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TITLE: LATE CENOZOIC EVOLUTION OF FORTYMILE WASH: MAJOR CHANGE IN DRAINAGE PATTERN IN THE YUCCA MOUNTAIN, NEVADA REGION DURING LATE MIOCENE VOLCANISM

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LATE CENOZOIC EVOLUTION OF FORTYMILE WASH: MAJOR CHANGE IN DRAINAGE PATTERN IN THE YUCCA MOUNTAIN, NEVADA REGION DURING LATE MIOCENE VOLCANISM

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ABSTRACT

Analysis of sedimentary provenance and altitude distribution of volcanic strata along Fortymile Wash, the primary desert wash east of Yucca Mountain, NV, indicates a major change in surface drainage basins related to late Miocene volcanic disruption. This event resulted in the establishment of the modern Fortymile Wash basin before 3 Ma, and probably by latest Miocene time. An understanding of this event is useful for evaluation of extensive alluvium east of Yucca Mountain and its relation to paleoclimate, hydrology and tectonics. To the northeast of Yucca Mountain, Fortymile Wash provides southward surface drainage from 60% of the area of the 11 Ma Timber Mountain caldera via Fortymile Canyon, a major breach in the caldera wall. In the southeast caldera moat, the distribution of volcanic units that predate and include the 9.4 Ma Thirsty Canyon Group and the characteristics of intercalated sediments indicate a northward paleoslope and sediment transport from a major drainage divide near Dome Mountain, a shield volcano now deeply incised by Fortymile Canyon. Eruption of the Thirsty Canyon Group from the Black Mountain area, 10 km northwest of the Timber Mountain caldera, is likely to have dammed a counterclockwise drainage system of the east moat. Following drainage disruption, the east moat filled with sediment up to the level of a new southward outlet at the saddle between Dome Mountain and the onlapping rhyolite of Shoshone Mountain. An older canyon south of this saddle received the overflow from the east moat and became the throughgoing Fortymile Canyon, integrating the east moat basin with a lower base level in Jackass Flats. Well-integrated southward drainage existed by the time the trachybasalt flows of Buckboard Mesa (2.8 Ma) were emplaced, because basal elevations of these flows slope southward about 100 m above modern Fortymile Wash. An older gravel exposed just south of Fortymile Canyon has a clast population distinctive from that for Quaternary gravels of Fortymile Wash; this older gravel is a deposit of the older lower canyon, preceding the establishment of a throughgoing Fortymile Canyon.

INTRODUCTION

The site characterization of Yucca Mountain, NV as a potential high level nuclear waste repository includes study of the surficial deposits as a record of the paleoenvironmental history of the Yucca Mountain region[1,2]. An important aspect of this history is an understanding of the evolution of paleogeography leading to establishment of the present drainage pattern. Establishment of drainage basin evolution is needed before geomorphic response to paleoclimate and tectonics can be assessed, because a major change in drainage basin geometry can predominantly affect the sedimentary record. Because alluvial aquifers are significant to regional hydrology[3], a major change in surface drainage resulting in buried alluvium could have hydrogeologic significance. In this paper, we report on geologic evidence for a major modification in surface drainage pattern in the Yucca Mountain region, resulting in the probable establishment of the Fortymile Wash drainage basin by latest Miocene time.

Physiography

Yucca Mountain, a ridge in the southwestern part of the Great Basin, is flanked by alluviated basins, and is located to the south of the upland of the southwestern Nevada volcanic field. Most of this upland comprises the northeastern and uppermost portion of the Amargosa River Basin, an ephemeral surface drainage system which grades southward for 90 km before entering Death Valley at its southern end. Fortymile Wash provides the surface drainage to a major part of the upper Amargosa basin (Fig. 1), including the highest uplands of eastern Pahute Mesa and Timber Mountain. The modern watershed of Fortymile Wash is characterized by a lower southern basin, including the east slope of Yucca Mountain and the west side of Jackass Flats, separated from an upper northern basin by the 25 km long Fortymile Canyon (Fig. 1), with a maximum depth of about 500 meters. The upper basin includes the east moat of the Timber Mountain caldera, formed during its latest cycle of collapse and resurgence about 11.4 Ma[4,5,6]. The timing of the establishment of Fortymile

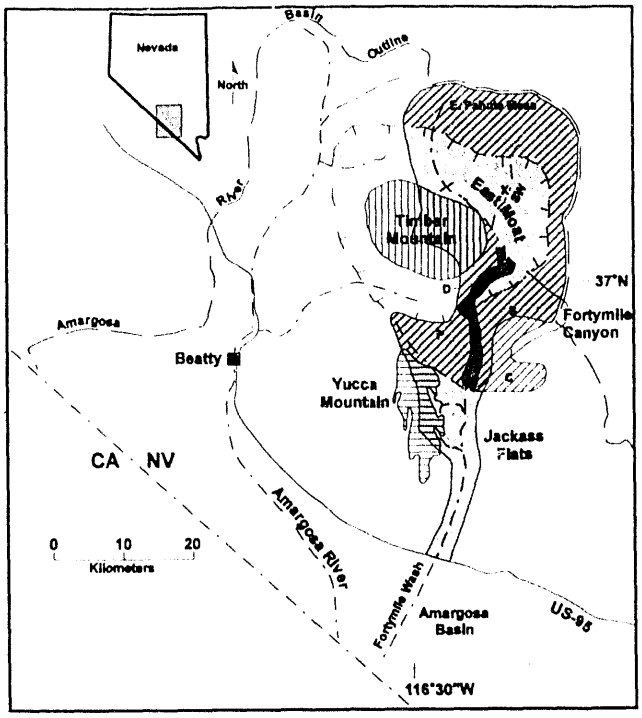


Figure 1. Geography of the upper Amargosa River surface drainage basin, showing major channels (dash-dot lines), the sub-basin of Fortymile Wash (light shading), Fortymile Canyon (dark shading), Yucca Mountain (horizontal lines), the boundary of the Timber Mountain Caldera (dashed, hachured line with hachures towards moat), and central resurgent dome (vertical lines). Other major uplands of the basin of Fortymile Wash are diagonally cross-hatched, including Dome Mountain (D), Pinnacles Ridge (P), Shoshone Mountain (S) and the Calico Hills (C). Other locations mentioned in paper are Rocket Wash (RW), Stockade Wash (SW), and well U18-J1 (X).

Canyon is significant in resulting in a four-fold expansion of the Fortymile Wash drainage basin. Previous hypotheses for the age of establishment Fortymile Canyon range from immediately following caldera resurgence[7] to middle Quaternary capture from Beatty Wash[8]. In this paper, we analyze the spatial distribution of volcanic stratigraphy, in combination with provenance considerations of intercalated sediments along Fortymile Wash, to infer the history of drainage-basin evolution leading to the establishment of Fortymile Canyon.

ALTITUDE DISTRIBUTION OF VOLCANIC STRATA

The volcanic stratigraphy of the southwestern Nevada volcanic field[4,5,6,9,10,11,12] is one of the more thoroughly studied sequences of caldera-related magmatism, and provides a geologic framework (Fig. 2) for understanding the Neogene drainage evolution in this critical area of the southern Basin and Range province. The volcanic units exposed along Fortymile Wash (Fig. 2) range in age from the 12.9 Ma rhyolite of Calico Hills to the 2.8 Ma trachybasalt of Buckboard Mesa[6,12]; we focus on the distribution of units that postdate the Timber Mountain Group. These units are mostly rhyolitic and basaltic flows extruded near ring fractures of the Timber Mountain caldera, though ash flows of the 9.4 Ma Thirsty Canyon Group originated from the Black Mountain center[6,12], northwest of the Timber Mountain caldera. Volcanic stratigraphy predating and including the Thirsty Canyon Group defines a paleogeography that contrasts with that of the modern Fortymile Wash basin. We infer major changes in drainage direction and paleogeography from an analysis of the altitude distribution of volcanic units along Fortymile Wash from previous high-quality geologic quadrangle mapping[13,14,15,16]. Units will be discussed in stratigraphic sequence, as well as northward from central Fortymile Canyon into the east moat of the caldera.

Fortymile Canyon

The former rhyolite of Fortymile Canyon consists of multiple rhyolite flows and pyroclastics exposed within Fortymile Canyon[15]. Recent work[9] demonstrated that much of the rhyolite of Fortymile Canyon, formerly defined as postdating the Timber Mountain Group[15], erupted during earlier magmatic cycles. Only the rhyolites of Chukar Canyon and Max Mountain (10.7 Ma by K-Ar date[9]; Figs. 2 and 3), emplaced within the southeast moat of the Timber Mountain caldera, postdate the caldera. These relations obviate any need to explain the distribution of rhyolite flows as evidence for ancestral canyons preceding the flows[7]. Within this well-exposed volcanic sequence of rhyolite flows, there are no recognized intercalated fluvial gravels requiring a former canyon.

Dome Mountain is a mafic shield volcano deeply incised along its east flank by Fortymile Canyon (Figs. 2 and 3). It overlies the 10.7 Ma rhyolite of Max Mountain[9] and is onlapped by the 10.3 Ma rhyolite of Shoshone Mountain[16,17]. The main outcrops of the mafic lavas of Dome Mountain[15,16,18] in central Fortymile canyon (Figs. 2, 3) are gently dipping flows that occur high on both sides of the canyon. However, mafic lavas of Dome Mountain have also been mapped near the central canyon bottom[15,16]. Correct recognition of the origin of these exposures is critical to understanding the evolution of Fortymile Canyon; we consider three explanations. First, exposures near the floor of Fortymile Canyon might represent very late flows of mafic lava of Dome Mountain that occurred after the canyon was cut. This scenario would require a pause in eruption long enough to cut Fortymile Canyon to its present depth. Marsh and Resmini[28] have estimated that phenocrysts in mafic lavas at Dome Mountain had residence times of about 10-20 years, indicating rapid magmatic evolution, consistent with rapid evolution of the earlier Paintbrush Group[6]. Thus the first explanation would require that Fortymile Canyon be cut to its present depth during the apparently rapid magmatic evolution of the shield volcano at Dome Mountain, then undergo no further deepening during the next 10 Ma. Such a scenario is implausible. Second, the exposures near the floor of Fortymile Canyon might have been misidentified. Our preliminary petrographic analysis of a thin section of mafic lava of Dome Mountain from an outcrop at the floor of Fortymile Canyon (location A on Fig. 3) shows significant olivine, orthopyroxene, and ilmenite, a combination of phenocryst phases absent in nearly all mafic units of the region, but characteristic of the andesitic, upper part of the mafic lavas of Dome Mountain. This confirms an earlier lithologic assignment[15], but the geomorphic position of these exposures is suggestive of landslides, a third explanation. Landslides of basalt are common within canyons cut deeply through basalt into underlying sediments, and can extensivcly preserve minimally deformed basalt in slump blocks[19]. Therefore, the lack of apparent deformation that we observe in some exposures, as at location A (Fig. 3) does not preclude their origin as landslides. We conclude that the outcrops of mafic lava of Dome Mountain near the floor of central Fortymile Canyon must be landslides.

A northeastward paleogeographic slope opposite the trend of Fortymile Canyon is defined by the altitudinal profile of the mafic lavas of Dome Mountain (Fig. 4), excluding the landslides described above. Altitudes of basal and upper surfaces of this lava sequence generally decrease northeastward along Fortymile Wash from the summit area of Dome Mountain, the inferred vent. There is no evidence for a pre-existing Fortymile Canyon at the time the lavas of Dome Mountain were erupted. Instead, the decrease in basal altitude and the gradual northward decrease in thickness of lavas of Dome Mountain along Fortymile Wash (Fig. 4) are evidence for a paleogeography in which most of the mafic lavass of Dome Mountain flowed northward from a topographically high area of the southeastern Timber Mountain moat that had been built up through extrusion of the only slightly older rhyolite of Max Mountain.

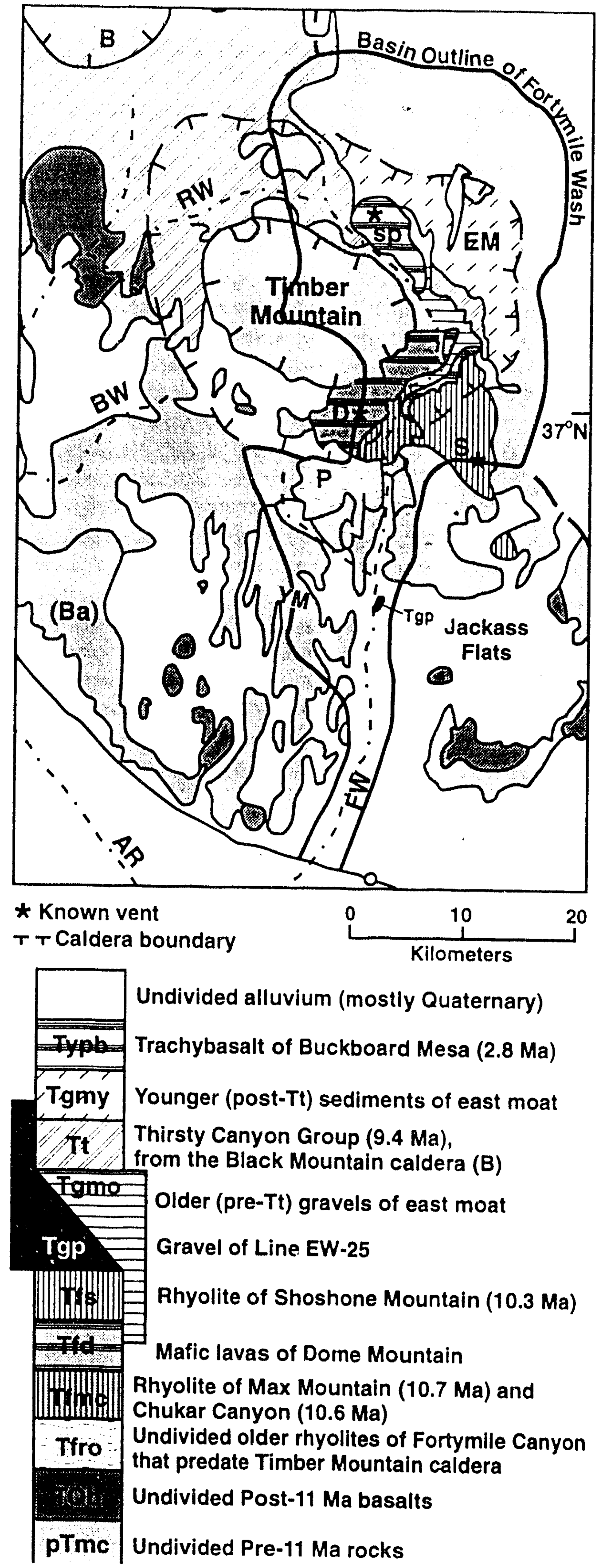


Figure 2. Geology of the region of Fortymile Wash[11,12], with age control[6,9,12,17]. Geographic locations indicated are Amargosa River (AR), Black Mountain (B), Bare Mountain (Ba), Beatty Wash (BW), the east moat of the Timber Mountain caldera (EM), Fortymile Wash (FW), Pinnacles Ridge (P), Scrugham Peak (sp), Shoshone Mountain (S), Rocket Wash (RW), and Yucca Mountain (YM). Approximate scale is about 1:600,000.

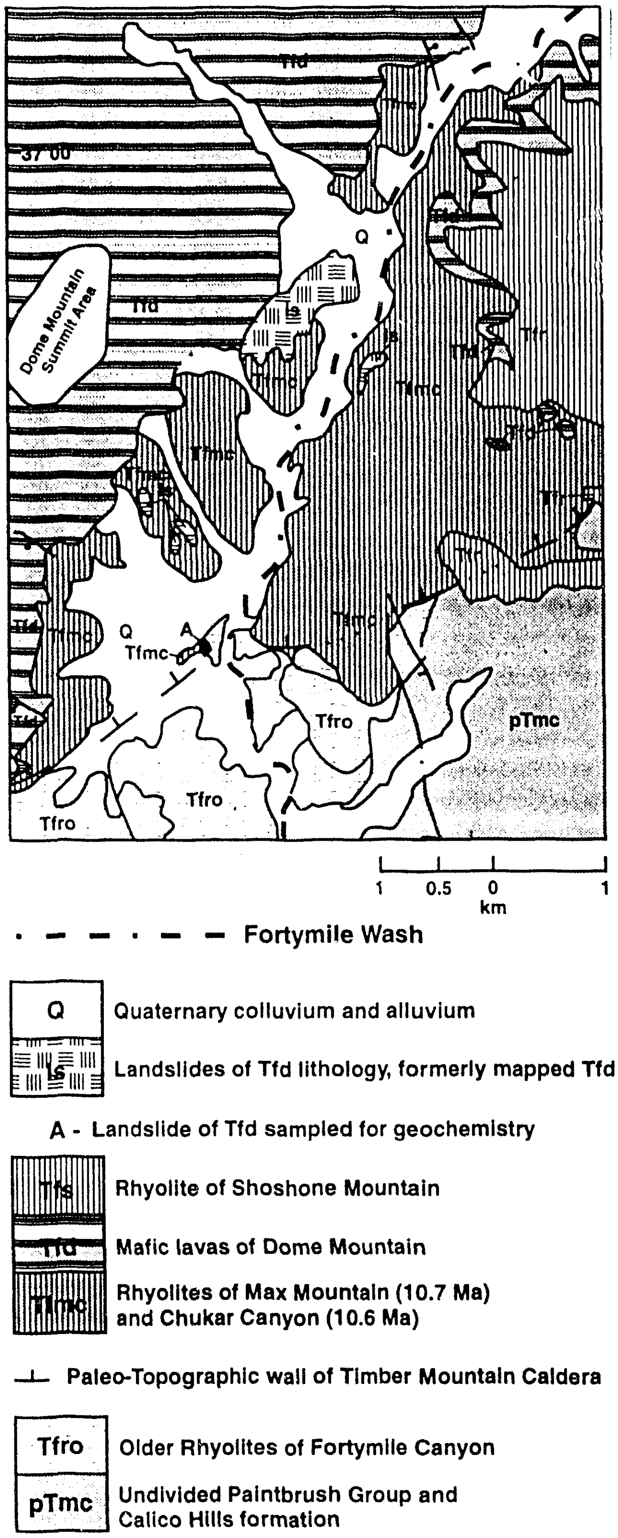
The rhyolite of Shoshone Mountain[16] (Figs. 2 and 3) overlaps the east flank of Dome Mountain and is only slightly younger[17] (10.3 Ma). Its surface also defines a northward constructional slope from a vent area marked by an intrusive plug at the summit of Shoshone Mountain[16]. Again, there is no evidence that Fortymile Canyon had been established prior to extrusion of Shoshone Mountain, as the basal altitude of its dissected western margin occurs at accordant elevations along the eastern rim of Fortymile Canyon. Instead, the northwest margin of the rhyolite of Shoshone Mountain appears to have localized the later establishment of a southwestward trending reach of Fortymile Canyon over the east flank of the Dome Mountain shield volcano.

The east moat of the Timber Mountain caldera

The Thirsty Canyon Group forms a critical datum in the east moat and in the evolution of Fortymile Wash, because it is the youngest stratigraphic unit to define a northerly paleoslope opposite to the modern slope of Fortymile Wash. The Pahute Mesa and Trail Ridge Tuffs of the 9.4 Ma Thirsty Canyon Group[6,12] are exposed in the east moat along Fortymile Wash beneath Buckboard Mesa and as a northeast-dipping cuesta within sediments of the east moat[11,12,13] to the southeast of Buckboard Mesa (Fig. 2). These ash flow tuffs thicken northwestward from the east moat toward their source in the Black Mountain caldera[20]. A northward component of dip is defined by the basal and upper contacts of the Thirsty Canyon Group in following Stockade Wash northeast from its confluence with Fortymile Wash at the south end of Buckboard Mesa to drill hole U18-J1[21] (Figs. 1 and 4). This northward dip is likely to reflect a northward paleoslope, because the Thirsty Canyon Group also thickens northward along this transect from 30 m at the south end of Buckboard Mesa to 55 m in drill hole U18-J1[21].

In contrast to the older volcanics of the post-Timber Mountain Group along Fortymile Wash discussed above, the 2.8 Ma trachybasalt of Buckboard Mesa [12,13,22,23,24] (Figs. 2 and 4) defines a southward slope in the east moat. The base of the flows of Buckboard Mesa, where unfaulted, slope southward , parallel to and about 100 m above the longitudinal profile of modern Fortymile Wash. Buckboard Mesa clearly defines a southward-trending paleovalley bottom at an altitude about 300 m lower than the highest exposed basal contacts of mafic lavas of Dome Mountain in Fortymile Canyon, requiring the existence of a throughgoing Fortymile Canyon at a probable grade about 100 m higher than present by about 3 Ma.

Figure 3. Geology of central Fortymile Canyon modified from previous work[9,13,14,15,16]. Approx. scale is 1:66,000.



We consider the slopes of volcanic units in Figure 4 to not have overiding components of structural rotation that would yield erroneous paleogeographic slope *direction*. Though significant tectonism in the past 10 Ma is known to have occurred outside the caldera, only minor faulting has cut the exposed units postdating caldera resurgence in the east moat. Furthermore, the general southerly trend of Fortymile Wash is sub-parallel to the direction of most faults in the area and to likely associated axes of tilting. Minor faults crossed by Fortymile Wash along more easterly jogs in its course are expressed as local reversals in the basal slopes of Dome Mountain and Buckboard Mesa flows, but inferred vent locations and thickness trends of these mafic flows provide further support that their original basal slope directions have not been tectonically reversed.

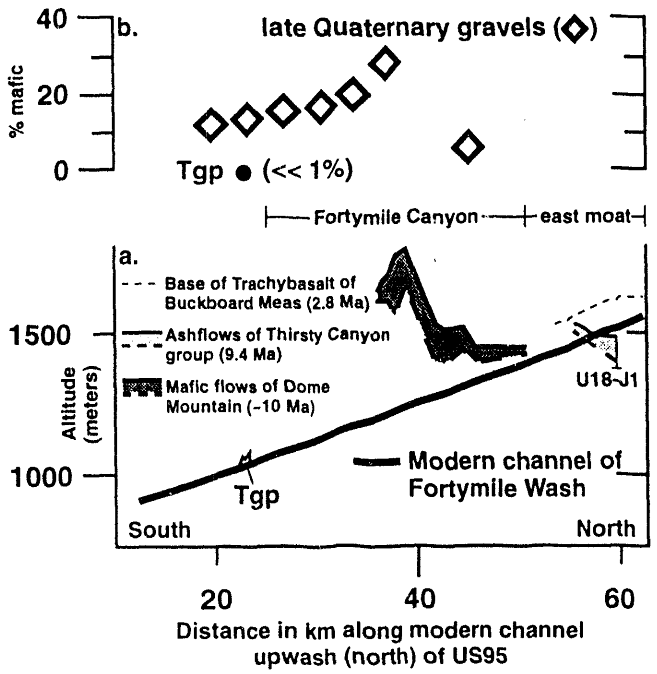


Figure 4. Longitudinal profiles of parameters along Fortymile Wash:
a. Altitude profiles of geologic units along Fortymile Wash. Altitudes of basal (dashed) and upper (solid) contacts of volcanic units are from published geologic quadrangles[13,14,15,16], and surface altitudes of gravel units are from published U.S. Geological Survey topographic maps.
b. Percent of mafic lithologies in Late Quaternary alluvium and older gravel of Jackass Flats along Fortymile Wash. Each data point for late Quaternary gravels represents a natural exposure where at least 85 clasts greater than 8 mm intermediate diameter, within a fixed distance from regularly spaced grid points, were classified as mafic or felsic . The data point for Tgp, the gravel of Line EW-25 (dot), represents 310 clasts counted at 3 sites.

SEDIMENTARY CHARACTERISTICS AND PROVENANCE

The sedimentary record, including the sediment characteristics of clast lithology, rounding, and size, as well as sedimentary structures, reflect the changing paleogeography inferred from the volcanic stratigraphy. To the north of Fortymile Canyon, sediments intercalated with the volcanic sequence in the east moat provide additional evidence for the formerly northward-sloping paleogeography of the east moat, opposite the modern drainage direction of Fortymile Wash. To the south of Fortymile Canyon, Quaternary gravels that postdate canyon establishment lithologically contrast with an older gravel interpreted to predate a throughgoing canyon.

Sediments of the east moat

The oldest sediments recognized within the east moat underlie the Thirsty Canyon Group and are intercalated with the mafic lavas of Dome Mountain[15,16,18] (Fig. 2); these sandy gravels to gravelly sands will be referred to as the *older gravels of the east moat*. They are moderately diagenetically cemented. In a northeast direction from Dome Mountain, opposite the gradient of Fortymile Wash, these older moat gravels thicken and become more fluvial in character; rounded cobbles and cross beds are common at the north end of Fortymile Canyon.

To the north of the mapped limit of mafic lavas of Dome Mountain[13], older gravels of the east moat are more extensively exposed just south of the northeastward-dipping cuesta of the Thirsty Canyon Group (Fig. 2). Like the stratigraphically lower sediments beneath the northern exposed extent of Dome Mountain lavas, these older moat sediments are predominantly fluvial sandy gravels, with common subrounded gravel clasts and cross bedding. The presence of mafic clasts in these sediments provides evidence for a northeastward direction of fluvial transport. Most mafic clasts are oxidized scoria which is not conducive to geochemical or petrographic identification. We have found some clasts that appear to be Dome Mountain lithology, although this hand-sample identification is provisional, pending geochemical and petrographic analysis. However, given their stratigraphic position, there are no other known potential sources of mafic clasts in areas north or east of the East Moat basin. The northeastward fluvial transport away from a Dome Mountain source is opposite the present drainage direction of Fortymile Wash.

In contrast, sediments which overly the Thirsty Canyon Group in the east moat (Fig. 2) show evidence for a major change in depositional environment from that of older gravels of the east moat. These *younger sediments of* *the east moat* are poorly exposed, but roadcut exposures typically show thinly bedded tuffaceous sands, unconformably overlain by gravels. The sands represent a distinct textural fining relative to the pre-Thirsty Canyon fluvial gravels; the fine bedding may represent lacustrine conditions. We interpret the fine, thinly bedded sediments as closed- basin deposits resulting from the disruption of the previous drainage system by the eruption of the Thirsty Canyon Group.

Gravels along lower Fortymile Wash

To the south of Fortymile Canyon, extensive Quaternary alluvium along Fortymile Wash[25,26] has generally buried most older alluvium that might correlate to sediments in the east moat. However, a distinctive older gravel of limited exposure, termed the *gravel of Line EW-25*, (Tgp, Figs. 2 and 4) has been recognized during recent mapping of surficial deposits near Yucca Mountain[26]. This older gravel is exposed as a rounded hill veneered by Quaternary alluvium along the east side of modern Fortymile Wash, 7 km east of the crest ofYucca Mountain, beneath a powerline (EW-25). The gravel of Line EW-25 is similar to the older gravels of the east moat in the degree of diagenetic cementation and sparse presence of mafic clasts, but is quite distinctive from adjoining Quaternary terrace gravels of Fortymile Wash (Table 1). The Quaternary gravels deposited by Fortymile Wash are not diagenetically cemented, and include a common and obvious component of mafic clasts. Though distinctive in its content of mafic clasts and cementation, the gravel of Line EW-25 is similar to the Quaternary gravels of Fortymile Wash (Table 1) as a cross-bedded sandy gravel with common rounded cobbles and boulders, in the abundance of spherulitic rhyolite and lithologies of the Calico Hills formation, and in the presence of aphyric obsidian from the rhyolite of Shoshone Mountain. These lithologies require a provenance that includes the area around lower Fortymile Canyon.

Table 1. Comparison of gravels of lower Fortymile Wash

Quaternary gravel	gravel of Line EW-25
differences	
common basaltic clasts (12-25%)	very sparse basaltic clasts
non-cemented to locally cemented in isolated caliche horizons	pervasive diagenetic cement
extensive along Fortymile Wash	very limited exposure
similarities	
sandy gravel	
common rounded cobbles and boulders	
common cross-bedding	
abundant spherulitic rhyolite clasts	
common oxidized rhyolite clasts, as well as aphyric obsidian of rhyolite of Shoshone Mountain	

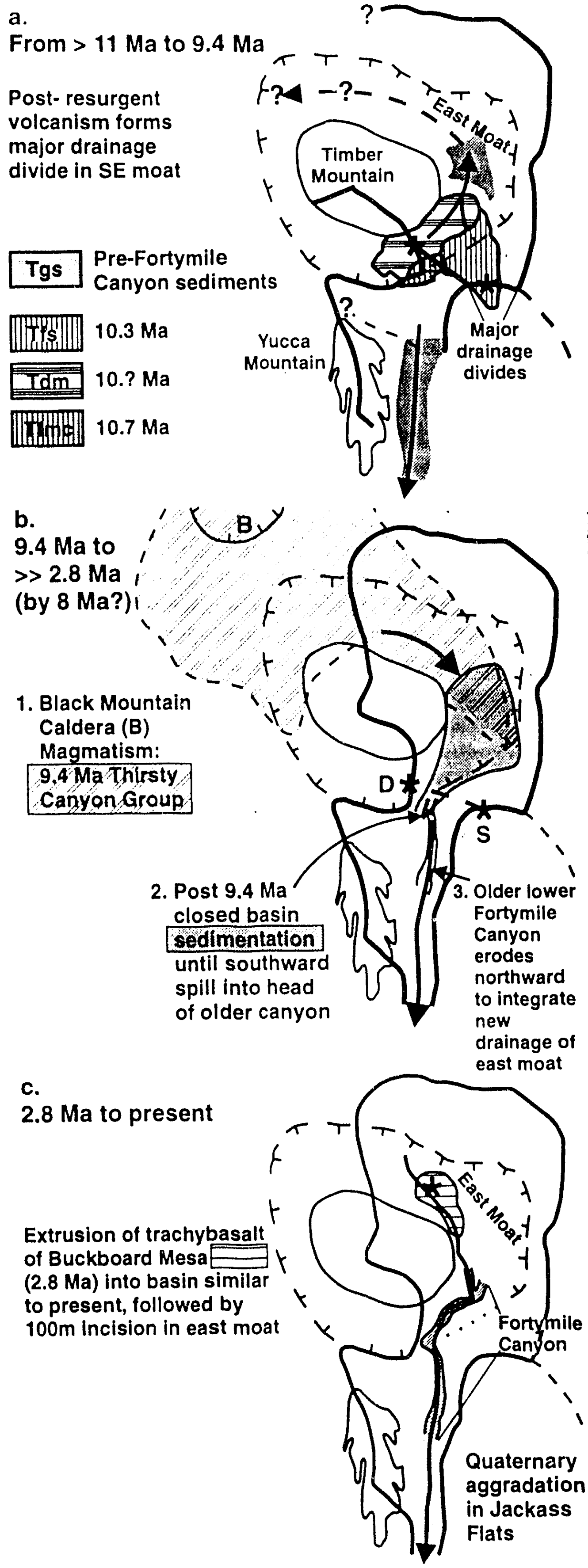
Clast counts of gross clast lithology (mafic or felsic volcanics) were made of late Quaternary alluvium and the gravel of Line EW-25 along Fortymile Wash to quantify differences that would reflect whether Fortymile Canyon existed when the gravel of Line EW-25 was deposited (Fig. 4b). The proportion of mafic lithologies in late Quaternary gravels of Fortymile Wash increases from 6% to 24% within upper Fortymile Canyon, then decreases more gradually down wash to about 12% south of the exposed gravel of Line EW-25 (Figs. 2 and 4). This pattern clearly shows that mafic lavas of Dome Mountain, incised by Fortymile Canyon, are the main source of the mafic clasts in the Quaternary alluvium. Downwash of the southern limit of mafic lavas of Dome Mountain, the proportion of mafic clasts in Quaternary alluvium decreases southward, probably as a result of addition of exclusively non-mafic sources in southern Fortymile Canyon, but remains higher than 12 percent south of the exposure of the gravel of Line EW-25 . In contrast, mafic clasts in this older gravel are very sparse relative to any of the Quaternary gravels of Fortymile Wash, comprising much less than 1 % (Fig. 4b). These mafic clasts, with typically abundant vesicles, are also likely to be derived from mafic lavas of Dome Mountain, based on preliminary hand sample identification.

The characteristics of the gravel of Line EW-25 provide a basis for estimation of its age. The presence of any Dome Mountain and Shoshone Mountain clasts requires Tgp to be no older than 10.3 Ma. We interpret the sparsity of mafic clasts in the gravel of Line EW-25 to preclude the existence of a throughgoing Fortymile Canyon when this gravel was deposited. Instead, the provenance of this older gravel included a drainage in the position of lower Fortymile Canyon which headed near the southern limit of Dome Mountain lavas at that time. Because the gravel of Line EW-25 is a coarse fluvial deposit similar to the Quaternary gravels, the major difference in their proportions of mafic clasts is unlikely to be a climatic effect. If the gravel of Line EW-25 predates the establishment of a throughgoing Fortymile Canyon, the timing of the canyon establishment after 9.4 Ma and well before 2.8 Ma provides a lower limit to the age of the gravel of Line EW-25 ; it was probably deposited in latest Miocene time.

DISCUSSION

We propose a new hypothesis for the evolution of Fortymile Wash (Fig. 5), based on the above volcanic and sedimentary stratigraphy along Fortymile Wash. In contrast to a previous hypothesis[7], we see no evidence for a throughgoing Fortymile Canyon prior to extrusion of any of the volcanic units along Fortymile Wash other than the 2.8 Ma trachybasalt of Buckboard Mesa. Within about one million years of the final collapse of the Timber Mountain caldera[6] (11.4 Ma), its resurgence was closely followed by a volcanic sequence in the southeastern moat that formed a major drainage divide (Fig. 5a). A persistent northward paleoslope from this divide into the east moat is defined by the upper and lower surfaces of volcanic units transected by upper Fortymile Wash (Fig. 4a), for units as old as the mafic lavas of Dome Mountain, and as young as the ash flows of the Thirsty Canyon group[6,12] (9.4 Ma). This northward paleoslope is also defined by northward fluvial transport in the east moat prior to eruption of the Thirsty Canyon Group. This fluvial transport must have either terminated in a closed basin (Fig. 5a) or an outlet existed. An outlet to northward drainage from the east moat could only have been in the northern moat, which is presently a topographic saddle between Rocket Wash and Fortymile Wash.

We suggest that the eruption of the Thirsty Canyon Group disrupted the surface drainage pattern of the Timber Mountain caldera, and led to a reversal of drainage direction in the east moat (Fig. 5b). A former counterclockwise drainage in the east moat would have been in a likely position to be deeply buried and disrupted by eruption of ash flows and silicic lavas of the Thirsty Canyon Group from the Black Mountain caldera,, located near the northwest margin of the Timber Mountain caldera. Following drainage disruption, closed basin sedimentation, with possibly lacustrine conditions represented by finely bedded sediments, filled the east moat to the level of a new southward outlet (Fig. 5b). The new outlet was at a pass between the constructional forms of the Dome Mountain shield volcano and the overlying rhyolite of Shoshone Mountain. With recently erupted tuffs of the Thirsty Canyon Group mantling the landscape, it is likely that basin filling was rapid until the level of the new outlet was



5. Paleogeographic history of Fortymile Wash:
a. Eruption of rhyolites of Max Mountain[9] (Tfmc, 10.7 Ma) and Shoshone Mountain[12,17] (Tfs, 10.3 Ma), and intercalated shield volcano of mafic lavas of Dome Mountain (Tfd) into southeast part of newly formed Timber Mountain caldera moat forms a major drainage divide, with northward and southward fluvial transport and aggradation from the Dome Mountain area prior to 9.4 Ma;
b. The 9.4 Ma Thirsty Canyon Group[6,12] is erupted from the Black Mountain Caldera to block outlet for drainage of east moat. This causes closed basin aggradation until new southward drainage is established for the east moat at new outlet between Dome Mountain (D) and Shoshone Mountain (S);
c. By 2.8 Ma, when the trachybasalt of Buckboard Mesa[13,24] is erupted, a well integrated southward drainage similar to the modern Fortymile Wash basin has been established.

reached; this initial establishment of southward drainage from the east moat probably occurred closer to 9 Ma than to 3 Ma. The uppermost portion of an older southward drainage system in the present position of lower Fortymile Canyon must have been located near the proposed outlet to receive this new overflow from the east moat. Subsequent integration of the east moat to the lower base level of Jackass Flats accompanied the cutting of upper Fortymile Canyon, probably as northward migration and diffusion of a nickpoint from the former saddle in the drainage divide, now located above the deepest part of the canyon. The altitude of the outlet at the inception of the southward drainage from the east moat is presently about 1525 m. Below 1525 m in the east moat, drainage courses were superimposed across and independent of former constructional volcanic slopes of Dome Mountain and Shoshone Mountain, providing evidence for sedimentary fill during the transition from northward to southward drainage.

The incision of Fortymile Canyon and integration of drainage within the east moat must have been well established before eruption of the 2.8 Ma flows of Buckboard Mesa (Fig. 5c). Basal contacts of flows extruded from the vent area at the north end of Buckboard Mesa define a southward sloping paleovalley, now a topographically inverted mesa parallel to but about 100 m above the present grade of Fortymile Wash (Fig. 4a).

Tectonic implications

Though we consider volcanism to be a probable factor in the drainage reversal in the east moat, the extensional tectonism resulting in the opening of the Jackass Flats basin may also have been significant in lowering base level. A geomorphic response to lowering of base level in Jackass Flats would be the headward erosion to the north of a canyon in the position of lower Fortymile Canyon. The presence of a southward drainage in this position is necessary to our hypothesis, and is supported by the characteristics of the gravel of Line EW-25 at the mouth of Fortymile Canyon, especially its clast composition. The exposure of this gravel of probable late Miocene age at the surface is potentially significant as evidence that perhaps much of the sedimentary fill in Jackass Flats took place in the late Miocene. However, until the nature of the distribution of this unit in the subsurface is better known, its very limited exposure warrants caution in this interpretation, especially considering the large volume of material eroded during the cutting of upper Fortymile Canyon and integration of the east moat.

Hydrogeologic considerations

A hydrologic implication of this proposed evolution of Fortymile Wash is that a former drainage in the northern moat of the Timber Mountain caldera may be buried by the Thirsty Canyon Group. A buried drainage system that included a coarse alluvial aquifer would probably be a zone of locally high groundwater transmissivity. It is possible that a volcanically buried alluvial aquifer could contribute to the anomalously low southwesterly gradient of groundwater potential from Pahute Mesa beneath the surface drainage divide of the north caldera moat towards Oasis Valley[27].

CONCLUSIONS

Fortymile Canyon must have been established after 9.4 Ma and well before 2.8 Ma, probably in the late Miocene. The spatial distribution and characteristics of volcanic and sedimentary stratigraphy in the upper Fortymile Wash basin indicate a northward slope and direction of fluvial transport from Dome Mountain, opposite the present drainage direction, prior to eruption of the Thirsty Canyon Group. These relations suggest that a former counterclockwise drainage system in the east moat of the Timber Mountain caldera was disrupted and forced southward by eruption of the Thirsty Canyon Group. A gravel exposed near the mouth of Fortymile Canyon, near Yucca Mountain, appears to predate the establishment of Fortymile Canyon.

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