Sapping processes and the development of theater-headed valley networks on the Colorado Plateau

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ABSTRACT

Ground-water sapping is an erosional process that produces landforms with unique characteristics. Sapped drainage systems differ in morphology, pattern, network spatial evolution, rate of erosion, and degree of structural control from their fluvial counterparts. Investigation of deeply entrenched theater-headed valleys in the Glen Canyon region of the Colorado Plateau indicates that ground-water sapping is the predominant mechanism of growth. The canyons occur in the Navajo Sandstone, a highly transmissive aquifer underlain by essentially impermeable rocks. Within this formation, two populations of valleys with markedly different features are identified. The first group exhibits theater heads: longitudinal profiles with high, step-like discontinuities and commonly asymmetric, structurally controlled patterns. The second group is characterized by tapered terminations; a relatively smooth, concave-up profile; and a more arborescent network. Because the valleys have developed under the same lithologic, stratigraphic, and climatic conditions, the differences in form are attributed primarily to structural constraints that determine the relative effectiveness of overland-flow and ground-water (sapping) processes. Of particular importance is the dip direction of the beds relative to that of valley growth, inasmuch as this relationship controls the occurrence and distribution of ground-water seepage at valley walls. Laterally flowing ground water also exploits fractures at depth, so that the drainage pattern of theater-headed valleys reflects that of the regional jointing pattern.

Martian valleys exhibit numerous morphologic similarities to canyons formed in the Navajo Sandstone. These include theater-shaped heads, nearly constant width from source to outlet, high and steep sidewalls, hanging outlets, and a large degree of structural control. Although the constituent materials, scale, climate, structure, and ground-water conditions of Mars cannot be replicated in any Earth analog, the striking similarities in form suggest that the gross geomorphic processes may be similar and that sapping processes have operated to create the Martian valleys.

INTRODUCTION

Deeply entrenched theater-headed canyons are common in relatively ancient terrains on Mars. The presence of strikingly similar theater-headed valleys on the Colorado Plateau led us to examine the processes of their development, in an effort to better understand the terrestrial examples as well as to infer the processes that may have operated on Mars. The valleys of the Colorado Plateau which were studied are tributaries to the Colorado and San Juan Rivers formed in the rocks of the Glen Canyon Group in the Glen Canyon region of southwestern Utah (Fig. 1).

Several key features are characteristic of both the Martian and the terrestrial drainages. These features include (1) theater-shaped heads of first-order tributaries, (2) relatively constant valley width from source to outlet, (3) high and steep valley sidewalls, (4) pervasive structural control, (5) frequent hanging valleys, (6) large scale, and (7) characteristic patterns. Most terrestrial networks grow by the interaction of three flow processes: overland flow, through-flow, and ground-water flow. The lack of any compelling evidence for rainfall or surface flow on Mars (Sharp and Malin, 1975; Pici, 1980) argues that control of the development of Martian valleys probably reflected subsurface processes. The major objective in the study of the valleys of the Colorado Plateau is to assess the relative roles of overland-flow, through-flow, and ground-water–flow processes in feature formation and to relate valley morphology and pattern to lithologic, structural, and hydrologic factors.

Overland flow is the principal process of drainage formation on Earth, and it plays a major role in the evolution of landscapes on the Colorado Plateau (Powell, 1875; Gilbert, 1877; Dutton, 1882; and others). Throughflow processes in the Glen Canyon region are limited by thin and poorly developed soil profiles and by pervasive jointing of the bedrock that permits infiltrated water to move more rapidly toward the ground-water system. Ground-water erosion results from water that enters the permanent ground-water system and emerges at a zone of seepage. Base flow, resulting from seepage into the channel, sustains a number of intermittent and perennial streams.

The principal geomorphic expression of ground-water flow is ground-water “sapping.” Sapping is here defined as the process leading to the undermining and collapse of valley head and side walls by weakening or removal of basal support as a result of enhanced weathering and erosion by concentrated fluid flow at a site of seepage. Sapping processes are commonly associated with the development of theater-headed valley terminations, and these features, as well as considerable field evidence of mass movement and ground-water seepage, led us to examine the extent to which ground-water erosional processes contribute to the development of selected valley systems on the Colorado Plateau.

Few studies have addressed the role of ground-water sapping in the evolution of drainages. Small-scale features have received the most detailed attention, and their origin is better understood than that of larger systems. Previous studies have primarily addressed throughflow sapping processes, such as the development of seepage lines in the soil profile (Hadley and Rolfe, 1955; Bunting, 1951; Sharpe, 1976; Anderson and Burt, 1978), rill development at beaches (Higgins, 1974, 1982), and network extension by piping (Gilman and Newson, 1980). These processes occur at shallow depths and produce features that are more transitory in nature than those formed by ground-water–flow processes.

The effectiveness of ground-water sapping has been recognized in diverse environments, al-
though little work has been done to detail the process involved. Sapping is acknowledged as a contributing factor in the development of the escarpment dry valleys of Europe (Small, 1964), stream systems in the Pleistocene area of the Netherlands (DeVries, 1976), small catchments in Vermont (Dunne, 1980), steep-walled box canyons in basalt of the Hawaiian Islands (Hinds, 1925; Wentworth, 1928), wadis of the Libyan desert (Peel, 1941), and numerous tributary canyons of the Colorado Plateau (Gregory, 1917; Bryan, 1928; Campbell, 1973).

**OBSERVATIONS ON THE MORPHOLOGY OF TRIBUTARIES TO THE LOWER ESCALANTE RIVER**

Insight into the relative roles of ground-water and surface runoff in the Glen Canyon area comes from an examination of the tributaries to the lower Escalante River. Preliminary observations of these valleys are presented here as background to more detailed discussions that follow.

The east and west tributary arms of the lower Escalante River vary in several important characteristics (Figs. 2 and 3). The western tributaries all exhibit valley widths that increase downstream and with increasing tributary order, tapered terminations of first-order tributaries, meanders, and longitudinal profiles that are concave upward (Fig. 4B). Eastern tributaries are less arborescent in pattern. They have nearly constant valley widths (Fig. 2) and have steep-cuspate valley-headwall terminations associated with a stepped discontinuity in the longitudinal profile (Fig. 4A). These observations suggest that fundamentally different processes may be
TRIBUTARY DRAINAGE OF THE LOWER ESCALANTE RIVER

Generalized Cross Section (A-A')

STRAIGHT CLIFFS

Kst Ktrd Jm Jse Jc JTn

Escalante River

Lung Canyon

Tm - Moenkopi Fm; Tc - Chinle Fm; Tk - Kayenta Fm; JTn - Navajo Ss; Jc - Carmel Fm; Je - Entrada Ss; Jse - Summerville Fm and Entrada Ss; Js - Summerville Fm; Jm - Morrison Fm; Ktrd - Tropic Shale and Dakota Ss; Ksc - Straight Cliffs Fm.

WATERPOCKET MONOCLINE

2250 m

2000

1750

1500

1250

1000

Figure 2. Tapered and theater-headed canyons developed in the Navajo Sandstone, attributed to the relative effectiveness of overland-flow or ground-water erosional processes. Dark shaded areas represent the valley floors. West-flowing canyons have theater-shaped terminations and show a greater width/length ratio than do east-flowing valleys. The morphology of theater-headed valleys is analogous to some Martian valleys.
responsible for the geomorphic development of these tributaries.

The morphologic differences between these basins cannot be explained by environmental or tectonic factors. Spatial variations in climate are negligible, owing to the small geographic area encompassed. In addition, there has been no local differential tectonism to account for the differences in scarp development.

A likely explanation for the difference in canyon morphologies involves the relative partitioning of overland and ground-water flow within basins. The western tributaries have considerably greater overland-flow volumes, owing to runoff from the less permeable rocks comprising the Straight Cliffs of the Kaiparowits Plateau, to higher topographic relief, and to larger drainage basins. Instead of displaying large headcuts, however, these tributaries exhibit fairly smooth, concave-up profiles (Fig. 3). Eastern tributaries have lower overland-flow volumes, owing to smaller drainage areas, and areally larger exposures of the more permeable Navajo Sandstone within their contributing areas. Where ground-water flow converges toward canyon walls and where surface-runoff volumes are low, headcuts develop. Where ground water flows downward away from valley heads (and seepage is minimal) and where surface runoff is high, profiles are concave up and theater heads do not occur. It thus appears that the explanation for the theater-headed valleys most likely involves ground-water-flow processes.

THE SAPPING PROCESS

Lithologic Controls

Of the regions of the Colorado Plateau displaying theater-headed valleys, the best-developed and most areally extensive canyons are found in the Glen Canyon area, formed by ephemeral or intermittent streams tributary to the Colorado, San Juan, and Escalante Rivers. These canyons are developed into rocks of the Glen Canyon Group, consisting, in ascending order, of the Wingate Sandstone, the Kayenta Formation of mudstones, siltstones, and sandstones, and the Navajo Sandstone. Canyon morphology appears to be related principally to the nature and occurrence of the Navajo Sandstone.

The Navajo Sandstone is considered by most workers to represent an extensive dune deposit of an ancient interior desert. Cliffs of the formation appear massive, showing horizontal bedding planes commonly >15 metres apart. Primary structures consist of large-scale, high-angle cross-strata. Thin, horizontally bedded units of limestone, siltstone, or shale are found at several levels (McKnight, 1940; Baker, 1946; Picard, 1977). These units act as barriers, permitting seepage at upper levels in the canyon walls (Fig. 5).

Studies by Jobin (1956, 1962) of regional ground-water transmissivity on the Colorado Plateau show the Navajo Sandstone to be the most transmissive of all lithologies, due to its permeability and geometrical configuration and continuity. Its porosity is conservatively estimated at 15% by Goode (1965) and at 25% to 35% by Cooley and others (1969). The recharge potential of the aquifer is high because of its widespread surface exposure at low-dip angles, essentially uniform permeability, and pervasive fracturing. Interception and infiltration are greater in areas where the surface is mantled by deposits of windblown sand and stabilized dunes.

The Navajo Sandstone/Kayenta Formation boundary has long been recognized as an important zone at which springs occur (Gregory, 1950; Cooley and others, 1969). The Kayenta Formation acts as an aquiclute because of the many interbedded seams of silt and clay that occur within it (Jobin, 1962).

Weathering Processes

Ground-water sapping occurs at the heads of canyons and locally along sidewalls as a result of seepage that emerges from the Navajo Sandstone, just above the contact with the Kayenta Formation (Fig. 5), and from perched ground water isolated by lithologic discontinuities in the Navajo Sandstone (Fig. 6). The sites of ground-water seepage from cliffs are commonly marked by cavities and alcoves that range in size from

Figure 3. Longitudinal profiles of tributaries to the Escalante River. The westward-flowing tributaries (Cow, Explorer, and Fence Canyons) show a distinct headscarp. Ground-water seepage emerges at the base of these scarps, above a permeability boundary formed by the Kayenta Formation. The canyons grow headward along this lithologic contact. The eastward-flowing tributaries (Davis Gulch, Willow Creek, and Fiftymile Creek) lack headscarpes because ground water moves downstream, away from the valley heads. Surface runoff from the Straight Cliffs further acts to degrade the profile.
Figure 3. (Continued).

centimetres to many tens of metres. The rock surfaces within a cavity are soft and crumbly and may be scaly in appearance. Salt crystals often occur as thin (100–200 µm in thickness), discontinuous encrustations on the surfaces of the back walls and roofs. Beneath the salts, there is a layer of sandy calcareous material, 1–2 cm in thickness, that is weakly adhering to the wall rock. Samples collected from the Weeping Wall in Zion National Park and examined with the scanning electron microscope suggest that the material is weakened by the deposition of very fine-grained or amorphous calcite in pore spaces from ground water highly loaded with calcium carbonate (Laity, 1983). The wedging action of the calcite decreases the strength of the Navajo Sandstone by separating interlocking sand grains. Furthermore, the calcite itself is vesicular and microcrystalline to amorphous in structure, yielding a less dense and therefore weaker cementing agent. Continued growth in thickness of the sandy calcareous layer eventually leads to loss of internal strength, and flakes 4 cm or less in thickness slough off. The removal of weakened material may be enhanced in winter by the freeze-thaw cycle. Icicles are observed to form on seepage faces on a diurnal cycle, and when they fall, owing to the combined effect of thawing and the weight of the ice, additional material is removed by plucking.

Ground water emerging at seepage springs slowly removes material that provides the basal support for cliffs and slopes. Undermining of the overlying structure leads to its eventual collapse. This process is facilitated by exfoliation joints that develop parallel to the canyon sidewalls and headwalls. The widening of valleys by the successive collapse of massive slabs, developed by exfoliation jointing and undermined by seepage, has been discussed by Bradley (1963) and by Robinson (1970).

Continued retreat of a canyon's head and walls requires removal of talus accumulated at the base of the slope. Mechanically weak sandstones shatter readily upon impact and are further comminuted by active weathering processes. Boulders are commonly friable, rounded in situ, and surrounded by aprons of loose sand. The interiors of talus cones exposed by slump failure into Lake Powell reveal a very high percentage of fine-grained material, attesting to the breakdown of rocks in place. The means by which material is removed from talus cones into the stream channel is not well documented. It is likely, however, that the finer material is moved by a combination of surface wash, subsurface flow, and undermining, gravity fall, and wind action. In general, the accumulation of debris at the foot of the Navajo Sandstone cliffs is very small, indicating effective removal of material.

The Longitudinal Profile

The longitudinal profile of theater-headed canyons reflects the interaction of surface runoff, sapping, and depositional processes. It is characterized by the presence of steep headwalls (120–150 m in height) that divide the profile into upper and lower zones (Fig. 3). In the upper reaches, surface runoff cuts a profile that is more or less concave upward. Below the headwall, sapping along the contact between the Navajo Sandstone and the Kayenta Formation has resulted in a profile that tends to approximate the dip of the beds and is usually fairly straight. This form is subsequently modified by incision resulting from overland flow and by episodes of deposition (Gregory, 1938; Cooley, 1962; Euler and others, 1979). Extensive terraces are present in most canyons, resulting from trenching initiated during the decade 1880–1890 (Gregory and Moore, 1941), and almost all streams presently flow on bedrock. In most tributary canyons, downcutting has been insufficient to allow a smooth juncture with the main perennial rivers, and hanging valleys have resulted.

It is commonly thought that the steep headcuts in the profile are the result of knickpoint retreat by waterfall erosion. Several factors argue against this hypothesis. First, headscarps in the study area are better developed in networks where the contribution of overland flow to the theater head is small. As the flow volume increases, the profile steps are smoothed out. This degradation is particularly evident in watersheds where a significant proportion of the contributing runoff is from non-Navajo lithologies within the basin, so that flow volumes are consequently greater (for example, Willow Creek, Fiftymile Creek). Secondly, theater heads are not developed in drainage basins where, owing to the dip of the beds, ground water moves in a direction away from the canyon headwalls. Thirdly, field evidence suggests that the scarps associated with theater heads do not result from waterfall erosion. The notches through which runoff flows at the top of the headwall are generally very narrow and represent an insignificant fraction of the total relief and breadth of the theater head. This geometrical relationship suggests that discharge carried to the falls is probably insufficient to create,
through spray radius and mechanical erosion, scars of the magnitude seen.

CONCEPTUAL MODELS OF DRAINAGE EXTENSION BY GROUND-WATER SAPPING

The development of drainage systems by sapping processes is a function of the distribution and the relative discharge of ground water along canyon walls. Campbell (1973) observed that alcoves in the Navajo Sandstone of northern Arizona develop from concentrated seepage along major joints, tapping an increasing ground-water source as the alcove grows. Similarly, Dunne (1980) observed channels developing by headward sapping as springs emerged from bedrock joints in a small drainage basin in Vermont. On the basis of these observations, he proposed a conceptual model of drainage extension by spring sapping or piping that may be applicable to large-scale processes.

A diagrammatic representation of valley growth by sapping is presented in Figure 7. It shows an undissected, low-angle tilted surface of Navajo Sandstone from which the overlying Carmel Formation has been stripped. The Kayenta Formation forms an impermeable lower boundary. At T1, ground water is flowing down the gradient of beds dipping toward base level. At T2, an irregularity intercepts the ground-water system, and the increased flow enhances local weathering and initiates the sapping process. The irregularity could be an outcropping joint or an erosional notch formed by overland flow. At T3, the canyon is migrating headward, and ground-water–flow lines are concentrated more intensely at the headwall than at the side walls. Tributaries grow as ground water, emerging along the valley sidewalls, exploits zones of greater hydraulic conductivity, usually joint planes.

The actual conditions that allow for drainage development by sapping in the Navajo Sandstone are considerably more complex than this.
large to form channels. As the drainage network enlarges, the channels deepen, eventually intersecting subsurface-ground-water flow in the Navajo Sandstone. Seepage at the exposed free face initiates the sapping process as ground-water flow converges at the valley head. At this stage in the development of the network, growth of the main canyon proceeds more rapidly than that of tributary canyons because of its initially larger subsurface drainage area. In time, a network of canyons is formed by the process of headward retreat by repeated mass movement. The spacing of tributary canyons is probably related to competition for ground-water discharge and to the spacing of major joints. The steep-walled morphology of the canyons is maintained because valley widening occurs by the mass movement of sandstone blocks associated with exfoliation jointing.

Given a constant climatic regime, growth rates by sapping probably decline as the system enlarges and the drainage area of spring heads lessens. It is important to note that the areal extent of a ground-water basin may differ from that of the surface-water basin. If the ground-water basin is larger, the canyons may extend beyond the original surface-water-basin boundaries.

In an advanced stage of valley development, the amount of lateral retreat by sideward seepage approaches that of headward retreat, and valleys widen. They may continue to grow until adjacent tributaries merge, leaving only isolated buttes and remnants of the original surface. In the final stages of this model, a new drainage system of surface erosion develops on the Kayenta Formation that floored the former canyon.

In summary, networks developed by sapping differ considerably from fluvial systems in their pattern of drainage development. Fluvial networks rapidly evolve to a branched network that fills a drainage basin and undergoes slow changes thereafter (Morisawa, 1964; Parker, 1977). Theater-headed-valley networks extend slowly headward into the basin, adding tributaries, one by one, that remain fixed in position. It can be generalized that the space occupied by a theater-headed network is dependent upon the age of the system. The space-filling characteristics of these networks provide an important clue to their erosional development and may be useful in evaluating the origin of Martian valleys.

DISCHARGE MEASUREMENTS AND ALCOVE DISTRIBUTION

The sapping model indicates that ground water should be greatest at the valley head and decrease distally from it. Seepage-discharge
Figure 7. A general model of drainage extension by sapping processes (after Dunne, 1980). Ground water flowing through the Navajo Sandstone toward base level ($T_1$) encounters an irregularity ($T_2$) (an outcropping joint or erosional notch) that causes ground water to converge at this point. The increased flow enhances local weathering and initiates the sapping process, causing headward migration of the valley ($T_3$). Tributaries grow as ground water, emerging along the valley sidewalls, exploits zones of susceptibility, usually joint planes. The rate of lateral weathering approaches that of headward retreat as the drainage area of the spring head declines ($T_4$).

| TABLE 1. COMPARISON OF DRAINAGE DEVELOPMENT BY OVERLAND FLOW AND GROUND-WATER FLOW |
|----------------------------------|----------------------------------|
| Overland flow | Ground-water flow |
| 1. Valley width increases with distance from the head and with stream order. | 1. Valley width is essentially constant. |
| 2. Valley heads are steep. | 2. Valley heads are steep. |
| 3. Longitudinal profile is usually concave. | 3. Longitudinal profile is more linear and approximates the dip slope. |
| 4. Knickpoints in the profile are well fitted to the drainage. | 4. Often without a distinct knickpoint or upper boundary. |
| 5. A well-developed network fills the drainage basin at all stages of its evolution, evolving rapidly in its initial stages of development, and undergoing slow changes thereafter. | 5. A network of tributaries develops in response to the effect of ground water and bedrock structure. |
| 6. Direction of flow is dominated by surface topography and exposed fractures. | 6. Valley growth is in response to the hydraulic gradient of ground-water flow. |
| 7. May be joint-controlled where fractures are well exposed on the surface but show no control when such joints are mantled by soil or debris. | 7. Valley growth reflects the regional joint pattern, even in Where joints are not controlled by ground water discharge. |
| 8. Streamflow increases downstream in perennial streams. | 8. Streamflow is affected by ground-water discharge increases in the headwaters and then decreases downstream. |

Note: italic type indicates factors important in process interpretation.

measurements and the distribution of alcoves formed by ground-water outflow should reflect these relationships. Two tributaries to Glen Canyon, Bowns and Explorer Canyons (Fig. 2), were examined for such effects. Bowns Canyon is 7.5 km long, 250 m wide, and 125 m deep; Explorer Canyon is 3.2 km in length and of similar width and depth. Both canyons are floored by the Kayenta Formation, and the canyon walls and the upper-plateau surface are of Navajo Sandstone. Joints are abundant and exposed, the dominant set trending N60°E, and minor sets range from N20°W to N70°W (Kelley and Clinton, 1960). Explorer Canyon is aligned with the principal joint set and is growing directly upflow along a uniform slope of 2.5°.

It has no tributaries. The lower half of Bowns Canyon is aligned with the trend of the minor joint set and is parallel to the strike of the bed. In its upper reach, the valley makes a right-angle turn, and is developed upflow on a 2° slope and parallel to the principal joint set. Its tributaries all enter from the upflow side.

To provide a quantitative estimate of ground water contributions from various segments along the canyon walls, the discharges of stream base flow and of contributing springs were measured. Measurements were made in March of 1981, when seepage rates are moderately high because of ground-water recharge by low-intensity winter rainfall. Ground water is discharged from point or line sources along canyon walls or directly into the channel from seepage zones along the length of the stream. Point and line sources include seepage from the water head and from various "wet" alcoves along the valley walls. Seepage from alcoves is often sufficient to create small streams that contribute to the mainstream. Ground water is also discharged from perched water tables associated with horizontal bedding planes or with seams of less permeable material exposed at upper levels in the canyon walls. Alcoves frequently develop at these sites, but because ground-water discharge is small and evaporation is high, there is no contribution to valley streamflow.

**Ground-Water Measurements and Interpretation**

Measurements of spring discharge and stream base flow were rather crude, but provide relative estimates of the proportion of ground-water discharge within various sections of the canyon. At the theater heads of both canyons, large seepage faces (15-15 m in height) discharge substantial quantities of water into ponds that overflow to form the stream source. In Explorer Canyon, discharge in the stream increases from 150 liters per minute (l/min) below the head seep to about 430 l/min at a point 1 km downstream. Two ancillary springs contribute to the flow, creating a combined discharge of 44 l/min (10% of total flow). As the head spring provides ~35% of the total streamflow, lateral seepage into the channel accounts for the remaining 55%. The significant percentage of discharge derived from the head spring can be attributed to the simple geometric configuration of the canyon, the lack of tributaries, and the orientation along fractures and directly upflow (Fig. 2).

In Bows Canyon (Fig. 9), a discharge of 150-190 l/min was measured for the combined flow of the double theater head, equivalent in amount to Explorer Canyon, and composing 20% of the total discharge. Seepage from 12 sidewall springs, including flow from minor tributaries, amounts to perhaps 30% of the total. The main tributary accounts for 7%, flowing at
of Bowns the minor the beds, right-angle slope and tributaries of ground-segments of stream were measured March of locally high by lower is dis-FIGURE 8. Schematic illustration of canyon development in the Navajo Sandstone. As the Carmel Formation (Jca) is eroded from the surface of the plateau, a network of surface runoff is initiated on the Navajo Sandstone (Jkn). Runoff is commonly concentrated along joints (A) that enlarge to form canyons as ground water converges at the valley head (B). A network of valleys is formed by the process of basal ground-water sapping (C and D). (E) shows the network in an advanced stage of development. The canyons occupy a very large proportion of the drainage basin and may continue to grow until adjacent systems merge. (F) illustrates two tributary networks to the Escalante River that occupy most of their drainage area. A new drainage system of surface erosion is developing on the canyon floor.

and stream de relative -water dis-; canyons. large seep- substant overflow at Canyon, 150 liters seep to dam. Two v, creating 3% of total 35% of the channell geometric of tributaries and discharge of combined significant in composing flow from 12 min of the total. flowing at ~60 l/m. The remainder of the flow (43%) is derived from lateral inflow to the channel. The relative discharge contributions of headwall seepage, sidewall springs, and seepage lines within Bowns Canyon are quite similar to those of Explorer Canyon. The differences probably result from the more complex network pattern of Bowns Canyon and its geometrical relationship to the monocline, the joint system, and the adjoining basins.

Examination of discharge along the valley length of Bowns Canyon shows that streamflow increases steadily from the headwall to the mid-section of the canyon and then increases only slightly to the outlet. Streamflow amounted to 170 l/min below the headwall, 300 l/min at a point 1.5 km downstream, and 790 l/min at a distance of 4 km. At 7 km downstream, near the valley outlet, discharge had increased to only 850 l/min (although some discharge may be lost downhill by percolation into bedrock, where the stream flows along strike). The significant headwall seepage and the very large contribution of base flow from the upper reaches of the valley suggest that ground-water discharge is greatest at the valley head and decreases distally from it.

Alcove habit and distribution indicate processes forming and modifying canyon walls. As noted earlier, alcoves commonly develop at three to four levels in the cliff face. The lowest level of alcove growth results from seepage at the Navajo Sandstone/Kayenta Formation contact. "Wet" alcoves typically support surface runoff and heavy vegetation. The base of a "dry" alcove is marked by rock staining or by sparse vegetation. Dry alcoves may represent contemporaneous features and/or alcoves that are presently enlarging at a slower rate than are wet alcoves. The distribution of alcoves in Bowns Canyon is shown in Figure 9. Wet alcoves are usually found at the heads of canyons and decrease in frequency of occurrence downstream. Dry alcoves occur downstream of wet alcoves, and their frequency also decreases distally.

STRUCTURAL CONTROLS OF DRAINAGE DEVELOPMENT

Canyon networks which developed in the Navajo Sandstone lack the randomly branching, space-filling dendritic pattern common to many stream systems in homogeneous, structureless materials. Canyon networks are often highly asymmetric, show unusual constancy of tribu-
Figure 9. Alcove and seepage distribution in Bowns Canyon. Seepage stream flow is most prevalent near theater heads and declines in frequency of occurrence distally. Wet alcoves (with observable seepage) are concentrated near canyon heads, whereas dry alcoves (noncontemporaneous features and/or alcoves that are presently enlarging at a much slower rate than are wet alcoves) are more common in the lower reaches of valleys.

Figure 10. Aerial photograph of small (1 km or less in length) tributary canyons to the Colorado River, located between the Escalante River and Long Canyon, opposite the Pollywog Bench. The direction of canyon growth is updp and parallels the strike of joints exposed in the Navajo Sandstone.
ary-junction angles into the mainstream, and exhibit pervasive parallelism of tributary orientation over large geographic areas. The patterns suggest strong control by lithologic or structural factors. Because ground-water flow is particularly sensitive to bedrock fractures and to changes in gradient resulting from regional folding, a strong correlation between these factors and canyon growth is anticipated if sapping plays a major role in canyon evolution.

**Jointing and Faulting**

The spatial relations of the regional joint pattern exert considerable control on drainages in large areas of southeast Utah (Fig. 10). A modified trellis pattern, with pronounced northeast-southwest elongation of valleys, is evident on topographic maps and aerial photographs. The parallelism of drainage has been recognized by Gregory (1950) and Campbell (1973) as representing some degree of joint control, whereas Stokes (1964) attributed the pattern to alignment with wind directions. Faulting is limited. Nevertheless, where faults occur, there is notable alignment of the drainage.

Jointing in the Navajo Sandstone affects the hydrologic regime of both deep canyons and runoff channels. The pervasive fracturing greatly increases the overall permeability of the bedrock surface. As a result, there is a relatively large contribution of precipitation to the ground-water system, and the percentage of surface runoff is diminished. The fractures also act at depth to increase the transmissivity of the bedrock. It is likely that laterally flowing ground water exploits the major joints, which act as conduits (Campbell, 1973). The water subsequently emerges at seepage points along cliff faces.

Well-exposed joints on the plateau also act to concentrate surface runoff, and they enlarge to form channels. Much of the runoff is probably lost through infiltration. The remainder is funneled toward the canyon head, where it flows through a small notch and falls as a cascade to the canyon floor.

**Drainage Development and Structure in the Glen Canyon Area**

Inspection of aerial photographs of the Glen Canyon region suggests that the main erosional trends of both entrenched canyons and plateau runoff channels are coincident with joint sets developed in the Navajo Sandstone. A quantitative measure of joint control is provided by a comparison of the azimuthal trends of jointing, canyons, and runoff channels for several basins in the region (Fig. 11). Numbers of mapped

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![Figure 11](image-url) Rose diagrams, comparing primary directions of canyon and runoff channel growth to joint orientations and bed dip for six drainage basins developed in the Navajo Sandstone, determined from geologic maps. Bed dips are indicated by arrows, showing the predominant directions. Comparable data on surface runoff for Iceberg Canyon was not available, owing to limited coverage on maps.
Figure 12. Structure relationships in the development of canyon networks. Presumed ground-water-flow directions are indicated by long arrows; sites of ground-water seepage, mapped from aerial photographs are indicated by thicker arrows within the canyons. Shaded areas represent canyon floors. Double lines in Annie’s Canyon represent faults.
joint strikes were counted and plotted on rose
diagrams in 20° intervals expressed as percent
frequencies. No method of determining joint
trends and intensity is entirely satisfactory in
tight of the difficulty encountered by most re-
searchers in getting consistent results from the
same data by different workers. Joint counts
tend to emphasize small features; nevertheless,
the diagrams reveal dominant orientations con-
sistent with the regional jointing pattern found
by Kelley and Clinton (1960) in this area and
are probably valid for the major relationships.
Channel and canyon orientations were deter-
bined by subdividing networks into straight-line
segments that reflect significant directional
changes in the channel or canyon course and by
compiling length and direction values with a dig-
itzer. The total channel or canyon length in a
given direction was expressed as a percent fre-
quency and likewise plotted in 20° intervals on
the rose diagram.
The results of the analyses are shown in Fig-
ure 11. The implications of each diagram are
discussed below.

Slick Rock Canyon. The plateau surface ad-
jaent to Slick Rock Canyon (Fig. 12) has an
extensive cover of windblown material that acts
to obscure jointing. Joints are best expressed in
the vicinity of the canyon rim, and orientation of
the main valley is coincident with their trend.
The canyon network is asymmetrical, and all
tributaries enter from the south. Ground-water
flow is inferred to be from the east and south-
west. Substantial seepage is indicated by the
presence of a heavy vegetation cover at the
theater heads of the tributaries.

The contributing runoff channels on the pla-
teau are exceedingly short and poorly incised,
suggesting low overland-flow volume with little
power for headward retreat by waterfall erosion.
Their orientation shows a fairly wide range of
azimuthal trends. Alignment of the main canyon
with the fracture trend, rather than along the
course of plateau surface stream flow, lends sup-
port to the hypothesis that ground-water flow is
responsible for the growth of canyons in this
basin.

Elmers Cove. The canyon network of Elmers
Cove is simple (Fig. 1). It has an elongated
mainstream coincident with sharply delineated
jointing and only one stubby tributary. Compar-
ison of runoff channels with canyons shows a
much wider range in orientation for the former.

Iceberg Canyon. Iceberg Canyon is well
developed in a symmetrically branched pattern.
The symmetry may arise from the canyon's or-
tonation within a gently plunging syncline,
which results in water converging toward the
mainstream canyon. The mainstream is aligned
along the axis of the fold and has grown in an
up-plunge direction. Tributaries branching from
the lower half of the main canyon receive
ground water from the limbs of the syncline and
follow the essentially unimodal fracture trend.
On the upland, runoff channels that flow across
the Navajo Sandstone tend to follow the joint
trend. Channels formed on the Carmel Forma-
tion do not follow this trend.

Bowns and Long Canyons. Bowns and Long
Canyons lie adjacent to one another on the
gently dipping western limb of the Waterpocket
Fold. In Long Canyon, runoff-channel growth
reflects, in orientation and proportion, the direc-
tion and relative intensity of well-exposed joint-
ing, particularly in the lower reaches of the
basin. In Bowns Canyon, joints are less well
exposed, and maximum channel length is devel-
oped in a direction that does not correspond to
the jointing maxima. Channel growth is proba-
ably more responsive to topographic factors in
this area. For both Bowns and Long Canyons,
runoff channels show a somewhat greater azi-
muthal range than do canyons of the same
network. Tributary canyons are asymmetric,
strongly aligned with the regional jointing, and
head in an updip direction.

Annie's Canyon. Valleys in Annie's Canyon
are not theater-headed but are narrow and taper-
ing in form, suggesting that surface runoff is the
most important erosional agent in this basin.
Runoff is increased by the topographically high
position of the less permeable Kayenta Forma-
tion and by the somewhat steeper (10°) dip of
the beds. The network is maze-like in form, as
the rocks are intensely fractured, with prominent
faults trending north-south and east-west
(shown by the double lines in Fig. 12).

Summary of Structural Analyses

Analysis of the rose diagrams and air pho-
tographs suggests that the structural conditions
affecting network growth are basically similar
for both channel and canyon systems. In many
cases, canyon growth parallels that of channel
growth; however, small differences in the re-
sponse of each system to structural features sug-
gest fundamentally different erosional mech-
nisms for the development of each drainage
type. Theater-headed canyons are found princi-
ally on surfaces with low-dip angles (1°-4°)
(Bowns, Long, Iceberg, Slick Rock, and Elmers
Cove Canyons). Such surfaces favor a large pro-
portion of infiltrated precipitation and thereby
have less water available for runoff. As the bed
dip and topographic slopes steepen, surface run-
off increases, and there is a resultant change in
canyon morphology toward narrower valleys
with tapered heads (Annie's Canyon). In addi-
tion, the observation that canyons have a more
restricted range in orientation than do channels
indicates that the canyons do not follow runoff
channel pathways in all instances. Theater-
headed canyons are never observed to head in a
downdip direction, regardless of the surface
topography (Fig. 13).

DISCUSSION

This study of canyon development in the
Navajo Sandstone has examined canyon mor-
phology; drainage pattern; space-filling of net-
works in drainage basins; the form of the lon-
gitudinal profile; observed seepage related to
sapping models; alcove distribution; small-scale
weathering processes; and structural, lithologic,
and hydrologic relationships. Observations sug-
gest an important role for ground-water pro-
ces in the formation of these canyons. The term
"sapping" is used generically, encompassing se-
veral processes by which the emergence of ground
water reduces the support of steep cliffs and con-
tributes to the collapse of superjacent topog-
raphy. In addition to these undermining proc-
esses, there must be others capable of breaking
down the debris produced by slope collapse and
transporting away the disintegrated materials.

Terrestrial sapping occurs in many permeable
materials of different material strengths and
scales of relief. Small, sapped networks occur in
fine-grained, poorly consolidated materials, but
canyon development requires materials with
greater competency. Materials with too great a
strength, however, or which have strongly
bonded constituent materials, do not allow can-
yon development by sapping because debris is
not broken down readily for transportation.
Moderate fine-grained, indurated, and perme-
able materials (for example, sandstones, vol-
canic tuffs, basalts, and so on) support canyon
growth by sapping.

Structural and environmental factors also
play roles in controlling sapping. In homogene-
ous, structureless materials with modest per-
meabilities, surface-runoff processes dominate
drainage development. The imposition of even
limited structure can drastically change both sur-
face and subsurface hydrological systems, per-
mitting treliss networks to be formed by both
runoff and/or ground-water sapping. The rate
and duration of precipitation are environmental
factors that affect the mode of drainage forma-
tion. High rates over short durations favor run-
off, whereas low rates over longer periods favor
sapping. Sapping in regions of high precipita-
tion (Hawaii, for instance) requires special con-
tions, such as enhanced permeability.

Owing to these complex lithologic, structural,
and environmental controls, sapping is a less
common process of drainage development than
is fluvial erosion. A more common phenom-
emon, piping, is related to sapping in that both
processes focus subsurface flow to the heads of
channels. Each is often associated with an under-
lying permeability barrier that promotes the lat-
eral flow of subsurface drainage. Small-scale
piping differs from sapping in being a continu-
ous, short-lived phenomenon that is weather-
dependent and that requires local rainfall to
initiate erosion. Ground-water sapping is a sus-
involve variation on the sapping theme. Ground-ice melting or subliming could permit a sediment cemented by ice to experience a sapping-like erosional history. This process, first suggested by Sharp (1973, p. 4071), is particularly attractive because the sediment, after being released from its cement, might be easily transportable.

CONCLUSIONS

1. The primary erosional mechanism for the development of theater-headed canyons in the Navajo Sandstone appears to involve groundwater processes, here called "sapping." Overland flow does not explain the geomorphic relationships as reasonable or as consistent a manner. The development of canyons by sapping processes involves a unique interplay of lithologic, structural, and stratigraphic factors. Whereas any one of the three can promote the process, all three act to constrain and permit it. It is important to note that within the same geologic and climatic environment, two populations of canyons have formed by predominately different processes. Structure, primarily bed dip, is the principal control of the relative effectiveness of overland-flow or groundwater processes to valley development.

2. Sapping is an erosional process that produces unique landforms. Sapped drainage systems differ from their fluvial counterparts in morphology, pattern, spatial evolution of the network, rate of erosion, and degree of structural control.

3. Valleys in the Navajo Sandstone exhibit numerous morphologic similarities to Martian valleys. Although the constituent materials, scale, climate, structure, and/or groundwater conditions of Mars are not necessarily identical to those of the Colorado Plateau, the striking similarities in form suggest that at least the gross geomorphic processes may be similar and that sapping processes may have produced the Martian valleys.

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