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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

LATE CENOZOIC EVOLUTION OF THE UPPER AMARGOSA RIVER DRAINAGE SYSTEM, SOUTHWESTERN GREAT BASIN, NEVADA AND CALIFORNIA

By

N. King Huber

Open-File Report 87-617

Prepared in cooperation with the
U.S. Department of Energy
Nevada Operations Office
(Interagency Agreement DE-AI08-78ET44802)

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards.

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LATE CENOZOIC EVOLUTION OF THE UPPER AMARGOSA RIVER DRAINAGE SYSTEM, SOUTHWESTERN GREAT BASIN, NEVADA AND CALIFORNIA

By N. King Huber

ABSTRACT

A major part of the upper Amargosa River drainage system is centered on Timber Mountain, a high central area within a volcanic caldera northeast of Beatty, Nevada, on the west margin of the Nevada Test Site. The basic drainage pattern in this area was established soon after caldera collapse and resurgent dome formation about 11 million years ago. The gross drainage pattern has changed little since then, although subsequent volcanic activity has temporarily blocked drainage channels. As there have been no significant changes in subbasin geometry, general tectonic stability of the region during this time is implied.

A major change in alluvial regimen occurred with the end of major alluvial-fan construction within the drainage system and the beginning of fan-head erosion that formed incised washes. The size and shape of incised channels differ, but they show a similar relation to the geomorphic parameters of their respective drainage basins--including such diverse-appearing washes as the deep Fortymile Wash and the wide, shallow wash on the Amargosa River downstream from Beatty. If the subbasin drainages have not changed appreciably during the Quaternary, then the forcing mechanism for the change in alluvial regimen is most likely either climatic or tectonic. Because this change appears to have occurred at about the same time throughout the upper Amargosa River drainage system, a climatic cause is preferred; its nature and timing are still speculative, but probably was increasing aridity that reached a threshold in the middle Pleistocene.

This analysis also concludes that a postulated Pleistocene drainage capture by the Fortymile Canyon drainage system did not occur and that a large Pliocene lake in the Amargosa Desert, the postulated "Lake Amargosa," is equivocal.

INTRODUCTION

The Amargosa River drains part of the southwestern part of the Great Basin section of the Basin and Range physiographic province. The Amargosa River originates near Pahute Mesa in southern Nye County, Nevada, and flows southward for about 90 km before making a U-turn westward and northward into Death Valley, California. The study area is the upper Amargosa and its many tributaries that drain generally southward into the Amargosa Desert (fig. 1). A recent summary of the general physiographic, geologic, and tectonic setting of the Basin and Range province provides a broad context for the present study (Dohrenwend, 1987).

This study analyzes the late Cenozoic evolution of the upper Amargosa drainage system as one element of a larger effort done in cooperation with the U.S. Department of Energy, Nevada Nuclear Waste Storage Investigations Project (Interagency Agreement DE-AI08-78ET44802), to elucidate effects of regional late Cenozoic tectonic history on a potential radioactive waste repository at Yucca Mountain (fig. 1). Field examination was precluded, and so this report

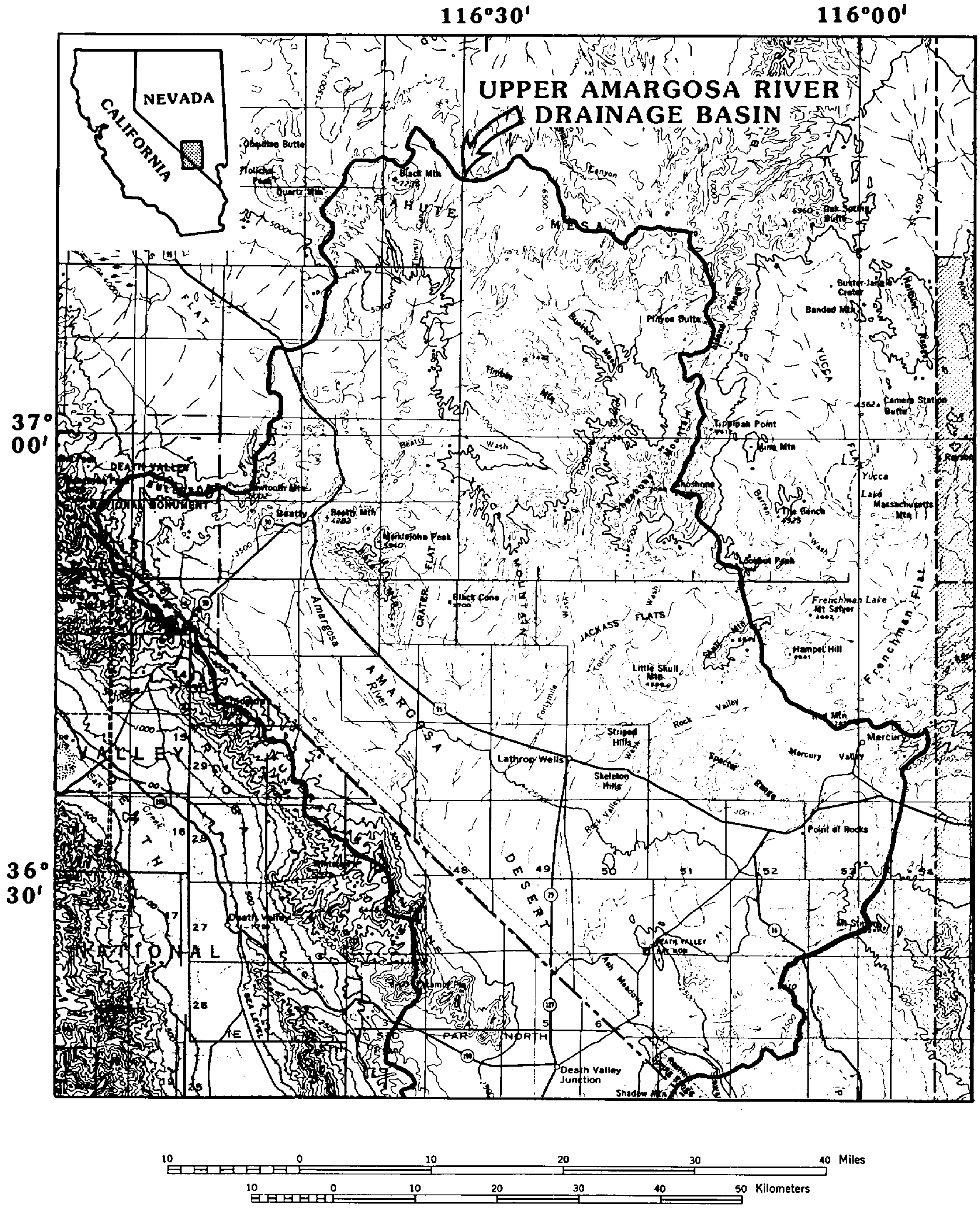


Figure 1.--Index map, upper Amargosa River drainage basin.

is based on published reports and geologic maps, topographic maps, and aerial photographs.

In this review the upper drainage system is not discussed in uniform detail. Emphasis is on areas and topics like the late Cenozoic volcanic stratigraphy of the region that reveal evolution of this drainage system, which may in turn aid in understanding the region's late Cenozoic tectonics.

The bedrock geology of most of the area of the upper Amargosa River drainage system has been mapped in considerable detail at 1:24,000 scale. But the most useful geologic maps to use with this report are compilations at a scale of 1:48,000: the Timber Mountain caldera area (Byers and others, 1976) and the Jackass Flats area (Maldonado, 1985). These compilations index the more detailed 1:24,000-scale geologic source maps. Maps in this report (figs. 3 and 4) are generalized from these published maps.

TIMBER MOUNTAIN AREA

A major part of the upper Amargosa River drainage system lies south of Pahute Mesa and is centered on Timber Mountain, a high central area within a volcanic caldera 25 to 30 km in diameter (fig. 2). The caldera formed by collapse as a result of the eruption of the Rainier Mesa and Ammonia Tanks Members of the Timber Mountain Tuff about 11.5 million years (m.y.) ago (table 1). Later extrusion of the Timber Mountain resurgent dome and eruption of minor intracaldera tuff and lava formed the Timber Mountain physiographic high in the center of the caldera.

From the high ground of the resurgent dome, drainage radiated into the surrounding caldera moat. Drainage was blocked to the north by extra-caldera Timber Mountain Tuff and older units on Pahute Mesa, and to the south by the high rim and resurgent core of a segment of the earlier Claim Canyon caldera. Drainage westward from the Timber Mountain area developed as Thirsty Canyon and Beatty Wash to the Amargosa River and thence south on the regional gradient. The southeast rim of the Timber Mountain caldera was breached via Fortymile Canyon where drainage from the eastern moat flows south to join the Amargosa River in the Amargosa Desert.

Fortymile Canyon Drainage Basin

Southeast of the Timber Mountain resurgent dome, Fortymile Canyon was eroded to at least its present depth before eruption of the rhyolite lavas of Fortymile Canyon, for remnants of these lavas lie on the present canyon floor (fig. 3) and their basal contact rises away from the canyon, which shows that a topographic low existed there at the time of the eruption. A test well drilled in Fortymile Canyon at the junction of Pah Canyon, just south of the caldera margin, penetrated about 12 m of alluvial fill, 45 m of the rhyolite of Fortymile Canyon, and bottomed in the rhyolite of Calico Hills (Waddell, 1985, table 1). The rhyolite of Calico Hills and the Paintbrush Tuff, both older than the Timber Mountain caldera, crop out discontinuously from Pah Canyon south along Fortymile Canyon and constitute the bedrock into which the canyon was incised before the eruption of the rhyolite of Fortymile Canyon. The age of the rhyolite of Fortymile Canyon is indefinite but it must be between that of the Timber Mountain Tuff (11.5 m.y.) and the rhyolite of Shoshone Mountain, (about 9 m.y. old) (table 1).

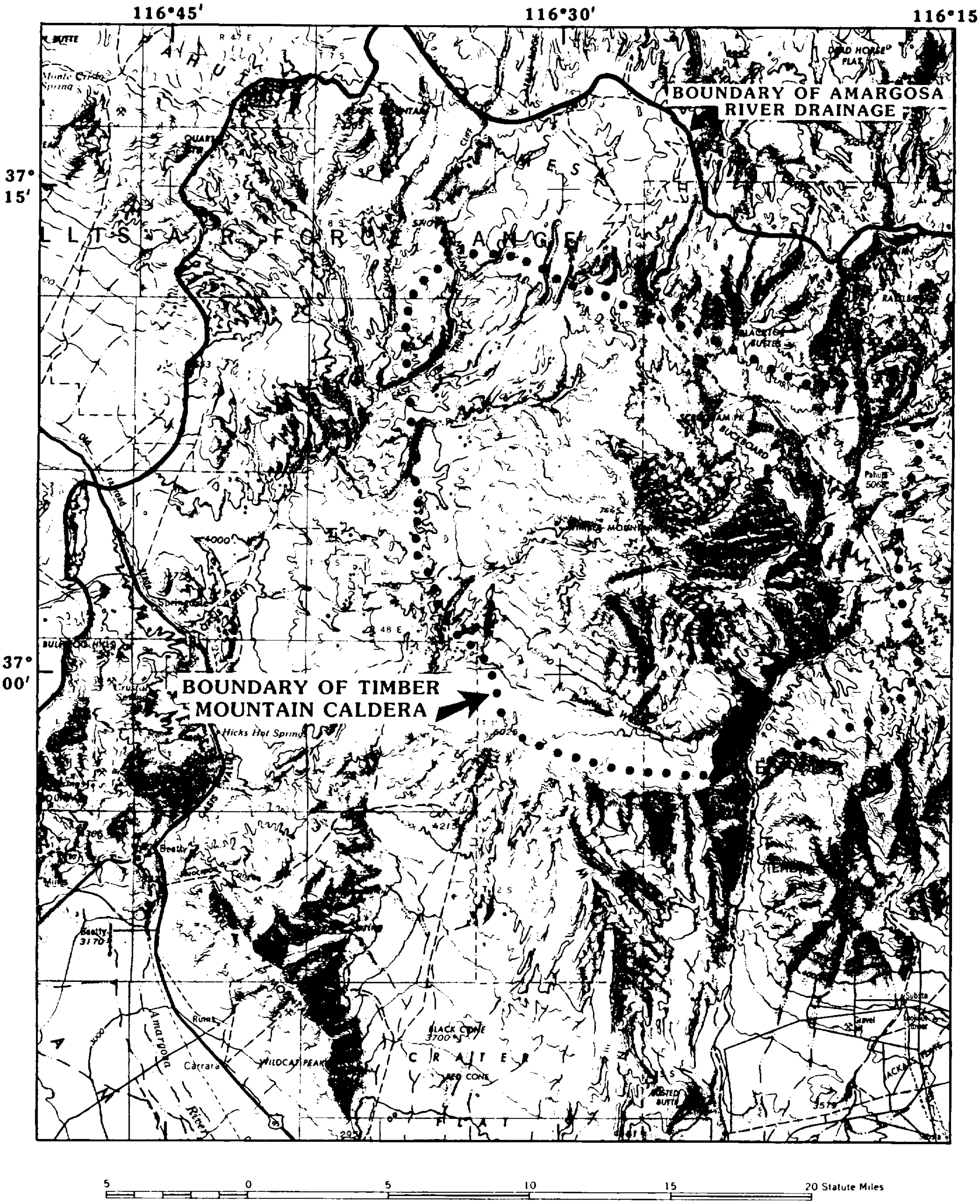


Figure 2.—The Timber Mountain area. Dotted line indicates approximate outer boundary of subsidence of the Timber Mountain caldera (Byers and others, 1976).

Table 1.--Generalized volcanic stratigraphic units in the Timber Mountain area mentioned in text

Stratigraphic Unit	Volcanic center or caldera	Approximate age (m.y.)
Trachybasalt of Buckboard Mesa	Scrugham Peak (east moat of Timber Mountain caldera)	2.8 1/
Basalt above Thirsty Canyon Tuff (Thirsty Canyon area)	Knob west of Thirsty Canyon? with triangulation station "Thirsty"	8 1/
Thirsty Canyon Tuff	Black Mountain	8 2/
Rhyolite of Shoshone Mountain	Shoshone Mountain	9 2/
Mafic lavas of Dome Mountain	Dome Mtn. (south moat of Timber Mountain caldera)	-
Rhyolite of Fortymile Canyon	Pinnacles Ridge (west of Fortymile Canyon)	-
Timber Mountain Tuff	Timber Mountain	11.5 2/
Pre-Timber Mountain Tuff rocks (Includes Paintbrush Tuff and ryholites of Calico Hills)	Various sources	>11.5 2/

1/ Age from R. J. Fleck (written commun., 1980)

2/ Age from Carr (1984, fig. 33)

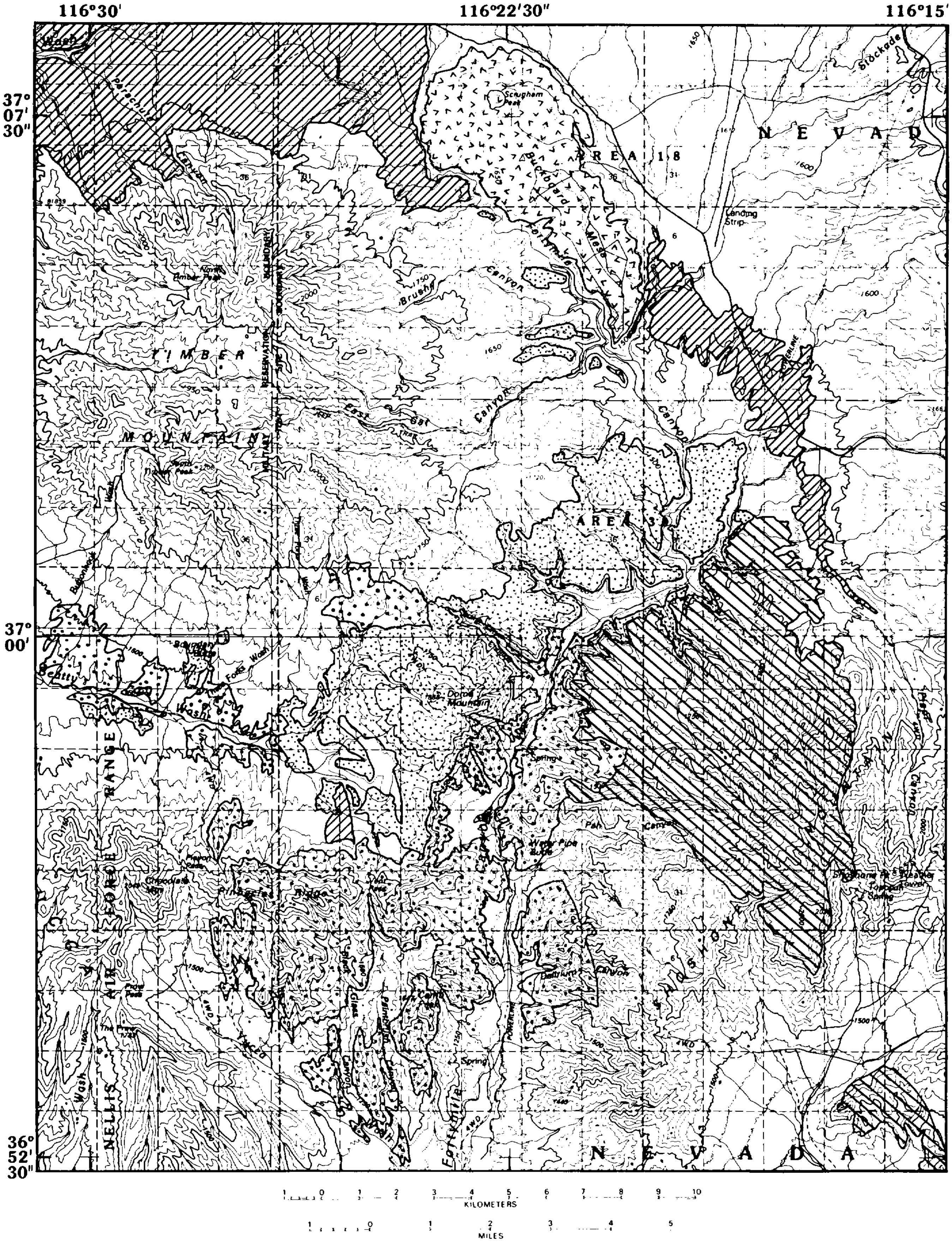


Figure 3.--Generalized geologic map of Fortymile Canyon area showing distribution of major post-Timber Mountain Tuff volcanic units.

EXPLANATION

TRACHYBASALT OF BUCKBOARD MESA
(PLIOCENE, 2.8, m.y.)

THIRSTY CANYON TUFF
(MIOCENE, 8 m.y.)

RHYOLITE OF SHOSHONE MOUNTAIN
(MIOCENE, 9 m.y.)

MAFIC LAVAS OF DOME MOUNTAIN
(MIOCENE, 9 m.y. > 11.5 m.y.)

RHYOLITE OF FORTYMILE CANYON
(MIOCENE, 9 m.y. > 11.5 m.y.)
(Includes rhyolite of Beatty Wash)

Geology generalized from Byers and others (1976).

Figure 3.--Continued

Thus the Timber Mountain caldera rim was breached and Fortymile Canyon drainage established in its present location soon after the resurgent dome formed within the caldera. The rhyolite of Fortymile Canyon consists of many flows erupted from vents near the south rim of the Timber Mountain caldera. Some of these filled Fortymile Canyon to a depth of more than 425 m near Delirium Canyon, and flowed northeast up Fortymile Canyon into the eastern moat of the Timber Mountain caldera. Eruption of the rhyolite into the ancestral Fortymile Canyon apparently was insufficient to divert the drainage, for the stream incised into the lavas and exhumed the earlier canyon nearly to its former level.

After the lower Fortymile Canyon was reexcavated nearly to its earlier depth, the mafic lavas of Dome Mountain were erupted into the canyon and part of the moat east of Timber Mountain (fig. 3). Mafic lava of Dome Mountain overlies rhyolite of Fortymile Canyon within Fortymile Canyon about 1.5 km north of the junction of Pah Canyon only about 30 m above the present streambed (Christiansen and Lipman, 1965). This outcrop indicates that Fortymile Canyon here had incised to near its present depth before eruption of the mafic lavas of Dome Mountain. Although these lavas filled Fortymile Canyon southeast of Dome Mountain by at least 180 m, their volume was insufficient to divert the stream, which then incised through the new obstacle.

The rhyolite of Shoshone Mountain was erupted about 9 m.y. ago (Table 1) near the southeast rim of the Timber Mountain caldera, and several flows advanced toward the main chasm of Fortymile Canyon (fig. 3). Because present outcrops form cliffs within the canyon, in places only 30 to 90 m above its bottom, probably the canyon was at least partly blocked though probably not to any great depth and not enough to divert the stream.

About 8 m.y. ago (table 1) the Thirsty Canyon Tuff erupted from the Black Mountain caldera, some 30 km northwest of Timber Mountain. This tuff probably blanketed much of the Timber Mountain caldera; it still fills most of the north and west moat and erosional remnants remain in the moat east of Timber Mountain and in the south moat in Beatty Wash (fig. 3). Most of the Thirsty Canyon Tuff that once blanketed the Fortymile Canyon drainage basin has been eroded and flushed out through the canyon.

Between eruptions of these major volcanic units, gravelly and tuffaceous sediment accumulated in the eastern moat. These materials are preserved as extensive alluvial and colluvial deposits that extend from the north and east caldera rim into Fortymile Canyon and its tributaries. As much as 80 m of this material underlies the Thirsty Canyon Tuff in Fortymile Canyon near the south end of Buckboard Mesa (Byers and others, 1966). Similar material stratigraphically above the Thirsty Canyon Tuff constitutes much of the present-day surface in the east moat. While the lower Fortymile Canyon was not temporarily blocked by volcanic flows or tuff, such gravel and sediment probably supplied most of the stream bedload that moved through the canyon and accumulated as an extensive alluvial fan extending into the Amargosa Desert.

About 2.8 m.y. ago the trachybasalt of Buckboard Mesa (fig. 3) erupted from a cinder cone (Scrugham Peak) northeast of Timber Mountain (table 1), and flowed southeast at least 7 km down the Fortymile drainage. Erosion has isolated the basalt as a mesa; the main trunk of Fortymile Canyon runs along the west margin of the mesa and has cut as much as 100 m (average rate of 3.6 cm/1000 yr) into older tuff (including Thirsty Canyon Tuff) and fan gravel beneath the basalt.

The presence of a layer of Thirsty Canyon Tuff within the gravel beneath the trachybasalt of Buckboard Mesa (Byers and others, 1966) indicates that Fortymile Canyon was deeper when the tuff was erupted than when the trachybasalt was erupted, and also indicates that the channel aggraded both before and after deposition of the tuff. Sometime after the eruption of the trachybasalt, Fortymile Canyon and its tributaries incised through the tuff and into the underlying gravel to leave the trachybasalt flows as an isolated mesa.

In summary, from about 11 to 8 m.y. ago, after the Timber Mountain caldera formed with its resurgent dome until eruption of the Thirsty Canyon Tuff from the Black Mountain caldera, the Fortymile Canyon stream from the Timber Mountain caldera was forced several times to cut through dams of tuff and lava flows. Yet the stratigraphic level of the main canyon leaving the caldera is nearly the same as when the canyon formed some 10 m.y. ago. During this time (especially since 8 m.y. ago) there has been little major change in the base level at the canyon mouth, where a braided stream in a bedrock canyon merged with an alluvial fan. There also has been little change in the size and shape of the Fortymile Canyon drainage basin.

During the millions of years that Fortymile Canyon has drained the east moat of Timber Mountain caldera, voluminous volcanic-rock and other eroded material has accumulated as a great alluvial fan extending from the canyon mouth southward into the Amargosa Desert. But now, fan construction has ceased, for the fan apex has been deeply incised by infrequent storm runoff from Fortymile Canyon to form Fortymile Wash. Fan incision of this magnitude is thought to start by reduced sediment load relative to water discharge (Hooke, 1967; Wasson, 1977; Wells and Harvey, 1987). Such changes are inferred to result from disturbance in the source area. Climatic change and tectonic movement are two commonly assumed causes of such disturbance if the general geomorphic characteristics (size, shape, average slope and relief, etc.) of the drainage basin have not otherwise been changed (Hooke, 1967; Bull, 1979).

It has been suggested that fan incision was initiated by increased discharge from Fortymile Canyon because of stream capture of the upper part of a drainage basin formerly draining through Beatty Wash until about 300,000 years ago (D.L. Hoover, cited by Carr, 1984, p. 77). This inference is based on a tentative age of about 300,000 years for the upper part of the fan deposit adjacent to the incised wash, as determined by the experimental uranium-trend dating method (U.S. Geological Survey, 1984, table 1). But the trachybasalt of Buckboard Mesa flowed into the upper part of the Fortymile drainage about 2.8 m.y. ago and the base of the basalt flow at its present southern extent in Fortymile Canyon is 150 m lower than the lowest point on the present divide between the Fortymile Canyon drainage basin and Beatty Wash. Thus as long ago as 2.8 m.y. the upper Fortymile Canyon basin could not have drained into Beatty Wash. The area of the present Fortymile Canyon drainage basin has probably changed little since its inception.

Eastern Thirsty Canyon Drainage Basin

The history of drainage on the west side of Timber Mountain is similar to that of Fortymile Canyon on the east side. The northwest moat of the Timber Mountain caldera drains southwest to the Amargosa River via two forks of Thirsty Canyon, the East Fork, and Rocket Wash (fig. 2). Rhyolite lava flows within the channels of both the East Fork and Rocket Wash where they breach the caldera rim have been correlated with the rhyolite lavas of Fortymile Canyon (Byers and others, 1976). Trachyandesite lava flows overlying the rhyolite flows are correlated with the mafic lavas of Dome Mountain (Byers and others, 1976). Although the rhyolite and trachyandesite in the Thirsty Canyon area (fig. 4) do not have the same eruptive source vents as the Fortymile and Dome Mountain units, they must be part of the same eruptive cycle as they are similarly sandwiched between the Timber Mountain Tuff and the Thirsty Canyon Tuff. Thus the northwest caldera rim was breached and external drainage established to nearly its present depth soon after the Timber Mountain resurgent dome formed. Later eruptions have produced a series of volcanic infillings and reexcavations within these western canyons. After a new channel was cut into the trachyandesite, the Thirsty Canyon Tuff and an overlying basalt were erupted into the drainage and then incised (fig. 4). The basalt, about 8 m.y. old (table 1), seems to represent the last eruptive event in the Thirsty Canyon drainage. Erosion since then seems to have been uninterrupted; locally Rocket Wash has cut about 60 m below the base of the basalt (average rate of 0.75 cm/1000 yr). Above its junction with Rocket Wash, Thirsty Canyon with its much larger drainage basin has cut down about 180 m below the basalt (average rate of 2.25 cm/1000 yr). Minor post-basalt faulting with northerly strike has occurred. But otherwise the basalt and the Thirsty Canyon Tuff are little disturbed; they exhibit very low, perhaps original, dips. Thus there has been little tectonic disturbance in the Thirsty Canyon area since eruption of the Thirsty Canyon Tuff some 8 m.y. ago.

Beatty Wash Drainage Basin

The southwest moat of the Timber Mountain caldera drains westward to the Amargosa River via Beatty Wash and its tributaries (fig. 2). An 8-km stretch of Beatty Wash is underlain by the rhyolite of Beatty Wash (fig. 4). This rhyolite is about the same age as the rhyolite of Fortymile Canyon. Both postdate collapse of the Timber Mountain caldera, and both are overlain by the mafic lavas of Dome Mountain. The presence of the rhyolite of Beatty Wash indicates that the wash was close to its present depth and gradient 9-11 m.y. ago. Since then erosion has removed post-rhyolite volcanic flows and tuffs and some of the rhyolite to exhume its earlier channel. Beatty Wash breaches the west rim of Timber Mountain caldera through a ridge of Timber Mountain Tuff. This barrier, and the small drainage area (175 km^2) behind it explains why Beatty Wash is not more deeply incised within the caldera moat. A 10-km stretch of Beatty Wash upstream from the caldera rim has a mean gradient of about 15 m/km. Beatty Wash continues west past the caldera rim through more Timber Mountain Tuff and other volcanic and volcaniclastic rocks to join the Amargosa River in Oasis Valley about 5 km north of Beatty. This western stretch has a gradient of about 18 m/km, 20 percent greater than that upstream within the caldera moat, which further shows the influence of the caldera-rim barrier on the long profile of Beatty Wash. Except for a few minor north- to north-northwest-trending faults cutting the rhyolites of Beatty Wash and the mafic lavas of Dome Mountain (Byers and others, 1976), there is little evidence for major tectonic disturbance within the southwest moat of the Timber Mountain caldera.

Summary of Drainage Evolution in the Timber Mountain Area

The resurgent dome of Timber Mountain and its surrounding caldera moat are drained by three separate tributaries of the Amargosa River: Fortymile Canyon, Thirsty Canyon, and Beatty Wash. These three systems have similar histories and evolved independently just after the caldera collapsed and the resurgent dome formed. Each breached the caldera rim to drain a portion of the caldera moat. The distribution of post-Timber Mountain volcanic rocks shows that Fortymile and Thirsty Canyons had breached the rim at least by 9 m.y. ago; Beatty Wash might not have breached the rim quite as early, for similar volcanic rocks in Beatty Wash are not known to have crossed through the rim-gap there. After external drainages were established, they each were repeatedly disrupted by emplacement of younger volcanic rocks and then reexcavated their channels. The last significant disruption occurred with the eruption of the Thirsty Canyon Tuff about 8 m.y. ago. Each reexcavation seems to have reached about the same depth as today's channels. The general base level of the Timber Mountain area has been little changed for many millions of years, except by temporary channel blockages by volcanic materials.

BLACK MOUNTAIN AREA

Black Mountain is located in the northwestern corner of the upper Amargosa drainage basin about 30 km northwest of Timber Mountain (fig. 2). Black Mountain is the site of the Black Mountain caldera, the source of the Thirsty Canyon Tuff (Noble and Christiansen, 1974; Noble and others, 1984), a volcanic marker bed helpful to unraveling the history of the Timber Mountain drainage system.

The south and east slopes of Black Mountain are drained by Thirsty Canyon and its West Fork, incised into the south-sloping surface of the Thirsty Canyon Tuff. Although partly diverted around a plateau underlain by 8-m.y.-old basalt (table 1), the drainage appears to be consequent upon the original slope of the Thirsty Canyon Tuff (fig. 4). The geology of this area has been only partly mapped in detail, but that mapping provides no evidence of tectonic control of the Thirsty Canyon and West Fork drainage systems. Faults later than the Thirsty Canyon Tuff are minor and strike northerly.

FORTYMILE WASH AND ALLUVIAL-FAN INCISION

Fortymile Canyon opens onto a low-gradient alluvial-fan deposit near the west edge of Jackass Flats. Near the fan apex the stream channel is incised 15 to 20 m into the fan surface. This channel, known as Fortymile Wash, shallows southward until it merges with the fan surface about 23 km from the canyon mouth. Fortymile Wash is the largest channel cut into alluvial-fan deposits in the upper Amargosa River drainage system. Is its origin anomalous with respect to the evolution of the rest of the upper Amargosa River drainage system?

Wells and Harvey (1987) describe fan deposition and incision resulting from an unusually intense, short-duration storm in northwest England. Although not in an arid environment, this event is a well-documented example

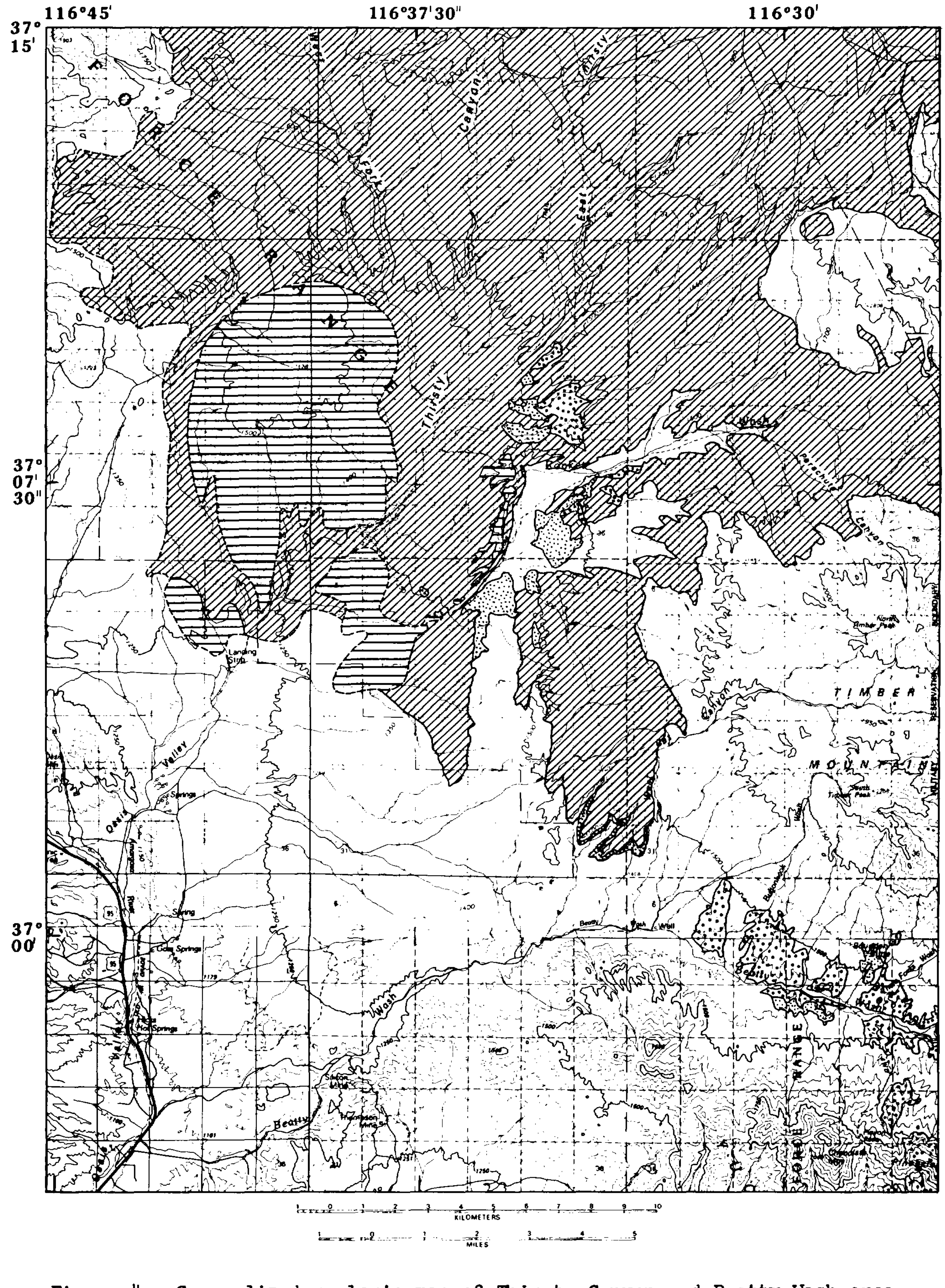


Figure 4.--Generalized geologic map of Thirsty Canyon and Beatty Wash area showing distribution of major post-Timber Mountain Tuff volcanic units.

EXPLANATION

BASALT ABOVE THIRSTY CANYON TUFF
(MIOCENE, 8 m.y.)

THIRSTY CANYON TUFF
(MIOCENE, 8 m.y.)

MAFIC LAVAS OF DOME MOUNTAIN
(MIOCENE, 9 m.y. > 11.5 m.y.)

RHYOLITE OF FORTYMILE CANYON
(MIOCENE, 9 m.y. > 11.5 m.y.)
(Includes rhyolite of Beatty Wash)

Geology generalized from Byers and others (1976); dashed boundaries in western part from reconniassance mapping by Cornwall (1972).

Figure 4.--Continued

of a catastrophic storm mobilizing sediment at source and transporting it into the fluvial system and onto fan surfaces. Fan deposition involved an early phase of debris flow followed by a systematic change to more dilute conditions, resulting in streamflow deposition and eventually in channel incision. A prolonged succession of such events would continue to enlarge the fan while leaving a moderately incised channel at the end of each event.

In arid regions it is even clearer that alluvial fans are constructed by debris flows mobilized during infrequent, episodic periods of intense precipitation. Beaty (1963, 1974) described some historic debris flows in the White Mountains of the western Great Basin and concluded that the alluvial fans there consist of superposed debris-flow deposits modifed only slightly by "normal" erosional and depositional processes. He also noted channel incision following passage of the debris flow and transition to less dense, higher-water-content material.

In a significant study of processes on arid-region alluvial fans, Hooke (1967) concluded that:

> "Material is transported to fans by debris flows or water flows that follow a main channel. This channel is generally incised at the fanhead, because there water is able to transport on a lower slope the material deposited earlier by debris flows. The main channel emerges onto the surface near a midfan point, herein called the 'intersection point.' On laboratory fans most deposition above the intersection point is by debris flows that exceed the depth of the incised channel. Fluvial deposition dominates below the intersection point. This depositional relation probably also occurs on natural fans" (p. 438). Thus fanhead "incision can be the natural result of an alternation of debris flows and water flows and fanheads are, so to speak, 'born incised'" (p. 457). "The depth of incision produced in these ways and uninfluenced by any other factors, may be called the depth of normal fanhead incision. In many instances fanhead incision is so great that overbank deposition on the adjoining fan surface is impossible. It is inferred that in these instances the fan-source system has been altered in some way * * *. Climatic change and tectonic movement are two common causes of such alteration " (p. 458).

If the depth of fanhead incision is so great that overbank deposition does not occur for a geologically long period of time, possible external causes for such incision should be considered.

Is the depth of fanhead incision at Fortymile Wash normal, in the sense defined by Hooke, or is it excessive and therefore indicative of a major change in stream regimen? Examination of 1:60,000-scale aerial photographs (AMS Proj. 109, Area G, 1952) reveals no evidence for overbank flow, whether by debris flow or water, upstream from the channel intersection point about 3 km north of U.S. Highway 95. At this point the channel spreads out into distributaries, where minor fan-surface deposition has taken place during recent times; lack of desert varnish gives these recent deposits a lighter tone on the photographs. On the photographs, the fan surface on both sides of Fortymile Wash appears remarkably smooth, unlike the hummocky one normally produced by debris flows. The surficial geology near Fortymile Wash has been mapped by Swadley (1983) who describes the fan surfaces as flat and smooth and consisting of stream-reworked windblown sheet sand deposits with almost no drainages developed within the sheets. It would appear that there has been no overbank deposition from Fortymile Wash during a geologically significant period of time. Age data obtained by the experimental uranium-trend dating method suggests that gravels in the upper part of the alluvial fan are no more than one-half million years old (Rosholt and others, 1985, Table 5) and thus fan construction in this area ceased sometime after one-half million years ago.

Flood-potential estimates for Fortymile Wash indicate that under present climatic conditions the 100-year, 500-year, and "regional maximum" floods would remain within the deeply incised channel, with considerable freeboard left over (Squires and Young, 1984). Moreover, the entire Fortymile drainage system is adjusted to the baselevel of this incised channel. Upstream within the lower Fortymile Canyon, the streambed is graded to the fanhead channel and is cut into terraces that are graded to the fan surface. Small streams tributary to the canyon have incised their own small fans to reach grade with the main channel. In the upper Fortymile drainage system, stream channels are also in equilibrium with the lower canyon, having cut into older alluvial deposits in the upper basin. Thus whatever caused the change from active fan construction to incision of the deep Fortymile Wash has had sufficient time to affect the entire drainage basin.

Tectonism may be the cause for excessive incision of some alluvial fans. Hooke (1967; 1972), for example, infers that fans on the west side of southern Death Valley have been deeply incised because of eastward tilting of the valley. If the Timber Mountain area were being uplifted in such a way as to tilt the Fortymile Canyon drainage to the south, a situation similar to, but perhaps more subtle than, the Death Valley situation might occur.

Carr (1984, p. 82) inferred Quaternary southward tilting of the Amargosa Desert basin citing the south-southeastward decrease in altitude of the top of "apparently continuous lake and playa deposits." The limit of such deposits has been taken as an "approximate limit of Lake Amargosa" and shown on a map of the Big Dune 15-minute quadrangle just west of lower Fortymile Wash (Swadley and Carr, 1987). Although acknowledging that the lake at times may have consisted only of spring-fed marshes and ponds, they further suggested that the "lake" extended to the south-southeast approximately 35 km beyond the quadrangle. Such a lake would have been more than 65 km long and filled most of the Amargosa Desert basin. But detailed study of carbonate rocks and marl in the basin led Hay and others (1986, p. 1501-1502) to conclude that the Amargosa Desert contained spring-fed playas, marshland, and short-lived ponds 2.1 to 3.2 m.y. ago and that there is no evidence, such as shoreline sediment or deep-water clay, for a large lake (p. 1495). As their convincing arguments cast doubt on the postulated "Lake Amargosa" shoreline, that hypothetical feature is not a valid basis for calculating an amount and rate for Quaternary tilt of the Amargosa Desert region as done by Carr (1984, p. 79. tables 2, 3).

Comparison of Fortymile Wash with Other Cases of Fan Incision

The change from alluvial-fan construction to fan incision is inferred to have been caused by some change in the fan-source system. The size of the Fortymile Canyon drainage basin apparently has not changed significantly since its inception shortly after the formation of the Timber Mountain caldera some 11 m.y. ago. Voluminous debris has been eroded and removed from the basin, but as no new rock types have been exposed the material supplied to the stream has remained constant. Bull (1979) ephasizes that reaches of streams at the critical-power threshold, the power needed to transport sediment load, are exceptionally sensitive to changes in baselevel including those caused by tectonism or climate, which may in turn result in changes in aggradation or degradation.

In a study of alluvial fans in Deep Springs Valley, California, an arid region east of the White Mountains, Lustig (1965) emphasized that if changes in the regimen of streams are induced by climatic change, features thought to attest to such changes should be widespread and common to most fans in the region. Among the features he cited as thought to be indicative of climatic change is that trenches in the apex regions of the fans are misfit relative to present flow conditions by reason of their excessive depth. Is Fortymile Canyon unique in the evolution of the upper Amargosa River drainage basin? How does the fan incision at Fortymile Wash compare with that of other fans in the region?

Fans in the upper Amargosa River region appear to be stable or are being incised at their apexes by infrequent flood runoff of the streams that originally constructed them. Examination of topographic maps of the region reveals that for significant large-scale incision to take place, runoff from a sizable catchment area must be focused through a narrow gap onto the fan head. Few areas in the upper Amargosa drainage basin meet these criteria. Some Amargosa tributaries, like the Mercury Valley drainage west of Point of Rocks and the Amargosa River itself south of Beatty, are focused through gaps but exit into alluviated valleys rather than onto fans. Washes that do meet the critera are Rock Valley Wash south of U.S. Highway 95, "upper" Topopah Wash in north central Jackass Flats, "lower" Topopah Wash southwest of Jackass Flats, and a wash below a small drainage basin on the east slopes of the Grapevine Mountains, containing McDonald Spring (fig. 5).

The importance of "gap focusing" on alluvial-fan incision is demonstrated by a flood-potential study of Topopah Wash and its tributaries in the eastern part of Jackass Flats (Christensen and Spahr, 1980). Upper Topopah Wash is most deeply incised just below the gap through which the discharge from its upper drainage basin is focused (c on fig. 5). Tributaries to Topopah Wash in eastern Jackass Flats drain an equally large area, but they are dispersed broadly across an alluvial fan surface and are not as deeply incised. Under present climatic conditions the statistical 500-year flood is estimated to exceed the discharge capacities of all channels in Jackass Flats except for upper Topopah Wash itself (Christensen and Spahr, 1980). Further estimates indicate that the maximum potential flood would inundate most of their study area, excluding the upper reaches on Topopah Wash where there would still be no out-of-bank flow. Similar study of Fortymile Wash (Squires and Young, 1984) indicates that the estimated maximum potential-flood discharge under current climatic conditions would also remain within the deeply incised channel of Fortymile Wash.

Rock Valley Wash just south of Highway 95 (fig. 5) is fed by a drainage basin much smaller than Fortymile Wash, but with similar stream gradient (table 2). The cross-section area of the Rock Valley Wash incision is much smaller than the Fortymile one, but the ratio of incision width to depth, and the ratio of cross-section area to drainage-basin area are similar. Under similar stream gradients, the smaller Rock Valley drainage has produced a scaled-down version of the larger Fortymile Wash.

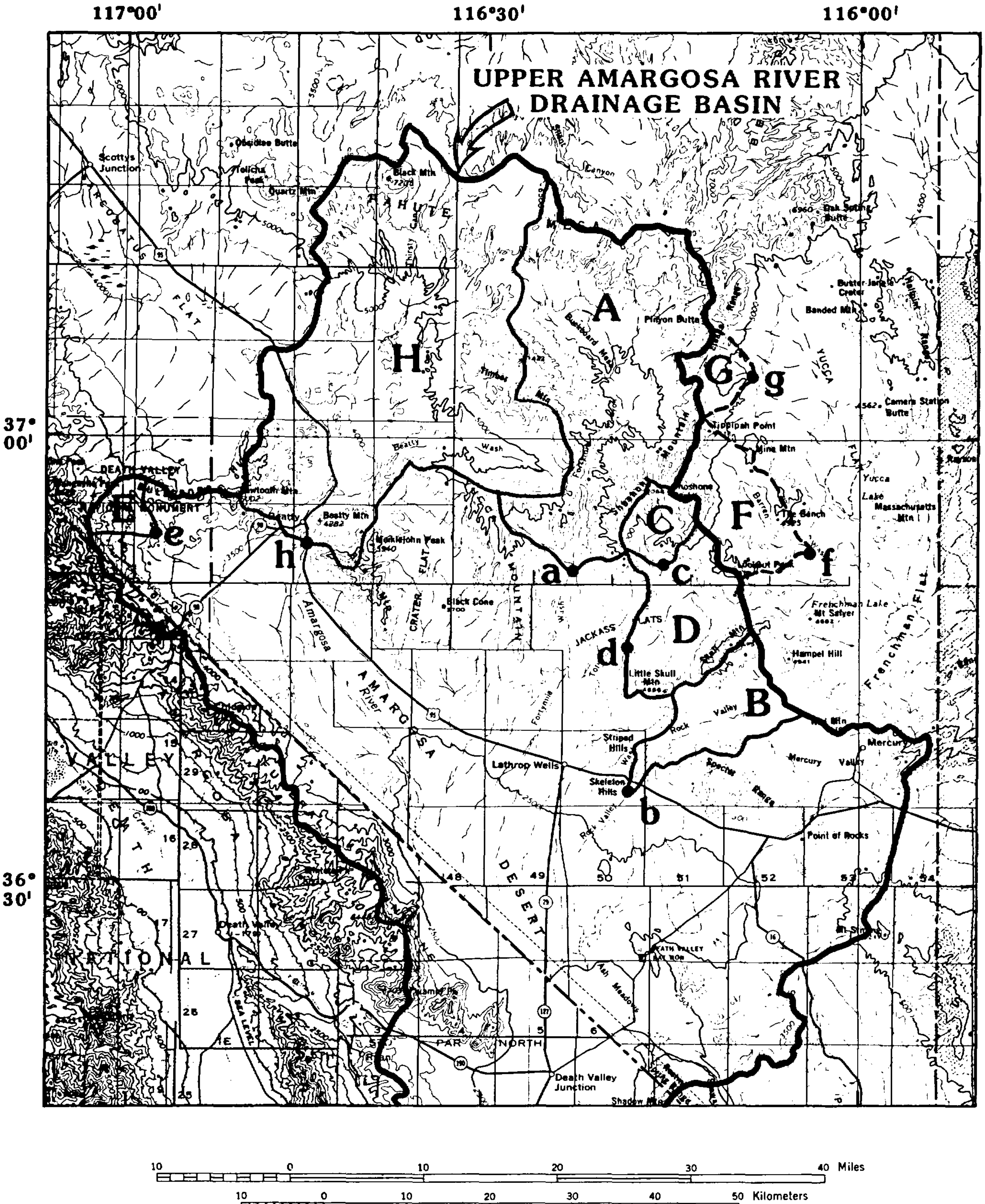


Figure 5.—The upper Amargosa River drainage system and location of individual drainage basins (upper -case) and incised alluvial fans (lower-case) described in text (table 2). A, Fortymile Canyon; B. Rock Valley; C, upper Topopah Wash; D, lower Topopah Wash; E, McDonald Spring; F, Barren Wash; G, Gap Wash; H, Amargosa River above Amargosa Narrows. Barren and Gap Washes are external to the Amargosa system, but in a similar setting.

Table 2.--Examples of alluvial fan incision [1]

	Fortymile Wash near fan head	Rock Valley Wash near Highway 95	Topopah Wash near fan head	Topopah Wash below Jackass Flats	McDonald Spring Wash, northwest Amargosa Desert	Barren Wash below Vitrophyre Wash	Gap Wash below Snycline Ridge	Amargosa River below Amargosa Narrows
7-1/2' topographic quadrangle	Busted Butte	Skeleton Hills	Jackass Flats	Jackass Flats	Bullfrog (15')	Yucca Lake	Tippipah Spring	Bullfrog (15')
Drainage basin area (km^2)	728	193	66	269	39	160	50	1234
Site of fan incision								
Elevation (m (ft))	1055 (3460)	838 (2750)	1250 (4100)	975 (3200)	1305 (4280)	1158 (3800)	1390 (4560)	951 (3120)
Dimensions (m x m) [2]	21 x 244 [4]	9 x 122	12 x 198	6 x 183	-	11 x 183	6 x 183	4 x 305
Area (m^2) [3]	5200	1115	2415	1115	930	1950	1115	1208
Width/depth	11.4	13.3	16.3	30	-	17.1	30	76.3
Channel gradient (m/km)	13.3	13.3	30.3	13.3	23	19	23	7.6
Cross-section area (m^2) / Drainage-basin area (km^2)	7.2	5.8	40.3	4.1	23.8	12.2	22.3	1

[1] All measurements are approximations made from topographic maps in U.S. Customary units; conversion to metric units and rounding creates some arithmetic discrepancies in the table.
[2] Approximate dimensions of incised channel (depth x width).
[3] Approximate cross-section area of incised channel.
[4] Cross-section dimensions approximated from site survey about 6 km downstream from junction of Yucca Wash with Fortymile Wash (Squires and Young, 1984, site FM-5).

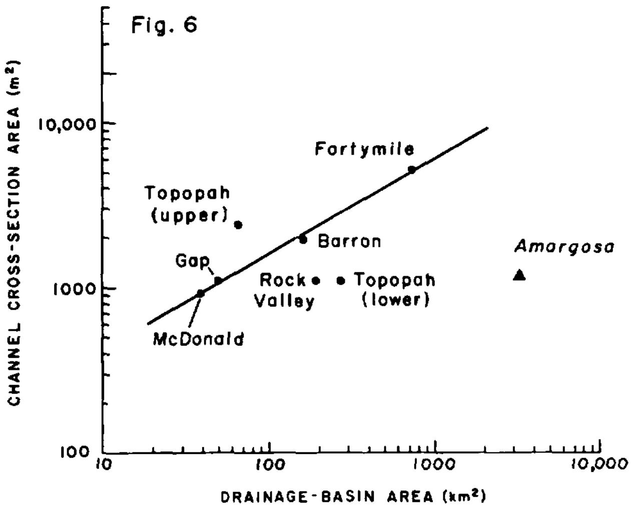
Topopah Wash, at the north margin of Jackass Flats (fig. 5), is fed by a drainage area only a tenth that of Fortymile Wash and with a stream gradient more than twice as great. The cross-section area of the fan incision at this location (fig. 5, site C) on Topopah Wash is 40 percent of that at Fortymile Wash and twice that at Rock Valley Wash. Moreover, the ratio of cross-section area to drainage-basin area is about 6 times that of either Fortymile or Rock Valley Wash (table 2).

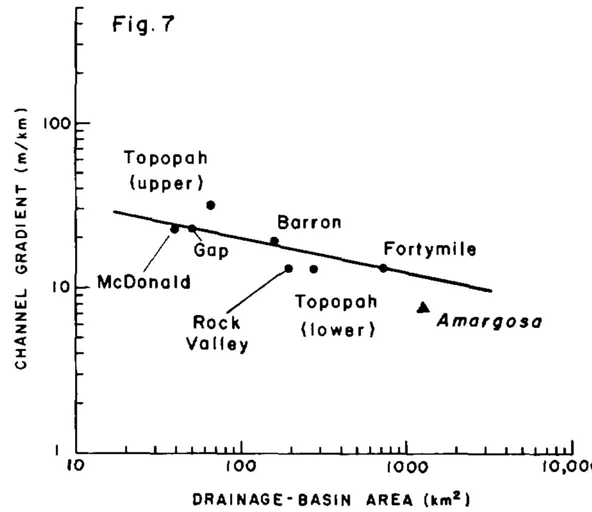
Topopah Wash continues south across Jackass Flats for almost 10 km and then passes through a gap between bedrock exposures (fig. 5). Below this gap, the wash again is incised into alluvial fan deposits. The drainage area of Topopah Wash above this channel incision is four times as large as that of the "upper" Topopah Wash and the gradient has decreased to one about the same as that for channel incision at Rock Valley Wash and Fortymile Wash (table 2). The ratio of channel cross-section to drainage-basin area is small, similar to those for the two other wash incisions, which suggests that this ratio may be related to channel gradient.

An alluvial fan near the far northwest corner of the Amargosa Desert is incised by a wash exiting through a narrow gap from a small drainage basin on the east slopes of the Grapevine Mountains containing McDonald Spring (fig. 5). An estimate of the geometry of this incision is less precise than others in table 2 because only a 15-minute, 40-ft-contour-interval map is available for this area. Nevertheless, an estimate has been included in the table and used for further analysis. Also included in table 2, are data for two other incised fans located to the east just outside of the upper Amargosa River drainage system: Gap Wash, draining to Yucca Flat, and Barren Wash, draining to Frenchman Flat (fig. 5).

Analysis of the data regarding alluvial-fan incision (table 2) is fraught with uncertainties, both as to the quality of the data and as to the differing character of each geographic example. The data, derived from topographic maps, involve considerable interpolation and lack the precision of on-site surveys. The sites selected have in common only incision into alluvial-fan deposits where runoff from a catchment area is focused through a narrow gap onto the fan head. The sites differ greatly in size of catchment area, channel gradient at the site, and topographic nature of the basin upstream from the gap. All sites but one have extensive alluvial-fan or valley deposits just upstream from the focusing gap; the exception is Fortymile Wash located at the mouth of a 20-km-long canyon with only a shallow bed of active alluvium. The Amargosa River south of Amargosa Narrows, near the town of Beatty, exits into an alluviated valley rather than onto a true fan and will be considered separately although data for it is included in table 2 and figures 6-8.

Despite limitations of the data, which are too few for statistically signifcant analysis, study of the fan-incision data from the upper Amargosa drainage system and vicinity is informative. Fortymile Wash has by far the largest cross-section area of fan incision and also by far the largest drainage basin. A plot of cross-section area vs. drainage area, however, does not show a clear relationship for the sites examined (fig. 6). An arbitrary line has been drawn through four of the data points. Of the three data points clearly anomalous to this line, the two points below the line represent two of the sites with the lowest channel gradients and the one above the line the





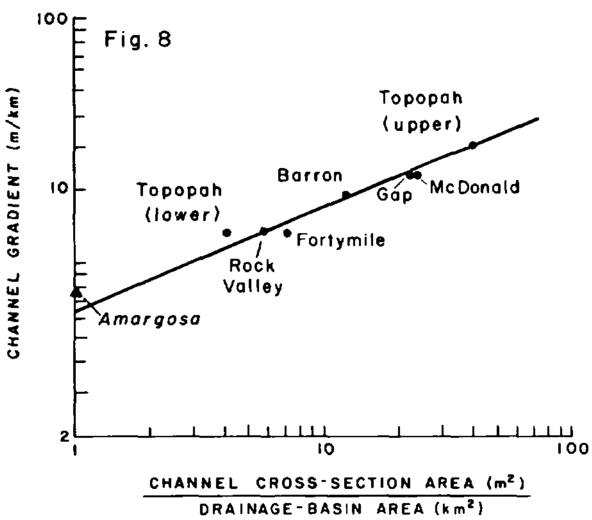


Figure 6.--Relation between cross-section area of incised channel and drainage-basin area. Locations are indicated on figure 5. Data for the Amargosa River (triangle) is shown here and on following graphs, but is treated separately in text.

Figure 7.--Relation between channel gradient and drainage basin area.

Figure 8.--Relation between channel gradient and the ratio of channel cross-section area to drainage-basin area.

site with the highest gradient (table 2). This suggests that channel gradient might have some significant influence on the degree of channel incision. Note that although not included in this analysis of incised fans the data point for the Amargosa River site, which has a lower gradient than any of the fans, falls farthest off the line.

Other factors being equal, fan (or channel) gradient is an inverse function of drainage-basin area (Schumm, 1977, p. 247-8). A plot of gradient vs. drainage area for the sites listed (fig. 7) shows only a general tendency toward this relationship, with the same three sites noted in figure 6 anomalous to the plotted line. This 'anomaly' can be explained by a secondary factor in the gradient-basin area relationship: the greater the ruggedness or average slope of the drainage basin, the greater is the gradient of the fan (Schumm, 1977, p. 248). The two sites with anomalously low gradients (below the line in fig. 7) are Rock Valley Wash and the lower Topopah Wash, which drain the least-rugged topography and have the lowest average upstream gradients of the sites listed. The other anomalous gradient (above the line in fig. 7) is at upper Topopah Wash, which drains the area with the highest local relief and the highest average upstream gradient.

To investigate the relationship among the three parameters--cross-section area of channel incision, drainage-basin area, and channel gradient--another graph (fig. 8) plots channel gradient against the ratio of cross-section area to drainage-basin area (a dimensionless number, area/area). On this plot the three sites that appear anomalous on figures 6 and 7 fall into line. This indicates that once channel-gradient differences are considered, all of the listed sites are shown as being incised under the influence of comparable conditions, and that the large cross-section area of Fortymile Wash is chiefly due to its large drainage-basin area and is not 'anomalous' with respect to other wash incisions in the upper Amargosa drainage system and vicinity. Furthermore, the overall similarity of effects at these diverse sites, sites that also differ in azimuth of drainage direction, suggests that the transition from alluvial-fan construction to fan incision more likely resulted from a major climatic change rather than from tectonic disturbance.

John Dohrenwend (oral commun., 1987) points out that the relation shown in figure 8 might be explained by the fact that fan or channel gradient is largely determined by debris size and discharge (Hooke and Rohrer, 1979), and that peak discharge is very strongly related to drainage area and channel cross-section. He further suggested that if the relation in figure 8 could be verified with a statistically significant data set and the ratio of channel cross-section area to drainage-basin area somehow related to discharge, it might provide an indirect method of estimating peak discharge where such information is not available. Such correlation would probably be difficult because of the very infrequent and variable discharge inherent in the arid-region alluvial-fan environment.

AMARGOSA RIVER SOUTH OF BEATTY

Downstream from the town of Beatty (fig. 2), the Amargosa River passes through the Amargosa Narrows gap. Upstream from this gap is a drainage basin of 1234 km^2, the largest listed in table 2, that includes the subbasins of Thirsty Canyon, Beatty Wash, and some smaller areas (fig. 5). The gap itself is underlain by resistant rocks of the Wood Canyon Formation (Stewart, 1970) that forms a bedrock ledge that forms the local base level for the drainage basin upstream.

Downstream from the Amargosa Narrows, the Amargosa River flows into the Amargosa Desert, through a broad alluvial valley flanked on the east by steeper alluvial-fan deposits along Bare Mountain and on the west by a gentler broad apron of fan deposits shed from the Bullfrog Hills, the Grapevine Mountains, and the Funeral Mountains. The stream incised wash below the Narrows differs from those associated with the incised fans described above in that it is shallow relative to its width (table 2). I attribute this chiefly to the low gradient of the channel, half of that at Fortymile Wash. The low-gradient stream tends to meander more than a steeper one and develop a highly braided channel rather than a narrowly confined one. Even with its large drainage basin the channel gradient here is low compared to others in the region (table 2, fig. 7). This difference is probably due to the low mean slope of the Amargosa drainage basin; the mean gradient of a 20-km reach of the river in Oasis Valley upstream from Beatty is only 10 m/km.

The present cross-section area of the Amargosa wash below the Narrows is low for the size of the drainage basin (fig. 6), but not greatly so when the channel gradient is considered (fig. 8). Unlike Fortymile Wash, whose incised-channel position has changed little since its inception, the active Amargosa channel is only one of many channels that have been active in the past and whose composite cross-section areas are much greater than that for the active wash alone. One largely abandoned wash is now fed only by meager runoff from Bare Mountain.

Additional evidence for lateral channel migration or channel branching is presented by the so-called Beatty scarp, 10 km long and truncating alluvial-fan deposits along the east side of the Amargosa drainage south of Amargosa Narrows. It has long been interpreted as a Quaternary fault (Cornwall and Kleinhampl, 1961; 1964; Cornwall, 1972; Carr, 1984), but recently has been reinterpreted as an erosional feature formed by lateral migration of the Amargosa River (Swadley and others, in press). A trench excavated adjacent to the scarp exposed fluvial gravel, sand, and silt typical of braided-stream deposits and lacked any evidence of fault displacement. A radiocarbon age of about 10,000 years on carbonized wood in the deposit suggests that the scarp was undercut in late Pleistocene or early Holocene time (Swadley and others, in press).

In summary, the gross differences in the size and geometry of wash incisions on the Amargosa River downstream from Beatty and at Fortymile Wash are consistent with the size and geometry of their drainage basins. Neither wash is anomalous with respect to the overall evolution of the upper Amargosa drainage system; each similarly responding to the geomorphic parameters involved. The similar responses by the several washes suggests that the change from alluvial-fan construction to fan incision reflects a drainagewide change in the upper Amargosa River system caused by some common factor. Regional tectonic processes, such as subtle tilt, would be unlikely to produce such a change given the diverse orientations of the drainages involved. A change in climatic conditions seems more likely, although the existence, nature, and timing of such an event is still speculative.

Remnants of low terraces at several localities within Fortymile Wash are identifiable on aerial photographs. These terraces, 5 to 10 m above the modern wash, are described as fill terraces by Taylor (1986), the result of a period of aggradation in the wash. On the basis of soil development, she correlates these terrace deposits with gravel deposits that have uranium-trend age determinations of 145,000 and 160,000 years (U.S. Geological Survey, 1984, table 2). If the correlation is correct, and these ages are in the correct range, then Fortymile Wash must have had nearly its present depth by about 150,000 years ago. Having cut down through these terrace deposits to reestablish an earlier base level (Taylor, 1986, fig. 3), Fortymile Wash apparently reached a state of near equilibrium with little aggradation or degradation at present.

The Tecopa basin about 85 km south of Amargosa Valley (formerly known as Lathrop Wells) (fig. 1) is situated on the Amargosa River drainage and can be considered a southern extension of the Amargosa Desert. During the late Pliocene and early Pleistocene, a climate that was appreciably wetter than today's sustained a moderately deep lake in the Tecopa basin (Hillhouse, 1987). The lake had no outlet until sometime after 0.5 m.y. ago, when the south margin of the basin was breached and the lake drained. The current water supply to the basin is inadequate to balance evaporation and sustain a perennial lake even if it had remained without an outlet (Hillhouse, 1987).

Studies of water-table decline during the Quaternary at Ash Meadows in the Amargosa Desert about 35 km south of the mouth of Fortymile Canyon summarize evidence for increasing aridity in the southern Great Basin during the Pleistocene (Winograd and Szabo, in press; Winograd and others, 1985). They attribute much of this decline to Pleistocene uplift of the Sierra Nevada and Transverse Ranges, the major orographic barriers bounding the southern Great Basin. Such uplift would contribute to progressive depletion of moisture from inland-bound Pacific storms during the Pleistocene epoch, independent of any world-wide climate cycles. It is possible that during such a decline, a threshold would have been reached wherein major alluvial-fan construction in the Amargosa Desert would have ceased. This would not be incompatible with such cessation having taken place sometime after one-half million years ago.

Addendum: Warren and others (1988) have presented new K-Ar age data that indicate that some of the rocks here included in the rhyolite of Fortymile Canyon (fig. 3) should be grouped with the Paintbrush Tuff as predating the collapse of the Timber Mountain caldera. Such rocks include those south of Pah Canyon for which ages of 13.5 to 11.3 m.y. were obtained. However, ages of 10.6 and 10.7 m.y. were obtained for rhyolite of Fortymile Canyon within Fortymile Canyon north of Pah Canyon; these rocks apparently postdate caldera collapse and the conclusions reached in this study are not negated by the new data (Warren, R.G., McDowell, F.W., Byers, F.M., Jr., Broxton, D.E., Carr, W.J., and Orkild, P.P., 1988, Episodic leaks from Timber Mountain caldera: New evidence from rhyolite lavas of Fortymile Canyon, SW Nevada volcanic field: Geological Society of America Abstracts with Programs, v. 20, no. 3, p. 241).

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