Title

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Abstract

When considering a watershed system in the context of restoration, it is important to understand the fundamental processes controlling the form and function of the stream environment. Among these fundamental processes are the lithologic and structural geologic controls on hydrology, especially when restoration includes complex systems like wetlands. Rodeo Creek in the Marin Headlands portion of the Golden Gate National Recreation Area has undergone numerous anthropogenic changes in the past century, including agricultural forcing as well as military development. In order to investigate the way the underlying bedrock is affecting the creeks' wetlands, the area was mapped for structural orientation and lithology. The bedrock was found to be generally oriented in a northwest to westerly fashion and dipping toward the southwest at angles ranging from 15 to 75 degrees from the horizontal. A bedrock geologic map was constructed using these data as well as existing survey work. Areas of known wetlands were then superimposed upon the underlying bedrock structure. Wetlands were found to exist in larger distributions over contacts between different rock types. Differential erosion is suspected of creating hollows within the bedrock where alluvium can collect and become saturated with groundwater creating wetlands. This holds relevance to stream restoration work, in that, this is a way to assess the spatial distribution of where wetlands naturally occur. This technique may provide guidance to restoration efforts by more effectively locating wetlands where the watershed "wants" them to be. Additionally, this may also be a way to assess the groundwater regime of similar watersheds.

Introduction

Among the most fundamental concepts in stream restoration involves the issue of the hydrology of the stream itself. Controls on how the water gets into the channel and from where are of paramount importance. In order to understand the morphology and function of the channel itself, the factors and processes that control the hydrologic regime of the watershed are fundamental. Often times the underlying controls on channel and the watershed are discounted in terms of the role they play in how the river establishes stability. In the context of river restoration, it makes no sense to try to restore the system into a state that it does not "want" to be in. In this study, the geologic structure and rock type are examined in order to understand some of the avenues by which the underlying bedrock affects the morphology and processes specific to wetland development in the watershed.

Streams draining mountainous regions often exhibit a distinctive stepped-bed morphology which typically follows a rhythmic spacing, often a function of factors including slope and channel width (Knighton, 1998). This idea of a stepped bed may be extended to model the way that steeply dipping bedrock may affect a stream channel. In this notion, resistant rock layers weather and erode differently than the less resistant rocks which may form pockets. Overlying all of this is a layer of colluvium and alluvium, thinnest above the resistant layers and thickest above the softer rocks. The areas of thinnest alluvium may tend to form channels, while the thicker pockets may allow the discharge to flow laterally as well as more deeply as it percolates through these pockets of porous alluvium. These are areas where wetlands may develop more extensively.

Study Area and Methods

Rodeo Valley is located in the southern portion of the Marin Headlands in the San Francisco Bay area of central California (figure 1). This area is included in the Golden Gate National Recreation Area (GGNRA) and is managed under the auspices of the National Park Service. The

Rodeo Valley watershed consists of the main stem of Rodeo Creek and a northern tributary known as Gerbode Creek, together they comprise approximately three square miles of watershed (Table 1, figure 2).

The area is underlain by the Franciscan Formation, which consists of a repeating sequence of cherts, altered basalts (greenstone) and sandstone (greywacke). These layers represent the wedge of sediments that accumulates at the edge of a subducting plate margin. This area has been mapped by several researchers and each has produced a slightly differing picture of the underlying bedrock lithology and structure (figure 4) (Bedrossian 1974, Wahraftig 1984, Blake et al, 1974). The variability of the geologic mapping is mainly due to the extreme heterogeneity of the area, with strata that are often discontinuous. Additionally, outcrops of bedrock are rare, as the area is mantled by a cover of hillslope colluvium and valley bottom alluvium. The general conclusion is that the beds are generally oriented striking to the northwest and dipping to the southwest (Wahraftig, 1984).

The geomorphology of the area is a direct reflection of the underlying bedrock. The ridge lines are composed of resistant layers of radiolarian chert. The hillslopes and valleys are cut into less resistant greenstone and sometimes into sandstone as well as the occasional pocket of mélange, a clay-rich matrix composed of many rock types. The slopes are mantled with a layer of colluvium composed of angular clasts of greywacke and chert (Wahraftig, 1974). Thickness of this layer is variable, often less than 20 cm thick at the ridges and accumulating at the valley bottoms in thicker packages. Soil formation on this colluvium is thin (Montgomery and Dietrich, 1995).

The climate of this area is distinctly Mediterranean, receiving approximately 90% of its precipitation between November and April. Mean annual precipitation is 26 inches and generally occurs in a series of winter storms (Lehre, 1974). Rain falls on the hillslopes and then moves into the ground by way of throughflow, where the water occupies the interstitial space between grains and is driven by a hydraulic wetting gradient. After the thicker portion of soil and colluvium are saturated, macropore flow responds and serves to transport water down slope. Overland flow occurs along the surface of unchanneled hillslopes when both throughflow and macropore transmissivities are exceed (figure 5) (Montgomery and Dietrich, 1995).

In order to test this "structural step-pool" idea, I examined the previous geologic surveys of Rodeo and Gerbode Valleys, looking for the general orientation of the bedrock. Numerous outcrops were surveyed in October of 2003 and strike and dip orientations of the bedding planes were measured. The lithology of the bedrock was also examined in terms of texture, erosion resistance, inferred permeability and composition. I conducted a visual reconnaissance of the valley from ridge tops and noted the presence and distribution of springs. Areas of wetlands are relatively easily inferred from vegetation differences and aerial distribution.

Discharge measurements of both Rodeo Creek and its north fork were taken. The north fork of Rodeo Creek, commonly called Gerbode Creek, was measured using a Pygmy flow meter in a portion of the channel that was reworked to be straighter and smoother and thus with more uniform flow. I measured depth and current velocity at five points across this channel and summed the individual values to obtain a discharge value (Rantz et al, 1982). To measure discharge in Rodeo Creek I used a "bucket and stopwatch" approach to determine the time required to fill a given bucket volume with streamflow several times and then averaged (table 2). This measurement technique was necessary because Rodeo Creek is so small and access points along were not suitable for a current meter measurement (figure 3).

After taking a number of strike and dip measurements of the outcropping rocks within Rodeo and Gerbode Valleys, these were plotted on a stereographic projection net. The stereonet is a useful device to analyze three dimensional data in two dimensions. The poles normal to the bedding planes of the rock units are plotted on the stereonet and frequency distributions of the data can be ascertained. In this case, the preferred orientation of the bedrock structure tends to lie in a northwest striking fashion and the beds dip to the southwest (appendix A).

This preferred orientation trend was then combined with a geologic basemap of the area and contacts were inferred in areas covered by colluvium. This allowed for the construction of a generalized bedrock geologic map of the area (figure 6). Based on this map, I drew a cross section, representing the idealized subsurface bedrock and its relation to the long profile of Rodeo Creek (figure 7).

By using maps produced by the National Park Service (NPS, 2003) I interpreted the extent of wetlands with respect to the channel. These maps depict Rodeo Valley's wetlands and classify them by the Cowardin System into several differing types of wetland environment (Cowardin et al, 1979). For the purposes of this study, areas of intermittent exposure and seasonal flooding were grouped into what could be considered as natural wetlands. This excluded areas that are saturated by artificial fill or diversion (figure 8). I then overlaid this map of wetland areas on top of the bedrock geologic map (figure 9). This allowed for direct comparison of wetland areas with bedrock lithology.

RESULTS

When areas of wetlands are superimposed upon the bedrock geology of Rodeo Valley (figure 9), a trend is found. In general, areas of wetlands extend laterally when the channel crosses a contact between different lithologic units, that is, different rock types. Wetlands also spread out laterally over top of softer and more permeable rock units such as the areas of mélange in upper Rodeo Creek.

The tendency for saturated alluvium to spread laterally away from the channel is especially apparent in Gerbode Creek, with distinct wetland “fingers” being found at several geologic contacts. Wetlands also exist in greater lateral extent over the lowest band of chert near the confluence of Rodeo and Gerbode creeks. The lateral spread of wetlands seems to be related to both the underlying rock type, as well as the contact itself.

Topography also plays a dominant role as well. In the upper reaches of the channel, where the slope is considerably greater, the saturated channel area tends to narrow when running across the middle of any given rock type. As slope decreases towards the lower reaches of the channel, the area of saturated alluvium spreads out.

DISCUSSION

The correlation between every geologic contact and an associated spread of wetlands is not especially strong. However, there are some common occurrences of increased wetlands over contacts and is indicative that contacts do play a role in the control of wetlands distribution and extent.

The occurrence of wetlands over top of contacts between different bedrock types is most likely explained by differential erosion of the rock. The contact surface between contrasting lithologies may allow for an increase in primary permeability which then leads to development of a weathering horizon within the contact zone. Once weathering has begun in this zone it is most likely accelerated by a positive feedback, accelerating the process. With an increase in weathering rates comes an associated breakup and removal of bedrock material. This leads to a hollow developing both laterally and to greater depth than the stretches of channel both above and below the contact. Pockets of alluvium collect in the hollows left by differential erosion and occupy local lows in the bedrock surface. Water fills the interstitial space between alluvial clasts and leads to the formation of saturated areas of wetlands (figure 10).

When considering the role of geologic contacts in this setting, a discriminating look at the contacts themselves is necessary. The stratigraphic sequence of a contact reveals the environment in which the rocks formed. In the case of a basalt overlying another rock type, there is certainly the possibility of contact metamorphism of the lower rock. As basalt is extruded in a mid-ocean ridge setting, the rock typically is in excess of 700˚C as it flows out of the spreading center and onto the ocean floor. The sediments making up the ocean floor are very quickly heated and their physical properties are altered in this sort of “baked contact”. This process tends to produce rock that is considerable more friable and less resistant to erosion (Best, 1982). This sort of contact is present in the lower regions of the Rodeo Creek drainage.

The contrast between lithologies is also crucial to consider in the stratigraphic orientation of the contacts. In Gerbode Creek, the contacts between the sandstone and the basalt and chert layers leads to increased wetlands development. This is likely due to the high erodability of the sandstone itself. In contrast to chert, the greywacke sandstone in Rodeo Valley is extremely susceptible to erosion and as a consequence, rarely occurs as outcrops (Wahraftig, 1974). The basalts of the Marin Headlands are extremely fractured and exhibit extensive jointing. Along these fractures and joints, the rock itself is altered somewhat from it original composition to include clay minerals. This amounts to an increased tendency to breakdown and erode, forming these pockets of alluvium development.

The structural orientation of the bedrock may also play some fundamental role as well. The leading edge of the downstream rock layer is at a considerably acute angle when beds dip as steeply as they do in this area (figure 6). This acute erosion edge acts as a nickpoint, along which the forces of weathering and erosion are concentrated and amplified. This process leads to an acceleration of the weathering front through the downstream rock layer (figure 10).

Structure also plays a role on a larger scale as well. There is a distinct difference in the geomorphology of Gerbode and Rodeo drainages. Gerbode has a well developed network of tributary valleys, in contrast to the simple plan form of Rodeo Creek with a distinct main stem, free of dendritic tributaries. This may be due to the presence of a series of faults in the bedrock forming the flanks of Gerbode Creek. The tributaries to Gerbode may be fault controlled, in that, the tributaries run in valleys incised along fault planes. This is a well documented phenomenon. As fault zones tend to develop materials within the fault itself that are very easily eroded as well as the surrounding rock being fractured and also less resistant to erosion. Without an accurate investigation of the presence of these faults, this notion of fault controlled incision is only speculation.

Even without the confirmation of this fault control, geologic contacts assume the role of a considerable geomorphic factor in landscape development. Resistant ridges of chert make up ridge lines as contacts between rock types begin to erode and become topographic lows. Tributary valleys develop along these contacts and tend to amplify the effects of erosion and alluvium deposition.

The large scale topography and geomorphology is also significant in the context of the geologic history of the area. During the Pleistocene (~2 Ma) global sea level was approximately 400 feet lower than today. Rodeo Valley extended a great deal further west and drained into the Pacific Ocean at a location that was likely miles away from where it drains today. This served to lower the base level of Rodeo Creek and thus stream power and incision where increased. As sea level rose along with glacial retreat, Rodeo Creek no longer was downcutting, but was instead aggrading and depositing alluvium in its lower reaches. This served to create intensified areas of ponding and are now realized in the modern form of Rodeo Lagoon. There are most likely very thick packages of alluvium in the lower reaches of Rodeo Creek (Barry Hecht, personal communication). This may explain the extent of wetland development in the vicinity of the confluence of Rodeo and Gerbode Creeks. These elements of erosion followed by in filling of alluvium are the fundamental wetland forming mechanisms in Rodeo Valley.

CONCLUSION

By understanding the processes that allow for the formation of wetlands within the Rodeo Creek watershed, the overall function of the watershed is better understood. This model for understanding the relationship between bedrock and wetlands may hold ramifications for the river restoration community in the form of increased effectiveness in both locating wetlands restoration sites as well as implementation of the restoration efforts. Additionally, this may prove to be a valid method to map and assess the groundwater regime of a watershed.

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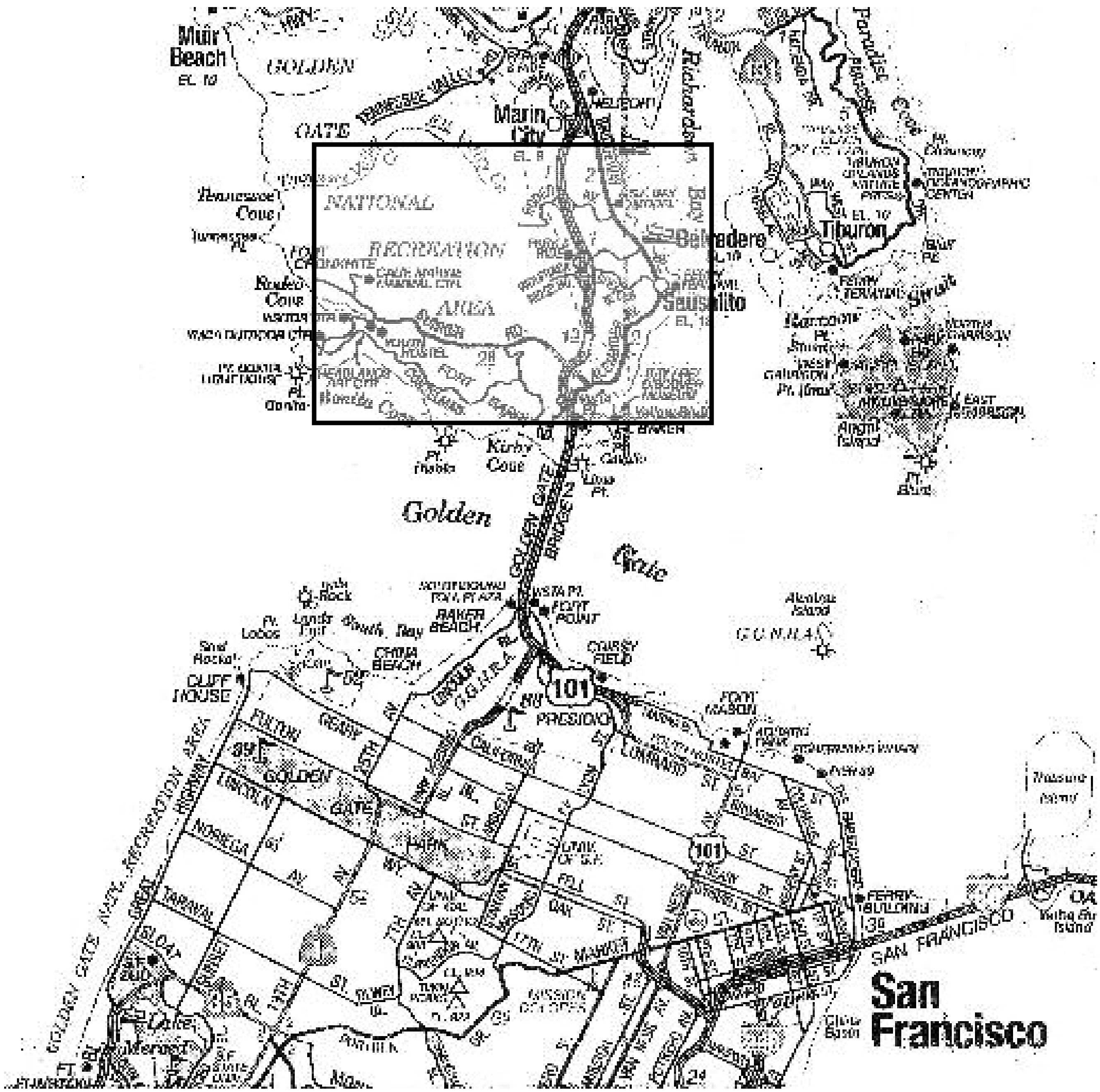


Figure 1. Map showing location of study area in relation to San Francisco Bay.
Box outline denotes study area.
(after California Automobile Association, 1997)

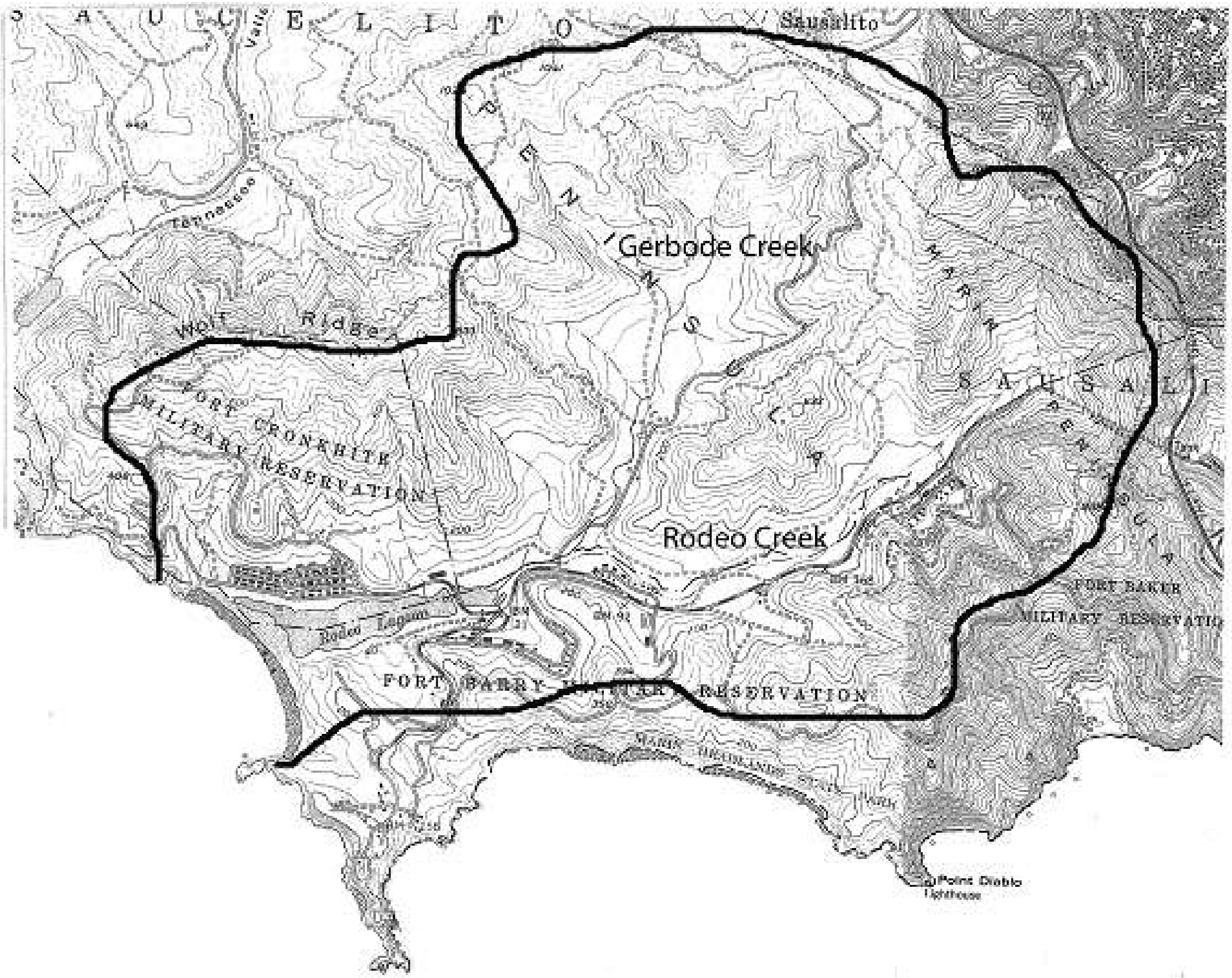


Figure 2. Topographic map showing the extent of the Rodeo Valley watershed (basemap, USGS)

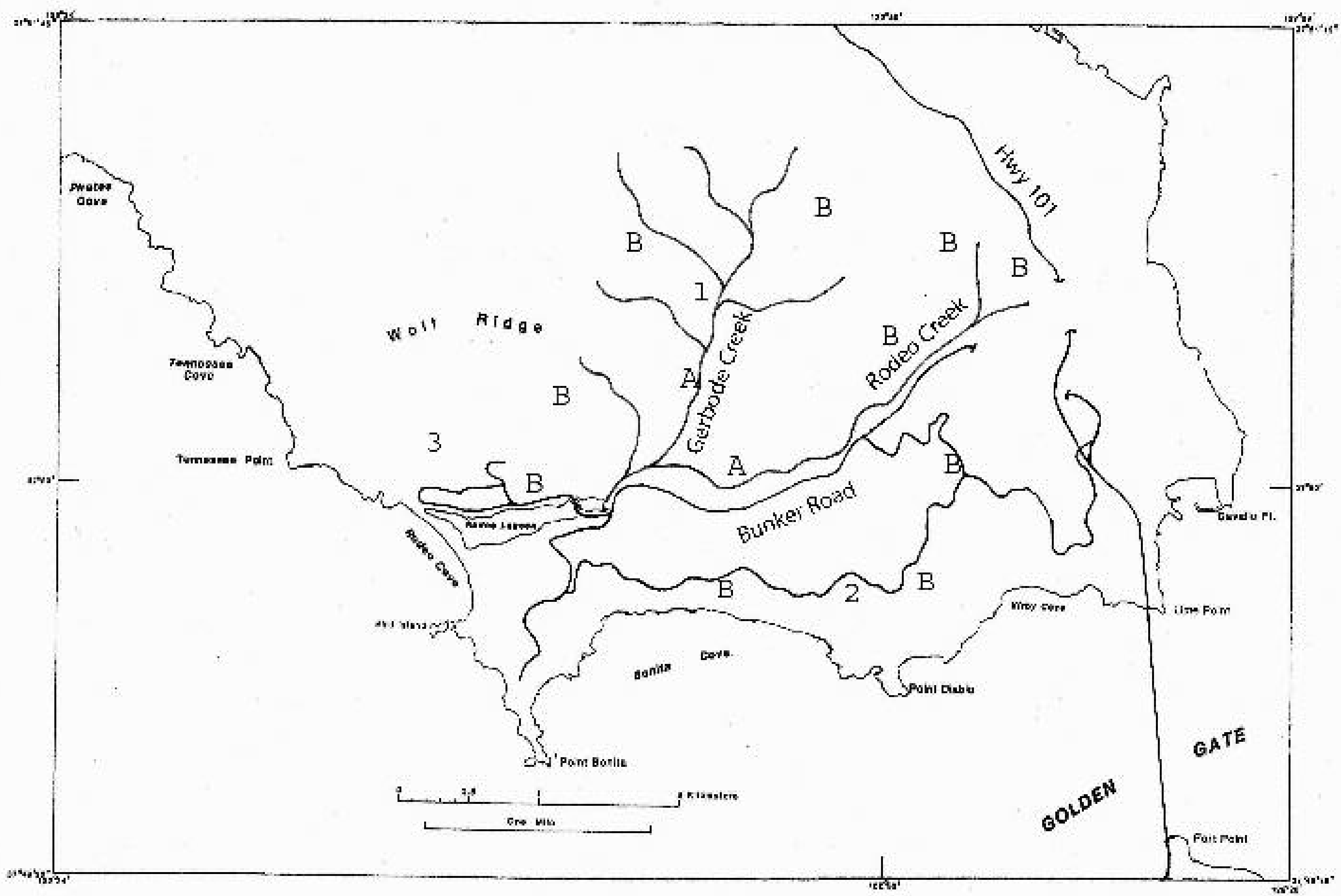


Figure 3. Map of study area showing location of (A) stream guagings, (B) measured bedrock outcrops, and (1-3) photographs. (after Wahraftog, 1984)

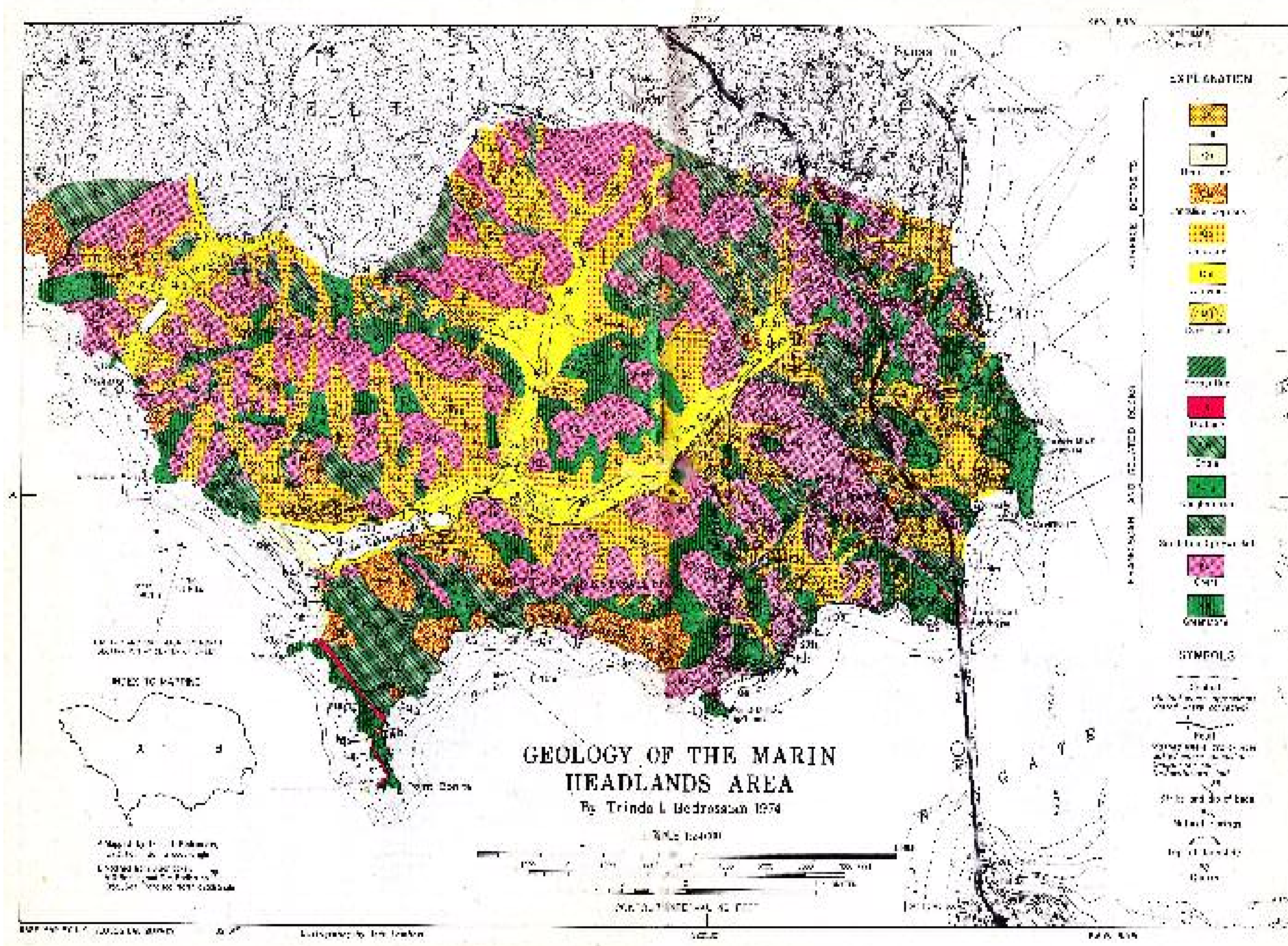


Figure 4. Geologic map of Marin Headlands, California. (Bedrossian, 1974)

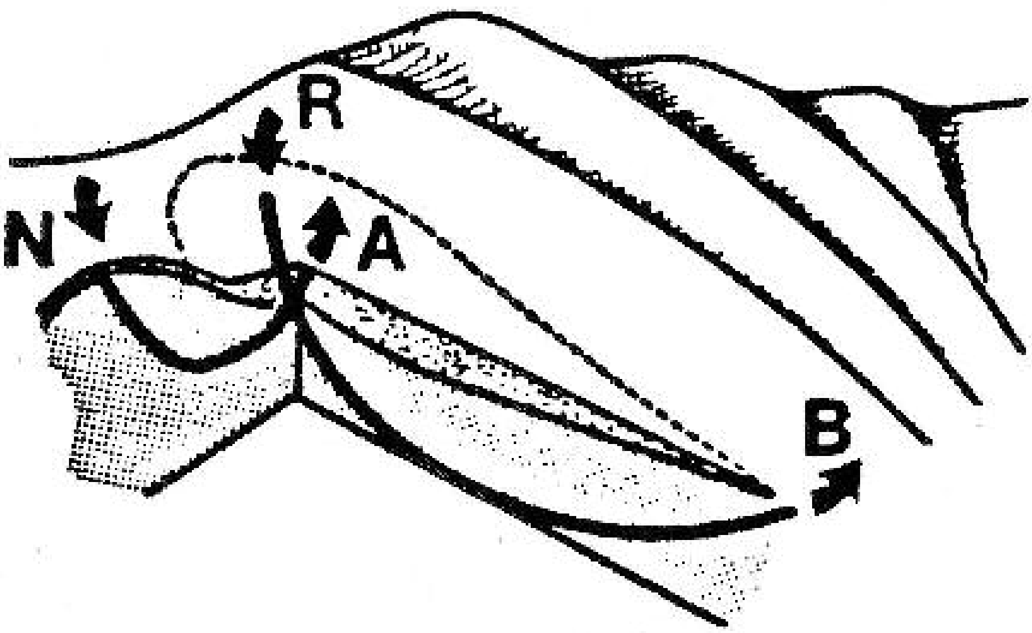


Figure 5. Idealized cross section of hillslope water flow in Marin County , California. Note down slope flow (R B) and cross slope flow (N-R). Colluvium is shown atop stippled area of bedrock. (Wilson and Dietrich, 1997)

Drainage Basin	Drainage Area (mi^2)	Length (mi)	Slope (ft/mi)	Annual Precip
Rodeo Creek	1.57	2.33	189	25
Gerbode Creek	1.44	1.74	279	27

Table 1. Drainage basin characteristics for Rodeo Valley (after Lehre, 1974)

Stream	Drainage Area (mi^2)	Q (gpm)	Q (cfs)	Date of Gauging
Rodeo	1.57	37.06	0.0825	26 Oct 03
Gerbode	1.44	7.46	0.0166	5 Oct 03

Table 2. Discharge values for Rodeo Valley

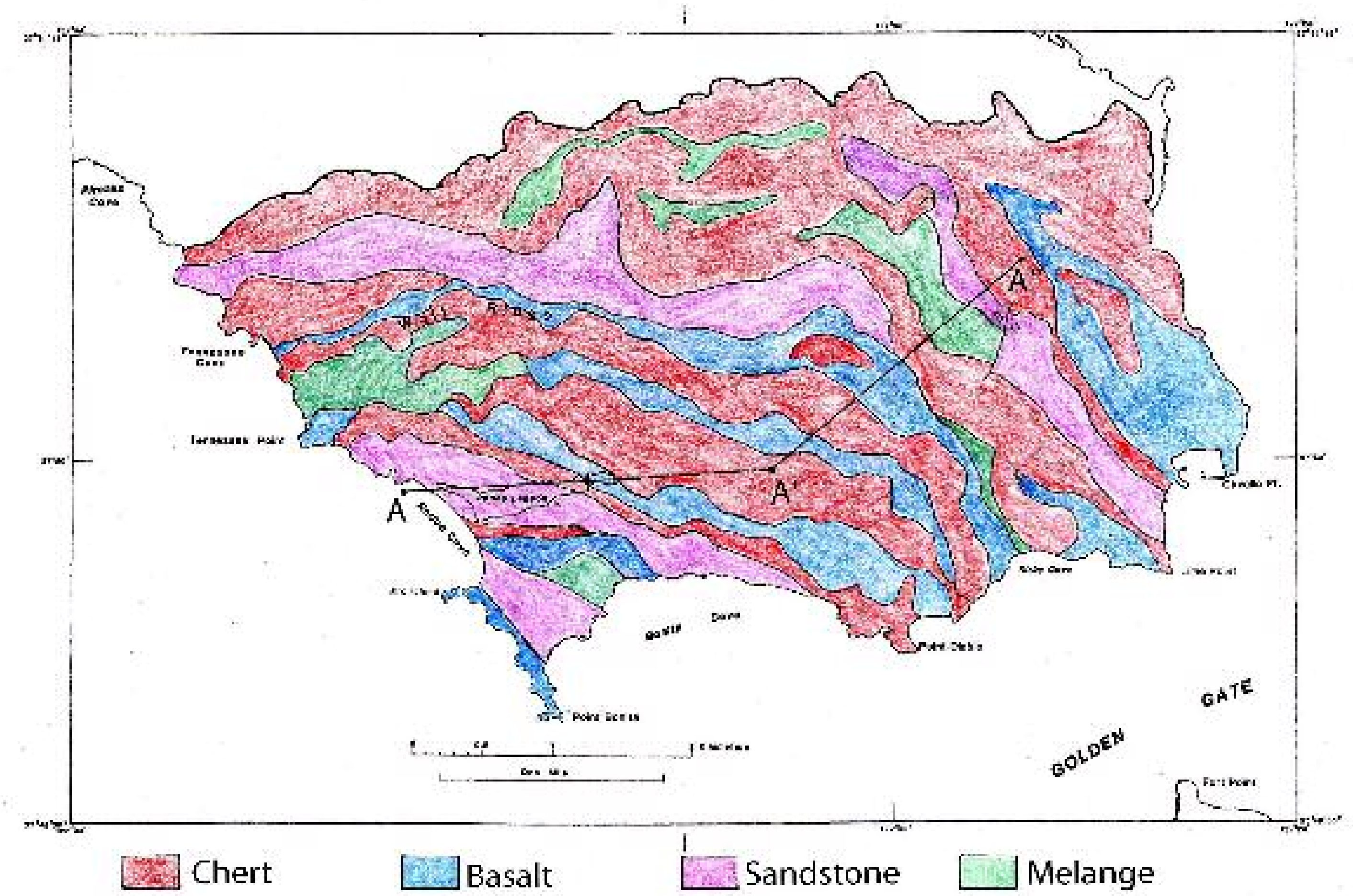


Figure 6: Bedrock geologic map of Marin Headlands with alluvium removed (after Wahraftig, 1984)

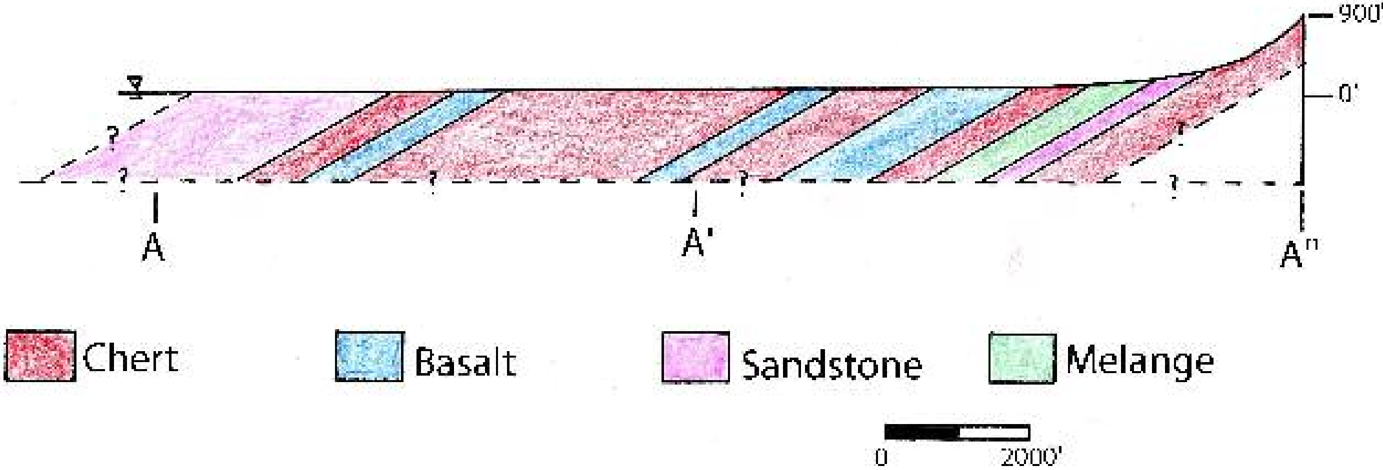


Figure 7: Cross section along A to A'' with alluvium removed (not to scale)

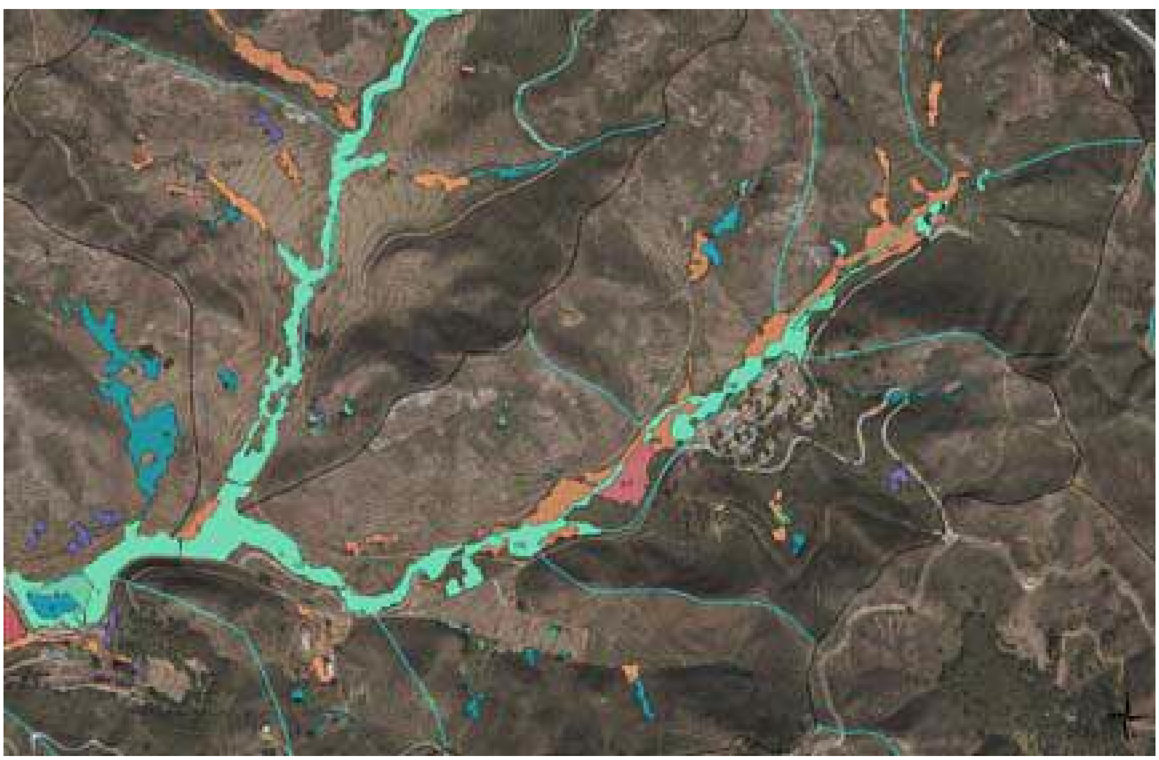


Figure 8: Map showing areas of wetlands in Rodeo Valley
Aquamarine and Orange areas denote wetlands
(National Park Service, 2003)

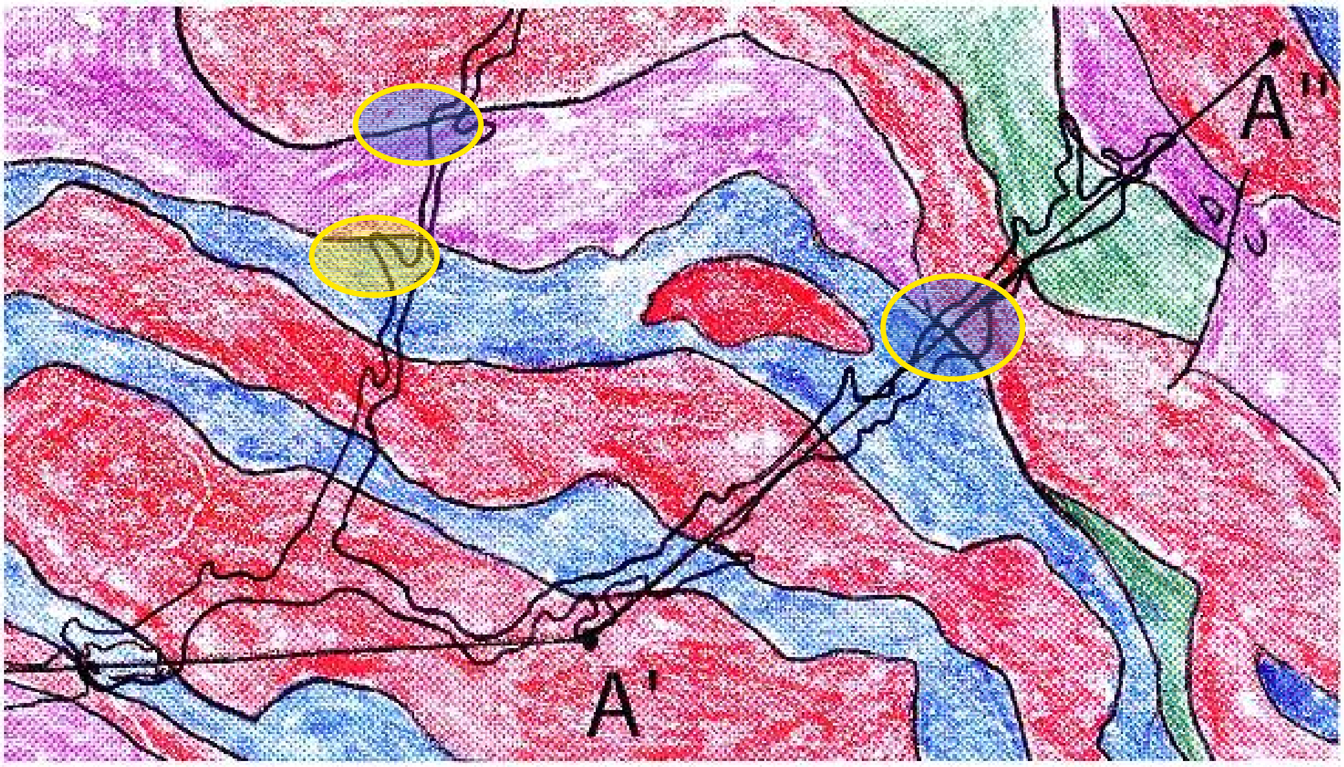


Figure 9. Bedrock geologic map with areas of wetlands superimposed. Yellow circles denote regions where wetlands develop with larger lateral extent over geologic contacts.

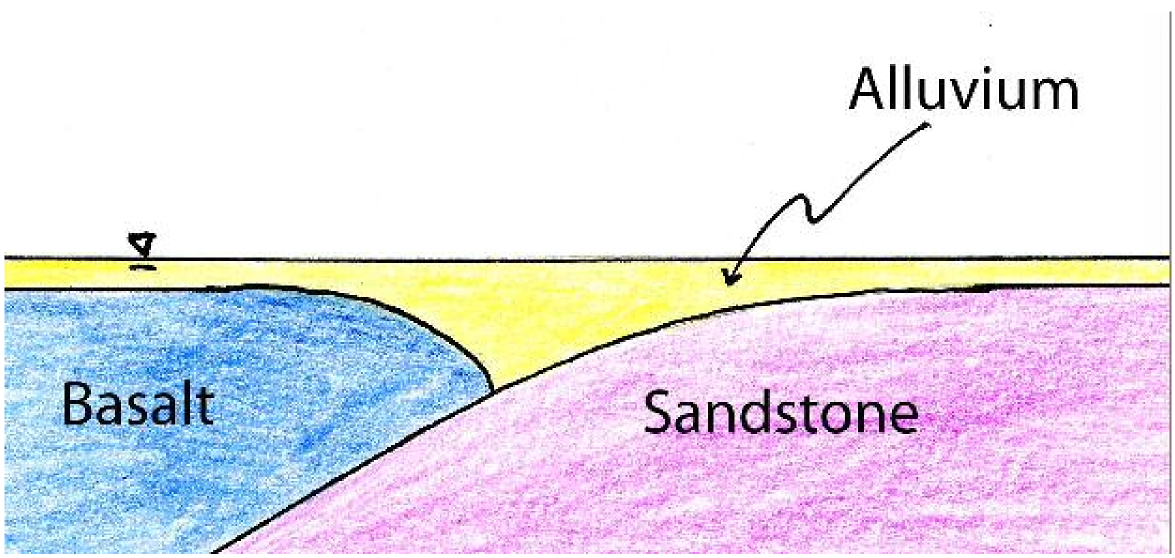
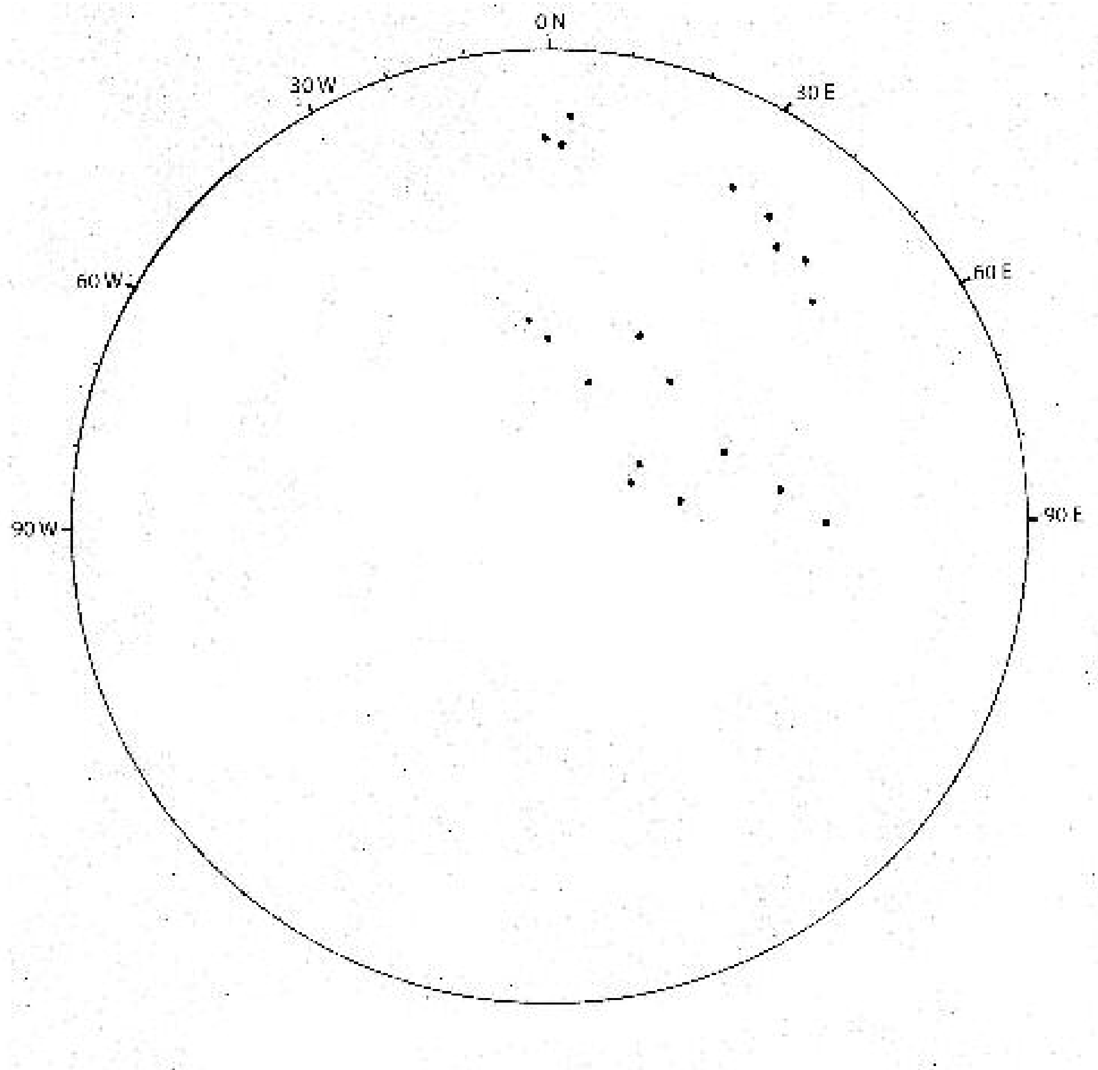


Figure 10. Cross section detail of differential erosion in areas of bedrock contacts where alluvium is allowed to collect and subsequently form wetland areas.



Appendix A. Stereographic plot of poles to bedding planes showing preferred orientation of bedrock as striking northwest and dipping southwest in Rodeo Valley.