Investigation into strath terrace production in the Mud Hills, California

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Abstract:

Rainbow Basin and Owl Canyon comprise deeply dissected uplands in the Mud Hills region near Barstow, California in the western portion of the Basin and Range geologic province. These erosional landscapes are formed in sediment deposited in a Miocene-time extensional basin. The basin was then filled with sediment before being inverted due to tectonic uplift beginning roughly 10 Ma. Sometime after 250 to 300 ka strath terraces were produced and preserved in the two drainage basins in Rainbow Basin, but not in the single drainage basin of Owl Canyon. The reason behind this difference is the main problem to be addressed by this study. This difference is ultimately explained by a contrast in critical stream power between the drainage basins stemming from a difference in the amount of sediment denuded from the hillslopes of the different catchments. Severe winter Pacific storms occurring between 11 and 14 ka may have led to the production and preservation of erosional strath terraces in Rainbow Basin while causing the aggradation of the channel in Owl Canyon. These severe winter storms tend to cause more denudation in larger drainages. Because the catchment of Owl Canyon is roughly three times the size of either of the catchments in Rainbow Basin, it is not unreasonable that this phenomenon would have raised critical steam power relative to stream power in Owl Canyon to a degree that it would cause aggradation in Owl Canyon while allowing strath production and sedimentation in Rainbow Basin.

Introduction:

Owl Canyon and Rainbow Basin are two adjacent dissected uplands in the Mud Hills roughly sixteen kilometers north of Barstow, California. The uplands are formed in an inverted, Miocene-time extensional basin. Throughout this report the two dissected uplands are referred to as Rainbow Basin and Owl Canyon. Rainbow Basin is drained by two separate drainage basins, while Owl Canyon is a single drainage basin. The extensional basins initially formed from the extensional collapse of the basement rock accommodated by the extension of the region 23 to 22 Ma (Ingersoll et al., 1996). This was followed by the deposition of the Mud Hills Formation sandstone and breccia (Ingersoll et al., 1996). Then, at roughly 16 Ma, the extension of the region ceased (Ingersoll et al., 1996). The region then underwent a period of transpression and uplift beginning roughly 10 Ma (Ingersoll et al., 1996). The uplift of the two dissected landscapes in question was caused by the Mud Hills thrust, which has produced slip rates of 0.4 – 0.8 mm/yr (Selander, 2015). Uplift of the region caused the removal of sediment from these former zones of accumulation. However, these basins have exhibited distinct responses to inversion. This is evinced by the contrast between the presence of planar strath terraces in Rainbow Basin and terraces consisting of alluvium deposited on bedrock along irregular contacts in Owl Canyon. The thickness of terrace alluvium in the Owl Canyon area is also greater than the thickness of terrace alluvium in the Rainbow Basin area. The objective of this study is to identify and describe these differences and to investigate their causes.

Methods:

In order for any of the observations made about the differences in the alluvium in these two study sites to be useful for identifying distinctly different stream responses to climate forcing, the alluvium in the basins needs to be correlated. This was accomplished primarily through the use of carbonate content in these sediments to infer their relative ages. The description and interpretation of the carbonate content in these sediments was guided by the work of Machette (1985). The sediments were then correlated using the methods described by Birkeland et al. (1990).

To identify and describe the differences observed between Owl Canyon and Rainbow Basin, the alluvium in both areas was mapped and the sediments were described and appropriate correlations were made between them. The contacts between these sediments and underlying bedrock were also described where possible and the thicknesses of these sediments were measured. Miocene-time sediments and sedimentary rocks were mapped as "undifferentiated bedrock". The thickness of alluvium and the height of alluvium above the bottom the stream channels was measured using a measuring tape and a hand level.

The size of the catchment area for all of the drainages described in this paper were attained using a Planix 10S Tamaya digitizing area-line meter on a 1:24,000 scale map of the area. In the absence of descriptions of the bedload in the streams in these canyons, differences in the bedrock contained in their respective catchment areas was used as a proxy.

Results:

Characterization of alluvial map units:

Qa1 surfaces have moderately well-developed desert pavement and moderately well-developed vesicular A horizons. Clasts on Qa1 surfaces have well-developed carbonate collars.

These three characteristics are the basis of the correlation of the Qa1 that exists on the top of the ridges separating Rainbow Basin and Owl Canyon (Map 1) to the low-lying Qa1 that is south of both canyons (Map 2). A cumulic carbonate horizon was observed in the low-lying Qa1 south of the canyon. A petrocalcic horizon was observed in a stream cut bank at location X (Map 2).

Qa2 surfaces have locally present, weakly-developed carbonate collars and weakly developed desert pavement. Qa2 was mapped in both Rainbow Canyon and Owl Canyon. However, the Qa2 in Owl Canyon has less well developed vesicles and more well developed carbonate collars than the Qa2 in Rainbow Canyon. These differences are minor and the degree of pavement formation in both locations is similar, so they are mapped as the same unit.

Qa3 is characterized by alluvium that is near to the active channel and that displays very little to no soil development. This sediment is interpreted to have been deposited more recently than the events that make up the focus of this paper.

All undifferentiated bedrock was labelled Tb, because the competence of the Miocene-time basin fill sediment in Rainbow Basin and Owl Canyon is typically similar and at the very least is comparable.

Thickness of alluvial units and the geometry of contacts of alluvium and Miocene-time basin fill:

The principle objective of this paper is to assess the factors leading to differing steam-process response to climatic forcing. The stream responses assessed in this report are interpreted from the nature of the contact between alluvium and bedrock at the base of terraces, and the thickness of alluvium that overlies the contacts.

The contact between Qa2 and Tb in Owl Canyon are planar in some areas of the canyon and irregular in others. Qa2 is also locally in buttress unconformable contact with Tertiary basin-fill sediments. The thickness of Qa2 varies greatly, ranging from 1.16m at Location I (Map 1) to 16.7m at Location H (2) (Map1).

The exposed contacts between Qa2 and Tb in Rainbow Basin are all planar, with strath terraces observed at sites Y and Z (Map 2). The thickness of Qa2 in Rainbow Basin ranges from less than 1 meter to 5.7 meters. In some locations in both Rainbow Basin and Owl Canyon, the bases of Qa2 are below currently active stream channels.

Drainage basin catchment areas and rock types:

The drainage area of Owl Canyon is 4.47 square kilometers. Rainbow Basin encompasses two distinct drainages. The total catchment area of the drainage basin in the western part of Rainbow Basin ("Rainbow Basin West") is 0.91 square kilometers. The total catchment area of the drainage basin in the eastern part of Rainbow Basin ("Rainbow Basin East") is 1.50 square kilometers.

In the absence of direct observation of the clast composition of alluvium in Rainbow Basin and Owl Canyon, the bedrock of the sediment source areas encompassed by the drainage basins is used to approximate the composition of the bedload in each drainage basin. The catchments of Rainbow Basin East and Rainbow Basin West encompass significant areas underlain by the Barstow Formation, which is composed of a 60 m thick sequence of alternating alluvial sandstone, mudstone, and conglomerate (Ingersoll et al., 1996). The Rainbow Basin East and Rainbow Basin West drainage basins also contain significant areas of plutonoclastic breccia and megabraccia, as well as sandstone of the Mud Hills Formation (Ingersoll et al., 1996). The most upstream portion of Rainbow Basin East and Rainbow Basin West also encompass a large area underlain by the Pickhandle Formation (Ingersoll et al., 1996), which is characterized as a sequence of mostly pyroclastic rocks which conformably overlie the Jackhammer Formation (Diblee, 1967). The Jackhammer Formation is not exposed in the catchment area of either of the Rainbow Basin drainage basins (Ingersoll et al., 1996).

The catchment of Owl Canyon encompasses many of the same formations as the two Rainbow Basin drainage basins. The catchment of Owl Canyon contains significant areas underlain by the Barstow Formation, the Pickhandle Formation, and the Jackhammer Formation (Ingersoll et al., 1996). The catchment of Owl Canyon also contains areas of plutonoclastic breccia and magabreccia, sandstone, and tuff of the Mud Hills Formation (Ingersoll et al., 1996). The most headward reaches of the catchment area of Owl Canyon is underlain by Mesozoic Granodiorite (Ingersoll et al., 1996).

Analysis:

Correlation of Map Units:

The Qa1 that lies in the area directly south of both of the studied canyons correlates to the Qa1 located on top of the ridge that is between Rainbow Basin and Owl Canyon (Maps 1 and 2) for two reasons. The first is the relative age of the sediments, which was determined through the observation of the calcium carbonate morphology of the sediments (Machette, 1985). The area of Qa1 south of the basins contains an extensive cumulic carbonate horizon and in one location an exhumed stage VI petrocalcic horizon at location X (Map 2). These observations are consistent with the observed high degree of desert pavement formation and well developed carbonate collars observed in Qa1 both south of Rainbow Basin and Owl Canyon and on the ridge between them. This similar stage of carbonate morphology correlates these two surfaces (Machette, 1985). The fact that the surface of Qa1 south of the basins in much lower than that of Qa1 on top of the ridges surrounding the basins (Maps 1 and 2) can be explained by the presence of Fault A between them (Selander, 2015), at the base of the mountain front (Map 2). This correlation was also made by Selander (2015).

The Qa2 that lies within each of the basins is likewise correlated based on the characterization of carbonate morphology observed. The Qa2 in both of the basins is characterized by locally present, weakly developed carbonate collars and weakly developed desert pavement. This indicates that the sediments in both of these basins are of similar ages and are both much younger than Qa1 (Machette, 1985; Selander, 2015).

Surficial Processes:

This report identifies the factor that led to contemporaneous strath formation in Rainbow Basin and aggradation in Owl Canyon. Differences in the topography of the bedrock that is buried by alluvium, which is a rough measure of the difference in the magnitude of sedimentation in Owl Canon relative to Rainbow Basin were identified by observing the distribution of thickness of alluvium in both canyons. The abundance of buttress unconformities in Owl Canyon and the absence of buttress unconformities in Rainbow Basin also provided insight regarding the magnitude of the difference in stream process response to climate forcing.

The variability in the thickness of alluvium in Owl Canyon far exceeds the variability in the thickness of alluvium in Rainbow Canyon (Table 1). In addition, all of the contacts between bedrock and Qa2 in Rainbow Canyon are straths. However, buttress unconformities in the contact between bedrock and Qa2 are common in Owl Canyon. When considered together with the lack observed straths in Owl Canyon and the presence of straths in Rainbow Canyon, this suggests that the topography of the bedrock underlying the alluvium in Owl Canyon has much higher relief than that of Rainbow Canyon. This indicates that during the deposition of Qa1 the streams in the two drainages in Rainbow Canyon were better able to laterally erode bedrock than was the stream in Owl Canyon.

The occurrence of lateral erosion in Rainbow Basin during a time when lateral erosion did not occur in Owl Canyon is the opposite of what was expected based on the observations made about the spatial characteristics of these three drainages. Predictions of erosive power in this study are made following the model laid out by Bull (1979) wherein the ability of a stream to form straths is a function of the relationship between stream power and critical stream power, where stream power exceeding critical stream power is a prerequisite for strath production. It has also been demonstrated that in a given stream system, straths form only where catchment area exceeds some threshold size (Merritts et al, 1994; Garcia, 2006). Bull (1979) defines stream power as the product of discharge, slope, and the specific weight of water. Critical stream power is defined as the power needed to transport sediment load, and is influenced by bedload mass and bedload composition (Bull, 1979). Owl Canyon is roughly three times larger than the bigger of the two drainages contained within Rainbow Basin (Map 3). The climate for the two drainages is identical as they are adjacent to one another. Therefore, the discharge in Owl Canyon is much greater than that of the drainages in Rainbow Canyon. The reason that both streams in Rainbow Canyon formed straths while the stream in Owl Canyon did not is likely due to a difference in critical stream power rather than discharge. Critical steam power is determined by variables that increase the likelihood of sediment deposition as they are increased (Bull, 1979). Bull (1979) considers sediment load, size, and hydraulic roughness as chief among these.

Climate Forcing Event and Effect on Geomorphology

This report identifies the climate forcing event that caused the streams in Rainbow Basin East and Rainbow Basin West to form strath terraces while causing Owl Canyon to aggrade. This is done using the ages of sediments in the drainage basins determined by Selander (2015). Selander (2015) considers Qa2, which he calls Q3a, to have been deposited sometime after 17 k.a.. There are two significant periods within this timeframe in which this magnitude of denudation and sediment transportation could have occurred (Harvey et al., 1999). These two periods occurred from 14-11 k.a. (late Pleistocene) and 11-8 k.a. (early Holocene) (Harvey et al., 1999).

The climate event that occurred during the late Pleistocene was characterized by heavy cyclonic winter rainfall (Harvey et al., 1999). This kind of rainfall occurs over large areas and is therefore capable of creating significant geomorphic activity in moderate to larger basins (Harvey et al., 1999). Because, Owl Canyon is roughly three times the size of Rainbow Basin East and Rainbow Basin West, it is possible that this difference in the amount of sediment denuded from hillslopes in the drainage basins in Rainbow Basin was less relative to the increased discharge than the amount of sediment denuded from hillslopes in Owl Canyon. This would explain why Owl Canyon was aggraded while both drainage basins in Rainbow Basin were able to maintain the stream power necessary to produce and preserve straths.

The climate event that occurred during the early Holocene was characterized by summer "monsoonal" storms (Harvey et al., 1999). This kind of storm is more likely to cause erosional slope processes to occur in relatively small drainage basins (Harvey et al., 1999). Summer monsoonal storms are also likely to cause geomorphic activity on fans fed by relatively small drainage basins as they in the Mojave during the Pleistocene to Holocene transition (Harvey et al., 1999). However, summer monsoonal storms cannot account for the different geomorphological responses to climate forcing observed in Rainbow Basin and Owl Canyon. In order to concretely identify the cause of the different stream responses to climate forcing, more precise dating of Qa2 (Map 1) is required.

It is important to note that the slopes of these channels at the time incision was occurring is an important factor in determining stream power that was not considered within the scope of this senior project. This variable will require more thorough investigation before an explanation for the difference in observed straths between these adjacent canyons can be considered definitive.

Conclusions:

The ability of a stream to form straths depends on its ability to laterally erode bedrock at a faster rate than it is downcutting (Montgomery, 2004). The presence of strath terraces adjacent to incising channels indicates that there is greater stream power than is needed for streams to incise at the rate of tectonically driven base level fall (Pazzaglia and Brandon, 2001) and straths form when available and critical stream power are equal (Pazzaglia and Brandon, 2001. Both of these processes require relatively high stream power (Bull, 1979; Pazzaglia and Brandon, 2001). Stream power in turn depends on the discharge of the stream and the slope of the channel (Bull, 1979). The discharge of Owl Canyon is greater than that of either of the catchments in Rainbow Basin and studying the slope of the channel at the time incision was occurring is beyond the scope of this report. The difference in the characteristics of terraces in Rainbow Basin and Owl Canyon, therefore, can only be accounted for by differences in critical stream power. Specifically, a difference in the amount of bedload delivered to the streams relative to the discharge caused by storms is likely the reason that strath terraces were produced and preserved in both drainage basins in Rainbow Basin but not in the single drainage basin of Owl Canyon. This was likely caused by a difference in the magnitude of slope processes that occurred in the drainage basins in response to high intensity storms that occurred between 14 and 11 ka. In the relatively small Rainbow Basin East and Rainbow Basin West catchments, there was just enough sediment delivered to channels relative to make critical stream power and available stream power equal, and straths formed. In the relatively large Owl Canyon catchment, there was enough sediment delivered to channels to make critical stream power greater than available stream power, leading to aggradation and backfilling of channels. A more precise dating of the Qa2 sediments in Rainbow Basin and Owl Canyon is required to confirm the specific timing of the climate forcing event.

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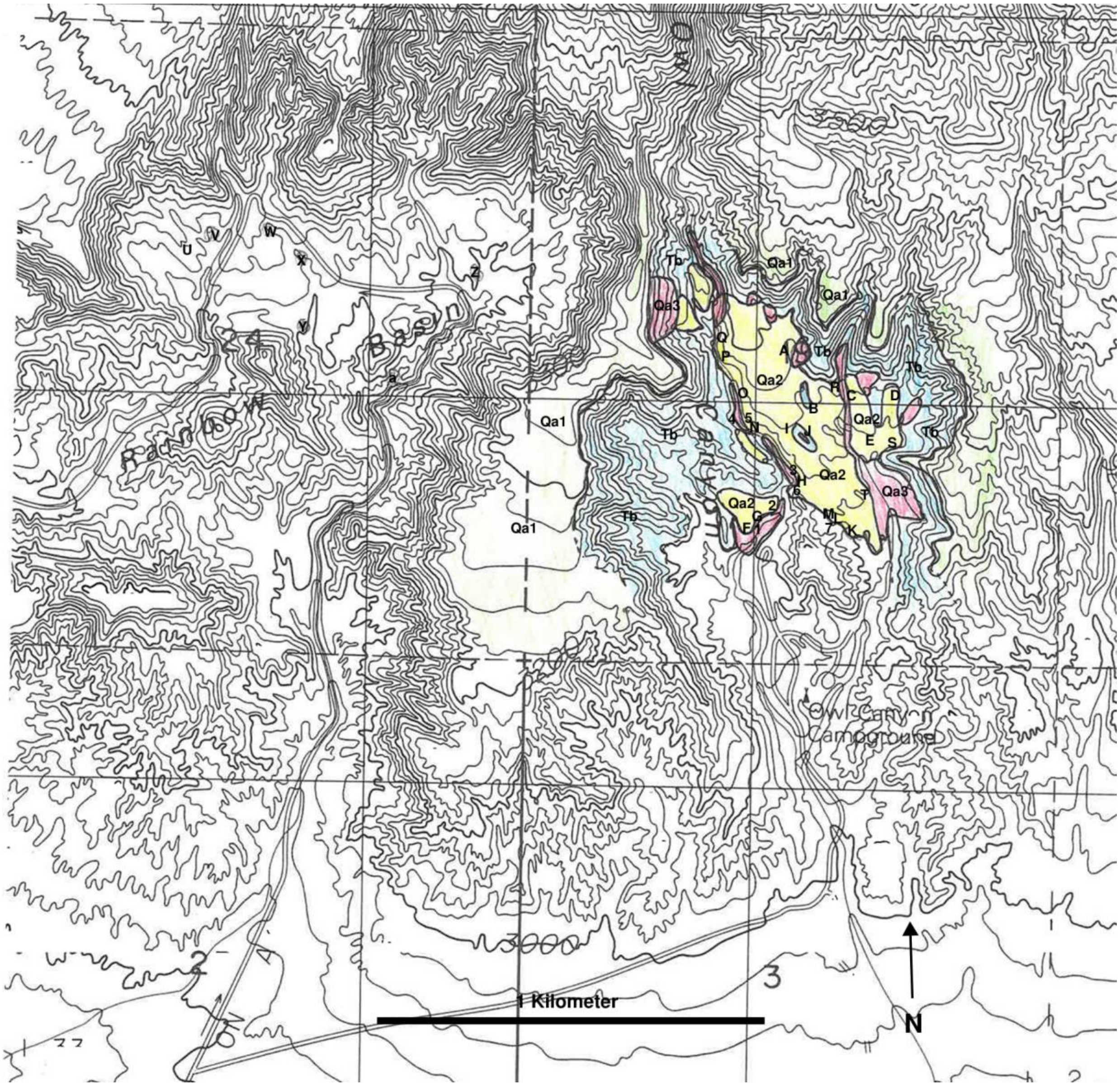


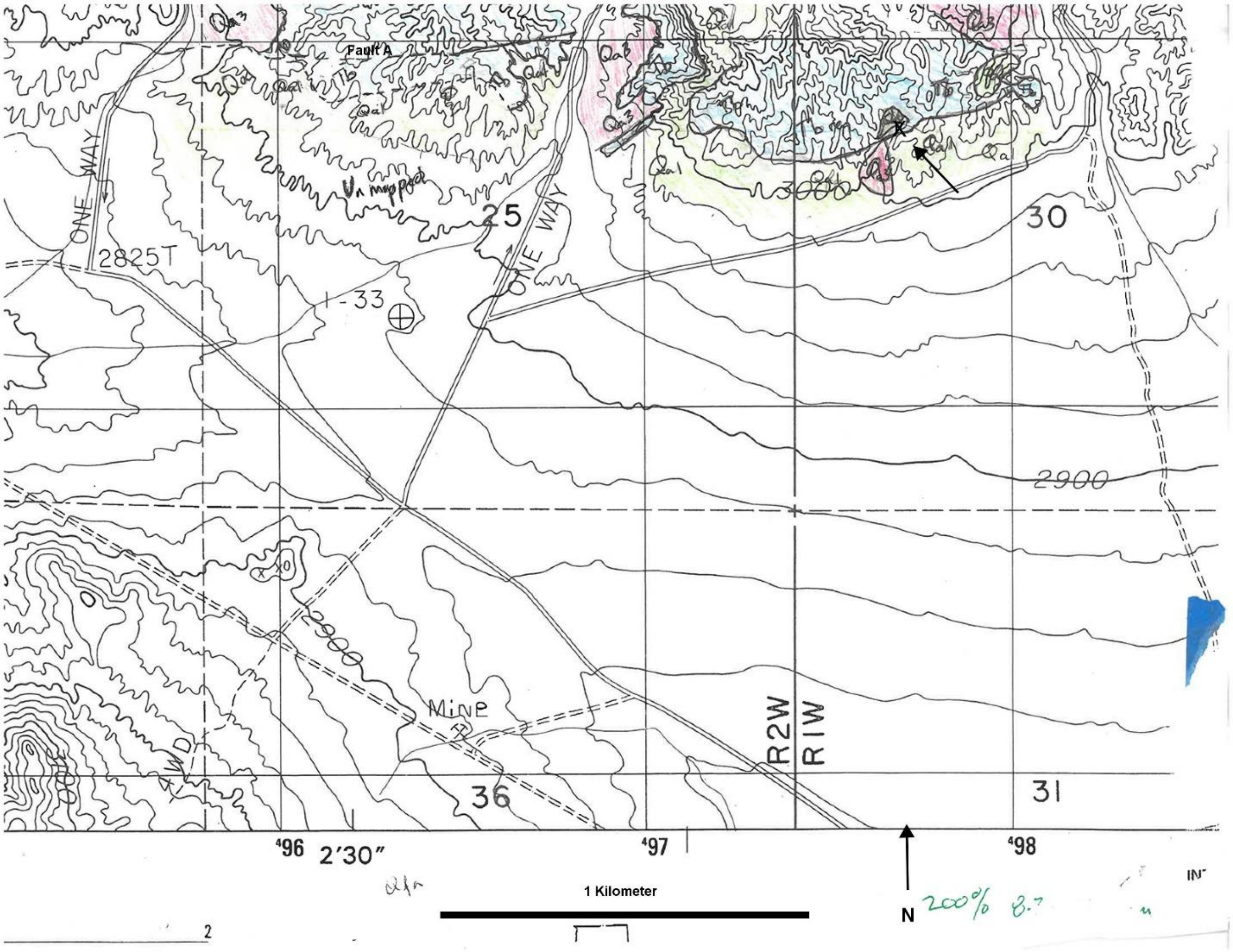
Map 1: This map shows contacts between different map units within Owl Canyon and Rainbow Basin as well as the locations of thickness measurements – marked with letters – and the locations of bedding attitude measurements – marked with numbers 1 through 7 – are also shown. Strath terraces observed at locations Y and Z. Map unit descriptions are on the next page.

🟩 Qa1: Characterized by moderately well-developed desert pavement, well-developed carbonate collars, and a moderately developed vesicular A horizon.

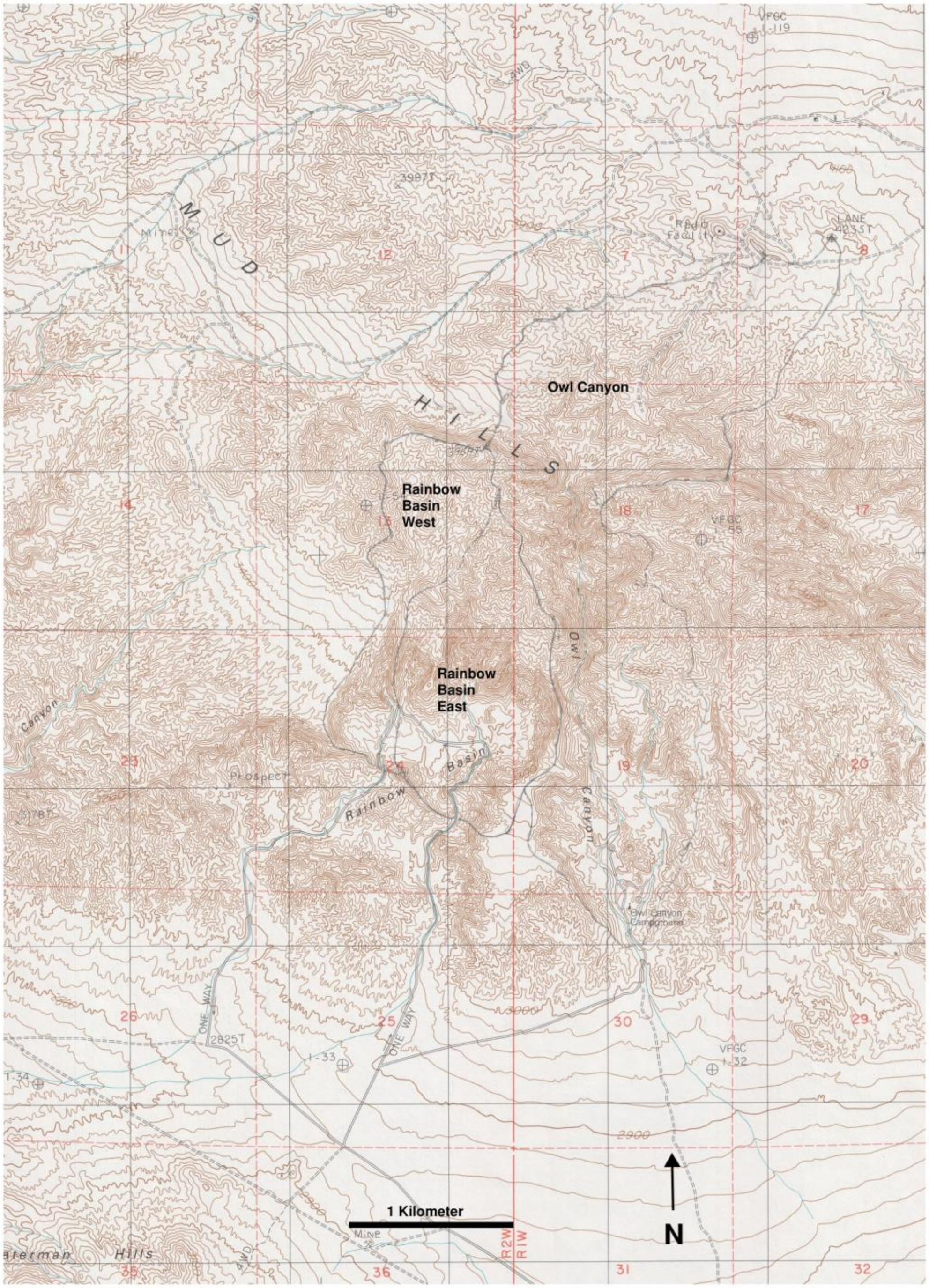
🟨 Qa2: Characterized by locally present, weakly-developed carbonate collars and weakly developed desert pavement. This unit was mapped in both Rainbow Canyon and Owl Canyon. However, the Qa2 in Owl Canyon has less well developed vesicles and more well developed carbonates than the Qa2 in Rainbow Canyon.

🟥 Qa3: Characterized by alluvium that is near to active channels and that has very little to no soil development. This sediment is interpreted to have been deposited more recently than the events that make up the focus of this paper.

🟦 Tb: Undifferentiated bedrock.



Map 2: This map shows the contacts between map units at the mountain front south of Rainbow Basin and Owl Canyon. The location of Fault A is also marked. Map unit descriptions are the same as for Map 1. The arrow points to the location of the observed petrocalcic horizon marked with an X.



Map 3: This map depicts the size of the catchment areas of each of the three drainage areas considered in this study: Rainbow Basin West, Rainbow Basin East, and Owl Canyon. The area of the Rainbow Basin West catchment is 0.91 km^2. The area of the Rainbow Basin East catchment is 1.50 km^2. The catchment area of the Owl Canyon catchment is 4.47 km^2.

Location	Alluvium Depth
A	2.61m
B	4.09m
C	1.5m
D	2.5m
E	2.2m
	3.52m
F	7.6m
G	3.2m
H	6.8m
	16.7m
	13.7m
I	1.16m
J	1.27m
K	2.76m
L	2.83m
M	3.76m
	2.82m
N	4.71m
O	7.31m
P	-
Q	8.74m
R	5.2m
S	2.7m
T	2.62m
U	<1m
V	4.47m
W	5.5m
X	5.7m
Y	-
Z	<1m
a	<1m

Location	Attitude
1	302/65
2	302/61
3	295/70
4	303/71
5	325/10
6	287/61
7	304/85

Table 1: Measurements made at each location. Locations shown on Map 1. Locations A through a are thickness of alluvium in meters. Locations 1 through 7 are measurements of bedrock attitude.