Tectonic Geomorphology of the Luke Air Force Range, Arizona

by

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Abstract

In arid and semiarid regions the relative rates of tectonic activity and the approximate age of the last major tectonic pulse can be ascertained by analyzing the landforms of the mountain fronts and their adjacent piedmonts. Tectonic activity triggers a change in the base level of fluvial systems that causes the development of a characteristic suite of landforms. It is these landform characteristics that are examined in making a tectonic geomorphic analysis of an area.

The Luke Air Force Range, an Air Force missile and gunnery training range in southwestern Arizona, is an area of typical basin-and-range topography of generally linear mountain ranges separated by broad, flat valleys. While overall the ranges are quite linear, the mountain fronts are, for the most part, highly sinuous, pedimented, and lacking a thick accumulation of recent alluvial material on the piedmont.

A tectonic geomorphic analysis of the Luke Air Force Range shows that the area has been almost entirely free of tectonic activity for at least the Holocene and Pleistocene epochs and probably for part of the Pliocene. A few mountain-front segments show signs of slight tectonic activity during the Pleistocene. One mountain-front segment displays landforms indicative of tectonism continuing into the Holocene.

Introduction

Southwestern Arizona has had a long history of tectonic and igneous activity. Large bodies of granite were intruded during the late Mesozoic which metamorphosed the preexisting sedimentary and metamorphic rocks. In the early and middle Tertiary violent volcanic eruptions poured out small, steep-sided flows of andesite and latite and blasted pyroclastic materials onto the adjacent landscape. A quieter phase of basaltic volcanism followed and covered a wider area than the previous activity. Middle to late Tertiary high-angle normal faulting broke southwestern Arizona into horsts and grabens, which resulted in linear, northwest-trending mountain ranges separated by broad, down-faulted basins. There were some minor basalt flows along some of these faults, apparently toward the end of the period of basin-and-range faulting. Additional basalt flows were poured out during the late Tertiary and early Quaternary. These flows were widely separated and apparently unrelated by either location or orientation to the basin-and-range faulting.

The major portion of the basin-and-range tectonism can be dated with fair reliability using the volcanic rocks and their relationship to the faulting as a guide. Volcanic rocks that are clearly pre-faulting, being either ruptured by the basin-and-range faults or uplifted to form mountain ranges, or both, fall generally into the 12-to-15-m.y.-age range (Eberly and Stanley, 1978). The volcanic rocks that are not uplifted and show no apparent evidence of faulting have ages from 3 to 1.75 m.y. in the Sentinel basalt flows (Eberly and Stanley, 1978) and from 1.0 m.y. to very recent in the Pinacate volcanic field (Lynch, pers. comm., 1979). This brackets the major, widespread, basin-and-range faulting fairly well as being within the 3-to-15-m.y. age range. However, the indicators for the cessation of regional faulting do not exclude the possibility that localized faulting could have occurred later than approximately 3 m.y. B.P.

The area of the Luke Air Force Range, which is the area being considered in this tectonic geomorphic analysis, has had five seismic events greater than magnitude 4 recorded in recent times. The dates, locations, and magnitudes are shown on Figure 1. The sources of these recent events and the existence of surface ruptures are presently un-

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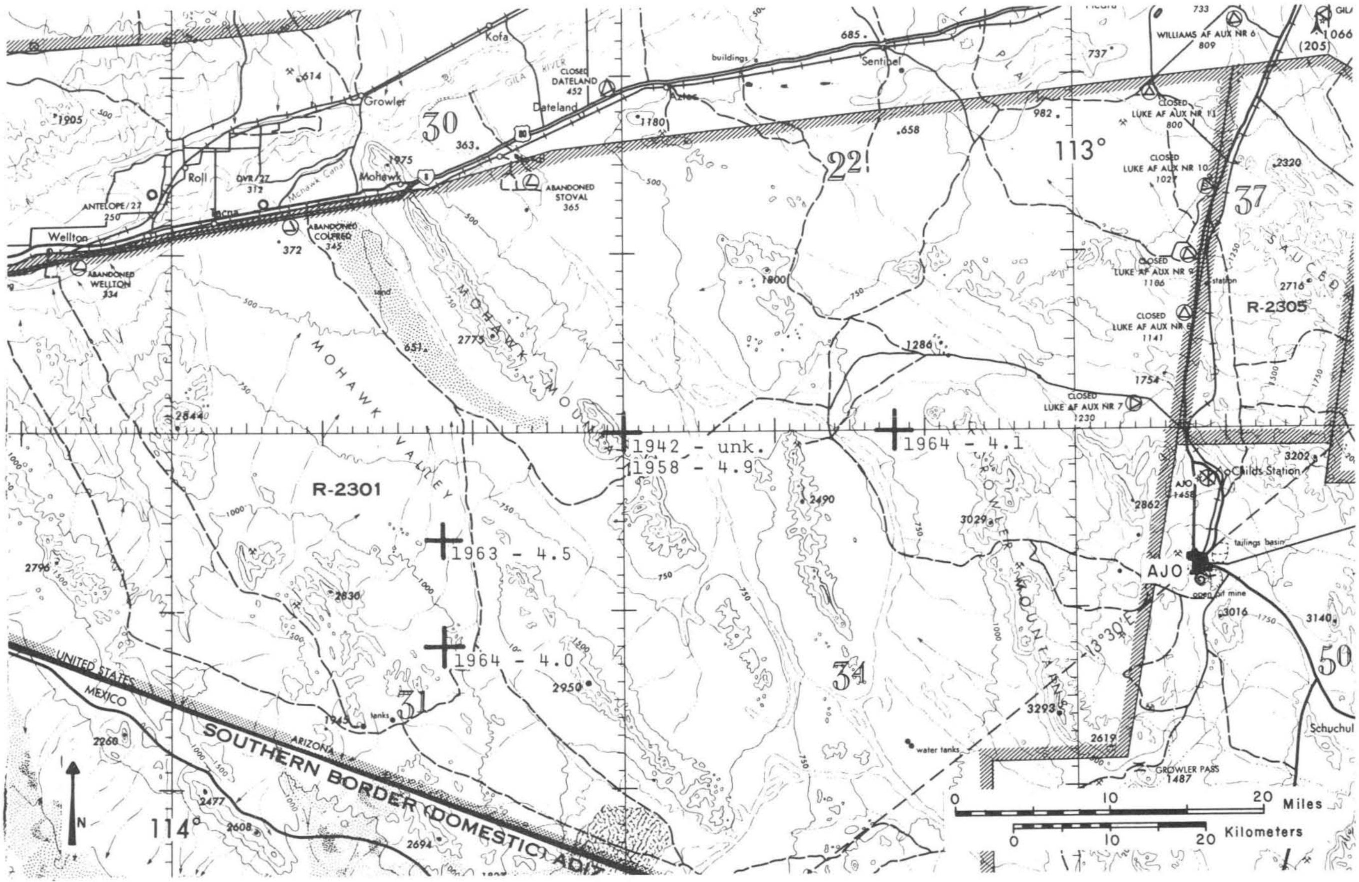

Fig. 1. Recent seismic events within the Luke Air Force Range. Year and magnitude of the event are given at each approximate epicenter location. -- Source: Bureau of Reclamation (1976).

known, but their occurrence, together with the proximity of known active tectonism along the nearby San Andreas fault—Salton trough—Gulf of California rifting, provides evidence for the possibility of tectonic activity in the area.

Many variables act together to form arid fluvial systems. Tectonic activity is the trigger that sets off the independent variable of tectonic base-level change. If tectonic activity causes a stream's base level to fall along part of its reach, the stream will erode more aggressively upstream from the point or points of ground rupture, will create fresh deposits of coarse clastics downstream from that point, and will transport these coarser clastics a longer distance downstream than would otherwise be possible with all other independent variables being the same. The presence of tectonic activity has partly controlled sedimentation, both from the standpoint of particle sizes as well as their areal distribution.

This report applies the concepts of tectonic geomorphology through landform analysis to assess the relative tectonic activity of mountain fronts or other structural elements during the Quaternary. In particular, it evaluates the areal variations in relative uplift of mountain fronts within the Luke Air Force Range portion of southwestern Arizona and applies this evaluation of late Cenozoic tectonism of the area to determine its effect on the distribution and nature of fluvial sediments. The analysis covers the entire 13,500 km^2 (5,200 mi^2) area of the Luke Air Force Range.

Evaluation of past tectonic activity has two important applications: seismic and sedimentologic. Tectonic geomorphic analysis has the potential for indicating which faults within a given study area have been active, including faults that have not been mapped by previous workers.

Rate of Tectonic Activity

The rate of tectonic activity within a given mountain range is an important factor in determining the size and rate of production of sediment from fluvial systems that originate within the mountain range and deposit their sedimentary load within the adjacent basin. Consider two different tectonic settings. The first is tectonically active: rapid uplift at the mountain front has resulted in rugged mountains with steep V-shaped canyons plunging down to the stream courses that transport sediment. In such a setting, coarse-grained sediments are produced in abundance and delivered directly from the hillslopes into the stream subsystem where they are immediately available for transport to the basin.

In a second setting of tectonic quiescence, the hillslopes are steep, but embayed mountain fronts and broad valley floors are typical. In this setting, gravel brought down from the hillsides to those reaches of the streams that have a U-shaped cross-valley profile is not generally delivered directly to the basin. Instead, it remains on the flat valley floor and only the gradual weathering of these boulders reduces the particle size to that which can be transported from the mountain subsystem to the depositional basin. Within a region tectonically active in the past and generally inactive during the Quaternary such as the Luke Air Force Range, one should expect to find fine-grained basin fills overlying coarser basin fills that were deposited at a time when the mountain fronts were tectonically active.

Local Base-level Processes

A process that changes the altitude of a point on a streambed is a local base-level process. Base-level processes include stream-channel downcutting in the mountains (w) and erosion (e) or deposition (s) on the piedmont. These three processes are interdependent and are affected by the relative uplift (u) of the mountain front. These four base-level processes, since they affect the activity and form of the stream, the hillslope development, and the location of deposition and erosion, are responsible for the topography of the basins (Bull, 1973).

The effects of continued and rapid uplift of mountains relative to the adjacent basins, either by continuous or pulsatory uplift, result in a distinctive suite of landforms. Figure 2 depicts the accumulation of thick alluvial-fan deposits adjacent to a faulted mountain front. Channel downcutting in the mountains will tend to cause the stream channel to become entrenched into the fan apex, which will cause the locus of deposition to be shifted downslope on the fan. Uplift of the mountains relative to the piedmont counteracts the tendency to entrench the stream channel into the fanhead. Continued channel downcutting in the mountains without trenching the fanhead can occur if the rate of uplift equals or exceeds the sum of the two local base-level processes that are tending to cause the fanhead trenching, as shown by Equation 1:

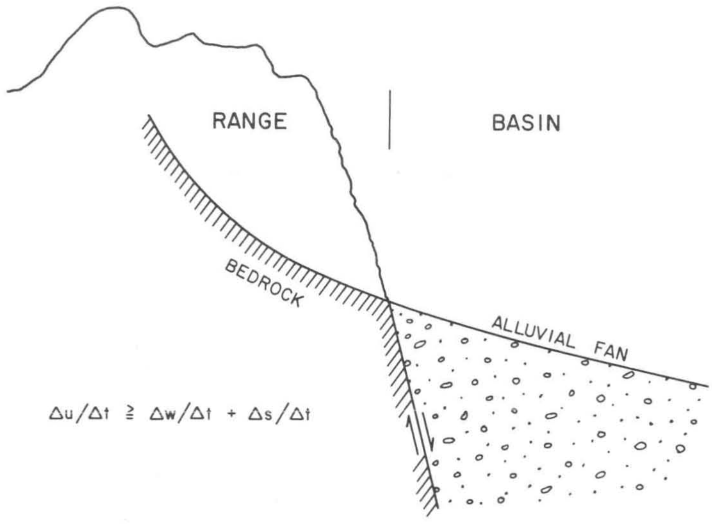

Fig. 2. Interrelations of local base-level processes conducive for the accumulation of thick alluvial-fan deposits next to a mountain front (Bull, 1973)

$$\Delta u/\Delta t \geqq \Delta w/\Delta t + \Delta s/\Delta t \qquad (1)$$

Equation 1 is one of five equations interrelating local base processes for the three different tectonic environments. The five equations shown in Table 1 form the basis of the three classes of relative tectonic activity of mountain fronts within a given study area during the Quaternary.

Tectonic Activity Classes

The assignment of a tectonic activity class for a given mountain front is based on parameters that describe diagnostic landform morphologies within both the erosional and depositional subsystems. The landforms described in Table 1 are only a few of the many diagnostic landforms for a given class. For example, Class 1 landscapes have more convex ridge crests, steeper footslopes, narrower and steeper canyons, less sinuous mountain fronts, thicker basin deposits next to the mountains, better preserved spur facets, and less soil-profile development on the piedmont than Class 3 landscapes (Bull, 1973). Thus, the tectonic geomorphology model defines the interrelations of tectonic base-level change (uplift) to other base-level processes by the equations of Table 1 and allows the assignment of an appropriate tectonic activity class by descriptions of selected landscape elements. Class 1 fronts occur in highly active tectonic areas generally characterized by active folding or faulting during the Holocene as well as the Pleistocene. Class 2 mountain fronts show evidence of activity during the Pleistocene but not the Holocene. Class 3 mountain fronts are tectonic but were inactive

Table 1. Tectonic geomorphic processes. -- Modified from Bull (1973)

Tectonic Class[1]	Local Base-level Processes[2]	Landforms: Piedmont	Landforms: Mountain
1	$\Delta u/\Delta t \geqq \Delta w/\Delta t + \Delta s/\Delta t$	unentrenched alluvial fan, or fan with only Holocene deposits on fanhead	V-shaped cross-valley profile in bedrock
2A	$\Delta u/\Delta t < \Delta w/\Delta t > \Delta e/\Delta t$	entrenched alluvial fan with Pleistocene surfaces on fanhead	cross-valley profile V or U shaped
2B	same as above	same as above	U-shaped cross-valley profile and embayed mountain front
3A	$\Delta u/\Delta t \ll \Delta w/\Delta t > \Delta e/\Delta t$	permanently dissected pediment	embayed mountain front
3B	$\Delta u/\Delta t \ll \Delta w/\Delta t = \Delta e/\Delta t$	undissected pediment	embayed mountain front
3C	$\Delta u/\Delta t \ll \Delta w/\Delta t < \Delta e/\Delta t$	erosional base-level fall due to contrasting piedmont and mountain lithologies; may have characteristics of tectonically active mountain front	

[1]Class 1 - generally active during Holocene; Class 2 - generally active during Pleistocene, but not Holocene; Class 3 - inactive throughout Quaternary.

[2]u - uplift; w - channel downcutting; s - piedmont deposition; e - piedmont erosion; t - time.

throughout the Quaternary (Bull, 1977).

Geomorphic Parameters for Tectonic Activity

For the purposes of this study, six parameters were used that are reliable and fairly easy to evaluate:

1. Degree of slope of alluvial fans
2. Fanhead trenching
3. Age of fan surfaces
4. Sinuosity of mountain–piedmont junction
5. Valley cross section
6. Preservation of spur facets.

A knowledge of the Quaternary geology of the study area is necessary for accurate assessment of the parameters, especially the distribution of alluvial surfaces of different ages. Active deposition of thick alluvial fans next to mountain fronts is indicative of Class 1 tectonic conditions. The age of the oldest geomorphic surface next to the mountain front is a good indicator of the length of time that has passed since Class 1 tectonic conditions last prevailed (Bull, 1977).

The Holocene surfaces (Q3) preserve the bars and swales of the original stream channels and have desert pavements with varying stages of development. The bars and swales give the Q3 surfaces a plumose pattern on aerial photography.

The late and middle Pleistocene surfaces (Q2) have lost all trace of bars and swales and have smooth desert pavements. On aerial photography these surfaces have a smooth, even-toned appearance and are very light toned, almost white, if formed of alluvium derived from granitic rocks. If formed from metamorphic-derived alluvium, they are dark toned. The Q2 surfaces of volcanic-derived alluvium are very dark, almost black, due to the heavy coating of desert varnish on the rocks making up the pavement. An exception to this is found in the older Q2 surfaces where the upper soil horizons have been removed by erosion. The pavement surface is formed on the Cca horizon and is a mixture of black-coated cobbles and caliche. On aerial photography, this surface has a medium-toned, stippled appearance in contrast to the plumose patterning of the Q3 surfaces.

The Q1 deposits of early Pleistocene to Pliocene age have lost all traces of their original upper surfaces and all the soil horizons, down to the petrocalcic horizon, due to the long period of erosion to which they have been subjected. Their present topography is low, parallel ridges separated by parallel ravines (see Fig. 5). The Q1 deposits are exposed only on piedmonts where the predominant fluvial activity has been erosive. Otherwise, these Q1 deposits would have been buried by younger alluvium. Since deposition on the piedmont is one result of tectonic activity, the presence of Q1 exposed along a mountain front is a clear indication of a lack of tectonic activity, at least during most of the Quaternary.

Alluvial-fan Morphology

Alluvial-fan morphology is also a useful indicator of tectonic activity. A bajada of steep (10°) alluvial fans accumulating a thick (100 m) deposit of sediments onto a gentle piedmont slope is one clear indication of a tectonically active mountain front. Thin, gently sloping (1° to 2°) alluvial fans only slightly higher than the adjacent areas of piedmont are most likely the result of climatic perturbations. However, between these two extremes there exist many alluvial fans that could have been caused by either or both of these changes to the fluvial system. Fanhead trenching indicates that a period of time has passed since the event, whether it be tectonic or climatic, which resulted in deposition on the head of the fan. An alluvial fan whose fanhead is entrenched and displays Q3 surfaces next to the mountain front indicates that fan formation activity ceased during the Holocene. This would suggest a Class 1 mountain front, if indeed the fan was caused by a tectonic event. An entrenched, Pleistocene-surfaced fan indicates activity during the Pleistocene or a possible Class 2 mountain front. To ascertain the cause of the fans, the rest of the mountain front and stream-channel morphologies must be examined.

Sinuosity of Mountain Fronts

The sinuosity of the mountain front is the next parameter to be examined. Tectonic activity will tend to keep the front coincident with the tectonic structure so that the junction between the mountains and the piedmont is a fairly straight or gently curving line. Opposing this is the tendency for streams to erode irregularities into the mountains. Thus, with the passage of time since the last tectonic event, the mountain front will become increasingly irregular. The mountains will retreat from the frontal structure forming pediments and the canyons will become embayed. The degree of erosional modification of tectonic structures can be measured by a mountain-front sinuosity index. Mountain-front sinuosity (S) is the ratio of the length along the edge of the mountain-piedmont junction (Lmf) to the overall length of the mountain front (Ls) as shown in Equation 2 (Bull, 1977):

$$S = Lmf/Ls \qquad (2)$$

Values of S are, in part, a function of the scale and detail of the maps or aerial photographs. Values will be higher for larger scale maps and photos as opposed to smaller scale, but in either case the proportions between individual mountain fronts will remain approximately the same.

Studies made elsewhere in the Sonoran and Mojave deserts show that each of the tectonic activity classes of Table 1 has fairly distinctive ranges of mountain-front sinuosity. Class 1 fronts generally range from 1.0 to 1.6, Class 2 from 1.4 to 3, and Class 3 from 2 to more than 7 (Bull, 1977). For the purpose of this study no attempt was made to obtain numerical values for the sinuosity index, rather the sinuosity was visually estimated for each mountain front and a category assigned based on the amount of sinuosity. Low sinuosity is the category for S values from 1-2: moderate sinuosity, S values in the 2-3 range; and high sinuosity, S values greater than 3.

Mountain Valley Morphology

Next to be considered is the mountain valley morphology, particularly the valley or canyon cross section adjacent to the mountain front. Continued mountain uplift will ensure that the streams will continue to erode their valleys downward, thus maintaining V-shaped canyons. After the cessation of tectonic activity, the stream will gradually lose its ability to erode downward and will erode laterally as the hillslopes retreat, resulting in a flat-floored or U-shaped valley. Eventually, the valley will become an embayment of the piedmont. In Class 1 landscapes, the canyons are distinctly V-shaped with the channel of the stream being essentially the same width as the floor of the canyon. In Class 2 terrains, the stream channel is significantly narrower than the floor of the canyon. The canyon is still a separate entity from the piedmont and has a noticeably steeper gradient. A Class 3 valley is simply an extension of the pediment.

Preservation of Spur Facets

The last parameter is the degree of preservation of faceted spurs. In tectonically active areas the ridge spurs will appear truncated along the tectonic structure, forming triangular spur facets. These spur facets will be subjected to erosional degradation once the tectonic activity has ceased. In Class 1 landscapes, the faceted spurs will be well preserved and easily discernible, since their faces will not have been subjected to the ravages of erosion. In Class 2 landscapes, the faceted spurs will be deeply gullied and dissected by streams. By the time Class 3 conditions have been reached, the faceted spurs will have been obliterated.

An exception to the normal tectonic geomorphic scheme that has been outlined here is the situation that can sometimes occur if there has been a drastic increase in the rate of erosion on the piedmont side of the mountain-bounding fault. If the fault is also a lithologic boundary, with the rock type on the piedmont side of the fault being considerably more easily eroded than the rock on the mountain side, there could be an erosional base-level fall with the fault as its mountain-side boundary. This would result in seemingly Class 1 landforms such as active alluvial fans, V-shaped valleys, and even faceted spurs, all of them lined up quite nicely along a mountain front that is otherwise Class 3. While the boundary between the contrasting lithologies does not necessarily have to be a fault, a non-fault contact would probably not have the distinct linearity of a fault. Close scrutiny of the total geologic and geomorphic situation is required to correctly analyze such a mountain-front base-level fall of strictly erosional, nontectonic origin. This type of mountain front is Class 3C on Table 1. While this type of front is tectonically inactive, it still represents a base-level fall and thus affects sediment distribution in much the same manner as a tectonically active front.

Strike-slip faulting presents a much different problem in tectonic analysis than does faulting of a primarily vertical nature. Strike-slip faulting that has only a small vertical component to change the base level of fluvial systems will not display the typical landforms of a tectonically active mountain front. Instead, strike-slip faulting will result in landscape features such as disrupted drainage patterns and offset ridge lines. Identification of strike-slip faulting is included in this report to give a more complete picture of the Quaternary tectonism of the study area and because some of the faults that were active during the late Cenozoic within the Luke Air Force Range probably had a strike-slip component.

Method of Analysis

A thorough search of the entire study area was made using the largest scale (1:24,000 and 1:62,500) topographic maps available. Mountain fronts with low to moderate sinuosity and marked linearities within the mountain areas were noted on both the large-scale maps and also on a 1:250,000-scale map of the entire study area. The available aerial photographic coverage was then plotted on the 1:250,000-scale map to facilitate the determination of which photos could be used to study a given area. Figure 3 shows the photographic coverage. From the aerial photographs, the mountain fronts were qualitatively described and evaluated for the geomorphic parameters that would indicate their tectonic activity class. Receiving particular scrutiny were those fronts that the topographic map search showed to have low to moderate sinuosity and other landforms suggestive of tectonic activity. Also analyzed was the interior of the mountainous areas to determine if there was any evidence of active tectonism or rejuvenation of old faults. The basin and piedmont areas were scanned for any disruption of drainage patterns or scarps that might indicate tectonic activity. To fill in the gaps in the aerial photographic coverage and to obtain a closer and more complete look at selected areas, an aerial reconnaissance and photographic survey was made of the entire study area on December 3, 1978.

Tectonic Geomorphology of the Luke Air Force Range

In this section, each mountain range and its mountain fronts are described in detail and evidence presented for the assignment of the individual mountain front segments to a tectonic activity class. Figure 4 shows the location of the mountain-front segments studied and their activity classes. Table 2 gives a summary of the tectonic geomorphology. Mountain fronts that are not assigned a tectonic activity class are judged to be either nontectonic in origin or lacking signs that would indicate tectonic origins. Individual mountain fronts are referenced with a letter (E for east, N for north, etc.) indicating the side of the mountain range that the front is on and a number to indicate the numerical order of the front segment from north to south or west to east.

Gila Mountains

The Gila Mountains are located close to the Gila and Colorado Rivers, which both show a history of downward erosion of their valleys (Hunt, 1969). The streams that drain the Gila Mountains empty into the Gila River causing a continual lowering of the base level of these streams. By lowering the base level, the streams have eroded deep channels through a sequence of alluvium that covers the entire Quaternary and perhaps into the latest Tertiary time as well (see Fig. 5). The exposure of this broad range of alluvial material with the oldest abutting directly against the mountain front indicates that the fluvial systems of the Gila Mountains have throughout the Quaternary experienced pulses of headward erosion along their entire reaches from the Gila River to the ridge crests of the mountains. There is no sign of any tectonic activity that would have caused the deposition of fresh alluvium along the mountain fronts and buried the older deposits.

Front E2, also known as the Sheep Mountain fault, is often referred to as an active mountain

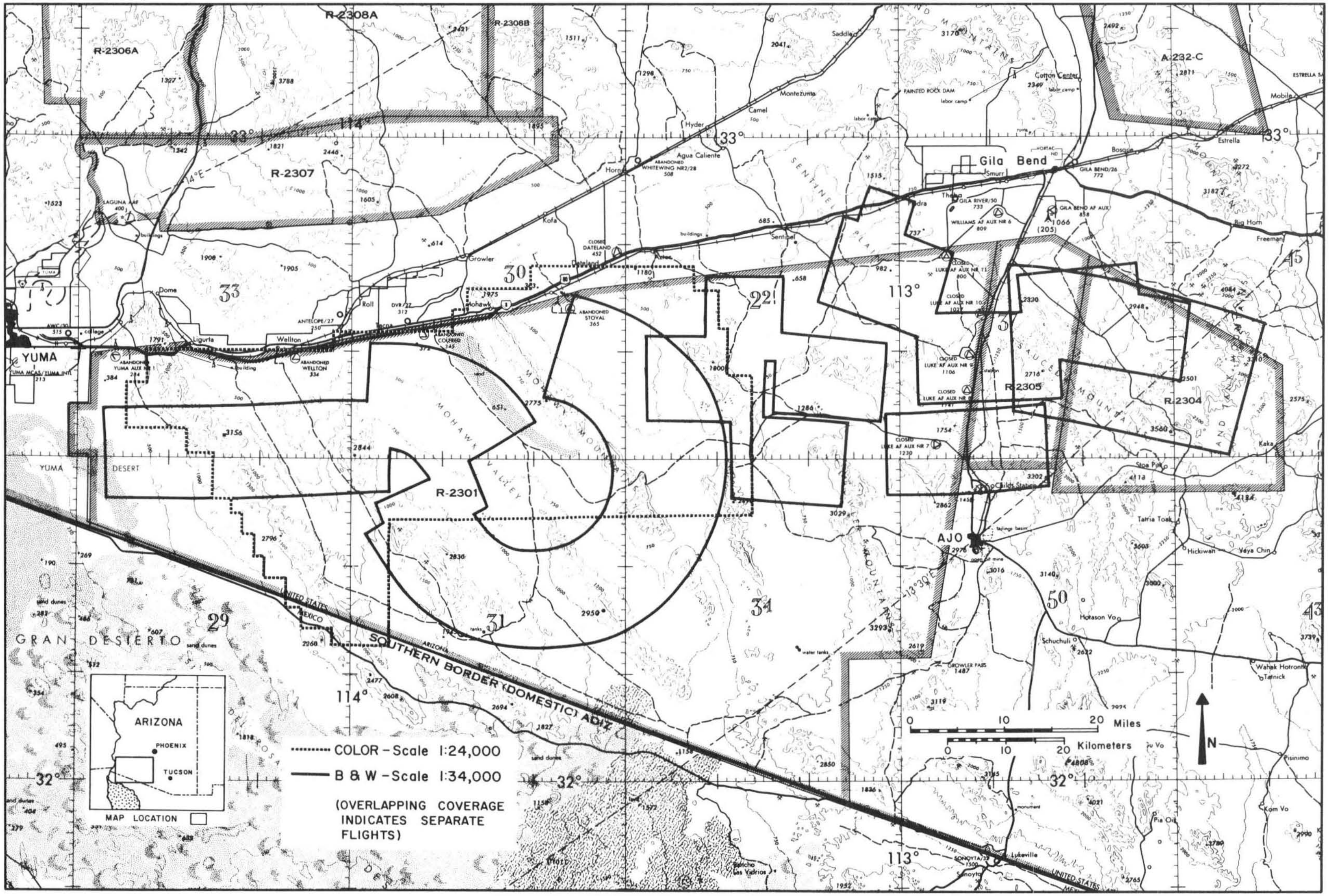

Fig. 3. Aerial photography coverage of the Luke Air Force Range, Arizona

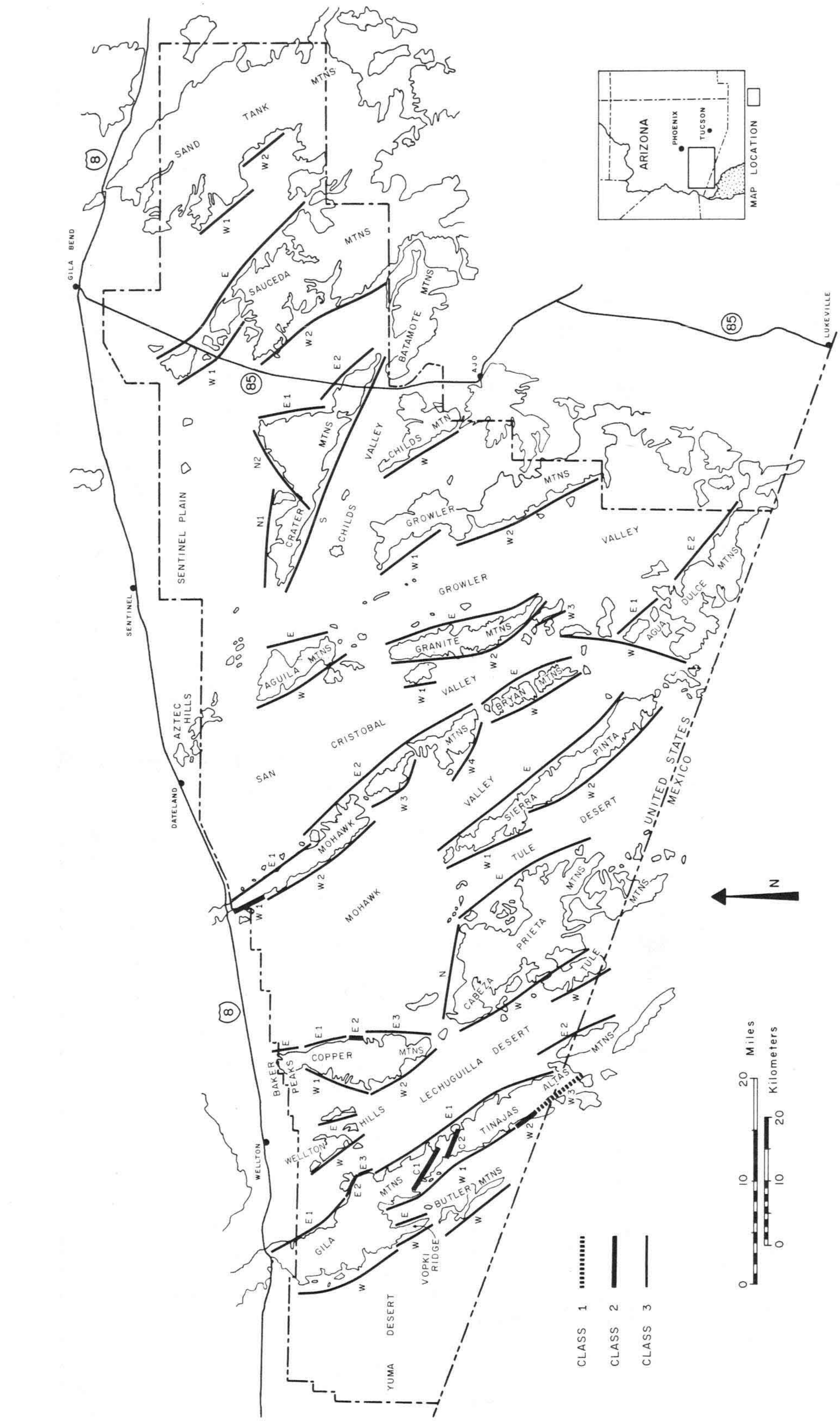

Fig. 4. Tectonic activity of the Luke Air Force Range, Arizona

Table 2. Tectonic geomorphic summary of the Luke Air Force Range

Mountain Front Segment[1]	Alluvial Landforms[2]	Fanhead Surface	Mtn-Front Sinuosity[3]	Valley X-Section	Triangular Facets	Tectonic Class	Remarks
Gila Mts.							
W	dissected fans, pediment	Q1	high	U-shape	none	3B	
E1	dissected fans, terraces	Q1	high	U-shape	none	3B	
E2	small high-angle fans	Q3	low	V-shape	dissected	3C	contrasting lithology, accelerated piedmont erosion
E3	dissected fans, pediment	Q2	high	U-shape	none	3B	
Vopki Ridge							
W	dissected fans	Q2	high	U-shape	none	3B	
E	backfilled valleys	none	high	U-shape	none	3B	east side of ridge buried by alluvium from Gila Mts.
Butler Mts.							
W	streams flow across range	none	high	U-shape	none	3B	range is buried by alluvium from Gila-Tinajas Altas Mts.
Gila-Tinajas Altas Mts.							
W1	low-angle entrenched fans	Q2	moderate to high	U-shape	dissected to none	3B	
E1	low-angle entrenched fans	Q2	high	U-shape	none	3B	
C1	medium-angle entrenched fans, disrupted drainage, backfilled valley	Q2-Q3	moderate	U-shape	dissected	2B	interior fault, possibly strike-slip; shows disruption of drainage patterns
C2	low-angle fans, entrenched and unentrenched	Q2-Q3	low	U-shape	undissected	2A	interior fault, possibly left-lateral strike-slip; ridgeline offsets same sense and amount
Tinajas Altas Mts.							
W2	low-angle entrenched fans	Q2-Q3	moderate	U-shape	dissected	2B	
W3	high-angle slightly entrenched fans	Q3	low	V-shape	dissected	1	short (5 km) front segment, very low sinuosity, no contrasting lithology to account for base-level fall
E2	exhumed pediment	Q2	high	U-shape	none	3A	

Table 2. Tectonic geomorphic summary--*Continued*

Mountain Front Segment[1]	Alluvial Landforms[2]	Fanhead Surface	Mtn-Front Sinuosity[3]	Valley X-Section	Triangular Facets	Tectonic Class	Remarks
Wellton Hills							
W	pediment embayments almost no fan activity	Q2	moderate	U-shape	none	3B and 3A	range partially buried in alluvium
Baker Peaks							
E	entrenched low-angle fans, exhumed pediment	Q2	high	U-shape	none	3B	
Copper Mts.							
W1	exhumed incised pediment, embayed valleys	Q2	high	U-shape	none	3A	
W2	entrenched low-angle fans	Q2	high	U-shape	none	3B	
E1	low-angle entrenched fans	Q2	moderate	U-shape	none	3B	
E2	moderate- to low-angle entrenched fans	Q2	moderate	U-shape	dissected	2B/3B	signs of activity very slight
E3	low-angle entrenched fans	Q2	high	U-shape	none	3B	
Cabeza Prieta Mts.							
W		Q2	high	U-shape	none	3B	
N		Q2	high	U-shape	none	3B	
E		Q2	high	U-shape	none	3B	
Tule Mts.							
W	dissected pediment		high	U-shape	none	3A	
Sierra Pinta							
W1	low-angle entrenched fans	Q2	high	U-shape	none	3B	
W2	low-angle entrenched fans	Q2	high	U-shape	none	3B	
E	low-angle entrenched fans	Q2	high	U-shape	none	3B	
Mohawk Mts.							
W1	high-angle entrenched fans	Q3	moderate	U-shape	dissected	2B	Holocene fan accumulation and thickness of deposits suggest Pleistocene activity
W2	moderate- to low-angle entrenched fans	Q2-Q3	high	U-shape	none	3B	
W3	moderate- to low-angle entrenched fans	Q2-Q3	high	U-shape	none	3B	

Table 2. Tectonic geomorphic summary—*Continued*

Mountain Front Segment[1]	Alluvial Landforms[2]	Fanhead Surface	Mtn-Front Sinuosity[3]	Valley X-Section	Triangular Facets	Tectonic Class	Remarks
Mohawk Mts.							
W4	low-angle entrenched fans	Q2	high	U-shape	none	3B	
E1	moderate- to high-angle entrenched and unentrenched fans	Q3	high	U-shape	none	3B	fans are thin, probably resulting from climatic changes
E2	low-angle entrenched fans, pediments	Q2	high	U-shape	none	3B	
Bryan Mts.							
W	low-angle entrenched fans	Q2	high	U-shape	none	3B	
E	low-angle entrenched fans	Q2	high	U-shape	none	3B	
Aguila Mts.							
W	low-angle fans, some entrenchment	Q2-Q3	high	U-shape	none	3B	
E	low-angle entrenched fans	Q2-Q3	high	U-shape	none	3B	
Granite Mts.							
W1	low-angle entrenched fans	Q2	high	U-shape	none	3B	
W2	low-angle entrenched fans	Q2	high	U-shape	none	3B	
W3	low-angle entrenched fans	Q2	high	U-shape	none	3B	
E	low-angle entrenched fans	Q2	high	U-shape	none	3B	
Agua Dulce Mts.							
W	pediment embayments, low-angle fans	Q2	high	U-shape	none	3A/3B	
E1	low-angle fans	Q2	high	U-shape	none	3B	
E2	moderate- to low-angle entrenched fans	Q2	high	U-shape	none	3B	
Growler Mts							
W1	low-angle fans	Q2	high	U-shape	none	3B	
W2	moderate- to low-angle entrenched fans	Q2	moderate	U-shape	none	3B	numerous slump blocks along north half of front
Childs Mt.							
W	moderate-angle entrenched fans	Q2	moderate	U-shape	none	3B	fans thin

Table 2. Tectonic geomorphic summary--*Continued*

Mountain Front Segment[1]	Alluvial Landforms[2]	Fanhead Surface	Mtn-Front Sinuosity[3]	Valley X-Section	Triangular Facets	Tectonic Class	Remarks
Crater Mts.							
S	moderate- to low-angle entrenched fans	Q2	moderate	U-shape	none	3B	
N1	low-angle fans	Q2-Q3	high	U-shape	none	3B	
N2	low-angle fans	Q2-Q3	high	U-shape	none	3B	
E1	low-angle fans	Q2-Q3	high	U-shape	none	3B	
E2	dissected pediment	none	high	U-shape	none	3A	
Sauceda Mts.							
W1	low-angle fans	Q2	high	U-shape	none	3B	
W2	no fans	none	high	U-shape	none	3B	mountains well dissected
E	fans low-angle to nonexistent	Q3 where present	high	U-shape	none	3B	
Sand Tank Mts.							
W1	no fans	none	high	U-shape	none	3B	
W2	low-angle fans	Q1	high	U-shape	none	3B	fans well dissected

[1]Key: W - west; E - east; N - north; S - south; C - central (interior fault scarp). Fronts numbered generally north to south and west to east.

[2]Low-angle fans - surface slope 1° - 2°; moderate-angle fans - surface slope 2° - 5°; high-angle fans - surface slope > 5°.

[3]Sinuosity index (see Equation 2, text): low sinuosity - S = 1 to 2; moderate sinuosity - S = 2 to 3; high sinuosity - S > 3.

Fig. 5. Gila Mountains front E1. Class 3B tectonic activity. Q1 Pliocene/Pleistocene alluvium next to mountain front.

front (Fugro National, Inc., 1975). The front has low sinuosity and faceted spurs, and the alluvial fans are quite steep (Fig. 6). However, close inspection of this front shows that outcrops of bedrock stick up between and even through the fans, some 200-meter-high hills are less than 1 km onto the piedmont from the fault, and there is a profound lithologic contrast between the mountains and the piedmont. The mountains are granite and the piedmont is amphibolite, which immediately adjacent to the mountain front is highly sheared, even mylonitic in places, and offers little resistance to erosion (Tucker, Steiner, and Budden, 1974). This is an example of aggressive headward stream erosion compounded by contrasting lithologies, which has resulted in an erosional scarp along an old, inactive fault having many of the geomorphic characteristics of an active mountain front.

Fig. 6. Gila Mountains front W2. Class 3C erosional scarp.

Vopki Ridge

Vopki Ridge has an overall linearity that suggests tectonic origins; however, the mountain fronts themselves are quite sinuous with the valleys well embayed with alluvial fills. Both fronts are buried in alluvium, the east front more so than the west.

Butler Mountains

Here is much the same situation of alluvium-buried mountains as Vopki Ridge but carried to extremes. The Butler Mountains are little more than a collection of inselbergs sticking up through the alluvial cover that has been washed down from the Gila and Tinajas Altas Mountains.

Gila–Tinajas Altas Mountains

Fronts W1 and E1 both display the same sort of features with low-angle, entrenched, Pleistocene-surfaced fans and high front sinuosity (Fig. 7) as well as a liberal sprinkling of pediment inselbergs across the piedmont. All of these landforms point to a lack of Quaternary tectonism for these fronts. One Holocene fan along front E1 makes its anomalous intrusion onto this scene, but this fan has been caused by a stream that changed course sometime in the late Pleistocene or early Holocene to cross a ridge spur, increased its gradient and sediment load, and deposited this alluvium onto the older piedmont surfaces. The two interior scarps of C1 and C2 show a somewhat different situation from the normal mountain fronts. Scarp C1, running mostly along the west side of the Gila Mountains and into Cipriano Pass, displays a markedly reduced amount of sinuosity when compared to the exterior fronts. It has triangular facets with only a moderate amount of stream dissection. The alluvial fans along this scarp have a very gentle slope, which tends to indicate a lack of vertical movement along this fault. In the Cipriano Pass area, there are some anomalous stream patterns. Backfilling with Pleistocene and Holocene alluvium is associated with this scarp. The tectonic activity along C1 was during the Pleistocene and was probably strike-slip. Scarp C2 is much the same situation as C1 except that it is marked by a line of offset ridge lines between the southwest end of Cipriano Pass and the south end of Raven Butte. All of these ridge line offsets are of the same sense (left-lateral) and of roughly the same amount (0.2 km). The facets formed by these offset ridges are largely undissected, but the intervening, Pleistocene-surfaced valleys show no disturbance or drainage pattern offset.

Tinajas Altas Mountains

Front W2 shows signs of increasing tectonic activity to the southeast with a progressive decrease in sinuosity and narrowing of valleys.

Fig. 7. Tinajas Altas Mountains, south end of front E1. Typical class 3B landscape.

The fanheads show enough Q2 surfacing to indicate Pleistocene activity. At the northwest end of W2 is a large abandoned alluvial fan with Holocene fanhead deposits (Fig. 8). The stream that built up this fan has been pirated and now enters the piedmont further to the northwest. This unusual feature may owe its origin to the apparent Pleistocene activity along the adjacent mountain-front segment. Front W3 has a sinuosity index that approaches 1 and is also marked by steep-sloped, Holocene-surfaced fans that are only slightly entrenched (Figs. 9 and 10). Prominent triangular facets complete this picture of a Holocene-active mountain front. This does not seem to be an erosional scarp like the Gila Mountains front E2. There is no contrasting lithology to indicate an erosional cause of the base-level fall. There are some 100-meter hills on the piedmont side of the fault, which would make this an internal front instead of a mountain-bounding front. This is consistent with the closely spaced horst-and-

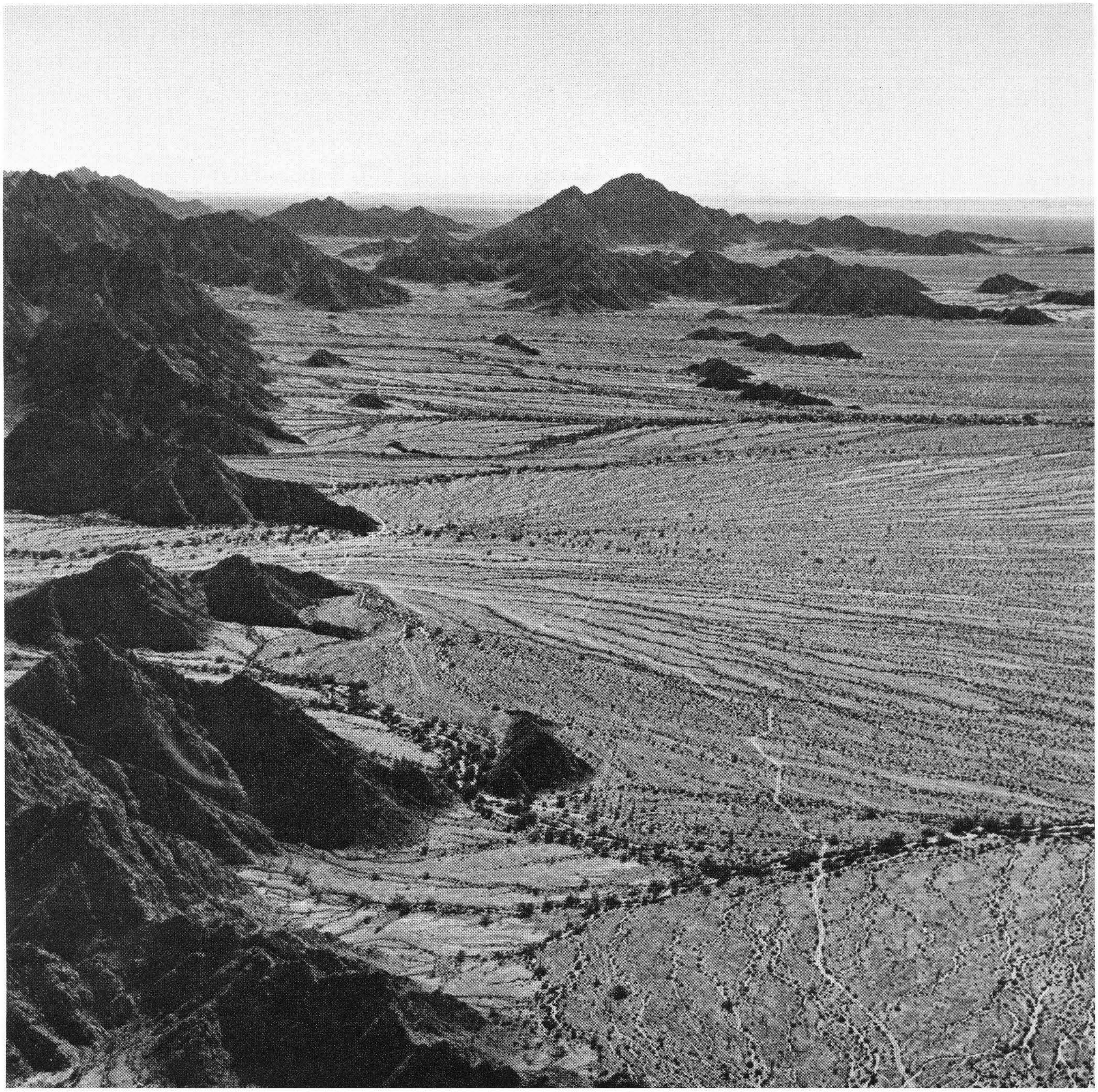

Fig. 8. Tinajas Altas Mountains fronts W1 and W2. Large abandoned alluvial fan in center of photograph no longer has any major stream channels emptying onto it. Class 2B front W2 beyond. Northwest end of front W3 offset to the right beyond front W2.

graben structure that appears to prevail in southwestern Arizona. Front E2 at the extreme southeast end of the range is a clear case of Quaternary inactivity with terraces and exhumed pediment indicating a piedmont that has had a predominantly erosional rather than depositional history.

Wellton Hills

The Wellton Hills are only slightly more than a grouping of inselbergs and give no indication of Quaternary tectonism. Scattered patches of dissected pediment confirm this conclusion.

Baker Peaks

Only the east side of the Baker Peaks displays anything approaching a tectonic front.

Fig. 9. Tinajas Altas Mountains front W3. Distant view.

Fig. 10. Tinajas Altas Mountains front W3. Class 1 tectonic activity. Cabeza Prieta Mountains in distance.

Fig. 11. Baker Peaks. Copper Mountains in background. Tinajas Altas Mountains in distance.

Fig. 12. North end of Copper Mountains. Exhumed pediment adjacent to front W1 indicative of a class3A front.

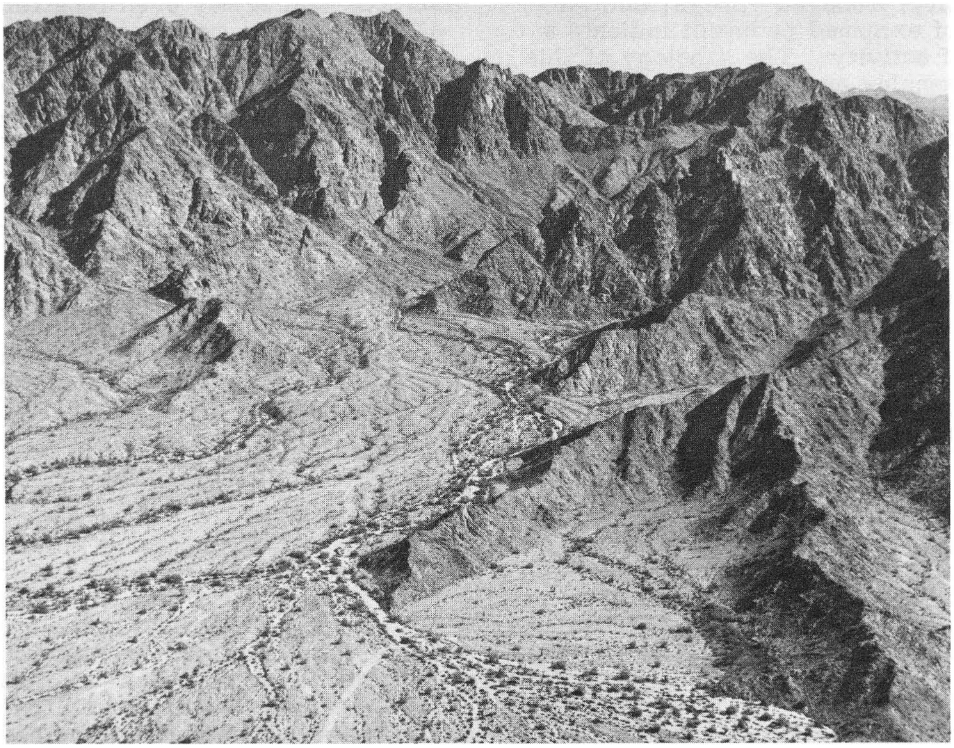

Fig. 13. West side of Copper Mountains. Front W2 in foreground. Erosional scarp in background. Lower right quadrant of photograph shows a good example of pediment embayment.

Fig. 14. Cabeza Prieta Mountains. Tinajas Altas Mountains, Raven Butte, and Gila Mountains in distance.

The high sinuosity, embayed valleys, and an extensive area of exhumed pediment indicate a profound lack of activity. The lithology of this range is quite complex and varied. Figure 11 gives an overall view of the Baker Peaks and the adjoining Copper Mountains.

Copper Mountains

The east front of the Copper Mountains is quite linear, especially in the north (Front E1), but this is largely due to the influence of a stream which closely parallels the front. Front E2 shows some slight hints of Pleistocene tectonism in the form of poorly preserved triangular facets and steeper than normal Pleistocene-surfaced fans. This front segment has been assigned a 2B tectonic classification, but only marginally. Front E3, with its high sinuosity and deep valley embayments, shows no signs of activity. The west fronts show a similar lack of activity, especially along W1. This front is marked by a considerable area of exhumed pediment with deeply incised stream channels (Fig. 12). Front W2 shows extensive embayment of its valleys (Fig. 13).

Cabeza Prieta Mountains

The entire range of the Cabeza Prieta Mountains with its chaotic landscape and complicated lithology is so deeply embayed and so highly sinuous that it may even be stretching things a bit to call the mountain fronts tectonic in origin (Fig. 14). The interior of the range is cut through with the traces of numerous northwest-trending faults and a few west-trending faults. This faulting carries through to the edges of the range and appears to give the mountain fronts, such as they are, a vague linear control along those two trends.

Tule Mountains

The west front of the Tule Mountains is a dissected pediment surface. The other front segment, also facing west, is almost entirely across the border in Mexico and was not considered here.

Sierra Pinta

All fronts of the Sierra Pinta have the same sort of features very typical of the tectonically inactive mountain fronts across southwestern Arizona. The mountain range may be quite linear, but the mountain fronts are highly sinuous, showing the great amount of erosional retreat from the structure or structures that formed this range. The alluvial fans have very gentle gradients, which continue right up to the sharply defined mountain edges (Fig. 15).

Fig. 15. Sierra Pinta front W2. Class 3B. Granite-metamorphic lithologic contact in center of photograph. Bryan, Granite, and Growler Mountains in distance.

Fig. 16. Mohawk Mountains front E1. Class 3B.

Mohawk Mountains

From a distance and on a small-scale map, the Mohawk Mountains and the Sierra Pinta look very similar. However, on a closer inspection, their mountain fronts are quite different. The north part of the range, specifically front segments E1, W2, and W3, has Holocene-surfaced alluvial fans of moderate gradient (Fig. 16). The small size of these fans, together with the high sinuosity of these fronts, indicates that their origin is probably climatic rather than tectonic. Front W1 has the same sort of fans, but thicker. However, this front is less sinuous than the others, and there are triangular facets visible. Therefore, it is a Class 2B front (Fig. 17). Fronts E2 and W4 are heavily embayed and have numerous inselbergs on the piedmont. There are many fault traces and erosional scarps in the interior of the Mohawks; none of them shows any signs of activity (Fig. 18).

Bryan Mountains

The Bryan Mountains have inactive mountain fronts of much the same form as the Sierra Pinta.

Aguila Mountains

The volcanic Aguila Mountains have deeply embayed mountain fronts, which display only vague hints of linearity, although the northwest-trending structural grain of the region is evident in the interior of the mountains.

Granite Mountains

The fronts of the Granite Mountains are virtually identical to those of the Sierra Pinta.

Agua Dulce Mountains

The Agua Dulce Mountains, a range of low hills, lack the sharply defined mountain-piedmont boundary of most of the ranges in southwestern Arizona. The west front is pedi-

Fig. 17. Mohawk Mountains front W1. Class 2B tectonic activity.

Fig. 18. Mohawk Mountains front E1. An erosional fault scarp running at a slight angle to the front can be seen in the mountains.

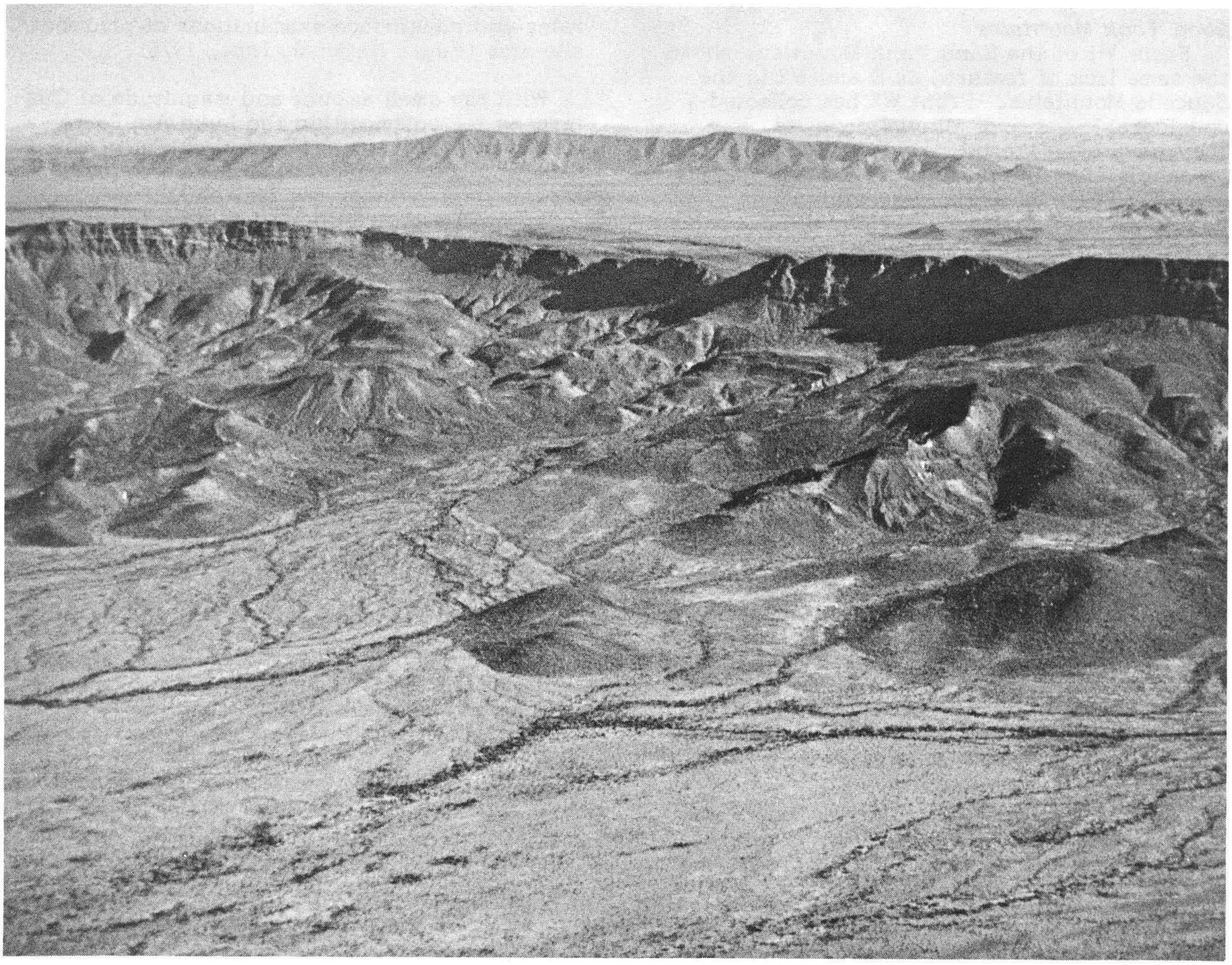

Fig. 19. Growler Mountains, north half of front W2. Slump blocks along the west face of the range.

mented, and the knobs and low hills rising to the main mountain mass along the east fronts suggest a developing pediment.

Growler Mountains

The west front of the Growler Mountains is an obvious scarp, although this appearance is exaggerated by the eastward-dipping basalt flows that cap the range. Both west front segments are moderately to highly sinuous, and the thin alluvial fans give no suggestion of tectonic activity. The north half of front W2 is much more irregular than the rest of the west front and appears to be covered with slump blocks (Fig. 19). The east side of the Growlers does not appear to be a tectonic front. The east-ward dipping basalt flows gradually merge with the valley of Daniels Arroyo to the east.

Childs Mountain

Only the southwest-facing side of Childs Mountain appears to be tectonic from its linearity and moderate sinuosity. None of the other landform features present gives any hint of Quaternary activity.

Crater Mountains

The south front of the Crater Mountains is much like the west front of Childs Mountain since it is linear and has no other signs of tectonic activity. Front N2 is the same situation. The other two fronts are so highly sinuous and so deeply embayed that even their original tectonic affinities are questionable.

Sauceda Mountains

The high sinuosity of front W1 of the Sauceda Mountains and the paucity of alluvial depositional activity along fronts E and W2 preclude any Quaternary tectonic activity.

Sand Tank Mountains

Front W1 of the Sand Tank Mountains shows the same lack of features as E and W2 in the Sauceda Mountains. Front W2 has collected a considerable array of alluvial deposits, but they have been steadily eroded resulting in old low-angle alluvial fans that have been well dissected. There is also a suggestion of exhumed pediments near the southeast end of the front. Any tectonic activity that occurred along front W2 did so before the Quaternary.

Conclusions

The area of the Luke Air Force Range in southwestern Arizona is almost entirely free of tectonic activity today. The shape of the mountains and basins is the result of a continuous process of erosion and deposition since the cessation of major basin-and-range tectonism in the late Miocene. What tectonic activity continued into or was initiated during the Quaternary occurred mostly in the Pleistocene with only one possible local occurrence in the Holocene. There is no evidence, other than some scattered magnitude-4 earthquakes, that any tectonism has occurred in recent times.

The magnitude of the Quaternary tectonism has, in all cases, been slight. None of the alluvial fans spawned by these pulses of uplift amounts to anything more than small deposits of coarse clastics that encroach no more than a few hundred meters onto the piedmont. Observations of streams in southwestern Arizona and the sediments they transport show that the coarse clastics picked up in the mountains are deposited on the medium-angle (5° to 10°) alluvial fans such as those found along front E2 of the Gila Mountains (Schenker, 1977) and other areas. With the small drainage basin areas that exist in the worn-down mountains of southwestern Arizona, the streams do not have sufficient power to transport anything coarser than small (10 cm) cobbles on the gentle (1°) gradient of the piedmont slopes.

Along any given mountain range, all other variables being the same, the front segment with the greatest level of tectonic activity will have the greatest rate of piedmont sediment accumulation. The amount of an entrenched alluvial fan that is buried by fine piedmont sediments can be roughly approximated by extrapolating the fan surface below the alluvial cover. For a small fan extending only a couple hundred meters from a mountain front and produced by minor pulses of tectonic activity on the order of a few tens of meters spread over most of the Pleistocene, as is apparently the case in the study area, the buried extent of the fan is probably less than 50 percent greater than its above-surface area. This approximation is based on piedmont sedimentation rates and subsurface examinations of piedmont alluvium (Fugro National, Inc., 1976).

With the small amount and magnitude of Quaternary tectonism within the Luke Air Force Range and the very small areal extent of the resulting fluvial deposits, it can be concluded that tectonic activity has had no appreciable effect on the distribution of sediments within this area during the Quaternary. However, the deep gravel deposits in the basin area (Fugro National, Inc., 1976) do indicate active tectonism in the late Tertiary.

Acknowledgments

This report has been prepared from material obtained during the course of research accomplished by the University of Arizona Department of Geosciences for the U.S. Air Force, Office of Aerospace Research, and is being published with the consent of the U.S. Air Force.

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