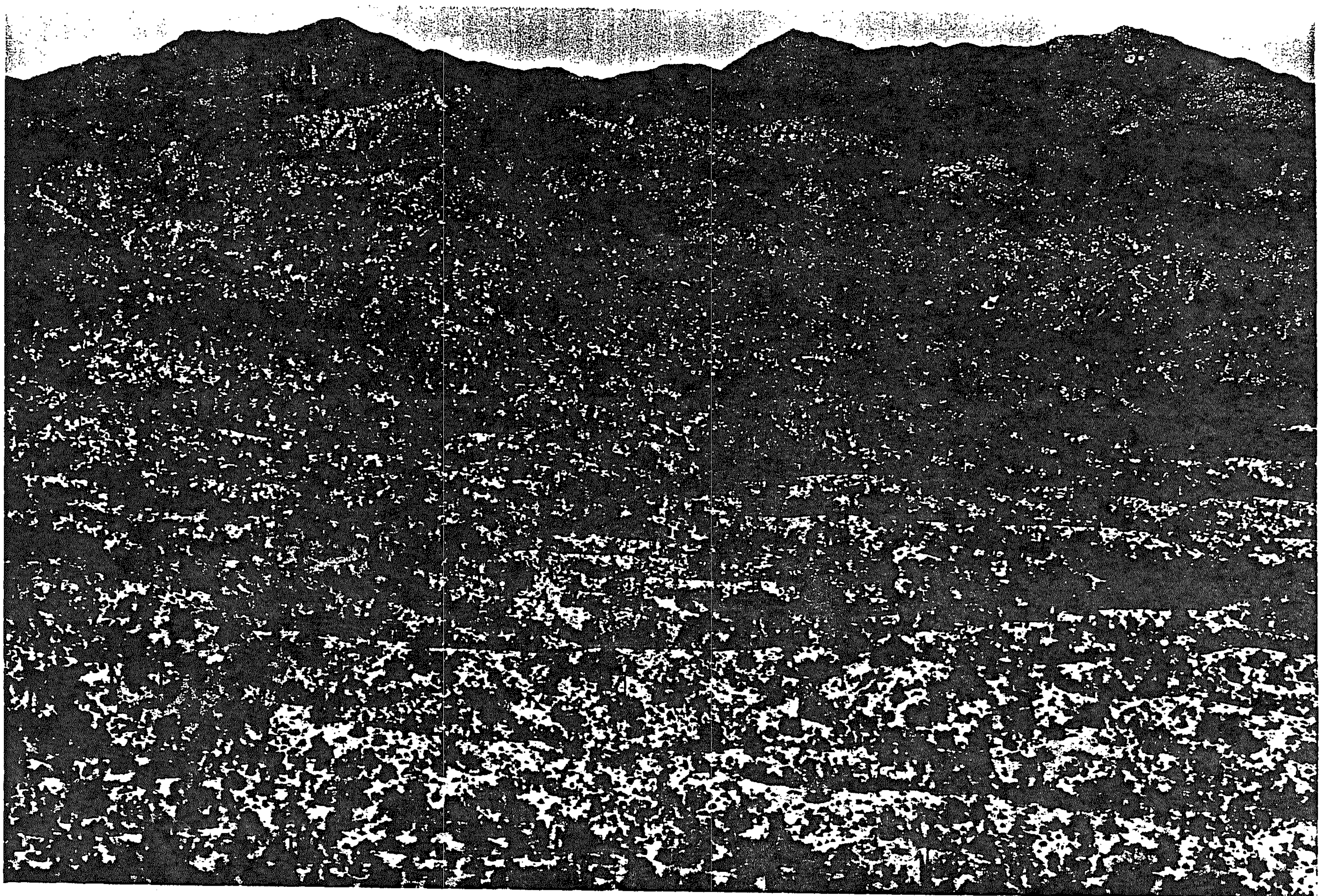


Fig. 5a

Figure 5a

Aerial view of the Sugarloaf scarp (61-90), a short distance northwest of the Payson highway, just south of Sycamore Creek. Photo looks northwest at the nearly north-trending, east-facing scarp. The scarp is developed along a fault contact separating Precambrian granite on the far side of the fault, from grussy basin fill sediments on this side of the fault. Figure 5b shows possible fault offset of young grus material within the densely vegetated area along the fault in right center of photo, at the right arrow.

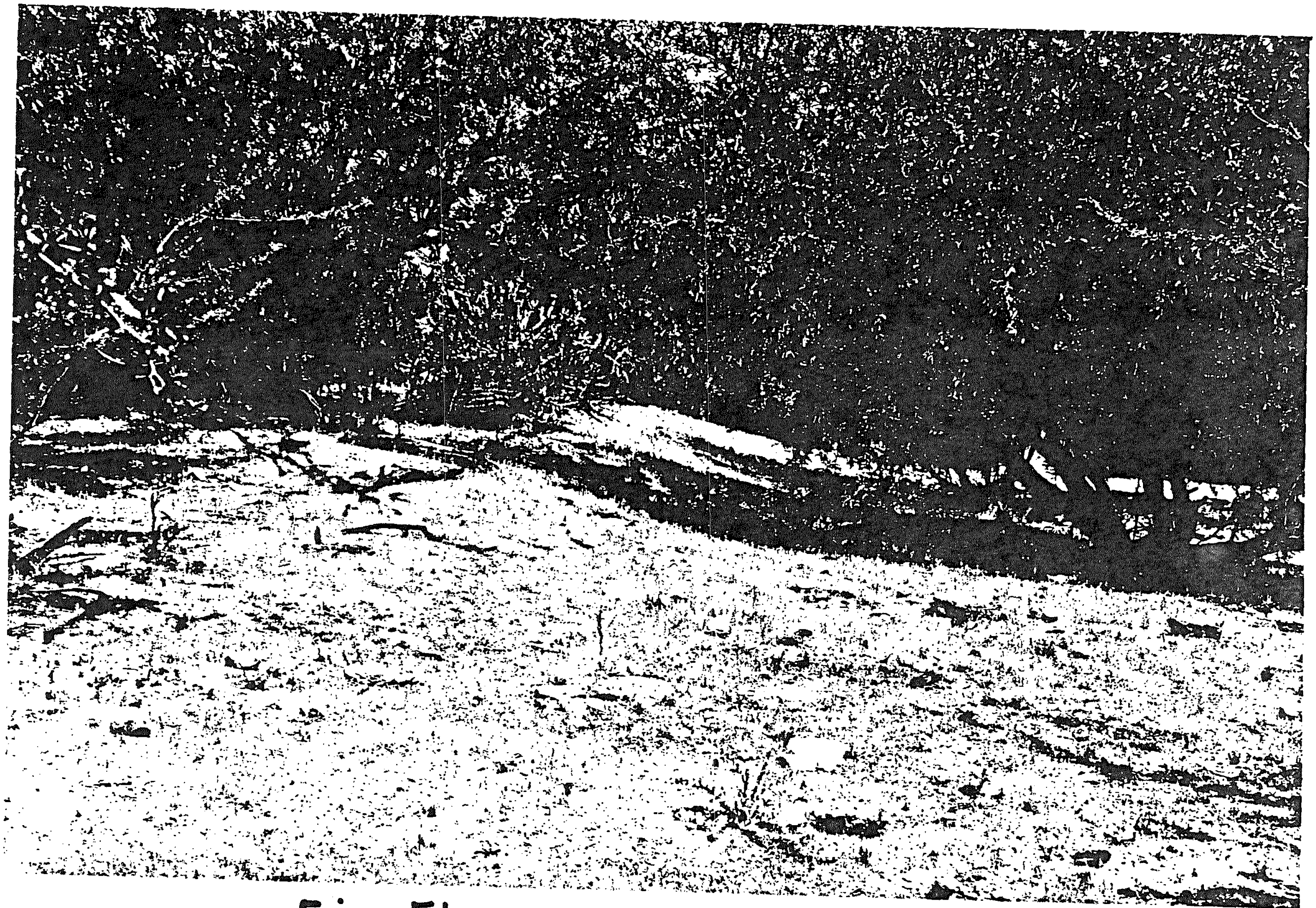


Fig. 5b

Figure 5b

Sugarloaf scarp, looking at small apparent offset of young (Holocene) grussy alluvial fan near a much larger, older bedrock scarp. Photo looks northward at the east-facing scarp. See last photo for location. This fault was judged to have late Quaternary movement in a previous report by FUGRO, Inc., based upon exposures farther south very near the Payson highway.

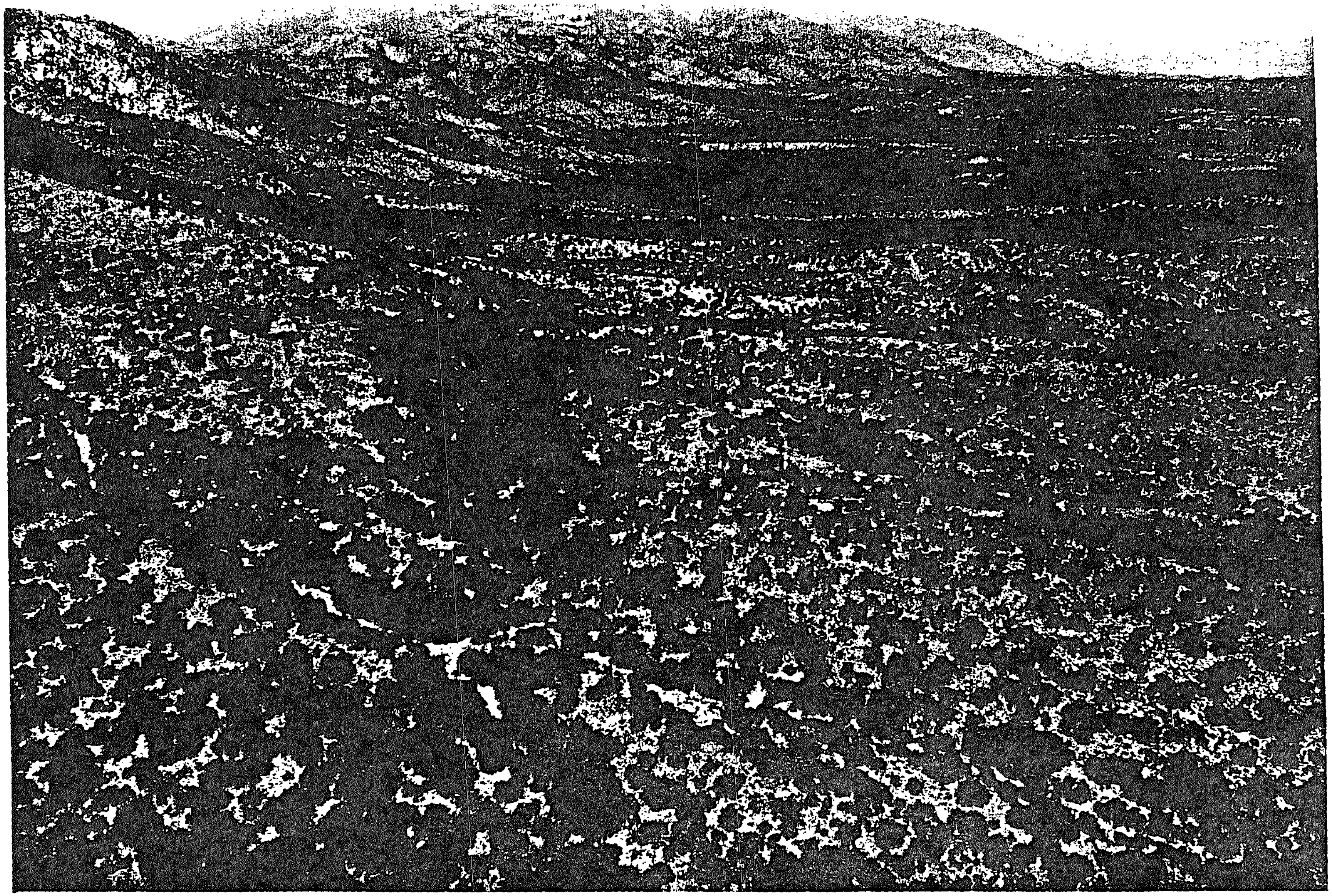


Fig. 6a

Figure 6a

Punkin Center scarp (59-292), looking north along the mountain-piedmont interface on the west edge of Tonto Basin. Dark vegetation lies within a topographic graben that obviously parallels the mountain front. The main east-facing scarp is convex upwards at the south end, just above the stream bottom seen in the foreground. Figure 6b looks across the graben. Another graben feature exists along the mountain front a few kilometers north of this point, within the scene of this photo, but out of view. Arrows indicate width of graben.

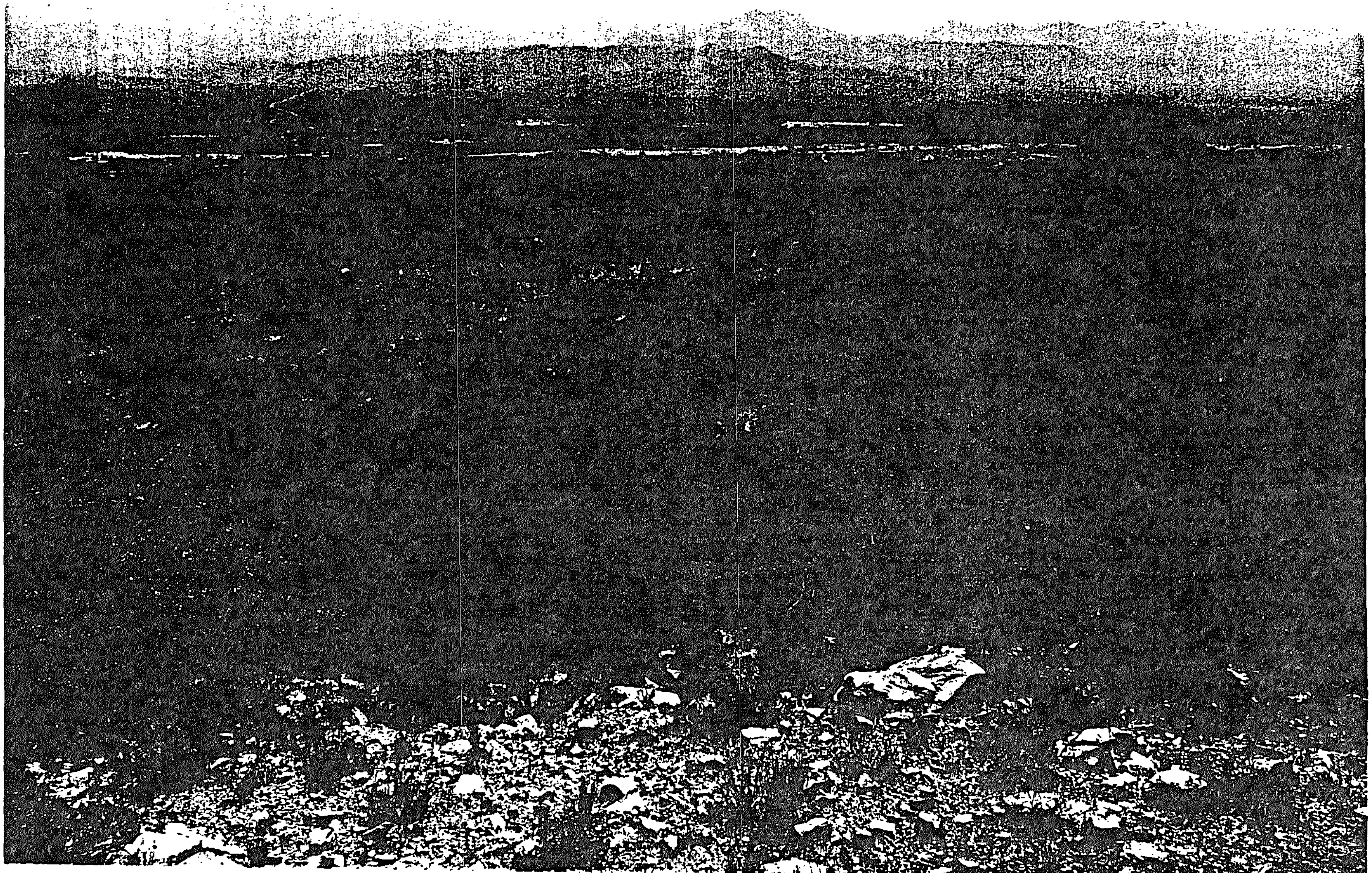


Fig. 6b

Figure 6b

Punkin Center scarp and graben, looking eastward toward the town of Punkin Center and the Sierra Ancha. View is across the 50m-wide graben, heavily vegetated, in foreground. Production of the graben by faulting is more likely than by fluvial processes.

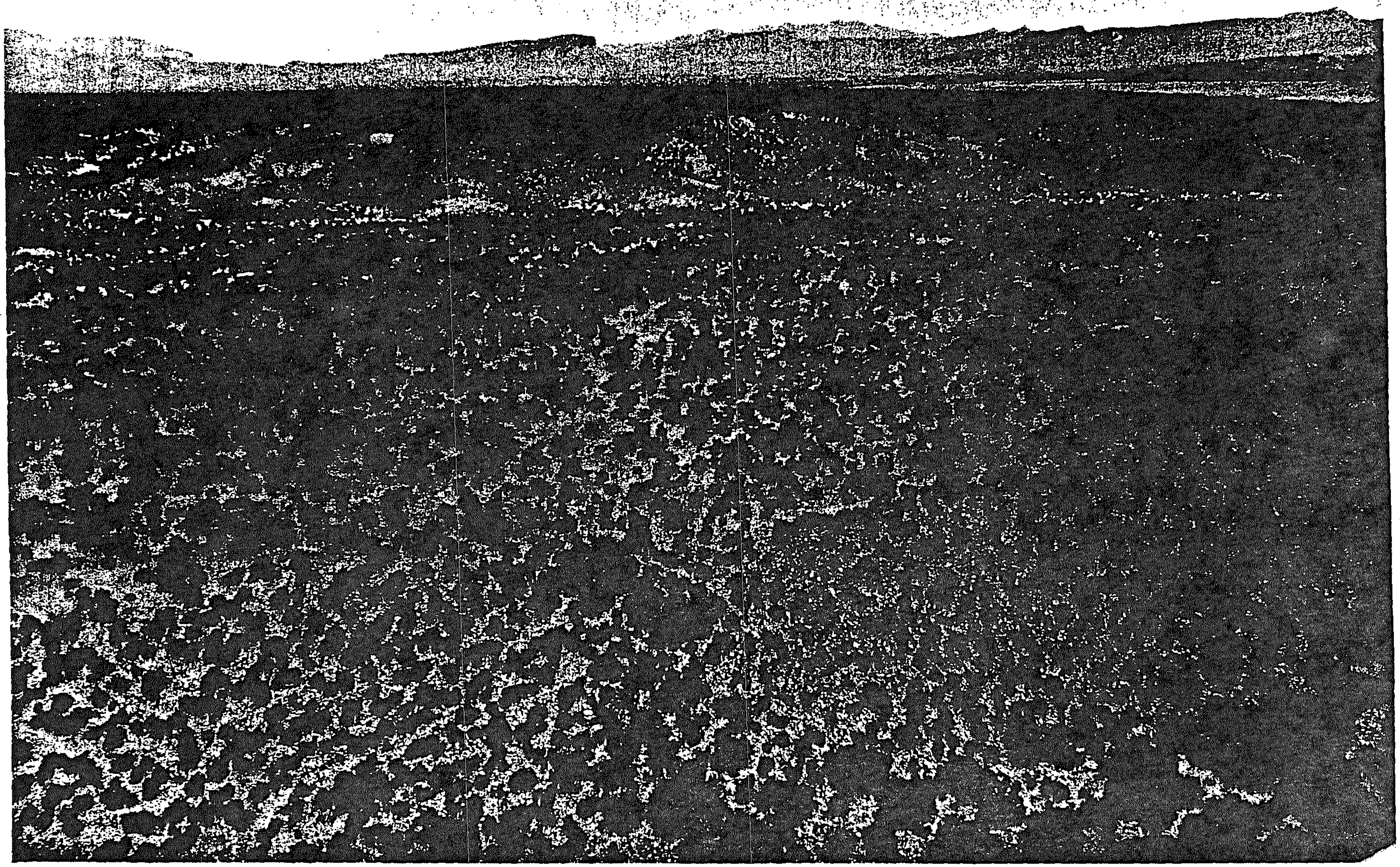


Fig. 7a

Figure 7a

Roosevelt Lake terrace scarp (59-86), just east of Lake Roosevelt, looking southward. The sparcely vegetated zone in the center of the photo is covered with fine-grained sedimentary fill, with an adjacent scarp upslope to the left. The fill appears to represent a graben-like depression, and occurs on a Pleistocene terrace. Graben oriented perpendicular to the main drainages in the area. Several parallel features exist on the terrace downslope to the right, out of photo view. Figure 7b shows a closeup of the small scarp upslope of this graben.

Fig. 7b

Figure 7b

Scarp associated with the graben feature of the last photo, looking eastward. The fine-grained sediment (graben fill?) can be seen in the foreground, contrasting with the bouldery/cobbley fill exposed along the scarp.

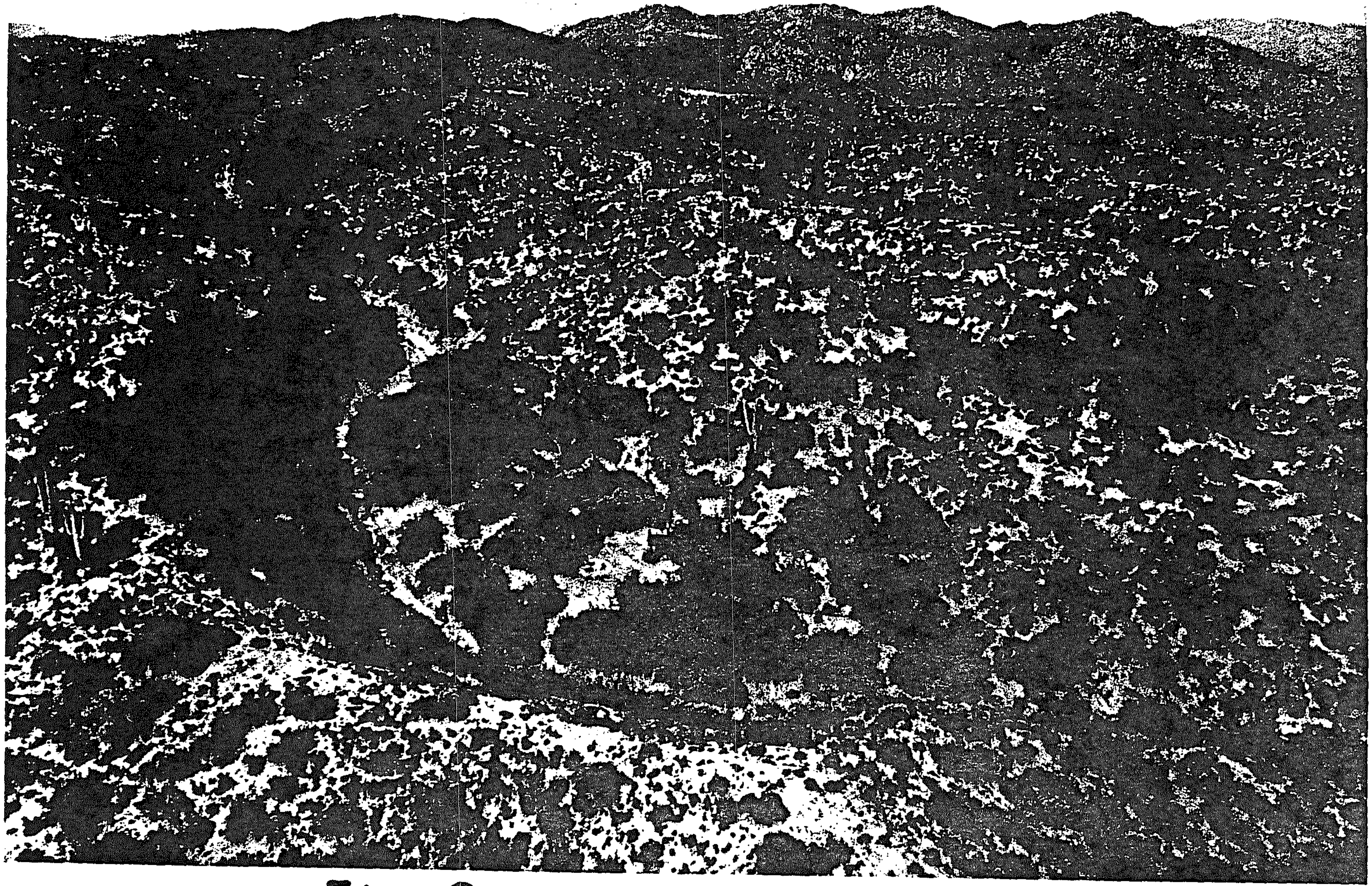


Fig. 8

Figure 8

Scarp just north of Roosevelt Lake (59-294), on the west side of the valley, low on the piedmont. Photo looks westerly toward the Mazatzal Mountains. Scarp follows a fault line marked by numerous seeps along canyon bottoms, as just left of center of photo. The fault has Precambrian granite on both sides. The escarpment is lined with heavy oak vegetation. The scarp parallels both the trend of Tonto Creek in the area and the mountain-piedmont junction.

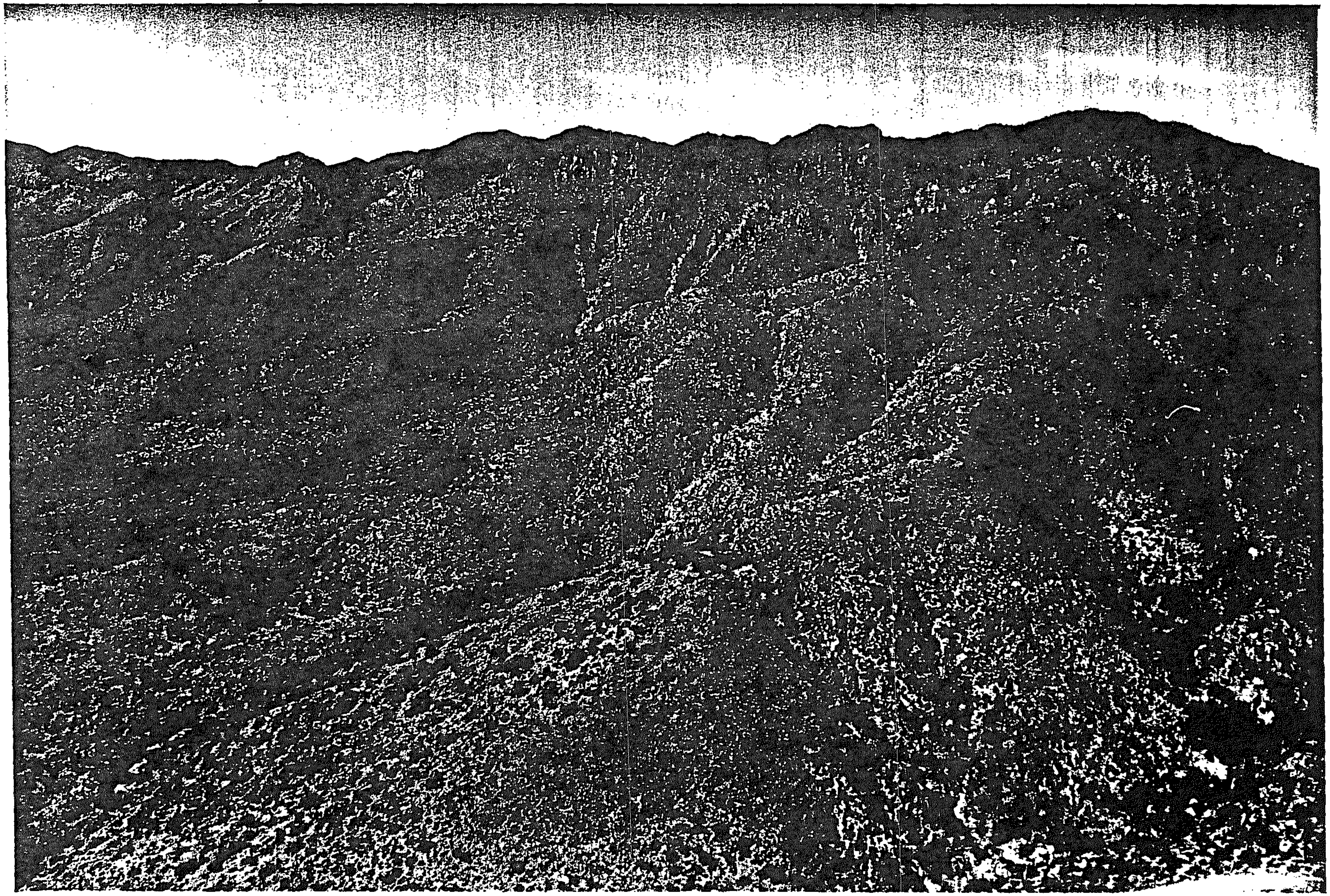


Fig. 9a

Figure 9a

Horseshoe scarp (53-72), looking southwesterly. No unambiguous neotectonic displacement has been found along this fault, but basin fill here lies juxtaposed with Precambrian granite, and numerous seeps lie along the fault trace, which, farther south, is intensely silicified and mineralized with copper-uranium, just north of Lime Creek.

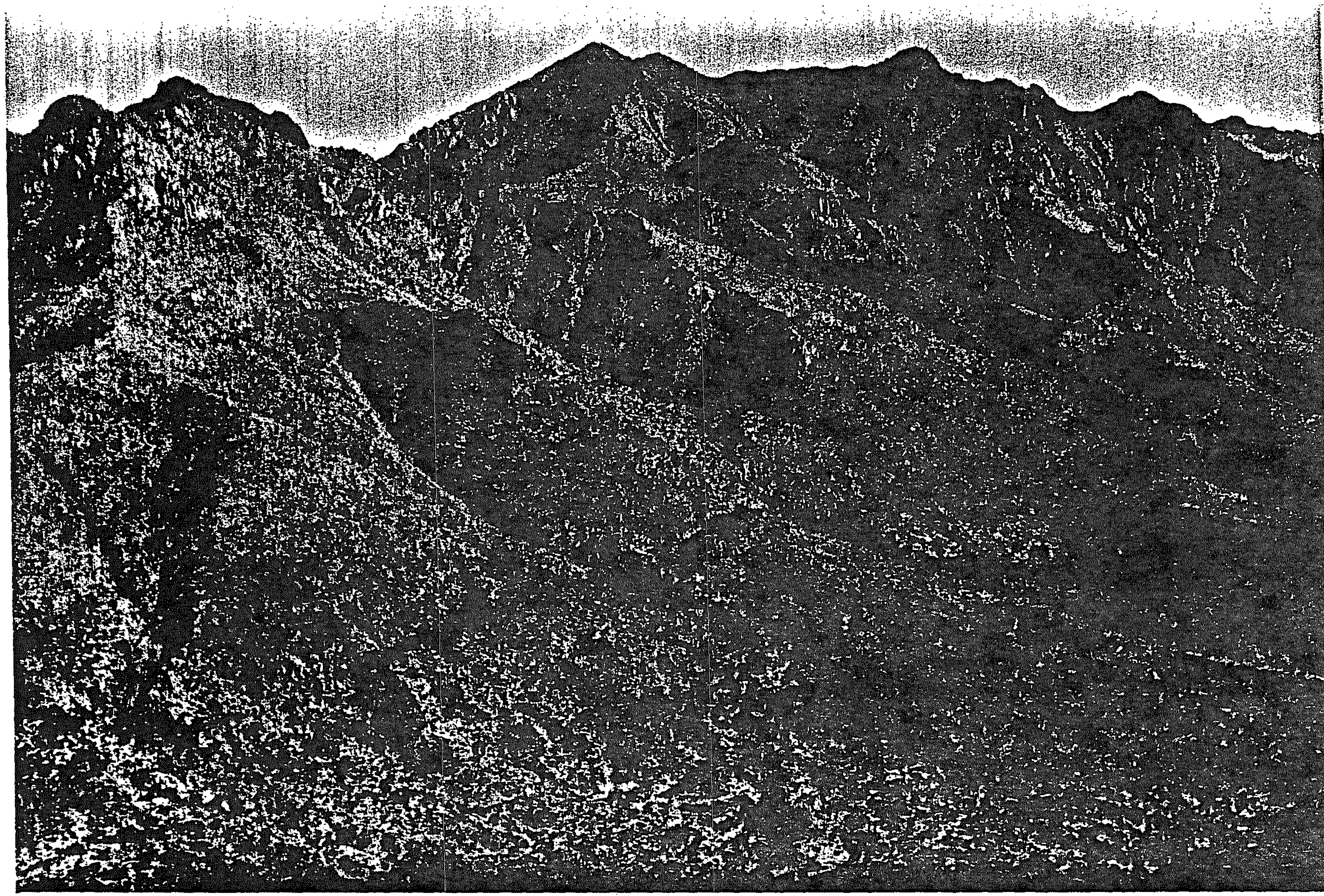


Fig. 9b

Figure 9b

Horseshoe scarp, west of Horseshoe Dam (53-74), looking north-westward. See Figure 9a for details.

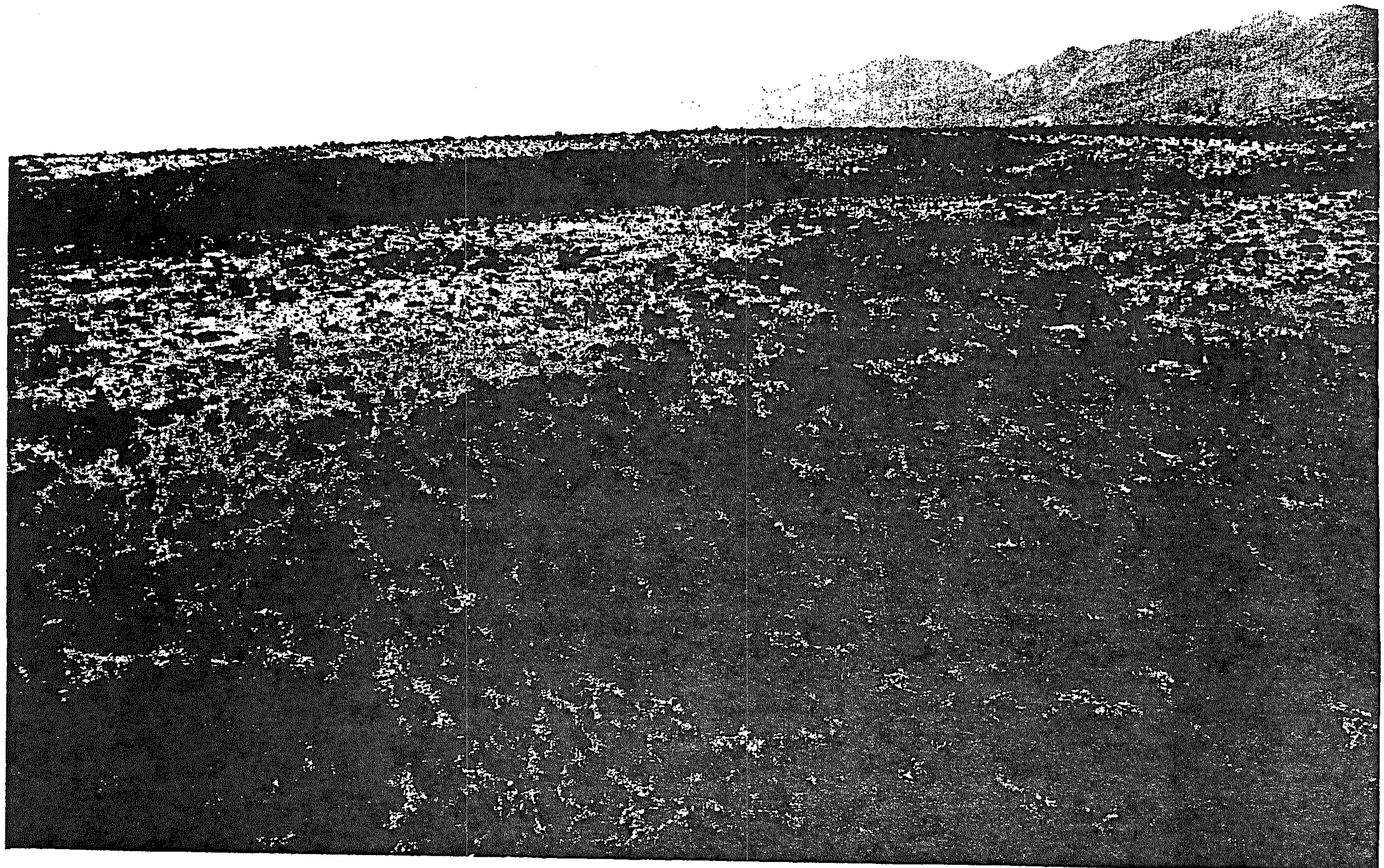


Fig. 10a

Figure 10a

Gentle swale developed on a Pleistocene piedmont surface, west of Cottonwood, Verde Valley (63-214). Photo looks south-southwest. A number of such features cut across the piedmont perpendicular to the deeply incised drainages in this area, suggestive of production by tectonic processes.

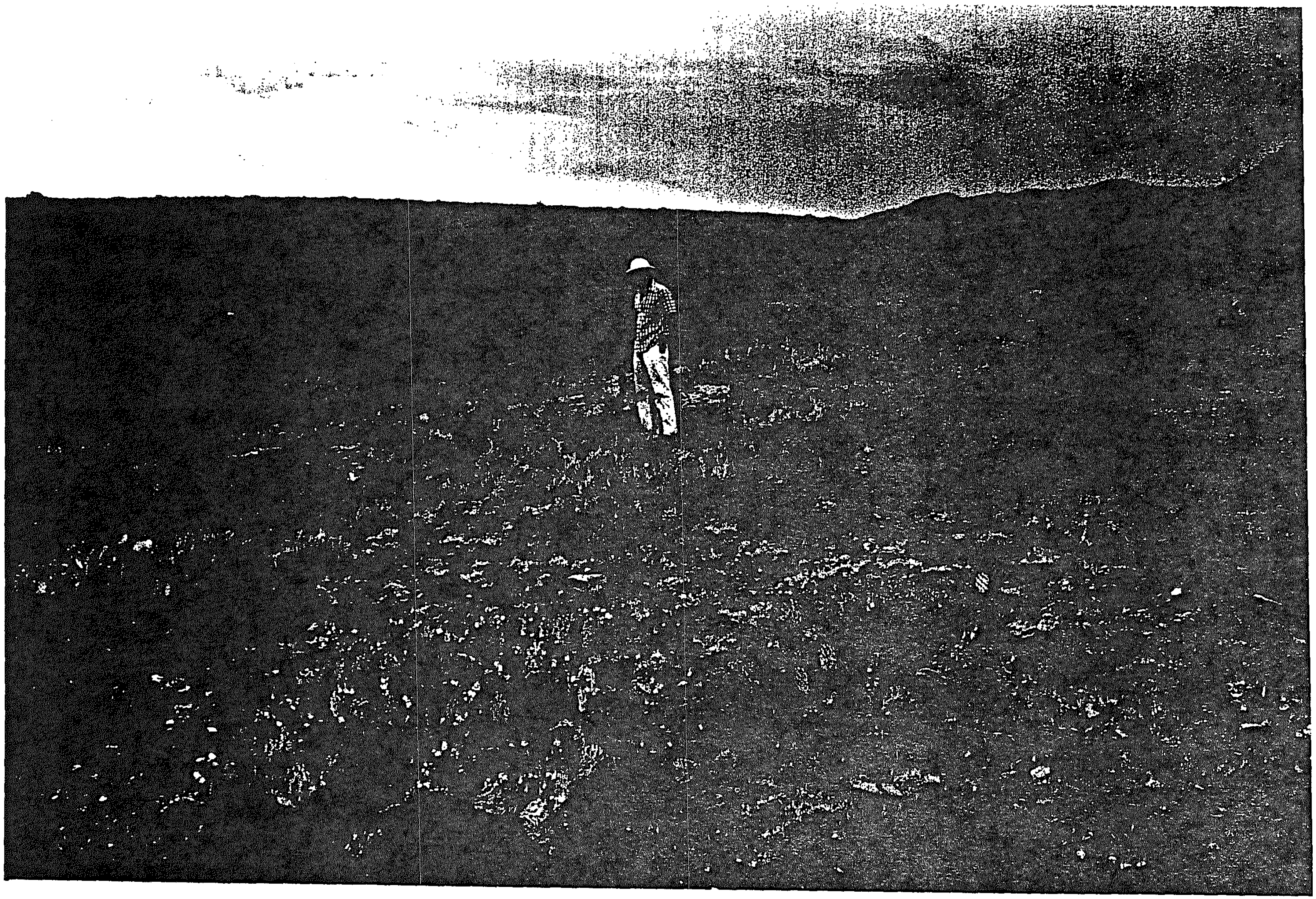


Fig. 10b.

Figure 10b

Ground view of a low scarp on a Pleistocene terrace in the Cottonwood area (not in last view). Man stands at upper edge of slope break, with sinous scarp below. Photo looks southward at the east-facing scarp. Behind man is an older Pleistocene terrace on the skyline that from helicopter reconnaissance does not exhibit the scarp.

Fig. 11a

Figure 11a

Camp Verde scarp (477-128), less than 1 kilometer south of I-17 freeway, west edge of Verde Valley. Photo looks southwesterly. Man stands at the base of a high, gradual scarp. Foreground is virtually level, perhaps due to warping of this once continuous piedmont terrace; now a small pond sometimes holds water in front of man. The piedmont slope of a few degrees is found on this Pleistocene surface both upslope and downslope of this scarp.

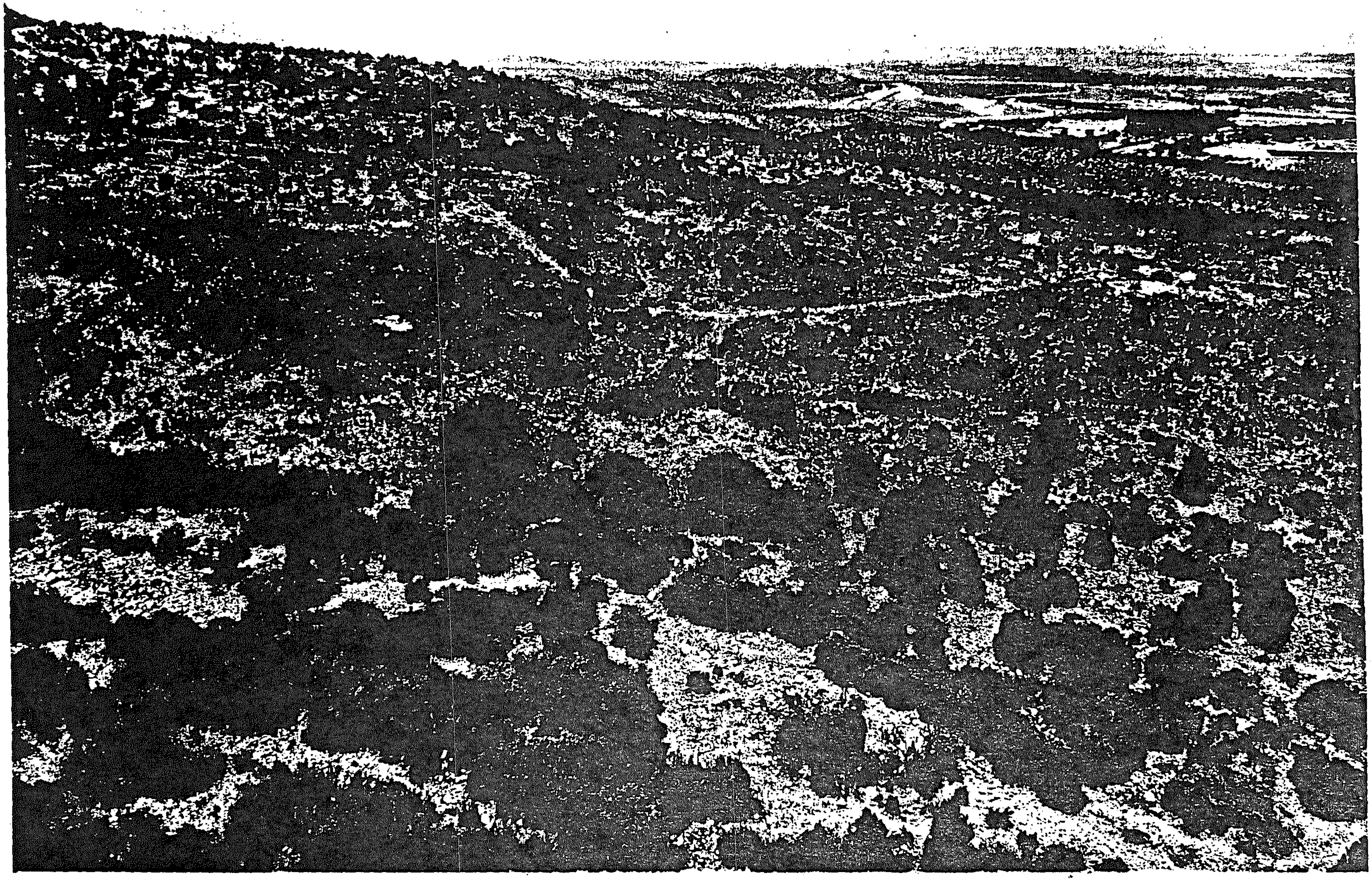


Fig. 11b

Figure 11b

Camp Verde scarp several kilometers south of Figure 9a (477-128), looking northward. East-facing scarp trends directly away from camera point, and is highlighted by a vegetation lineation that crosses the dirt road where the road takes a sharp bend. Lower elevation stream valley in foreground.

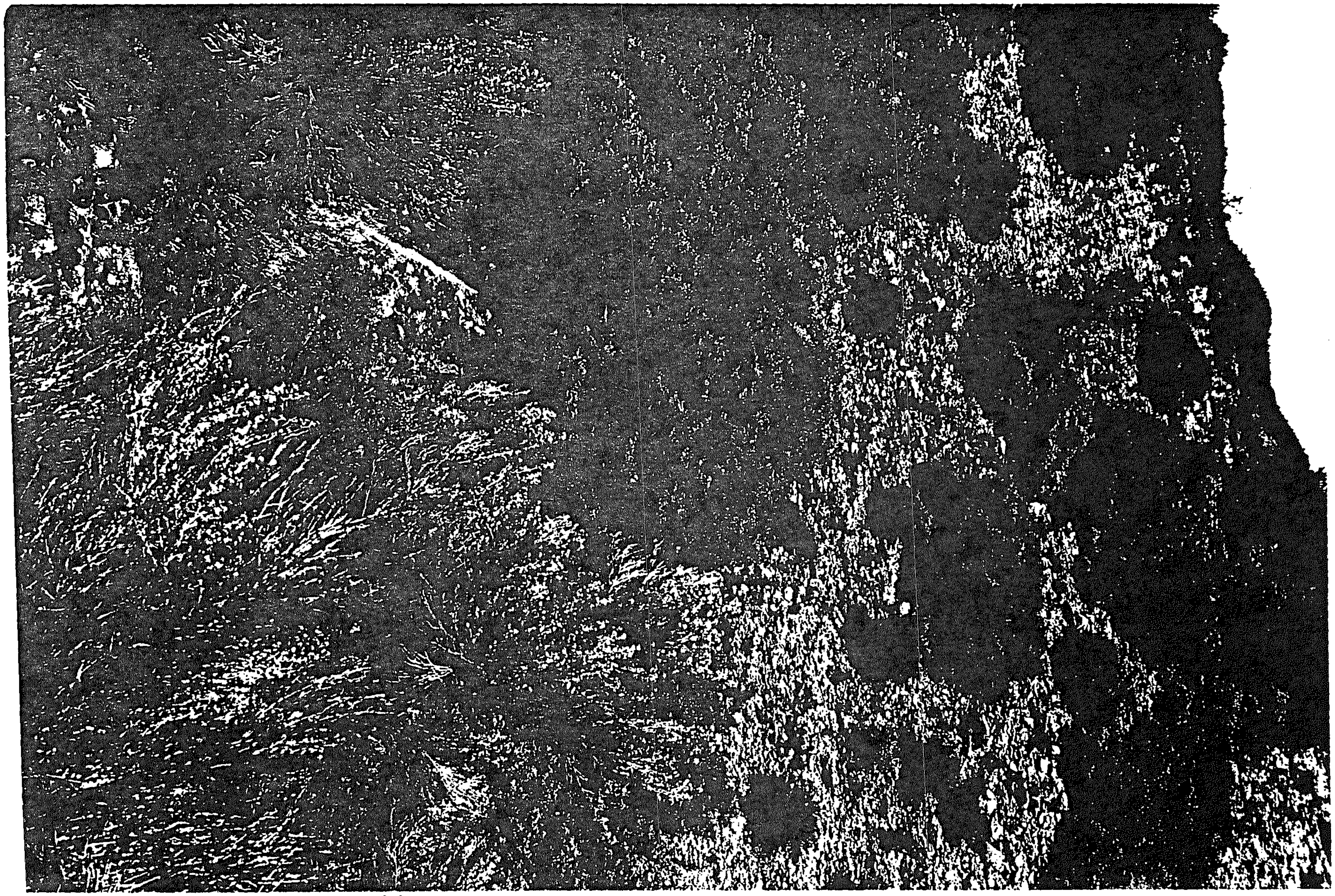


Fig. 11c

Figure 11c

Closeup of Camp Verde scarp (477-128), nearly in view on far part of scarp of Figure 9b. View shows the exposed fault plane, calichified, in bottom of small canyon, projecting up to a topographic scarp, nearly out of view in upper right hand corner. This is the scarp visible in Figure 11b. Photo looks southward.

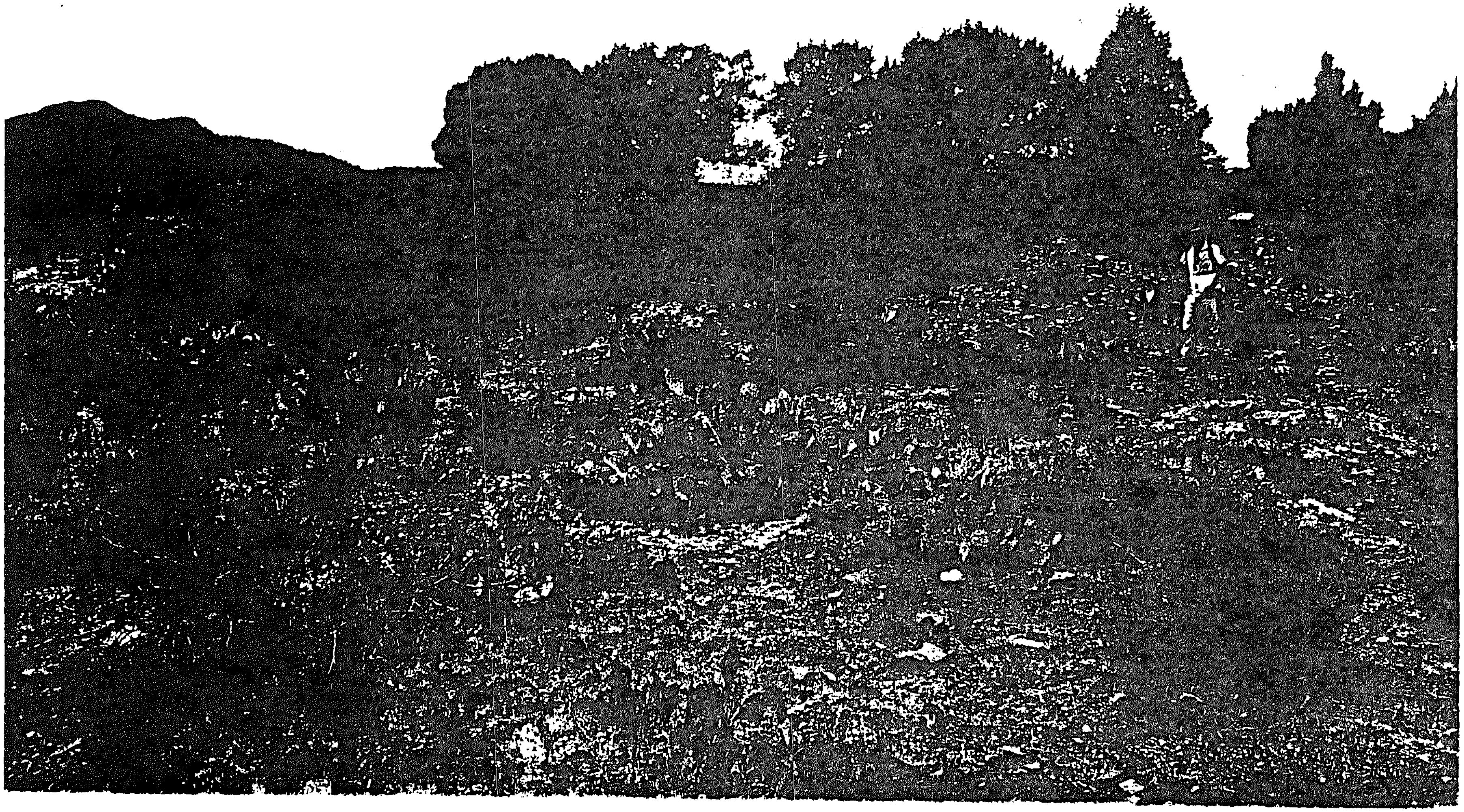


Fig. 11d

Figure 11d

Closeup of Camp Verde scarp (477-128), looking southwest. Man stands at the base of the steepest portion of an 8m high fault scarp formed by recurrent fault movement. Sideview of this scarp is shown in Figure 9c.

Figure 12

Chino Valley fault scarp, not in study area proper. Photo looks northward. The main fault scarp through center of photo faces southwestward. Also easily seen is a graben on the downthrown side (west, or left side) of the fault. The sedimentary fill of the graben is far less vegetated than the surrounding areas to the extent that one can easily see the track of the antithetic fault that defines the west edge of the graben.

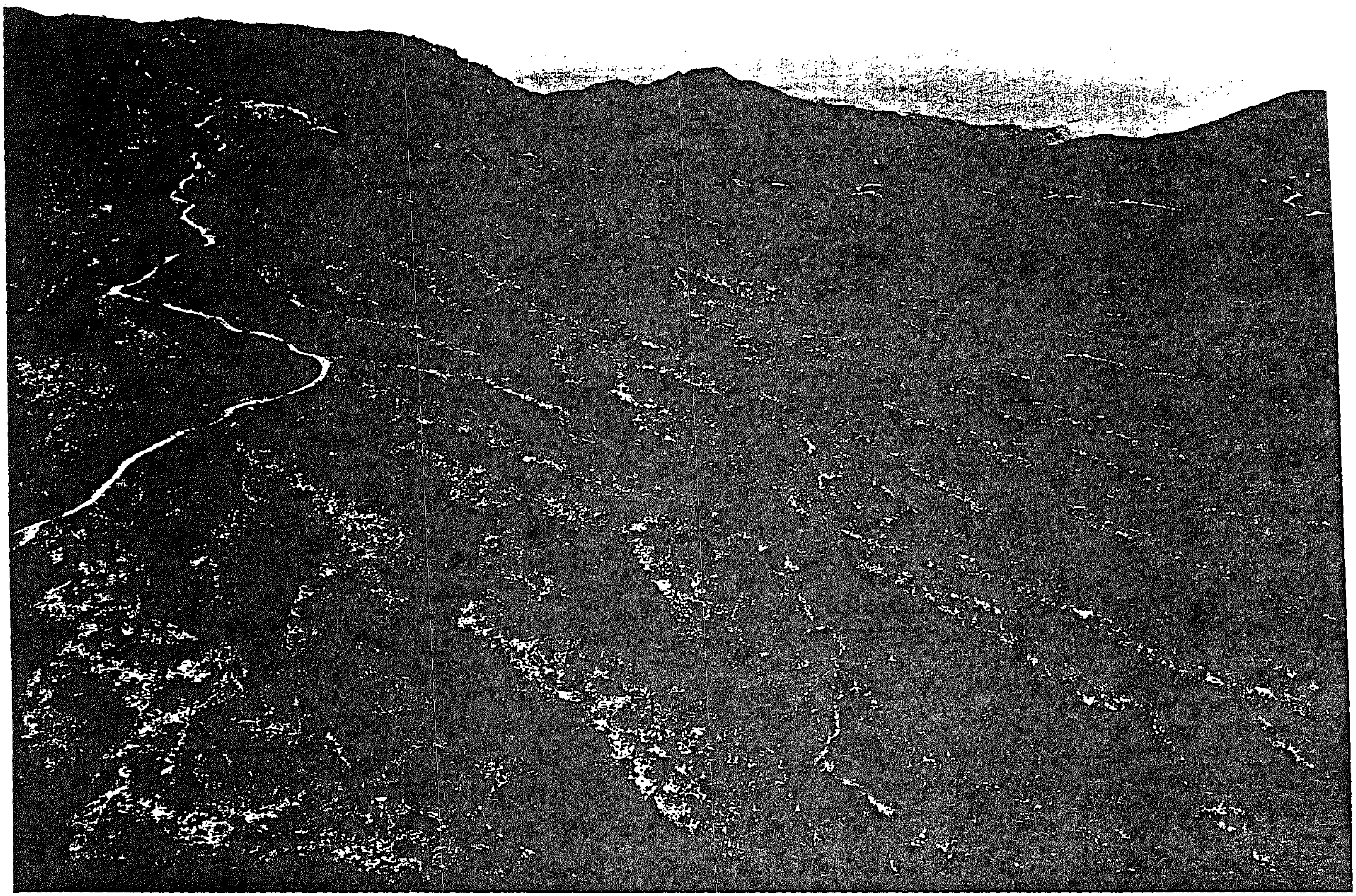


Fig. 13

Figure 13.

Highly dissected topographic scarp on grus-covered granite pediment south of Horseshoe Lake and northwest of Bartlett Dam (53-68). Scarp runs directly away from camera point through center of photo. Main drainage direction here is southerly; scarp trend is northeasterly, parallel to photo look direction. Scarp stands out on vertical aerial photos.

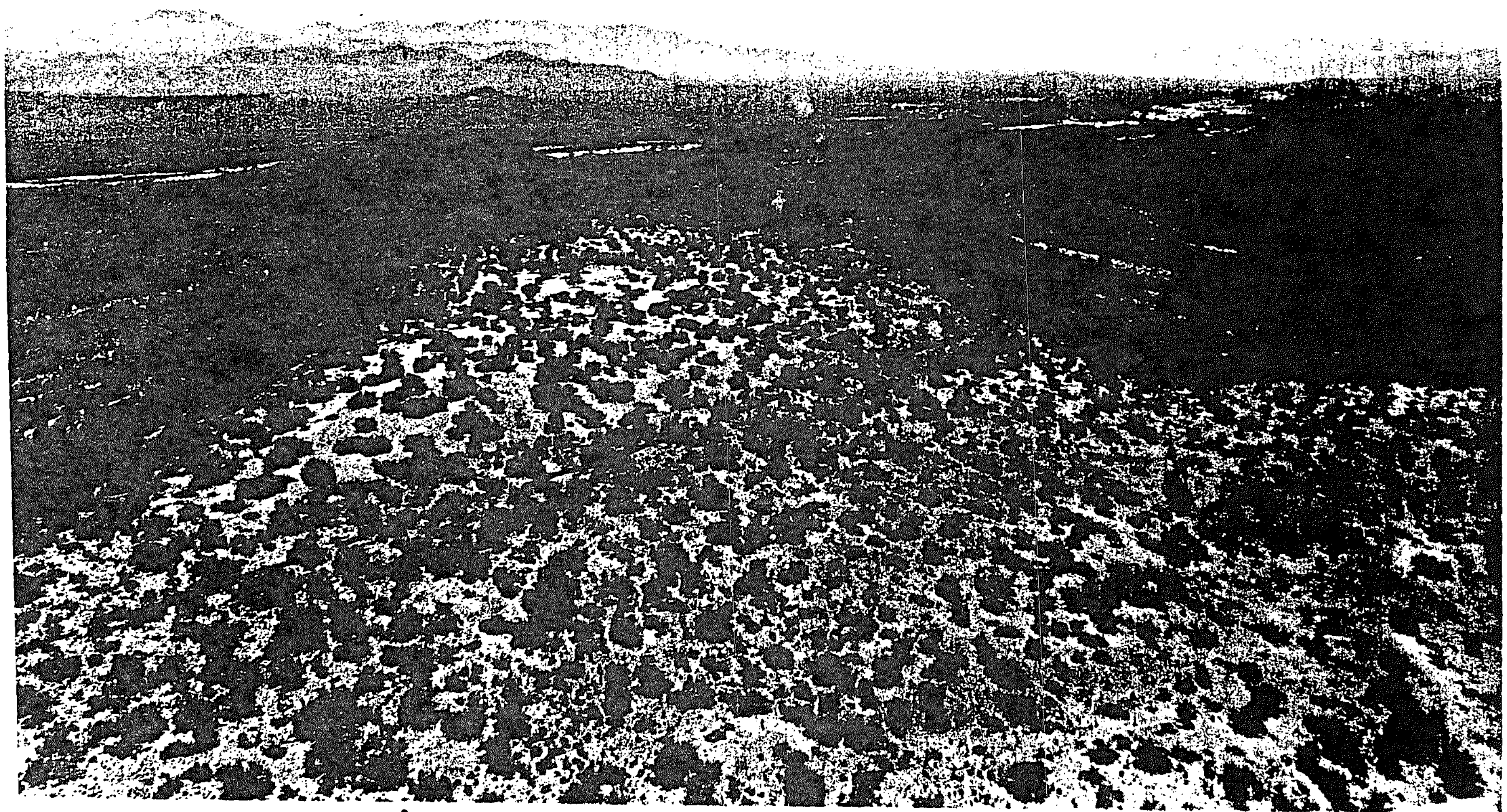


Fig. 14

Figure 14

Scarp in Tonto Basin (59-292), north of the graben feature noted in Figure 6. Photo looks southeasterly toward Tonto Creek (visible) and the Sierra Ancha. Scarp lies on a high-level Pleistocene surface, roughly one-third the way from the valley center toward the mountain front, and is west-facing, even though it is on the west side of the valley. The scarp bends just before reaching the stream valley on the right side of the photo, and the scarp then parallels the upper edge of the valley. It is likely that this feature is a terrace scarp, not tectonically produced. Dashed line follows upper edge of scarp.