# Chapter 2: Controls on Meadow Distribution and Characteristics

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## Introduction

Meadow complexes are located in distinct geomorphic and hydrologic settings that allow groundwater to be at or near the ground surface during at least part of the year. Meadows are manifestations of the subsurface flow system, and their distribution is controlled by factors that cause localized zones of groundwater discharge. Knowledge of the factors that serve as controls on groundwater discharge and formation of meadow complexes is necessary to understand why meadows occur where they do and how anthropogenic activities might affect their persistence and ecological condition. In this chapter, we examine physical factors that lead to the formation of meadow complexes in upland watersheds of the central Great Basin. We then describe variations in meadow characteristics across the region and parameters that produce differences in the nature of meadow complexes at basin scales. In subsequent chapters, we examine the geomorphic, hydrologic, and vegetation processes that operate within individual wet meadow complexes.

## Factors Affecting Meadow Distribution and Development

### *Precipitation*

Wet meadows require a reliable supply of groundwater that supports high water tables year after year and that sustains the phreatophytic vegetation characteristic of these discrete ecosystems (Castelli and others 2000). The ultimate supply of this water is precipitation. Annual precipitation varies from 150 mm/year to approximately 700 mm/year in the study area (Oregon Climate Service 2009) and falls mostly as snow in winter. Observed spatial variations in precipitation closely parallel changes in elevation (figs.1.2 and 1.4). Watersheds that have a significant portion of their drainage area located at high elevations should be able to capture more rain and snow and, therefore, have more available water. In fact, it has been demonstrated that stream discharge and flow duration are proportional to and can be estimated by the size of the drainage basin and the percentage of the drainage basin that is located at elevations above 3050 m (Hess 2002).

The highest elevations within the six mountain ranges in the study area (Shoshone, Toiyabe, Toquima, Monitor, Roberts, and Hot Creek Ranges) occur in the central and southern portions of the Toiyabe, southern Toquima, and central Monitor Ranges (fig. 1.2). The highest annual precipitation values are recorded in the central and southern Toiyabe and southern Toquima Mountains (fig. 1.4) and, as expected, meadow complexes are abundant in those areas. In contrast, basins located in sections of mountain ranges that do not have significant area at high elevation (greater than approximately 2500 m) and that are characterized by limited annual precipitation contain relatively few meadows. For example, much of the Shoshone Range and the northern and southernmost portions of the Toiyabe, Toquima, and Monitor Ranges are lower in elevation and receive less precipitation. Therefore, meadow complexes are uncommon in these regions. Analyses of color-enhanced satellite images of the region reveal that meadow complexes also are uncommon in low-elevation mountain ranges in the surrounding area, including the Pancake Range, Antelope Range, the Park Range, and Simpson Park Mountains.

### *Geologic, Stratigraphic, and Hydrologic Controls*

Groundwater along riparian corridors of most basins is typically located well below the ground surface (usually greater than 3 to 5 m), even when an ample supply of groundwater would be expected based on the watershed's elevation and precipitation. Thus, meadow complexes represent an anomalous condition where groundwater levels are elevated compared to adjacent upstream and downstream reaches of the riparian corridor. These spatial changes in subsurface water levels raise two important, interrelated questions: (1) Is the water that is found within meadows entirely derived from its down-valley movement through valley fill? and (2) Are other factors causing groundwater levels to rise locally? The meadows may be products of localized inputs of water to the valley that raise water levels, of changes in hydrologic flow conditions that produce upwelling, or of some combination of the two. The answers to these questions require an understanding of the geologic, stratigraphic, and geomorphic settings of meadow complexes.

***History and Timing of Sedimentation Events.*** The geomorphic characteristics of the valley bottoms, including those in the vicinity of meadow complexes, largely reflect erosional and depositional events that occurred during the late Holocene (approximately 4500 years BP to the present). The geomorphic history of the basins was documented primarily by examining and dating alluvial stratigraphic deposits in approximately 30 upland watersheds spread across the central Great Basin (Miller and others 2001, 2004). The most detailed studies occurred in the Big Creek, Barley, Kingston, San Juan, Cottonwood, and Indian Valley basins (fig 1.7). Results indicated that while sediment was always being produced, transported, stored, and exported from the upland basins, significant temporal variations in sediment production and transport dynamics occurred during the late Holocene often in response to discrete changes in climate. During the Neoglacial (4500 to 2500 years BP), a period of cooler, moister conditions and relatively high vegetation abundance, the landscape was relatively stable and little sediment was transported to alluvial fans located at the mouth of tributaries (called side-valley alluvial fans) or to the alluvial valley floor (Chambers and others 1998; Miller and others 2001). As a result, soils formed in the stable valley fill and alluvial fan deposits (Miller and others 2001). Landscape stability changed, however, with the onset of the post-Neoglacial drought that began in this area approximately 2600 years BP. The post-Neoglacial drought was a time of relative aridity, during which upland vegetation changed substantially toward dryland assemblages. Available paleoecological data (primarily from woodrat middens) indicate that the number of plant taxa present decreased from a relatively high level to the lowest levels observed during the Holocene (Miller and others 2001; Tausch and others 2004). The decrease in vegetation cover apparently led to erosional stripping of hillslope sediment when infrequent but intense rainfall events occurred. The eroded sediment was redeposited on side-valley alluvial fans and throughout the valley network from approximately 2580±70 to 1980±60 years BP. A high frequency of wildfires also may have accompanied the drought, as indicated by a large amount of charcoal in alluvial deposits that were created during the time period. Presumably, destruction of vegetation by wildfires facilitated soil erosion and sediment accumulation in the valleys.

The sediment that was generated during the post-Neoglacial drought buried the soils that had developed in earlier deposits. Thus, a paleosol dated to approximately 3500 years BP can be found at the base of most post-Neoglacial deposits throughout the region and marks the beginning of widespread sedimentation. Stratigraphic data from stream-cut exposures and sediment cores indicate that deposition within the valley and on the fans usually resulted in deposits 0.5 to 2 m thick. In addition, stratigraphic profiles revealed that sediment that was eroded from the hillslopes was routed through low-order tributaries to the side-valley fans causing fan progradation. Fan sediments were then eroded and routed down higher-order channels and axial valleys resulting in contemporaneous deposition along major trunk streams. The process created an interfingering relationship between fan and axial valley deposits (fig. 2.1) (Miller and others 2001). This alternating sequence of deposition and erosion allowed much of the coarser sediment (cobbles and boulders) to be stored in side-valley fans and more of the finer-grained materials (pebbles, sand, silt, and clay) to be redeposited along the axial drainage system.

A product of fan progradation into the axial valleys was a reduction of channel gradients immediately upstream. The reduced gradients appear to have further promoted accumulation of sediment along the axial valley (fig. 2.2). In some cases, radial fan profiles indicate that fan deposits traversed the entire width of the valley, effectively blocking down-valley movement of water and sediment. Although these blockages were probably breached rapidly, they may have promoted sediment aggradation temporarily by reducing downstream flow velocities.

Since about 1980 years BP, the stream systems throughout the region have undergone periods of stability that were separated by episodes of channel incision. Interestingly, incision appears to have begun prior to the end of more typical moisture conditions during the Holocene (Tausch and others 2004). Miller and others (2001, 2004) argue that the onset of incision was related to depletion of fine-grained sediment on hillslopes and reduced sediment loading to the axial valley, an argument that is supported by a general increase in grain size of the valley-fill deposits through time. The inability of the current hydrologic regime to move sediment from the hillslopes likely produced the current tendency for modern channels to incise in response to natural or anthropogenic disturbances.

The depositional history of the upland basins led to a rather simple stratigraphic sequence throughout most of the valley bottoms (fig. 2.1). However, detailed studies have revealed that the stratigraphy upstream of prograding fans

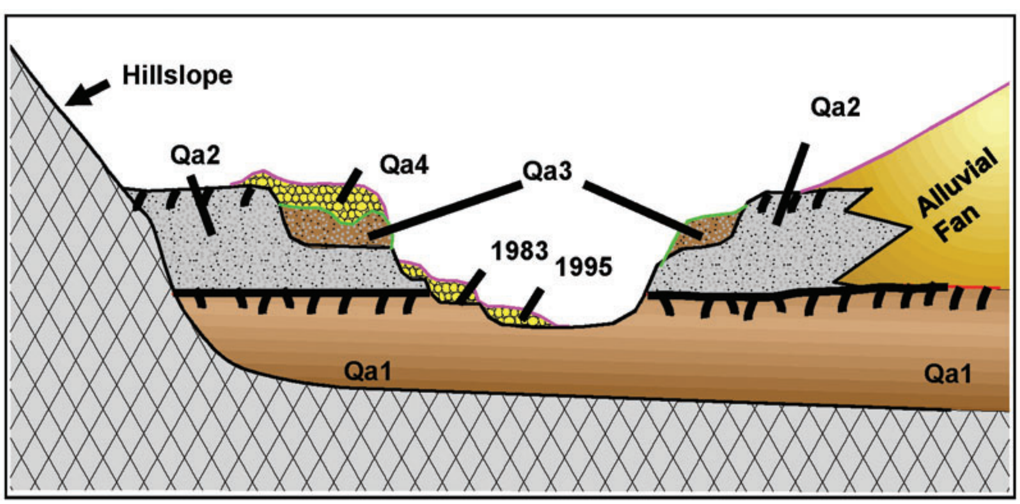



**Figure 2.1.** Generalized valley fill stratigraphy found between wet meadow complexes. The different Quaternary alluvial units (Qa1 to Qa4) show the ages of the valley fill.

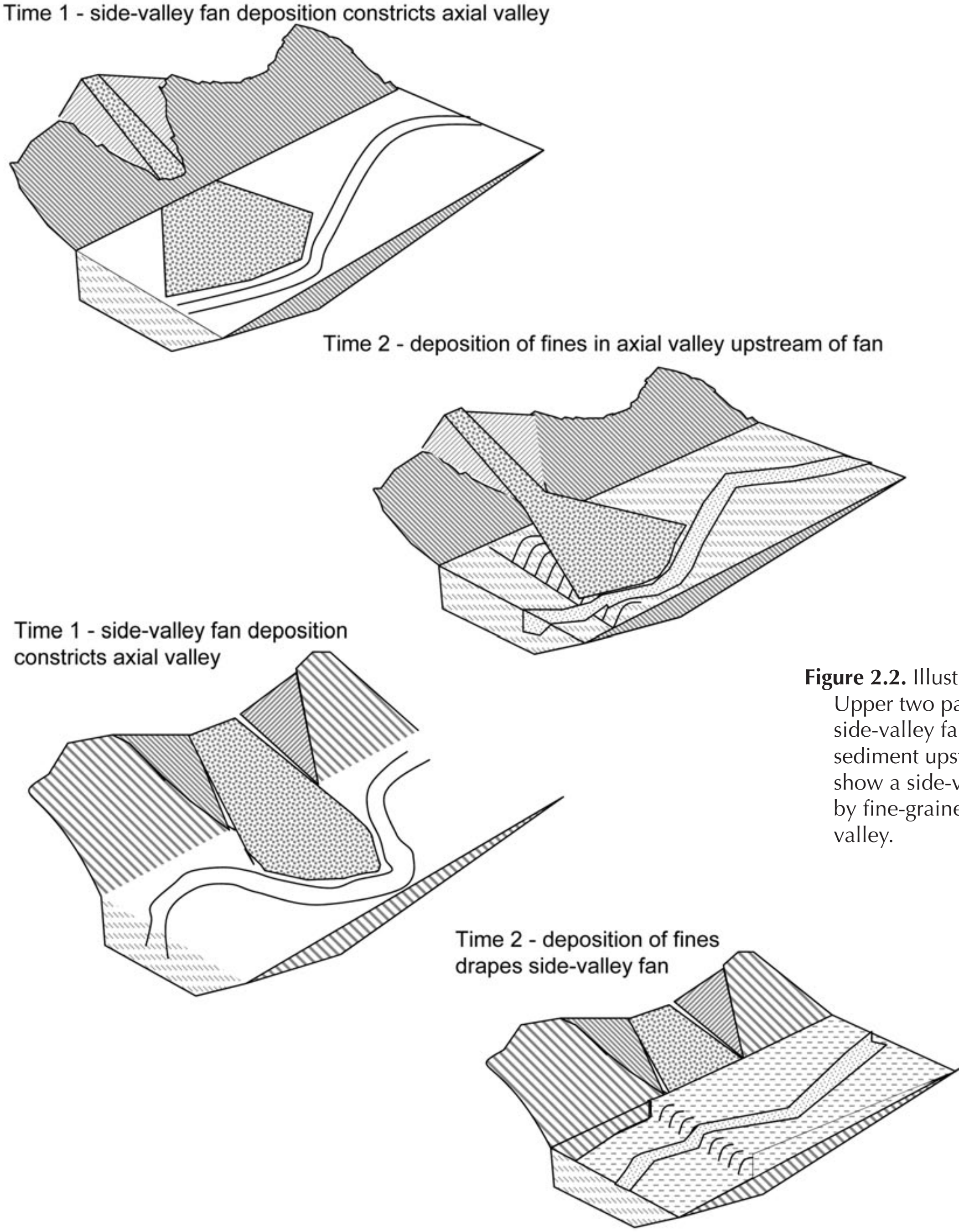



**Figure 2.2.** Illustration of fan controls. Upper two panels show a prograding side-valley fan trapping fine-grained sediment upstream. Lower two panels show a side-valley fan that is buried by fine-grained sediment in the axial valley.

and of other areas with dramatically reduced valley width is enormously complex. This complexity results from several factors: (1) interfingering of axial valley and fan deposits; (2) abrupt downstream variations in stream sediment transport capacity upstream of the fans as a result of reduced channel gradients and the damming effect of the fans; and (3) geologically frequent episodes of channel avulsion associated with localized aggradation of the axial channel. Although localized aggradation and avulsion might seem to contradict the fact that most channels are currently incising, investigations of the avulsion process show that it is associated with the temporary influx of coarse sediment to the reach during high-magnitude runoff events. Avulsion is significant in that it produces discontinuous lenses of coarse-grained sediment that are surrounded by finer-grained materials, creating deposits that are sedimentologically variable.

Data from sediment cores collected in Barley, Birch, and Kingston indicate that the greatest volume of Holocene sedimentation occurred from approximately 5250 to 8650 years BP (unpublished radiocarbon data). Sediment dated through this time period ranges from 2.40 to 12.75 m below the surface of the valley fill and pre-dates the Neoglacial. The character of these deposits is similar to that found in younger materials, suggesting that the processes responsible for formation of deposits during the past 2580 years have been repeated many times, creating the stratigraphic architecture that comprises valley fill in these drainage basins.

**Table 2.1.** Watershed groups derived from an analysis of basin sensitivity to disturbance.

| Category | Geology | Relief characteristics | Basin shape | Fan influence and longitudinal profile | Incision and terraces |
|---|---|---|---|---|---|
| **Group 1** | | | | | |
| Flood-dominated | Volcanic rocks | Rugged, high stream power, high hypsometric integrals | Equant, low shape factor | Low fan influence | Localized incision, discontinuous terraces |
| **Group 2** | | | | | |
| Deeply incised | Volcanic rocks | Rugged, high stream power, high hypsometric integrals | Elongated, high shape factor | Low fan influence, smoothed longitudinal profile | Deeply incised, many continuous terraces |
| **Group 3** | | | | | |
| Fan-dominated | Sedimentary and metasedimentary rocks | Low stream power, low hypsometric integrals | Elongated, high shape factor | High fan influence, stepped longitudinal profile | Localized incision, discontinuous terraces |
| **Group 4** | | | | | |
| Pseudo-stable | Intrusive igneous and siliciclastic rocks | Moderate to high stream power, high hypsometric integrals | Equant, low shape factor | Low fan influence, stepped longitudinal profile | Localized deep incision, discontinuous terraces |

Field observations revealed that incision not only varied along a given channel but between basins, despite the fact that timing of deposition and observed stratigraphic relationships within the valley fill were similar. This indicated that different watersheds differed in sensitivity to natural and anthropogenic disturbance (Germanoski and Miller 2004). Landscape sensitivity can be defined in many ways (Allison and Thomas 1993), but it is defined here after Brunsden and Thornes (1979) as “the likelihood that a given change in the controls of the system will produce a sensible, recognizable, and persistent response [in the landform of interest].” The concept of sensitivity arises from the recognition that many fluvial systems are subjected to similar types and magnitudes of perturbation but often respond differently (Schumm 1991). In the central Great Basin, study watersheds were subdivided into four groups with respect to style of geomorphic adjustments during the late Holocene and to sensitivity of the axial channel to change (table 2.1; Germanoski and Miller 2004). The causes for observed differences in landscape sensitivity among basins cannot be explained entirely using watershed-scale parameters (such as basin relief, area, shape, drainage density, etc.) but are partly explained by differences in basin geology. For example, basins that developed in volcanic rocks were found to be relatively sensitive, probably because volcanic assemblages produce small bed-material sediment (which can be more easily transported than larger debris) and significant runoff.

Detailed mapping of incision depths along the axial valley of basins with continuous channels revealed that the amount of entrenchment is highly variable along the riparian corridor and is controlled in many cases by bedrock and coarse-grained fan deposits. These deposits often form steps in the longitudinal valley profiles and serve as local base level controls that dictate the amount of erosion that occurs upstream of the side-valley fans.

The region’s geomorphic history has had several significant influences on both the nature and distribution of meadow complexes. First, the stratigraphic units that resulted from various erosional and depositional events vary dramatically in their ability to store and transmit water. Because meadow complexes are groundwater-dependent, variations in the units’ permeability have profound influences on subsurface flow along the valley bottom, in general, and meadows, in particular. There is some evidence that fine-grained stratigraphic units at or near the ground surface are required in order for meadows to form. Second, the localized, stratigraphic complexity of the valley fill that is often more pronounced beneath meadows complicates the observed hydrologic responses of meadows to external disturbances like stream incision. Third, the geomorphic development of the basins has led to sites along the valley bottom where valley width and, presumably, depth to bedrock are abruptly constricted, thereby decreasing the area through which subsurface waters can flow. Not one of these factors necessarily results in meadow complexes, but in combination they can result in groundwater levels near or at the Earth’s surface.

***Down-Valley Constrictions of the Unconsolidated Flow Field.*** Groundwater levels along the valley bottom of most basins are located several meters below the surface, except beneath meadows. A reduction in the cross-sectional area of the valley fill can reduce the area through which water that is moving down-valley through unconsolidated sediments can flow. This mechanism is similar to the effect of a funnel; the constriction at the neck of the funnel causes water to pool above it. Constriction of a valley’s cross-sectional area has

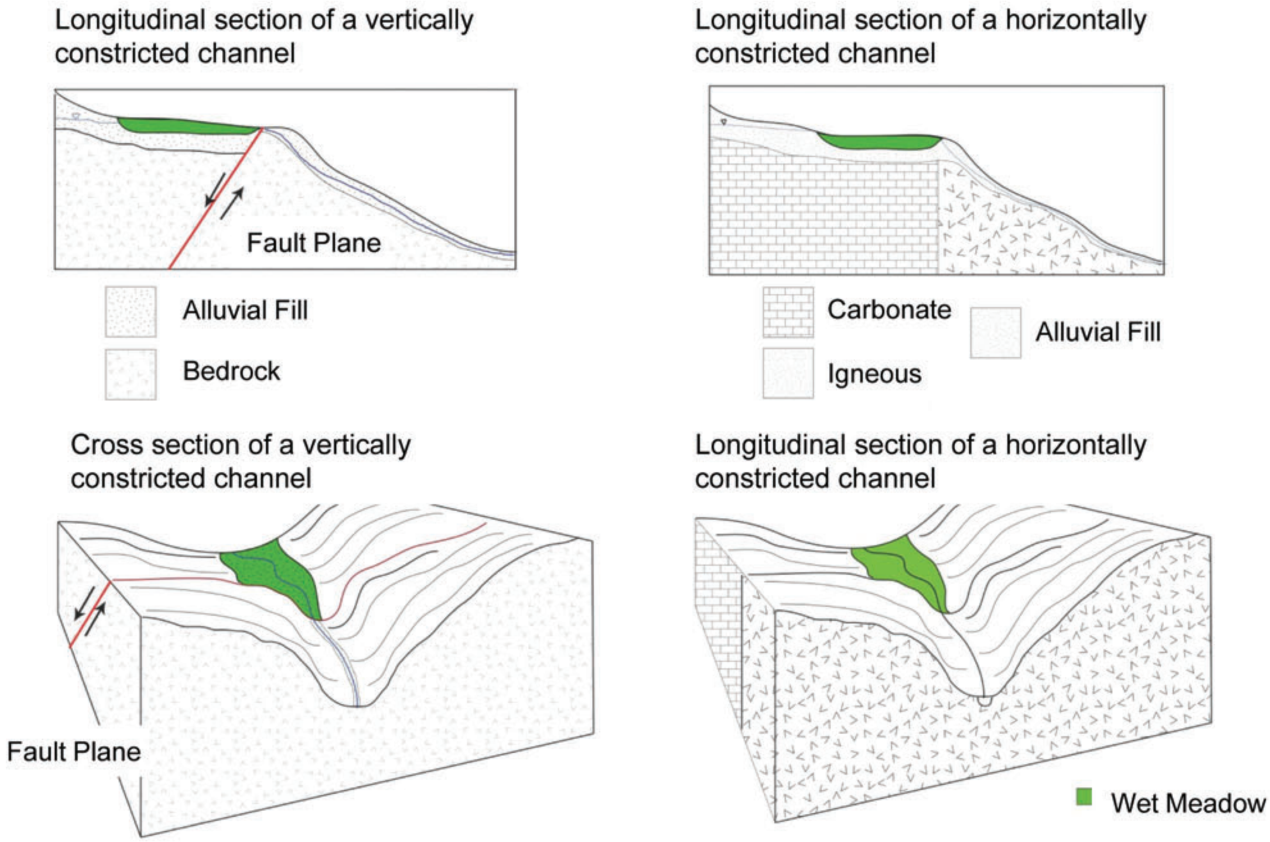



**Figure 2.3.** Lateral and vertical constriction formed by resistant bedrock.

the potential to cause localized pooling, significantly raising subsurface water levels. Most meadows are located immediately upstream of valley constrictions that are created either singularly or in conjunction with: (1) bedrock protrusions from the valley sides; (2) bedrock highs beneath the valley fill; and/or (3) accumulation of sediment associated with side-valley alluvial fans.

***Bedrock Constrictions.*** The hydrologic damming effect of a bedrock constriction is straightforward because permeability of bedrock is generally less than that of unconsolidated alluvial valley fill. Thus, the rate at which water can move down-valley is greatly reduced by bedrock constrictions. Horizontal protrusions of bedrock into valley fill occur primarily at three distinct locations: (1) where the geology changes, from upstream to downstream, from a less to more erosionally resistant rock unit (fig. 2.3); (2) where the channel locally follows the trace of a fracture or fault and remains in the same location though time rather than migrating laterally and widening the valley floor as in other areas (fig. 2.3); and (3) near the mouth of a tributary where bedrock drainage divides project from the hillslope into the axial valley and constrict valley width (fig. 2.4). Valley width changes that are associated with faults may or may not be associated with regional tectonic structures.

While horizontal protrusion of bedrock into a valley can be easily observed in the field and on aerial photographs, upward (vertical) protrusion of bedrock into the valley fill cannot be directly observed. Seismic analyses were used to determine if upward protrusions represented a viable mechanism for reducing the cross-sectional area of the valley fill (Sturtevant 2007). More specifically, bedrock offsets associated with thrust and normal faults that were known to cross upland valleys were evaluated to determine if they created bedrock highs and caused decreased thickness of the alluvial fill. Meadow complexes often occur at sites where faults align with tributary channels and obliquely traverse upland valleys. Bedrock highs could be produced by differences in erosional resistance of bedrock units and different rates of stream channel incision during valley development.

Seismic (geophysical) analyses of six meadows within the Barley, Big Creek, Birch, Corcoran, Kingston, and Indian Valley basins determined that both topographic highs and faults were present within some but not all of the rock units beneath meadows (fig. 2.5) (Sturtevant 2007). Four different structural combinations were found: rock units that contained both faults and topographic bedrock highs, rock units that contained only faults, rock units that contained only topographic highs, and rock units that contained neither (table 2.2). Importantly, where bedrock highs were found, they often occurred immediately downstream of meadows in locations where they could exert strong control on groundwater level. Also, topographic highs along the bedrock-valley fill contact that were observed in the geophysical surveys were collocated (overlain by) with side-valley alluvial fan

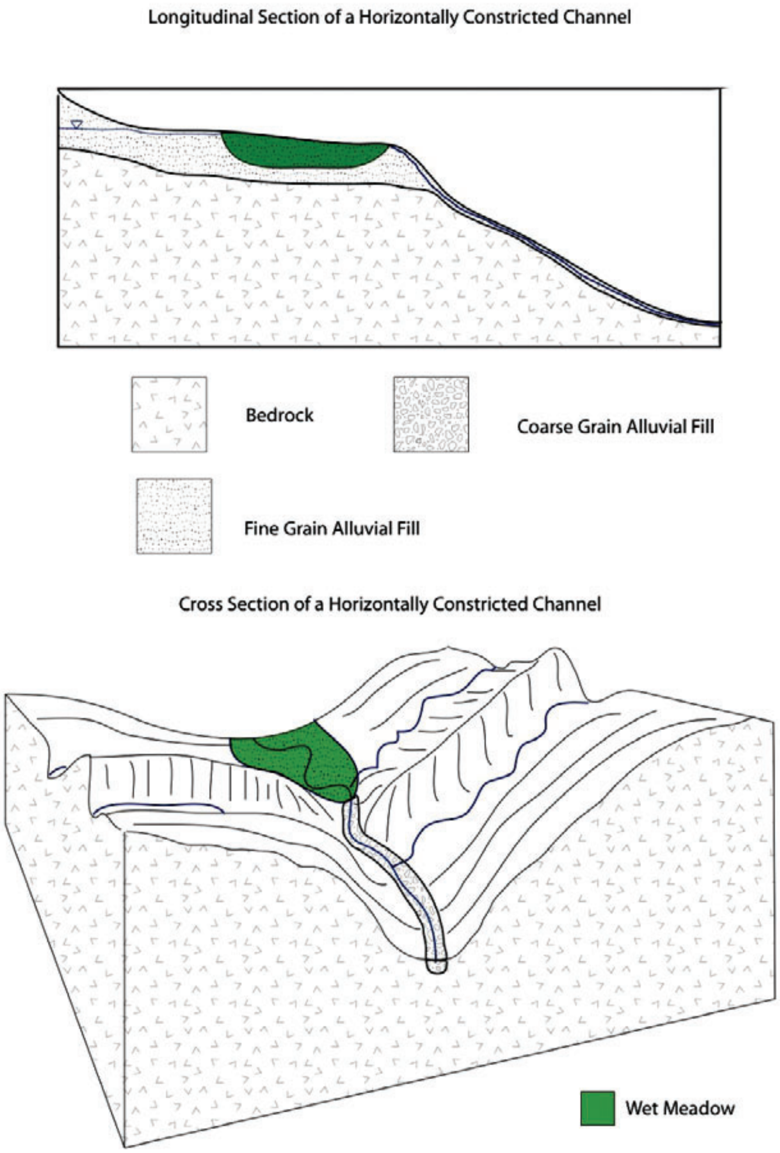



**Figure 2.4.** Lateral constriction formed by a drainage divide.

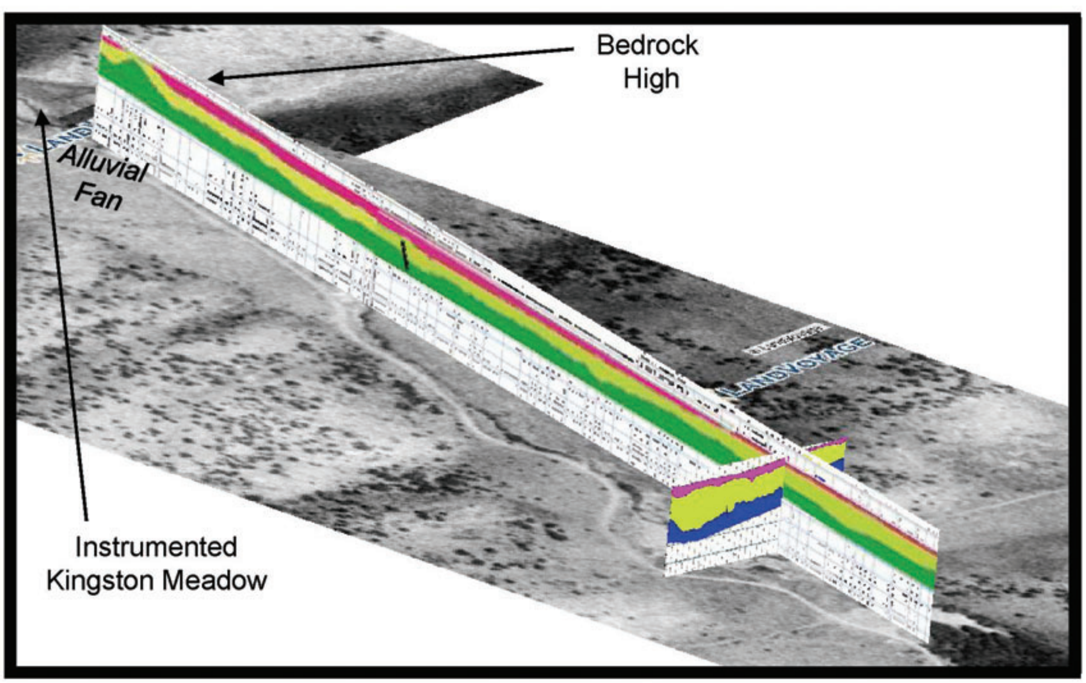
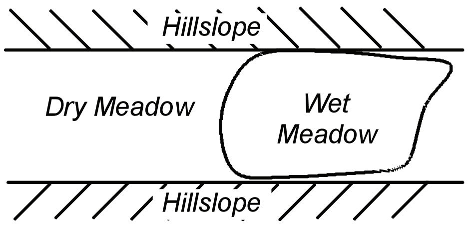
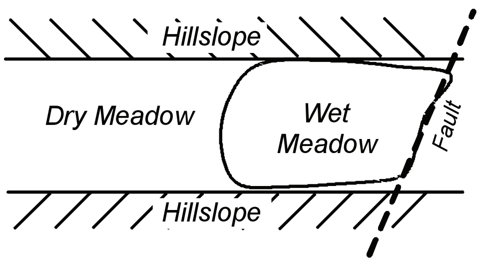
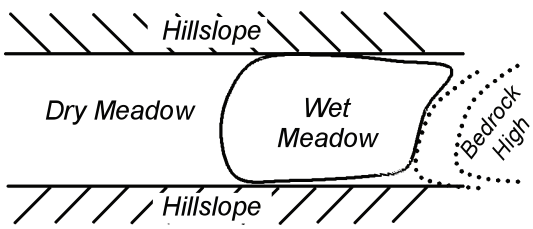
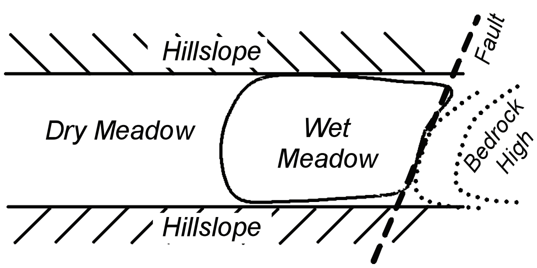



**Figure 2.5**. Seismic refraction tomography profiles in Kingston Canyon. The vertical panels that represent the seismic stratigraphy are superimposed on an aerial photo of the meadow to show the location. The bedrock layer is shown in the blue/dark green layer. Light green and magenta layers are unconsolidated sediment. The fault (black line) from the reflection data is superimposed onto the refraction tomography. Note the bedrock high in the upper left corner of the image, which is the end of the wet meadow complex.

**Table 2.2.** Summary of types and extent of bedrock control on meadow ecosystems (modified from Sturtevant 2007).

| ***Skematic Diagram*** | ***Geologic Control*** |
|---|---|
|   | *None* |
|   | *Fault(s) Present* |
|   | *Bedrock High Beneath Alluvium or Constricting Valley Width* |
|   | *Fault(s) Present*<br><br>*Bedrock High Beneath Alluvium or Constricting Valley Width* |

deposits (fig. 2.6). The joint occurrence of fans and topographic highs may result from protection of the bedrock from erosion by side-valley fan deposits as the axial channel eroded rock units during valley development. Deposition on the fans would tend to confine the channel to the opposing side of the valley, thereby limiting the amount of bedrock erosion that could occur beneath the fans. Regardless of the mechanisms responsible for fan formation, the geophysical data suggest that, in some cases, bedrock protrusions likely play a role in meadow development.

***Constrictions Created by Side-Valley Alluvial Fans.*** As many as 39 of the wet meadows that were studied are located immediately upstream of side-valley alluvial fans. Where side-valley tributaries have delivered large quantities of sediment to the axial valley, alluvial fans prograde into, or even entirely across, the axial valley floor. Thus, fan deposits and the landforms that they create can be viewed as forming another type of valley constriction in the central Great Basin. Side-valley fans occur as two distinctly different morphological types: (1) fans that have distinct alluvial fan morphology and that prograde onto the valley floor (fig. 2.7a); and (2) fans that lack a distinct fan-morphology but that grade smoothly onto the valley floor (fig. 2.7b). The classic prograding fan morphology is easy to recognize and the valley constriction is self-evident (fig. 2.7a). Effects of graded fans on valley morphology are less obvious to the untrained eye, but the physical effects of fan deposits on the mainstem axial valley are no less significant (fig. 2.7b).

**Figure 2.6.** Wet meadows upstream of side-valley fans in Kingston Canyon, Toiyabe Range.

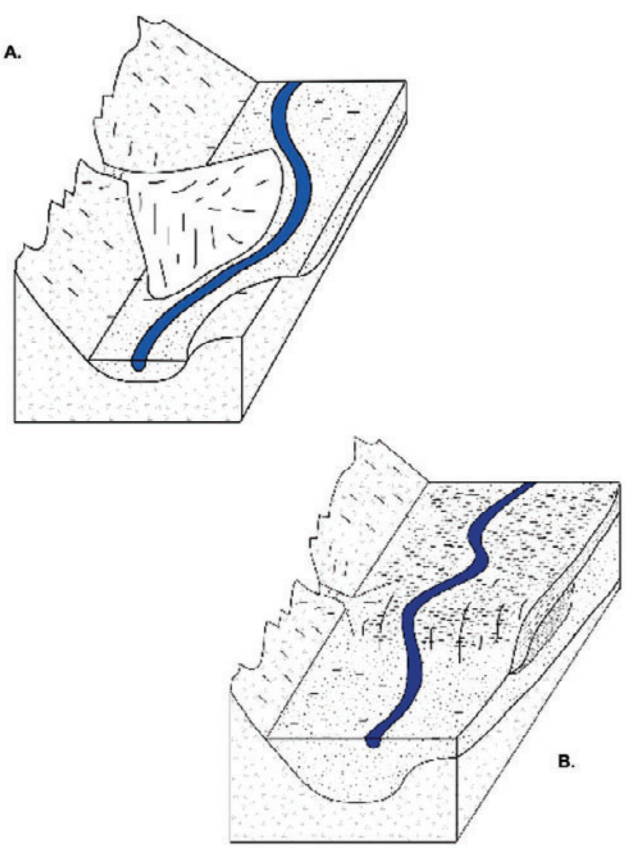



**Figure 2.7.** A. Meadow upstream of a prograding side-valley fan. B. Meadow upstream of a plunging side-valley alluvial fan.

The development of prograded versus graded fans is determined primarily by the morphology of the tributary valley, which in turn is influenced by the overall geomorphology of the drainage basin (Germanoski and Miller 2004). Where tributary drainage basins are long and have gentle gradients, the tributary valleys have more accommodation space for sediment to be stored and, thus, greater sediment accumulation. In such circumstances, side-valley fans are more likely to grade into the axial valley fill or to be buried by axial valley fill sediments. Where tributary drainage basins are short and have steep gradients, tributary valleys have little space to accommodate sediment storage and more sediment is delivered to the axial valley. In this case, side-valley fans are more likely to prograde into the axial valley. Short tributaries and prograding fans are most common in elongate drainage basins.

Some prograding fans can be found in basins that do not, at first glance, possess an elongate form. For example, Big Creek possesses a much more equant morphology than Kingston. However, it is clear from evaluating satellite images and aerial photos that the Big Creek drainage basin's morphology appears equant in plan view because it consists of two major tributary channels. The Big Creek drainage basin is bisected by a drainage divide rather than by the trunk channel of a dendritic drainage network as drainage basin morphometric analysis assumes. Thus, the elongation ratio (3.6) underpredicts the likelihood that tributary channels will be short and steep and that side-valley fans will be significant landforms. Corcoran basin, located in the southeastern section of the Toquima Range (fig. 1.7), is

**Table 2.3.** List of meadows and the geomorphic controls on each meadow's development. BR = bed rock; DD = drainage divide; Fan = alluvial fan; TC = tributary confluence.

| Meadow | Control | Meadow | Control | Meadow | Control |
|---|---|---|---|---|---|
| Lebeau | Fan | Mohawk | BR | Willow (Monitor Range) | DD |
| Emmigrant 1 | DD | South Crane | Fan | West Dobbin | DD |
| Emmigrant 2 | Fan | Indian Valley | Fan/TC | Stargo | Fan |
| Cahill 2 | Fan | Cloverdale | Fan | East Dobbin | Fan |
| Cahill 3 | Fan | Corral 1 | Fan/BR | Wadsworth 1 | TC |
| Johnson 1 | Fan | Corral 2 | BR/Fan | Wadsworth 2 | Fan |
| Johnson 2 | Fan | West Northumberland | DD | Wadsworth 3 | Fan |
| Johnson 3 | Fan | Corcoran Main 1 | DD | Wadsworth 4 | DD |
| Birch Tributary | Fan/DD | Corcoran Main 2 | Fan | Mosquito | Fan |
| Birch 1 | DD | Corcoran Main 3 | Fan | Danville | BR |
| Birch 2 | Fan | Corcoran 1 | Fan | Green Monster | BR |
| Big Creek | Fan | Corcoran 2 | Fan | Barley | Fan |
| Kingston 0 | Fan | Corcoran 3 | Fan | Barley Trib. | DD |
| Kingston 1 | Fan | Corcoran 4 | Fan/TC | Fandango 1 | Fan |
| Kingston 3 | Fan | Corcoran 5 | Fan | Fandango 2 | Fan |
| Washington | Fan | Meadow 1 | Fan | Little Cow | DD/BR |
| Cottonwood | Fan | Meadow 2 | Fan | Six Mile 1 | Fan |
| San Juan 1 | TC | Round Mountain | TC | Six Mile 2 | Fan |
| San Juan 2 | Fan | Red Canyon | DD | | |

another example of a basin with an equant shape overall. However, the basin is composed of two major tributaries that drain from the north (North Fork) and east (Corral Canyon), and it has a morphology that facilitates side-valley tributary control because individual sub-basins have elongate geometries that favor the influence of side-valley fans. Although the elongation ratio of a drainage basin is a good indicator that side-valley fan constrictions will be common, these examples illustrate that some drainage basins that are equant in shape may have two elongate sub-basins that facilitate side-valley fan development.

***Hydrologic Effects of Side-Valley Alluvial Fans.*** Unlike bedrock protrusions, the effects of side-valley alluvial fans on groundwater are more indirect because fan sediments are unlikely to reduce the rate of groundwater flow. Field observations and sediment cores taken from five drainage basins in the study area indicate that most fan deposits are coarser-grained than axial valley fill sediments. Thus, fan deposits are likely to possess higher permeabilities and hydraulic conductivities than valley fill. However, fan progradation often results in deposition of fine-grained sediments immediately upstream. Observations of 56 meadows in the central Great Basin indicate that sedimentation upstream of side-valley alluvial fans and tributary junctions is the most common factor influencing development of meadows, followed by sedimentation upstream of bedrock-related geomorphic constrictions (table 2.3). The importance of these fine-grained units, which possess low permeabilities, is that they are likely to reduce down-valley groundwater flow rates, resulting in a rise in water levels. Slug test data showed that deposits beneath the meadows locally possessed relatively low hydraulic conductivities, on the order of $10^{-5}$ cm/s (unpublished data from Lord and Jewett). Our observations also indicated that the formation of wet meadows, in general, requires accumulation of relatively impermeable fine-grained sediment near the ground surface that: (1) retards the ability of the water to rapidly discharge at the surface and drain the underlying aquifer; (2) creates artesian flow conditions, which allow the meadows to remain saturated over long periods of time; and (3) forces the water to flow through underlying deposits that are finer-grained within the meadow than upstream and downstream and that reduce the rate of groundwater flow.


**Figure 2.8.** Meadow upstream of the junction of two high-order tributaries.

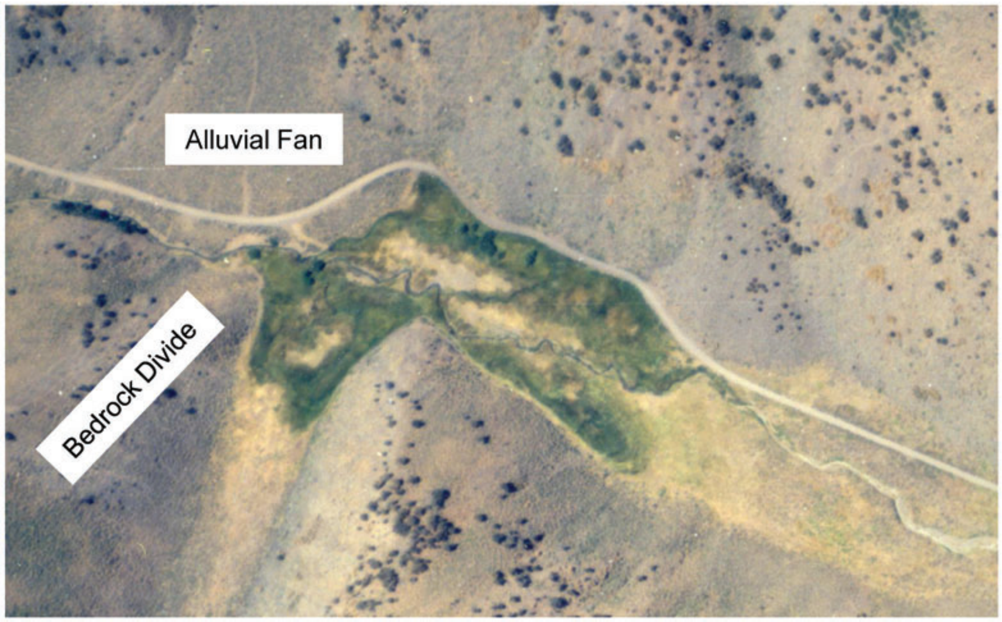



**Figure 2.9.** Valley constrictions downstream of the Kingston 3 meadow in Kingston Canyon.

A few meadows are located where fine-grained sediment has accumulated above tributary junctions (fig. 2.8). However, in this case, enhanced fine-grained sediment accumulated as a result of temporary sediment damming upstream of a tributary valley without the formation of side-valley fan deposits. This process appears to be most prevalent in systems where tributaries are underlain by poorly welded volcanic tuffs that produce disproportionately large volumes of fine-grained sediment in comparison to basins underlain by sedimentary rocks, crystalline rocks, massive welded tuffs, or crystalline rhyolite. In addition, the characteristics of sediment deposition from side valley sources appear to be related to tributary size. Prograding fans tend to form where sediment producing tributaries are steep first- or second-order channels, while graded fans form when side-valley channels are lower gradient, perhaps third-order channels, and tributary junction sedimentation occurs where two higher-order tributaries join.

Fine-grained sediment deposition also may be an important component of meadow development upstream of bedrock constrictions. Fine-grained sediment often is produced upstream of bedrock drainage divides that are associated with tributary channels that project into the axial valley, a situation that is commonly observed in the headwater areas of a drainage basin. Also, more than one type of fan and/or valley constriction may be present, all of which contribute to the development of a meadow (fig. 2.9). An excellent example occurs in Kingston Canyon, located on the east side of the Toiyabe Range (fig. 1.7), which is underlain primarily by a complex set of sedimentary and metasedimentary rocks of Cambrian and Ordovician age and exhibits an elongated morphology with a shape factor of 5.1. As previously noted, elongate basin shapes increase the probability that prominent side-valley fans will form by prograding into the axial valley. A meadow in Kingston Canyon (Kingston 3) is located immediately upstream of a prominent, prograding side-valley fan. However, the axial valley is further constricted by protrusion of a bedrock hillslope that the fan deposits abut against and a graded side-valley fan from a tributary on the east (fig. 2.9). These features cause a significant decrease in the gradient of the longitudinal profiles of the axial channel and valley floor upstream of the constrictions. The decrease in slope facilitates the accumulation of fine-grained sediment, which reduces groundwater flow rates through the valley fill.

Although the type of valley constriction that occurs in a basin depends on its plan view morphology, every meadow is unique, and the causative factors of meadow formation are likely to vary even within individual watersheds. For example, Corcoran Canyon is located on the east side of the southern Toquima Range, is underlain by volcanic tuffs of Tertiary age, and has two major tributaries. The main branch has an elongation ratio of 5.2, whereas the west branch has an elongation ratio of 4.1. The elongated geometry of these basins facilitates development of side-valley fans that have the potential to prograde into the axial valley. The eight well-developed meadows in Corcoran Canyon are found in similar, but slightly different geomorphic settings (fig. 2.10). Meadows within the main branch of Corcoran Canyon (labeled Main 1, 2, and 3) all terminate downstream at graded, side-valley alluvial fans with some of the fans partially buried by axial valley-fill sediment. However, the geomorphic setting of meadow 1 differs in that it is perched upstream of a fan that grades onto the valley floor just upstream of a bedrock constriction. The position of this meadow likely reflects the combined effects of a bedrock constriction and graded alluvial fan on sediment deposited upstream of the constriction (fig. 2.11). Similarly, five meadows occur in the west branch of Corcoran Canyon, but only the first three meadows (labeled 1, 2, and 3) are positioned upstream of side-valley alluvial fans that are graded to the axial valley floor. Meadows 4 and 5 differ somewhat and are located in a northern tributary of the West Fork of Corcoran Canyon just upstream of tributary confluences (fig. 2.11). Although


**Figure 2.10.** Eight meadows in Corcoran Canyon.


**Figure 2.11**. Corcoran Meadow-fan and bedrock control.

detailed stratigraphic data are lacking, geomorphic architecture of the valleys suggests that fine-grained sedimentation within the valley of the West Fork of Corcoran Canyon reduced the rate of groundwater flow moving down-valley along its tributary channels, creating meadows immediately upstream of the confluence. In other words, sediment deposition in the axial valley blocked sediment from entering from the northern tributary, thereby allowing fine-grained deposits with low hydraulic conductivity to accumulate in the tributary above the channel junctions. The net effect is that meadows 4 and 5 are in a geomorphic setting different from those elsewhere, although the basic factors contributing to meadow formation (water supply, fine-grained sediment accumulation, and constrictions on flow rates) are present.

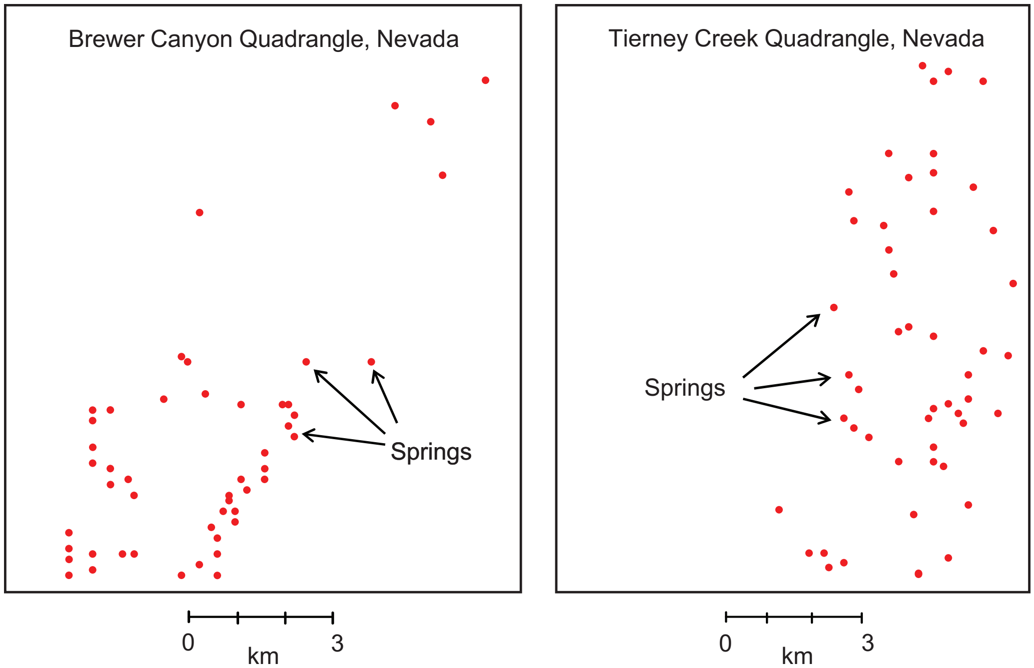



**Figure 2.12.** Location of springs mapped on 7.5 minute USGS Topographic Sheets. Note linear alignment of springs.

## *Source of Meadow Waters*

The general assumption has been that the primary source of water to the meadows is precipitation in upstream portions of the basin that flows down-valley through unconsolidated fill to the meadow complex. While flow through valley fill is undoubtedly an important groundwater source, two other sources can be important. First, where meadows exist immediately upstream of side-valley alluvial fans, some subsurface water is derived from movement of water through the tributary valley fill that forms the fan. The importance of this source is detailed in Chapter 3. Second, groundwater may be supplied to some meadows as it emerges from faults and fractures in the underlying bedrock that traverses the axial valleys, as observed in Kingston 3 and Big Creek. Faults were found within the bedrock at a number of sites (Sturtevant 2007), and it is possible that the water at these locations originated in other, adjacent basins. Movement and discharge of water along bedrock faults and fractures is supported by maps of spring locations on 1:24,000 scale topographic sheets (fig. 2.12). Although springs are present in most meadows, springs often occur without meadows and, more importantly, frequently align along linear trends (fig. 2.12) indicative of structural features such as fractures and faults.

## Summary

Local and regional analyses show that meadows are located in specific geomorphic and hydrologic settings. However, each meadow complex is a unique feature and cannot be unequivocally described by any single set of causative factors without geomorphologic investigation. Most meadows result from a combination of factors, the most important of which are an adequate water supply and some mechanism that retards down-valley movement of groundwater and causes a rise in groundwater levels. The reduction in goundwater flow may be produced by several different factors, including the vertical or lateral constriction of the valley fill by bedrock and/or a change in grain size of the valley-fill deposits. Reductions in grain size, and permeability of the resulting deposits, are commonly associated with deposition upstream of side-valley alluvial fans and bedrock protrusions. Meadows usually exhibit relatively impermeable, fine-grained sediment near the ground surface that: (1) slows the water and prevents it from rapidly discharging at the surface and draining the underlying aquifer; (2) creates artesian flow conditions that allow meadows to remain saturated over long periods of time; and (3) forces water to flow through underlying deposits that are finer-grained in the meadow than upstream and that reduce the rate of groundwater flow. These factors are discussed in more detail in Chapter 3.

Given that meadow complexes are supported by groundwater and that an adequate water supply is needed for their continued existence, it is important to determine the source of groundwater to the meadows. Several sources, occurring either individually or in combination, have been identified, the most important of which are: (1) water that is derived primarily from precipitation that flows down-valley through unconsolidated valley fill; (2) water that moves through alluvial fill and fan deposits within adjacent tributaries; and (3) water that is discharged from bedrock faults and springs and that may be derived from other watersheds. Any activity that reduces the supply of groundwater to the meadow risks negatively affecting the meadow's ecological condition.

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