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GEOMORPHIC HISTORY OF THE VIRGIN RIVER IN THE ZION NATIONAL PARK AREA, SOUTHWEST UTAH

U.S. GEOLOGICAL SURVEY OPEN-FILE REPORT 95-515

Prepared in Cooperation with the
National Park Service

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by

Richard Hereford[1], Gordon C. Jacoby[2], and V.A.S. McCord[3]

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ABSTRACT

This study traces the geomorphic development of the alluvial valley of the Virgin River in the Zion National Park region of southwest Utah. The purpose is to identify, date, and interpret the patterns of erosion and deposition that formed the alluvial valley over the past 1,000 years. This information is a basis for understanding how the geomorphology of the alluvial valley changes under essentially natural flow conditions.

Sediment in the alluvial valley is classified as mainstem or tributary in origin. Mainstem alluvium is the largest volumetrically; it is mainly light-colored sand derived from upstream sources that accumulated on now abandoned floodplains (or terraces) by overbank deposition. Tributary sediment is typically dark colored, coarse-grained sand or gravel transported to the alluvial valley by streamflow or debris-flow. Tributary and mainstem sediment are interbedded near the margin of the valley, and the older deposits are truncated parallel to the river, suggesting that in time the river removes both its own deposits and those of tributaries. In the natural flow regimen, the river probably maintains a balance between erosion and deposition of mainstem and tributary deposits.

Four terraces and the active channel and floodplain are widespread along the Virgin River; from oldest to youngest these are the prehistoric, settlement, historic, and modern terraces. Dating was done by archeologic context, tree-ring methods, historic documents, relocation of early photographs, and correlation with other streams on the southern Colorado Plateau. Results indicate that prehistoric deposition ended by about A.D. 1100-1200, deposition of the settlement alluvium was from about A.D. 1400-1880, development of the historic terrace was from after 1883 until 1926, deposition of the modern alluvium was from 1940-1980, and development of the active channel and floodplain was after about 1980.

The principal deposits (prehistoric, settlement, and modern alluviums) are separated by two periods of stream entrenchment and channel widening referred to as the prehistoric and historic arroyo cutting, respectively. Erosional activity of roughly similar age occurred in most southern Colorado Plateau streams. The early erosion is not well dated in the study area, although regional relations suggest A.D. 1200-1400, if not somewhat earlier. Historic arroyo cutting began after 1883 in the study area and continued until around 1940 when deposition of the modern alluvium began. Both erosions affected the human population of the region. The Anasazi abandoned the region during prehistoric arroyo cutting, partly because of adverse environmental conditions. Likewise, historic arroyo cutting caused major losses of property and economic hardship among Anglo settlers.

Erosion and deposition were largely contemporaneous with variations in streamflow. Long-term streamflow of the Virgin River was estimated from calibration of annual tree growth with measured streamflow. Results indicate that erosion was during unusually high streamflow and that deposition was during relatively low streamflow. These relations are best illustrated by historic arroyo cutting and subsequent deposition of the modern alluvium. Precipitation and runoff immediately before and during historic arroyo cutting were the most unusual of the past 300 years; they varied from the driest immediately preceding erosion to the wettest during erosion. Deposi-

tion of the modern alluvium was during relatively low runoff after 1940.

High runoff destabilizes the channel, enhancing the effectiveness of floods. Conversely, relatively low runoff increases channel stability, reducing the erosional effect of floods and enhancing floodplain deposition. Adjustments in the width and depth of the channel are frequent, even after relatively small, short-term variations of streamflow. The normal pattern of geomorphic change requires streamflow that varies from high to relatively low. Regulated streamflow would likely alter this pattern through moderation of flow rates and reduced sediment loads.

INTRODUCTION

This study addresses the alluvial geomorphology of the upper Virgin River in southwest Utah during the past 1,000 years, the late Holocene of geologic time. The study area lies in and near Zion National Park and includes the North Fork (Virgin River) in Zion Canyon below The Narrows, East Fork (Virgin River) in lower Parunuweap Canyon, and the Virgin River downstream of the park to Virgin, Utah (fig. 1). The question of how natural variations of discharge and sediment load alter the alluvial valley and channel was the research topic. This information is necessary to understand the role of discharge variability in the recent geomorphic development of the alluvial valley, which in turn effects riparian and aquatic resources. These resources are linked to changes in the alluvial valley, because alluvium is the substrate for riparian vegetation and the alluvial channel is the habitat of six species of native fish (Deacon, written commun., 1993). Results of this study suggest that the alluvial valley has changed rapidly in response to natural discharge variations.

The Virgin River retains its presettlement discharge regimen; the only impoundment in the study area is Kolob Reservoir with capacity of 6.89 hm^3 (5,586 ac-ft). The reservoir is located near the headwaters of North Fork, and its affect on streamflow and the alluvial valley is unknown, although streamflow is probably not decreased much (fig. 1; Everitt, 1992). Rapid population growth in the St. George and Hurricane area (fig. 1) creates a demand for additional water supplies. This demand could be met through construction of reservoirs. Ninety two-reservoir sites are identified in the Virgin River basin (Utah Division of Water Resources, 1988), and several large reservoirs are proposed for construction in or near Zion National Park. Downstream of the reservoirs, alluvial valleys in the park will quite likely change as the channels adjust to regulated streamflow, as suggested by studies of other alluvial rivers (Williams and Wolman, 1984; Andrews, 1986). Flow regulation will eliminate the high flow rates that over time widen and deepen the channel, and reduced sediment loads will eliminate or curtail channel and floodplain deposition. In short, the magnitude of geomorphic change will probably decline from the unregulated regimen. Understanding the scope of geomorphic change in the recent past is necessary to comprehend the effects of regulated streamflow on geomorphic development of alluvial valleys in Zion National Park.

Previous Studies

The late Holocene geomorphic history of the Virgin River in the Zion National Park area has not been studied. Gregory (1950, p. 44, 170-177) recognized that most valleys in the Zion Park region and the southern Colorado Plateau in general are filled with a considerable thickness of alluvial fill of Holocene age. He concluded that the surface and upper portion of this fill are very young, because historic documents and anecdotal reports revealed that most streams, including the Virgin River, flowed in fairly well-defined channels with floodplains during the 1700s to the late 1800s.

Streams in the Zion National Park region underwent a catastrophic change in the late 1800s that Gregory (1950, p. 174) compared with earthquakes and volcanic eruptions. This destructive change of the alluvial val-

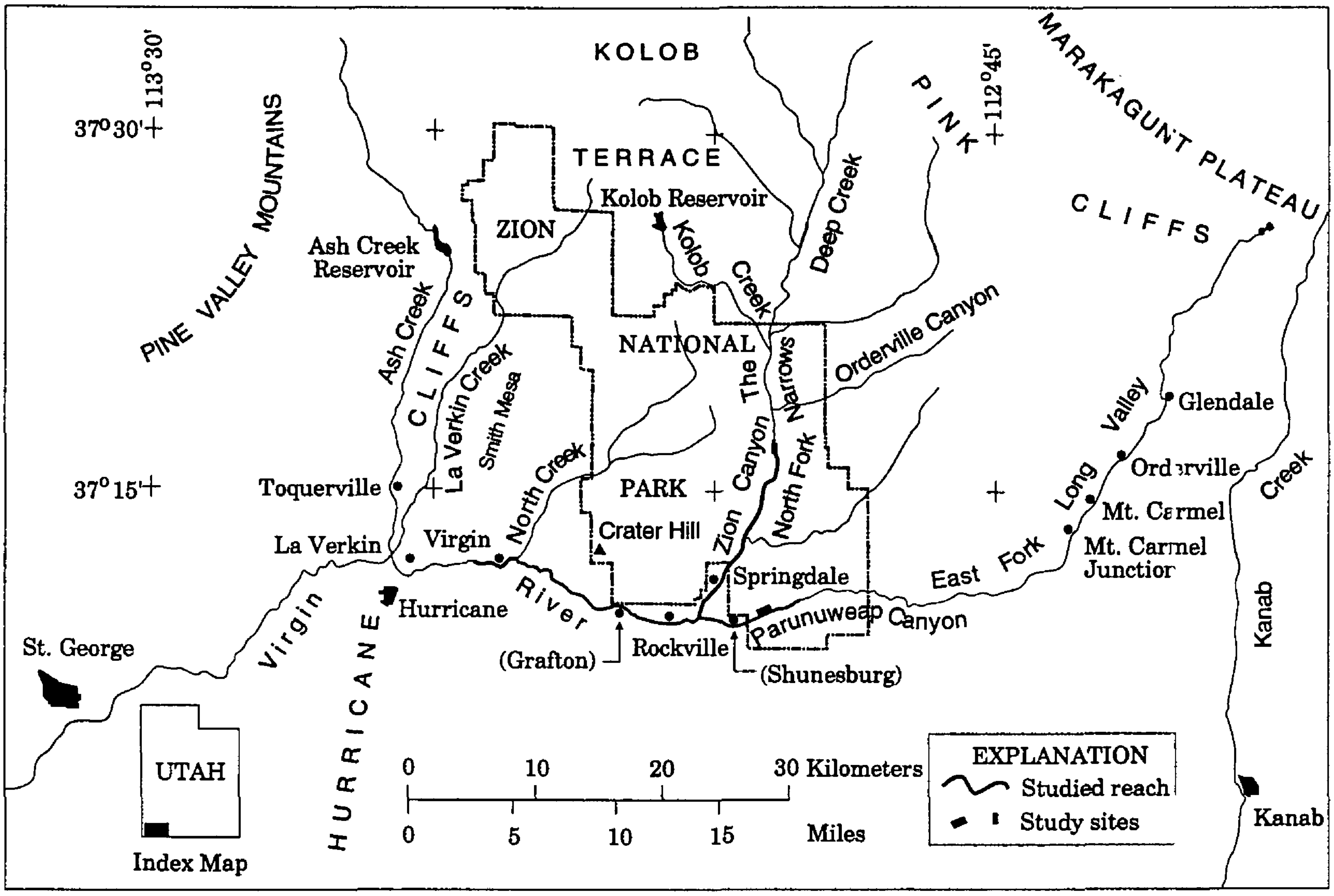


Figure 1. Study area in southwest Utah.

leys involved downcutting of stream channels up to 24 m (80 ft) followed by extensive channel widening. This historic stream entrenchment, or arroyo cutting, caused the abandonment or movement of settlements, relocation of roads, and the destruction of arable land, dams, reservoirs, and irrigation ditches. Indeed, the agricultural history of the region was largely determined by floods and the resulting changes in stream channels (Larson, 1961). Stream entrenchment of the type described by Gregory (1950) was widespread in the Southwest around the turn of the century, eventually affecting almost every stream (Bryan, 1925).

The causes of historic arroyo cutting in the Southwest have been a topic of debate for more than 90 years (Graf, 1983). Three explanations are put forth in numerous publications, these are summarized by Cooke and Reeves (1976), Graf (1983, 1988), and Webb (1985). Overgrazing, climate change, and internal adjustments of the channel system unrelated to either climate or landuse are the main explanations (Graf, 1988, p. 220-224). The argument for overgrazing as the cause of increased floods and stream entrenchment in southwest Utah was aptly made by Bailey (1935). He concluded that overgrazing during settlement of the region reduced and modified the plant cover on hillslopes and valley bottoms, leading to increased runoff and entrenchment. Explanations for arroyo cutting based on climate are somewhat contradictory with entrenchment from increased precipitation, decreased precipitation, and from variation of precipitation intensity.

The overgrazing explanation fails to account for arroyo cutting during prehistoric time in the absence of domestic livestock. Furthermore, precipitation over the southern Colorado Plateau during historic arroyo cutting was the largest of the 20th century (Balling and Wells, 1990; Hereford and Webb, 1992), resulting in high streamflow and large floods (Webb, 1985; Graf and others, 1991). Widespread instrumented rainfall and streamflow records, however, begin after entrenchment, and association of high rainfall with the initiation of regional arroyo cutting is conjectural. A local rainfall record that predates arroyo cutting has a small number of low-intensity events and a large number of high-intensity events before and during entrenchment (Leopold, 1951). These rainfall characteristics are thought to enhance runoff by destabilizing vegetation. Briefly, historic arroyo cutting was associated with settlement of the region, introduction of livestock, and unusually high precipitation and large floods.

The third explanation is that streams alternately erode and fill as channel gradient adjusts to locally oversteepened segments. This is the semiarid cycle of erosion as developed by Schumm and Hadley (1957), which was further elaborated by Patton and Schumm (1981). Although channels in small basins are affected by this process, large basins with drainage area greater than perhaps 10 km^2 (3.9 mi^2) are probably not altered by these adjustments of channel gradient (Graf, 1988, p. 223). In addition, temporal correlation of modern deposits indicates they are synchronous both within a particular basin and among separate basins (Hereford, 1986; 1987a); regional correlation is not expected if channels erode and fill episodically. Results of the present study suggest that both historic and prehistoric arroyo cutting of the Virgin River were contemporaneous with increased streamflow, although overgrazing could have increased the severity of historic arroyo cutting.

The recent geomorphic history of streams on the southern Colorado Plateau east of the Virgin River is addressed in several studies. The timing and causes of the historic entrenchment of nearby Kanab Creek (fig. 1) and the Escalante River were studied by Webb and others (1991) and Webb (1985), respectively. Other studies showed that entrenchment had largely ended by about 1940 and that deposition was the main process until at least the early 1980s (Hereford, 1984; 1986; 1987a; Graf, 1987). This deposition since 1940 is widespread in the western United States, as noted by Emmett (1974) and Leopold (1976). Older deposits, those predating arroyo cutting, were studied in the Black Mesa region of northern Arizona by Karlstrom (1988) and in Chaco Canyon and the eastern Colorado Plateau of New Mexico by Hall (1977).

Methods

Several methods were used to study the late Holocene geomorphic history of the Virgin River. Geologic field work was done by the senior author over three months in the fall of 1992 and spring of 1993 and 1994. This work consisted of mapping, dating, and classifying the deposits of the alluvial valleys of North Fork and East Fork. The sequence of terraces and associated deposits identified at these sites was then traced downstream to Virgin, Utah (fig. 1). The historic-age terraces were dated by V.A.S. McCord in a dendrogeomorphic study of riparian trees, principally cottonwood, associated with the terraces at the two sites. A long-term history of annual discharge of the Virgin River was developed from a dendrohydrologic investigation by G.C. Jacoby. This consisted of calibrating tree-ring chronologies obtained at two semiarid sites to the gaged streamflow record, resulting in a 303-year streamflow reconstruction from A.D. 1690-1992. The reconstructed and measured streamflow are used to interpret dated episodes of erosion and deposition.

Changes in the size and shape of the channel of the Virgin River were studied using relocated historic photographs obtained from a number of archival sources. The position of the original camera site was relocated and the scene was rephotographed in 1993-1994. The early photographs show the channel of the Virgin River in Zion Canyon as early as 1873. The photographs display a sequence of changes beginning with a relatively stable, unentrenched, and probably narrow channel in 1873. This early-settlement channel was followed by a wide, entrenched channel with a braided pattern in the early 1900s. Contemporary photographs show a relatively narrow, stable, and locally meandering channel.

Generalized Hydrology of the Virgin River

North Fork and East Fork, both with drainage area of about 900 km^2 (348 mi^2), head in the Pink Cliffs region at the southern boundary of the Markagunt Plateau in the high plateau section of the Colorado Plateau physiographic province (Hunt, 1967, p. 278). The average elevation of the two basins is about 2,240 m (7,350 ft). North Fork flows through the central portion of the Kolob Terrace in spectacular Zion Canyon. East Fork flows through Long Valley to Parunuweap Canyon in Zion National Park. The two streams join downstream from Springdale. From there, the Virgin River flows west across the Hurricane Cliffs where it enters the Basin-and-Range physiographic province. Flowing to the south-southwest, the river crosses southwest Utah, northwest Arizona, and southeast Nevada to the junction with the Colorado River at Lake Mead.

The Virgin River is a perennial stream with baseflow from groundwater in the Navajo Sandstone (Jurassic), the dominant rock at the surface in Zion and Parunuweap Canyons. Precipitation is biseasonal with rainfall during the warm season of summer and early fall and rain or snow in late fall through early spring. Most of the annual runoff volume above baseflow is during spring from March through early June. This runoff typically results from melting of the winter snowpack. The snowpack forms in the relatively high elevation of North Fork and East Fork basins from winter frontal-type precipitation.

A second runoff season results from rainfall in the summer and early fall seasons. Although the runoff volume is substantially less than the spring snowmelt, the annual flood, or the largest instantaneous discharge of the water year, is typically between July and September. On average, 59 percent of the annual flood peaks of the Virgin River at Virgin are between July and September, a season with higher flood peaks than during spring. The annual flood, however, can happen in any month and can result from snowmelt, rain on snow, or rainfall.

Mean annual discharge of East Fork (which is only an estimate because of the short record) and North Fork near Springdale (fig. 1) is 1.4 and 2.8 m^3/s (50 and 100 ft^3/s), respectively. These average figures obscure the extreme variability of daily discharge. Maximum daily flow rates range from 4-70 times larger than the minimum flow rate for any given day. This variability results from year-to-year fluctuations in precipitation that increase either the depth of the winter snowpack or the amount of summer rainfall. Finally, streamflow depletions for irrigation and other purposes is estimated to account for only 3.7 and 6.6 percent of the mean annual flow of North Fork (96.9 hm^3/yr, or 78,600 ac-ft/yr) and East Fork (55.5 hm^3/yr, or 45,000 ac-ft/yr), respectively (G.E. Diaz and W.R. Hansen, written commun., 1994). During July when demand is high and flow is low, depletion is 80-90 percent of monthly flow volume. Nevertheless, in terms of annual flow volume, the Virgin River in the study area is little affected by agricultural or domestic water consumption.

GEOLOGIC SETTING OF THE ALLUVIAL VALLEYS

The geologic setting of the Virgin River in the Zion National Park region is relevant to understanding the late Holocene geomorphology of the alluvial valleys. The present elevation and course of the river result from extensive bedrock erosion, or canyon cutting, that occurred in the past 1-2 million years. Canyon cutting was controlled by movement along the Hurricane fault, which parallels the Hurricane Cliffs west of Virgin (fig. 1). Pauses in canyon cutting during the late

Figure 2. Photograph of Crater Hill volcanic field and Virgin River valley. Dark hill in upper center is Crater Hill. Basaltic lava flows are dark, smooth, and flat areas above river. Base of youngest lava flow is 20-30 m (66-98 ft) above channel of Virgin River. Line indicates axis of ancestral Virgin River, dashed where covered by lava flows.

Pleistocene were accompanied by deposition of gravel that is preserved at several levels along the margin of the alluvial valley.

The Hurricane fault is usually considered the physiographic boundary between the Basin-and-Range province to the west and the Colorado Plateau to the east (Hunt, 1967, p. 277-347). A system of faults, the Hurricane fault extends north from Grand Canyon through southwest Utah. In the Zion National Park region, the fault has normal displacement of 600-850 m (2,000-2,800 ft); movement on the fault was mainly in the Quaternary (Anderson and Mehnert, 1979). The eastern block or footwall of the fault has moved up while the western block remained stationary (Hamblin, 1984). Repeated, episodic uplift of the eastern block of the fault is the principal cause of canyon cutting. This uplift increased the gradient of the ancestral Virgin River, resulting in increased stream power and the erosion of Zion and Parunuweap Canyon as well as the other canyons in the region (Gregory and Williams, 1947). The fault has not caused surface rupture in the study area in historic times (Anderson, 1978). Thus, historic arroyo cutting of the Virgin River is not related to tectonic activity, a conclusion that quite probably applies to erosion and deposition during the late Holocene as well.

The Virgin River was probably within 20-30 m (65-100 ft) of its present elevation and the canyons were eroded to near their present depths by at least 293 ka (which is 293,000 years before present). This interpretation is based on the inferred age of basaltic lava flows associated with Crater Hill (fig. 2), a volcanic field on the north side of the valley. Two periods of volcanism and four lava flows are recognized by Nielson (1977). The older flows are assigned to Stage-II relative geo-

Figure 3. Photograph (upstream) of alluvial valley of Virgin River in Rockville area. Alluvial valley is flat, vegetated area extending diagonally across mid-ground. Moenkopi Formation borders valley, resistant sandstone bed in right mid-ground is Shinarump Sandstone Member of Chinle Formation (Late Triassic). Late Pleistocene gravel deposits form terrace to right of road junction in foreground.

morphic age and the younger flows are assigned to Stage-III relative age by Nielson (1977). This classification system is used to establish relative age of basalt flows in southwest Utah based on geomorphic evidence of weathering and erosion (Hamblin, 1970). Stage-II flows were deposited about 60-90 m (200-300 ft) above the present drainage, and Stage-III flows were deposited about 5-30 m (20-100 ft) above the present drainage. Lava flows during the Stage-II period of volcanic activity filled the ancestral valley of the Virgin River (fig. 2), eventually causing the bedrock channel to shift 1-2 km (0.6-1.2 mi) south of the previous course, as noted originally by Threet (1958). The absolute age of the Stage-II flows and the minimum age of the ancestral valley is uncertain, although Hamilton (1987; 1992) reports a date of 500 ka for possible Stage-II flows in the Crater Hill area.

Basalt flows of the younger Stage-III episode are related to the present course of the Virgin River. Although the absolute age of the Stage-III flows at Crater Hill is unknown, a Stage-III flow near Hurricane was dated by the Potassium/Argon method at 293 ± 87 ka (Hamblin, 1984). The Stage-III flows at Crater Hill could also be this age, in which case the river was essentially in its present position by 293 ka.

Figure 3 illustrates the alluvial valley of the Virgin River in the Rockville area. The width of the valley is controlled by the underlying bedrock. In this area (fig. 3), the valley is wide as the river flows across the non-resistant, slope-forming Moenkopi Formation. Generally, the valley is relatively wide where the river crosses the less resistant

Figure 4. Photograph showing late Pleistocene gravel with interbedded sand in quarry south of Rockville. Note scale on left, 1.4 m (4.6 ft) long with 20 cm (5.08 in) divisions. This is topographically the lowest and youngest gravel.

bedrock of the Moenkopi, Chinle, Moenave, and Kayenta formations. The age of these formations is Early Triassic, Late Triassic, and Late Triassic to Early Jurassic, and Early Jurassic, respectively. The upper Holocene alluvium occupies most of the valley from side-to-side in the wide reaches. Upstream in Zion Canyon, the valley is relatively narrow where the bedrock is the resistant, cliff-forming Navajo Sandstone (Jurassic). In the slot-like canyons of The Narrows (North Fork) and in upper Parunuweap Canyon (East Fork; fig. 1), very little sediment accumulates and alluvial terraces are mostly absent because of the high water velocities produced in the narrow, bedrock-lined channels.

Gravel deposits of late Pleistocene age are present locally in the wide reaches of the Virgin River downstream from the forks and in East Fork (fig. 4). These deposits form several discontinuous terraces rising 30-50 m above the floor of the alluvial valley. The terraces are best developed in the reach downstream from the Shunesburg area to Grafton. According to Dalness (1969), the gravels consist of two units. The older gravel, informally termed the Parunuweap formation, is well-consolidated fluvial gravel with locally derived, subrounded to rounded clasts. Large, angular boulders up to several meters on an edge are present locally and were derived from nearby rockslides. This older gravel mostly predates the Crater Hill volcanics, as the gravel was deposited in the ancestral valley that was subsequently filled by the older Stage-II lava flows.

The younger gravel unit, informally referred to as the Orderville gravel, is generally unconsolidated, although otherwise it resembles the Parunuweap gravel. This younger gravel post-dates the Crater Hill volcanics, therefore the gravel is probably younger than 293 ka. The younger gravel is well exposed in a quarry south of Rockville (fig. 4). These deposits are substantially thicker and much coarser-grained than the upper Holocene alluvium, which is mainly fine- to medium-grained sand with only minor gravel. The gravel deposits probably result from increased competency of the Virgin River during the late Pleistocene as well as increased mechanical weathering that produced abundant gravel-size sediment from the ledge-forming Cretaceous-age sandstone in the headwaters of the basin (Sable and Hereford, 1990).

The geologic setting of the alluvial valley of East Fork is similar to that of the Virgin River downstream from the forks, as discussed above, except that bedrock is the Chinle and Moenave Formations near river level. The North Fork in Zion Canyon, however, differs substantially in that the alluvial valley is underlain by lacustrine deposits that predate the upper Holocene alluvium. These deposits accumulated in a lake that formed upstream of a large landslide that originated on the west side of Zion Canyon about 5 km (3.1 mi) upstream of Springdale; the landslide measures about 2.4 km (1.5 mi) long and 1.2 km (0.75 mi) wide (Grater, 1945). The landslide blocked the entire width of the canyon near river level, and the resulting lake was up to 115 m (377 ft) deep and extended up the canyon at least 4.3 km (2.6 mi; Grater, 1945; Hamilton, 1992, p. 59-60). The minimum age of the lake is 3.6±0.4 ka based on a radiocarbon date from plant material associated with the lake deposits (Hamilton, 1992, p. 59).

The landslide and related lake deposits lower the gradient of North Fork through Zion Canyon (Hamilton, 1992, p. 25). In addition, the slide debris is a fixed baselevel control that limits erosional downcutting. This baselevel control is probably why the upper Holocene stream terraces in the canyon have very little topographic separation. Similar terraces in East Fork and the Virgin River downstream of the forks are each separated vertically by several meters.

LATE HOLOCENE SURFICIAL GEOLOGY AND GEOMORPHOLOGY

In this section of the report, the geology and geomorphology of East Fork and North Fork are discussed. The alluvial valleys were studied in lower Parunuweap Canyon upstream from the abandoned, pioneer settlement of Shunesburg and in Zion Canyon downstream of The Narrows (fig. 1). The study consisted of mapping, classifying, and dating the various deposits and terraces at the two sites. Mapping was done in the field using low-altitude (approximate scale 1:4,000) color-aerial photographs taken in June 1992. Ground control surveyed by W.R. Hansen of the National Park Service was used to develop 1:2,000 scale planimetric base maps of the two areas; these maps were used to compile the surficial geology mapped on the aerial photographs. Dating was done by archeologic context in the case of the prehistoric deposits and by tree-ring methods in the case of the historic deposits. The sequence of terraces at the two sites is broadly similar, and the terraces were traced as far downstream as Virgin, Utah (fig. 1). Therefore, the Virgin River downstream of the forks as well as East Fork and North Fork have similar geomorphic histories.

Generally, the streams have undergone several episodes of aggradation and erosion in the past 1,000 years. Aggradation builds up the channel and alluvial valley, erosion lowers the channel and partly removes previously deposited alluvium and tributary deposits, producing terraces, or abandoned floodplain surfaces. The timing and number of erosional and depositional events of the Virgin River is generally similar to other streams on the southern Colorado Plateau. This suggests that erosion and deposition are triggered and maintained by regional factors. These factors are climate over the long term as well as landuse during the historic period.

Mainstem and Tributary Deposits

Sediment in the alluvial valleys comes from upstream sources as well as from nearby, adjacent hillslopes. Mainstem deposits are transported by the Virgin River from distant sources. Tributary deposits are transported to the alluvial valley by fluvial activity of tributary streams, gullies, and rills, as well from debris flow and landslide. Near the margin of the alluvial valley, mainstem and tributary deposits are interbedded.

Mainstem deposits are primarily yellowish gray, poorly to moderately well-sorted, very fine to medium-grained sand and minor subrounded to rounded gravel. The alluvium is well bedded; beds range in thickness from only several centimeters to as much as 50 cm (1.6 ft). These beds are primarily flood deposits, the result of overbank floods at relatively high discharge levels. The exposed thickness of the mainstem alluvium ranges from 1-5 m (3-16 ft). Mainstem deposits form several terraces and the active channel and floodplain. Surficial geologic maps, discussed in a following section, show that mainstem alluvium is the principal deposit in the alluvial valleys.

Although of minor volumetric importance, tributary deposits are conspicuous along the margins of the alluvial valley and on the steep hillslopes leading to the valley. Tributary deposits result from streamflow, debris flow, landslide, and rockfall. Tributary streamflow deposits are in the active channel and in terraces of the relatively small, ephemeral, and typically unnamed tributaries of the Virgin River. These deposits consist of sand and subrounded gravel of cobble to boulder size. Debris-flow deposits are in tributary channels, in debris fans at the junction with the Virgin River, and as levees extending down steep hillslopes to the alluvial valley. Debris flow is a gravity induced mass movement of sediment with mechanical characteristics that differ from streamflow (Costa, 1984). The debris-flow deposits in East Fork are distinctive because of the wide range of particle size ranging from clay to angular boulders 1-3 m (3-10 ft) on an edge and because of the reddish-purple color of the clay-size component. Debris-flow deposits have a wide range of thickness, ranging from only a few centimeters where they are interbedded with mainstem alluvium to several meters at the valley margin.

Landslide deposits are mainly coherent blocks of local bedrock that have slid downslope into the alluvial valley. The size of the landslide blocks ranges from a few square meters, the typical case, to several square kilometers (Grater, 1945). Rockfall deposits typically consist of isolated blocks of resistant bedrock that have fallen from steep ledges down the hillslopes into the alluvial valley.

The older mainstem and tributary deposits are confined to the margins of the alluvial valleys. Generally, the margin of the deposits is truncated parallel to the river, forming the older terraces. This truncation or erosion is evidence that in time the river removes both its own deposits and those of tributary origin. In the natural flow regimen, the river maintains a balance between erosion and deposition of mainstem and tributary deposits. If tributaries were unaffected by mainstem erosion, sediment input from tributary sources would probably block the river forming small lakes and ponds.

Surficial Geology and Geomorphology of the Alluvial Valleys

The two study sites differ in physical and floral setting. East Fork is a relatively open valley formed in the slope-forming, easily eroded Moenave Formation (Jurassic). Vegetation is mostly shrubs with subordinate grass and a sparse woodland of cottonwood (*Populus fremontii*). On the other hand, North Fork is a confined valley with nearly vertical cliffs of Navajo Sandstone (Jurassic). Woodland with a grass understory is the dominant vegetation. These differences in vegetation result mainly from aspect; North Fork is well shaded because of the high cliffs, narrow canyon, and the north-south orientation. Of the two streams, East Fork has the most complete record of upper Holocene geology and geomorphology. For this reason, the composition, age, and interpretation of the deposits in East Fork are discussed first.

East Fork Virgin River

The surficial geology of the East Fork site is shown in figure 5. The east boundary of the map is near Stevens Wash 2.6 km (1.6 miles) upstream from Shunesburg (fig. 1). The surficial geology consists of five deposits of late Holocene age and a gravel deposit of Pleistocene age. Four terraces and the active channel and floodplain comprise the Holocene deposits of East Fork. From oldest to youngest, the terraces are referred to as the prehistoric, settlement, historic, and modern terrace.

Pleistocene gravel deposits crop out in three mound-shaped hills that rise 30-40 m above the modern terrace (cross-section A-A', fig. 5). The base of the gravel is not exposed; at least 30-40 m of gravel is exposed locally, which is probably close to the maximum thickness. Although poorly exposed, the deposit is coarse-grained sand and granule- to boulder-size gravel. The gravel is well rounded, and the clasts are derived from distant bedrock sources exposed near the headwaters. The sedimentary clasts are mainly coarse-grained sandstone of Cretaceous age, clasts of fine-grained Navajo Sandstone, and finely crystalline limestone of the Carmel Formation (Jurassic). Well-rounded basalt clasts derived from lava flows in the Long Valley area are present sparingly.

The gravel once filled an ancient channel in Parunweap Canyon. The contact of the deposit with bedrock rises steeply from below the level of the prehistoric terrace to the top of the deposit; this contact defines the margin of the ancient channel. Parunuweap Canyon has widened and deepened substantially since deposition of the gravel. Erosion deepened the canyon at least 40 m (130 ft) and the canyon widened as much as 100-200 m (330-660 ft), as shown by retreat of bedrock that formed the margin of the channel. Subsequent widening and downcutting removed most of the gravel, leaving only the three isolated outcrops. These deposits are probably equivalent to the gravel at river level in the Rockville area (fig. 4). The gravel at Rockville post-dates the Crater Hill volcanics; therefore the gravel in Parunuweap Canyon is younger than 293 ka.

The prehistoric terrace is the oldest Holocene terrace identified in East Fork. The terrace is confined to the margin of the alluvial valley and is situated 6-10 m (20-33 ft) above the modern terrace (cross-section A-A', fig. 5). The principal exposures are the mouth of Stevens Wash, the unnamed wash on the south side of the river, and the unnamed wash near the west end of the mapped area (fig. 5). At these localities, the plan-form of the terrace resembles an alluvial fan that has been eroded along the distal margin. A highly eroded exposure of the prehistoric deposits is also on the north side of the river near survey control point 1205.17 m. At this locality, the alluvium is overlain by 1-2 m (3-7 ft) of historic-age debris-flow sediment that forms the surface.

Alluvium underlying the prehistoric terrace is poorly exposed, but it appears to consist mainly of light-colored very-fine to medium-grained sand interbedded with numerous dark-colored beds of debris flow origin. Gravelly debris-flow deposits are present on the surface at the outcrop near the west boundary of the map and at the outcrop on the south side of the river. The surface gravel is patinated with a brown- to dark-brown rock varnish. Beneath the surface, clasts are coated with a very thin, mostly continuous coating of calcium carbonate. This evidence of soil development indicates that the surface has been exposed to long-term weathering.

The age of the prehistoric terrace and related deposits is not well constrained. The base of the deposit is not exposed and the beginning of deposition could not be determined. However, dateable cultural remains of the Virgin branch of the Kayenta Anasazi (Altschul and Fairley, 1989) are present near the top of the alluvium at two localities. On the south side of the river about 50 m (160 ft)

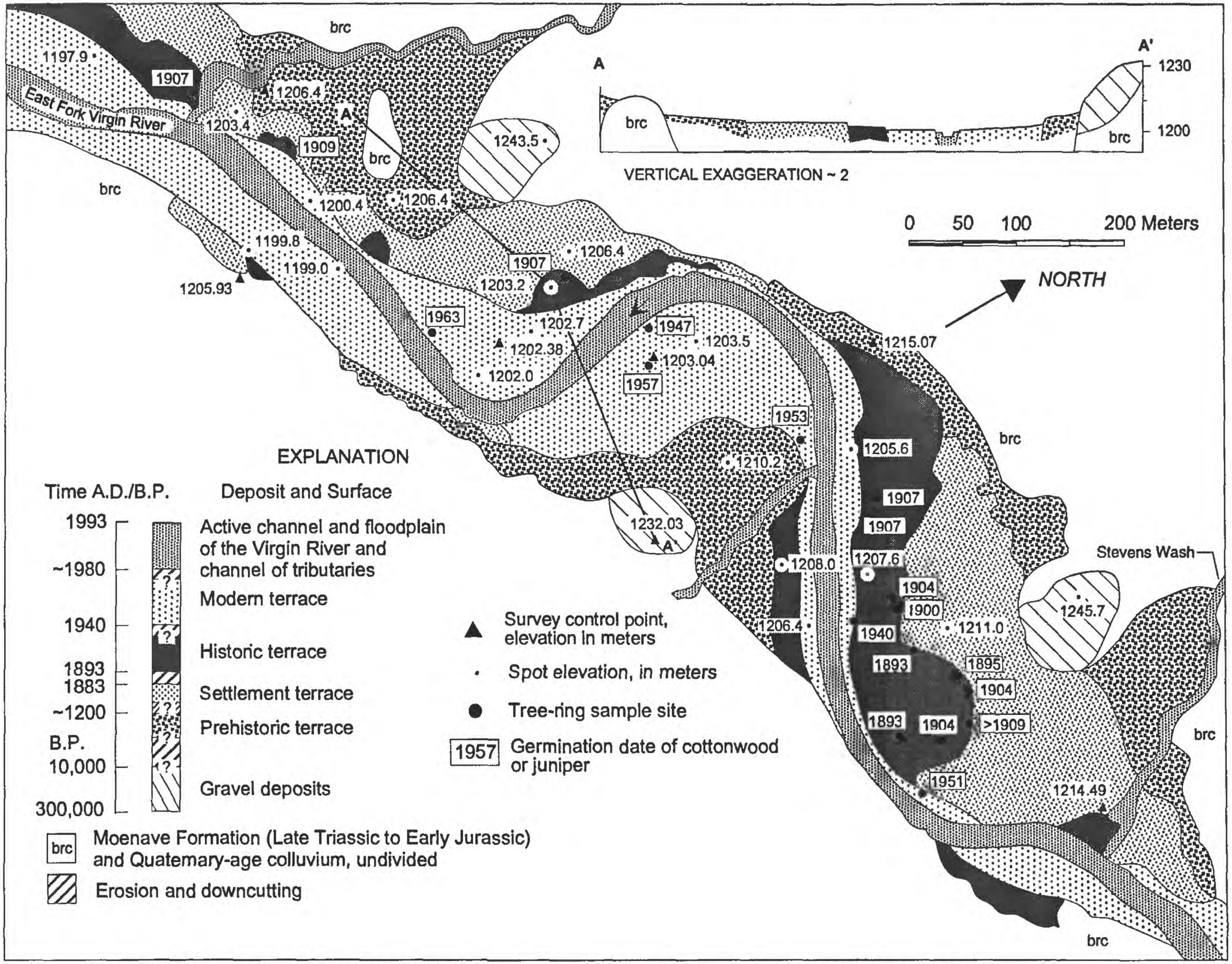


Figure 5. Surficial geologic map and cross-section of East Fork study site (fig. 1).

northwest of spot elevation 1210.2 m (fig. 5), a small structure of upright slaps is present 1 m (3 ft) beneath the surface. Ceramic material associated with the site is tentatively assigned to the early Pueblo I to middle Pueblo-II periods, which is A.D. 800-1100. On the north side of the river 0.6 km (0.4 mi) downstream from the west boundary of the map, a midden containing dateable ceramics lies 1 m (3 ft) below the surface of the prehistoric alluvium. The ceramic material dates to the Pueblo-I period, which is A.D. 800-1000. A third site on the east bank of Stevens Wash has several small structures and a midden extending from the surface of the prehistoric terrace to a depth of more than 2 m (7 ft). Ceramic material near the top of the site dates to the late Pueblo II period, or A.D. 1100 to 1200 (L. P. Naylor, written commun., 1994).

The stratigraphic context of these archeologic sites indicates that the Anasazi were living on the floodplain of East Fork between A.D. 800 to at least 1100-1200. The prehistoric alluvium had aggraded to its present level by late Pueblo II time (A.D. 1100-1200). In short, deposition of the prehistoric alluvium was well underway by A.D. 800-1100 and probably ended after A.D. 1100-1200, although the beginning of deposition is not well known.

The settlement terrace is situated 2-4 m (7-13 ft) below the prehistoric terrace (cross-section A-A' fig. 5). The settlement terrace and related alluvium are named for historic archeologic material and evidence of agricultural activity on the surface. This terrace is present on the north side of the river, except for two small outcrops on the south side of the river west of the unnamed wash (fig. 5). The composition of the deposits resembles the prehistoric alluvium, except that coarse-grained debris-flow sediment is not abundant. At the exposure on the south side of the river, the alluvial sand is well bedded with light-colored beds ranging in thickness from 10-50 cm (0.3-1.6 ft). Thin beds of dark-colored silty sand derived from the bedrock exposed on the nearby hillslope are interbedded with the alluvium.

The alluvial valley upstream of Shunesburg was farmed extensively beginning in spring 1862 (DeMille, 1977). Evidence of this and subsequent farming is found on both the surface of the prehistoric and settlement terraces, but is characteristic of the lower terrace. Pieces of cut and milled wood, small rock piles, steel wire, and other artifacts are on the settlement terrace. Grass and Russian thistle on these terraces suggest that the area was farmed historically and abandoned (L.D. Potter written commun., 1993). Vegetation was probably removed from all of the settlement terrace and large parts of the prehistoric terrace. The terrace rise separating the terraces is rounded and subdued, whereas the terrace rise between younger terraces is steep and sharp. This subdued topography probably resulted from plowing and vegetation removal by the pioneer settlers.

Remnants of irrigation ditches excavated into the prehistoric terrace are on the south and north side of the river. The two remnants were traced as far downstream as Shunesburg, and the north-side ditch was traced upstream of Stevens Wash for 0.8-1.5 km (0.5-1 mile), where the inlet structure for the ditch was probably located. The north-side ditch is evidently not the same ditch portrayed in a 1903 map of arable land in the Virgin River basin (Adams, 1903, p. 208-209). The inlet of the north-side ditch shown in the 1903 map was at the mouth of Stevens Wash. Remains of the 1903 ditch could not be found downstream of Stevens Wash, probably because it was constructed in the historic-age channel and was subsequently eroded or buried by younger sediment.

The north-side ditch is well exposed in a gully near survey control point 1215.07 m (fig. 5); figure 6 is a cross-section of the ditch exposed in the west side of the gully. The light-colored sand beds outline the perimeter of the ditch, which extends vertically from the base of the collapsible shovel to the trowel. Deposits in the ditch are light-colored mainstem alluvium interbedded with dark-

Figure 6. Photograph showing irrigation ditch filled with sediment and overlain by debris-flow deposits. id = cross-section of irrigation ditch; df = debris-flow deposits; p = prehistoric alluvium interbedded with debris-flow sediment.

colored tributary deposits. The mainstem deposits accumulated when streamflow was diverted into the ditch; the tributary deposits resulted from sheetwash originating on the nearby bedrock hillslope. The present physical setting of the ditch demonstrates the rapid and extensive changes that affected the alluvial valley. Sometime after 1862 and before at least 1903, the top of the ditch, which corresponds with the prehistoric terrace, was covered by 2 m (7 ft) of debris-flow sediment; enlargement of the tributary channel then eroded through the debris-flow sediment, irrigation ditch, and terrace; this erosion was probably coincident with entrenchment of East Fork between 1883 and 1893.

Upstream from Stevens Wash to near the inlet area, the older north-side ditch crosses the prehistoric terrace to the level of the settlement terrace; in the inlet area, the ditch is low on the settlement terrace near what must have been the active channel at the time the ditch was constructed. This level is several meters above the present channel of East Fork, which at this locality has deepened at least several meters since the late 1800s.

The age of the settlement terrace could not be determined directly due to the lack of dateable material. The inset topographic relation with the prehistoric terrace (cross-section A-A', fig. 5) indicates that the settlement terrace and related alluvial deposits are younger than the prehistoric terrace. Moreover, Anasazi cultural remains are not present on the terrace nor have remains been found in the alluvium. Altschul and Fairley (1989, p. 107) suggest that the Virgin Anasazi abandoned the Arizona Strip area around A.D. 1225. This is largely consistent with Larson and Michaelsen (1990) who estimate that the area was abandoned by A.D. 1200. Deposition of the alluvium forming the settlement terrace, therefore, is younger than about A.D. 1200-1225, or simply A.D. 1200. As previously discussed, Anglo settlers utilized the terrace for farming and portions of the pioneer settlements of Rockville, Grafton, and Virgin City (fig. 1; Larson, 1961, p. 85-100) were located on the terrace between 1859-1862. The upper part of the alluvium and terrace, therefore, are mostly older than to partly contemporaneous with early Anglo settlement of the region. Historic descriptions discussed in a following section of the report suggest that the settlement terrace was the active channel and floodplain of the river in the early 1860s. In short, deposition of the alluvium forming the terrace was after A.D. 1200 until at least about A.D. 1880.

The historic terrace is an abandoned channel situated about 3 m (10 ft) below the settlement terrace and 1-2 m (3-7 ft) above the modern terrace (cross-section A-A', fig. 5). The historic terrace is present mainly on the north side of the river where it occupies meander-like features eroded into the settlement terrace (fig. 5). On the surface, the deposits resemble mainstem alluvium except that the sand is coarser grained and cobble to small-boulder size gravel deposits are present locally, such as the near spot elevation 1207.6 m in the eastern part of the map. Although the deposits are poorly exposed, they are probably very thin and do not represent substantial deposition. Photographs of the channel near this area from the early 1900s show that the channel was flat-floored without sites of overbank deposition. The historic terrace, therefore, is considered to be largely an erosional feature resulting from channel widening and deepening. Archeologic material dating from early settlement of the area is absent on the terrace; evidence of agricultural activity and stone or wood structures were not found on the surface in the mapped area.

The date of downcutting from the settlement terrace to the level of the historic terrace as well as the age of the historic terrace was determined by tree-ring dating. Twelve cottonwood and one Utah juniper (*Juniperus osteosperma*) growing on or just beneath the terrace were sampled and dated. The location of the trees and results of this dating are shown in figure 5. The germination dates range from 1893-1909. The dates show that historic downcutting of the East Fork alluvial valley happened by 1893 and that the floodplain and channel of the historic terrace were in place through 1909.

The modern terrace is present almost continuously on both sides of the river throughout the mapped area (fig. 5). The terrace forms two large point bars on the north and south side of the river west of the south-side unnamed wash (fig. 7). Elsewhere the terrace is a recently abandoned floodplain on both sides of the active channel. The terrace is only 1-2 m (3-7 ft) above the active channel and it shows little evidence of recent flooding. Modern flood debris is present on the terrace and consists of automobile tires dating from the 1960s to early 1970s, tin cans, abundant cut driftwood, and short lengths of steel cable. Plastic was not found on the terrace, suggesting that exposure time was long enough for the plastic to deteriorate. A flood on August 29, 1993 with discharge calculated at 54.9 m^3/s (1,940 ft^3/s) and recurrence interval of about 10 years flowed on the modern terrace locally, wetting the base of cottonwood trees near the channel margin (E.D. Andrews, written commun., 1994).

Tree-ring dating of cottonwood was used to date the modern terrace. Cottonwood is widely distributed across the terrace as distinct, arcuate zones along the margin of the two point bars and in linear zones along the near-channel margin of the floodplain (fig. 7). Although they were not excavated, these trees are growing beneath the terrace, as indicated by the absence of root collars and the fence post-like appearance of the trunks. The distribution of sample sites and the tree-ring dates are shown in figure 5. Seven trees were sampled; germination dates range from 1940-1963. These dates indicate that the alluvium began to aggrade by at least 1940 and that deposition continued after 1963.

Figure 7. Photograph showing alluvial valley of East Fork and prominent point bar of modern terrace on south side of valley. a = active channel; m = modern terrace; p = prehistoric terrace.

Alluvium of the modern terrace is well exposed in the cutbanks of the active channel and floodplain. Figure 8 shows the alluvium on the south side of the river just upstream of a large rockfall clast southeast of spot elevation 1202.0 m (fig. 5). The alluvium consists of two units, a basal sand about 50 cm (1.6 ft) thick and an upper stratified sand. The basal unit is massive without distinctive stratification, largely the result of fluvial reworking. A cottonwood tree resembling those on the modern terrace that date between 1940-1963 is rooted on the top of the basal unit, suggesting that the unit predates 1940-1963. The upper unit in the right side and upper portion of the exposure (fig. 8), consists of yellowish-gray beds of very fine to fine-grained sand of mainstem origin with interbedded dark-reddish brown silty and clayey sand derived from erosion of nearby hillslopes. The deposits are extensively burrowed, disrupting the continuity of the stratification. Nevertheless, six-mainstem beds are present in the upper unit, indicating that the unit accumulated from at least six-overbank floods.

The active channel and floodplain are 1-2 m (3-7 ft) below the level of the modern terrace. A steep cutbank typically rises above the floodplain and channel to the level of the modern terrace. The channel and floodplain are not subdivided in figure 5, because they are too small to show separately at the compilation scale (1:2,000) of the map. Channel deposits are mainly gravel of pebble to cobble size. The channel contains discharge up to bankfull, which is about 7 m^3/s (240 ft^3/s; E.D. Andrews, 1993, written commun.). Floodwater spreads across the floodplain above this discharge level. Floodplain deposits are mainly very fine to fine-grained sand that is poorly to moderately well sorted. Two

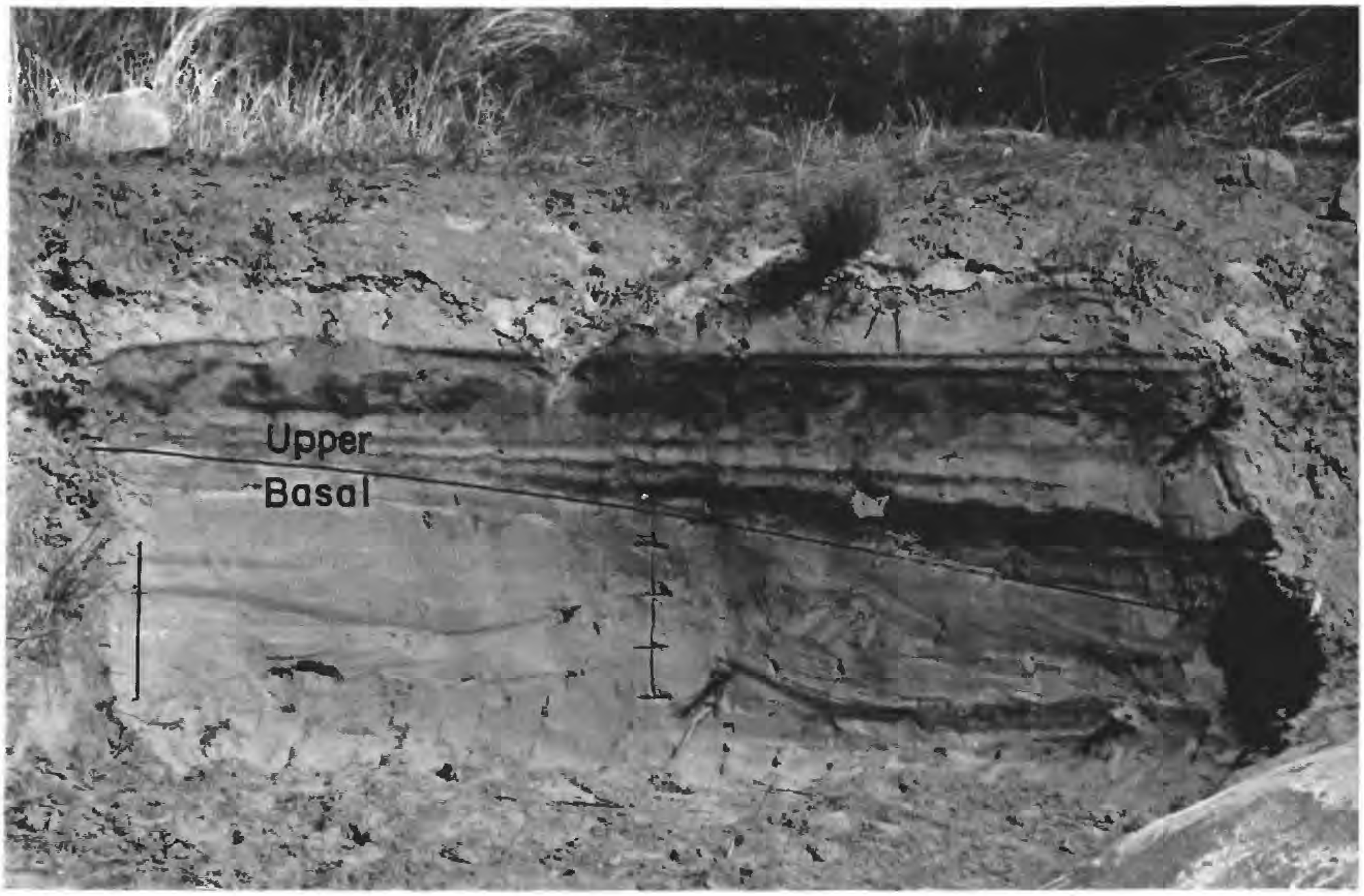


Figure 8. Photograph showing exposure of basal and upper unit of modern alluvium in East Fork. Vertical bar is 30 cm long. Light-colored beds are mainstem deposits; dark-colored beds are sheetwash deposits of clay, silt, and sand.

saltcedar trees (*Tamarisk chinensis* Lour.) growing beneath the surface of the floodplain were dated by ring counts. The germination dates were 1980, indicating that the floodplain began to aggrade after 1980 and that the modern terrace had been incised by that date.

North Fork Virgin River

Figure 9 shows the surficial geology of the North Fork study site in Zion Canyon. The northern boundary of the map is 0.37 km (0.23 mi) south of The Narrows parking area. Bedrock exposed at river level and in the walls of Zion Canyon is the Navajo Sandstone. This formation is well cemented and lacks clay and silt, therefore, it resists slope failure by debris-flow. Rockfall is an important process, however, and the slopes at the base of the cliffs are covered with rockfall debris. The geologic map of Zion National Park (Hamilton, 1987) shows upper Holocene lacustrine deposits in the mapped area (fig. 9). As previously discussed, these deposits accumulated in a lake that formed in Zion Canyon sometime before 3.6 ka upstream of a large landslide (Grater, 1945; Hamilton, 1992, p. 59). However, in the study area only fluvial deposits are present on the surface and in cutbank exposures. Sampling with a 2 m (7 ft) boring tool shows that lacustrine deposits are not present in the shallow subsurface, although lacustrine deposits could be present at depth.

Pleistocene gravel deposits are not present in upper Zion Canyon, the result of nondeposition, burial by lacustrine sediment, or lack of preservation in the relatively narrow canyon. The valley consists entirely of alluvial deposits and terraces that are similar in age and number to those in East Fork, although the upper Holocene terraces of North Fork have significantly less topo-

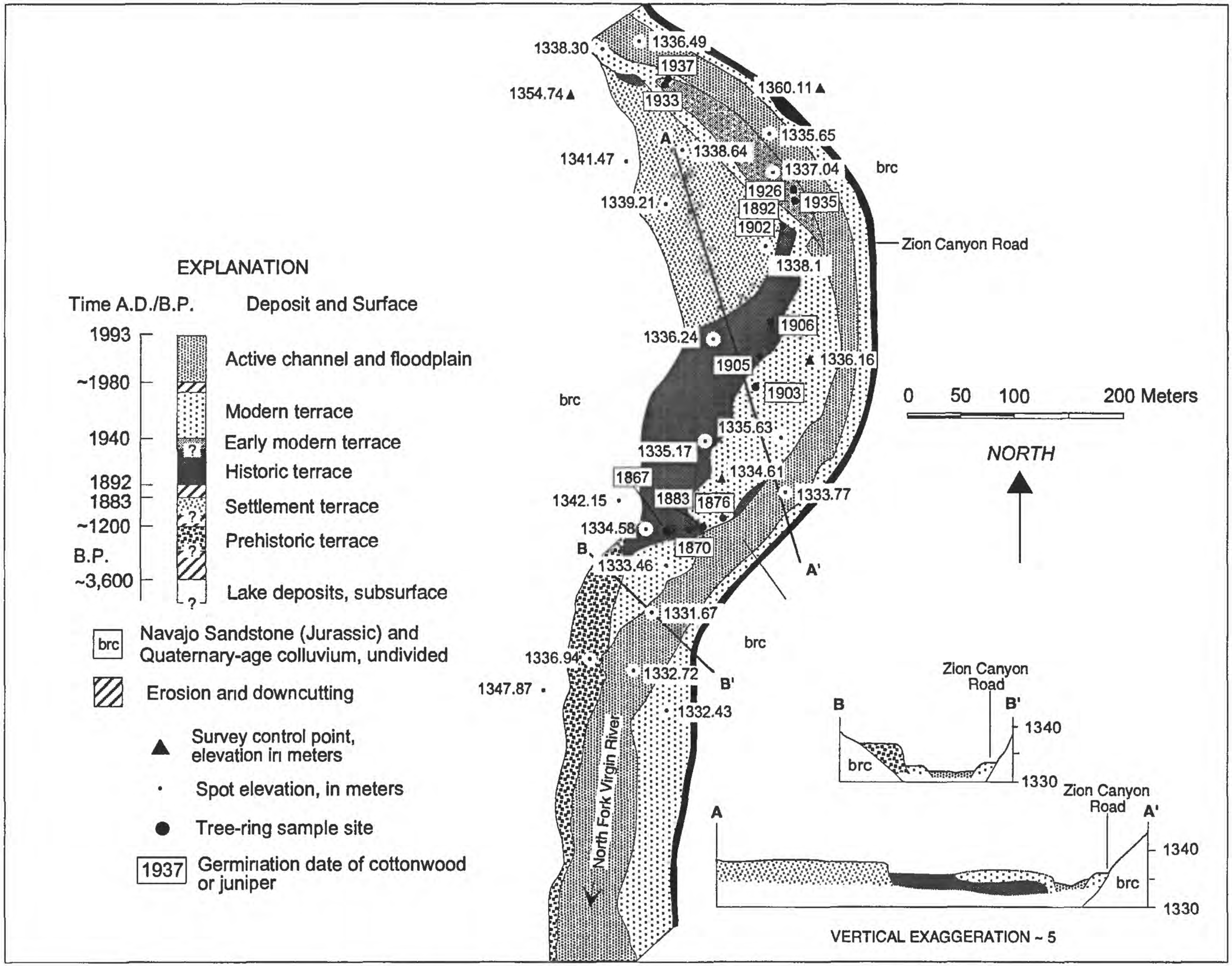


Figure 9. Surficial geologic map and cross-sections of North Fork study site (fig. 1).

graphic separation than those of East Fork. In addition, some uncertainty is added to correlation of the terraces by flood deposits of the modern terrace. These deposits resulted from the largest flood of the gaged record on December 6, 1966. This flood carried sand far out of the channel onto the historic terrace and locally onto the settlement terrace.

A terrace about 3-4 m (10-13 ft) above the active channel and floodplain is present on the west side of North Fork. This terrace is probably equivalent to the prehistoric terrace in Parunweap Canyon. The deposits are very poorly exposed, but they are mostly fine-grained sand. Sandstone clasts on the surface have a very thin coating of calcium carbonate on their undersides. This degree of soil development is similar to the prehistoric terrace in Parunuweap Canyon. Archeologic remains were not found on the terrace in Zion Canyon; thus correlation with East Fork is inconclusive based on archeologic context. Nevertheless, the high terrace in North Fork is probably correlative with the prehistoric terrace in East Fork based on degree of soil development and position above the active channel and floodplain.

The equivalent of the settlement terrace is present on the west side of the river at the north end of the mapped area (fig. 9). Here the settlement terrace is about 3 m (10 ft) above the active channel and 1-2 m (3-7 ft) above the historic terrace (cross-section A-A' fig. 9) in the north part of the map area. Vegetation is a woodland (L.D. Potter, written commun., 1993) of Gambel oak (*Quercus gambelii*) with subordinate boxelder (*Acer nugundo*). A photograph (Anderson, Number 249) taken from the saddle near The Pulpit in 1909 shows this terrace just upstream of the map boundary. The photograph shows that the terrace was furrowed as if it had been plowed, and the river channel appears adjacent to and immediately below the level of the terrace. A map of agricultural areas in the Virgin River basin published in 1903 shows irrigated farmland in this area (Adams, 1903, p. 208-209). This information and the position of the terrace in the valley suggest that this surface is equivalent to the settlement terrace of East Fork.

As cross-section A-A' (fig. 9) shows, the historic terrace is present below the settlement terrace in the north portion of the map area. The woodland vegetation on the historic terrace differs from the settlement terrace in that gambel oak is largely absent; the dominant tree of the historic terrace woodland is velvet ash (*Fraxinus velutina*) with subordinate boxelder and minor cottonwood near the river. When traced south-southwest from the line of cross-section A-A' (fig. 9), the topographic separation between the settlement and historic terrace becomes indistinct, indicating that the historic alluvium was locally deposited on the settlement terrace in this downstream location.

Tree-ring dating of cottonwood and velvet ash was used to date the settlement, historic, and early modern terraces. The location of the sampled trees and the dates are shown in figure 9. The 13 dates fall into three categories: 1867-1883, 1892-1906, and 1926-1937. The older dates are from four cottonwood trees at the southernmost outcrop of the settlement terrace. These trees appear to have germinated on or very near the surface, although the exact germination position is difficult to determine because of the large size. It seems likely that the trees germinated on the floodplain or high sand bar of North Fork between 1867-1883. Between 1883-1892, this floodplain was abandoned and the channel was deepened, causing the river to flow at the lower level of the historic-age channel.

The intermediate-age category is from five trees associated with the historic terrace, although a velvet ash dated at 1903 is within the zone of the modern-terrace flood deposits of December 1966, which are discussed below. Two cottonwood trees dated at 1892 and 1902 germinated on the surface of the historic terrace. Erosion of the settlement terrace and deepening of the channel to the level of the historic-age channel was probably from 1883 to 1892. Finally, dates from the early modern terrace indicate that a floodplain had formed below the historic terrace between 1926-1937.

The modern terrace has three topographic levels that are shown as two map units in figure 9. The oldest and highest level of the modern terrace is the elevated island or bar-like feature at the north end of the map area, this is mapped as the early modern terrace. The lower level is on the east side of the bar extending downstream to south of survey control point 1334.61 m. There is virtually no topographic separation between the historic terrace and the modern terrace at this location (cross-section A-A' fig. 9). The deposits of this intermediate level are moderately sorted, light gray, fine- to medium-grained sand, which is coarser grained and lighter colored than the nearby historic terrace. Flood debris is sparse, consisting of a rubber hose and a piece of milled wood. Woodland vegetation on the surface resembles the historic terrace, except the trees are partly buried by the light-colored sand. These deposits are probably related to the December 6, 1966 flood with a discharge of 260 m^3/s (9,150 ft^3/s). This is the largest flood of the gaged record (1926-present) on North Fork. The lowest level of the modern terrace is in the vicinity of spot elevation 1333.46 m (cross-section B-B' fig. 9). This level is about 1 m (3 ft) below the intermediate level of the terrace. Two saltcedar trees were sampled and dated from a grove along the terrace rise between the historic terrace and the lower level of the modern terrace south of spot elevation 1334.58 m. The germination dates were 1969 and 1971, suggesting that the lower level of the terrace developed by at least 1969.

The active channel and floodplain are typically separated from the modern terrace by steep cutbanks or gently sloping banks that range in height from 0.5-1 m (1.6-3 ft). Deposits in the channel consist mainly of pebble to cobble-size gravel. Floodplain deposits are very fine to fine-grained sand with minor silt and clay. Bankfull discharge at this locality is 21.8 m^3/s (770 ft^3/s; E.D. Andrews, 1993, written commun.). Three saltcedar trees, which are partly buried in floodplain alluvium, yielded germination dates of 1983, 1985, and 1990. These dates indicate that the channel and floodplain attained their present position by at least 1983.

Late Holocene Alluvial History

Deposition of the prehistoric alluvium was ongoing at A.D. 800-1100. This deposition continued for some time after A.D. 800-1100, because an additional 1-2 m (3-7 ft) of sediment accumulated above the dated archeologic horizons. Sometime after A.D. 1100-1200, the prehistoric alluvium was entrenched. Entrenchment deepened and widened the channel, which was subsequently filled by the settlement alluvium. The date of entrenchment is poorly known, but deposition of the settlement alluvium was after A.D. 1200, based on the absence of Anasazi cultural remains. Accumulation of the settlement alluvium continued until at least A.D. 1880 on both tributaries. The alluvium was entrenched after 1883 on North Fork, and the river was flowing at the level of the historic terrace by 1892. Entrenchment of East Fork happened after 1873 based on photographic evidence, and the river was at the level of the historic terrace by 1893. Geomorphic similarities between the two tributaries suggest that East Fork was also entrenched after 1883.

The historic terrace was the channel of the river beginning about 1892 or 1893, on North Fork and East Fork, respectively. The river was near this level in 1906 on North Fork and in 1909 on East Fork. By about 1926 the channel of North Fork was deepened to the early modern level and the historic channel was abandoned. The basal unit of the modern alluvium at East Fork (fig. 8) probably corresponds with the early modern terrace. This correlation is suggested by a tree of the 1940-1963 age group that is rooted on the basal unit. Deposition of the modern alluvium began by 1940 in East Fork and continued until as late as about 1980, when the channel lowered slightly to the present level of the active channel and floodplain.

The modern alluvium at North Fork consists mainly of the December 1966 flood deposit. Early deposits of modern age were either removed during the flood or were covered by the flood deposit. The lower level of the modern terrace dates to sometime before 1969, and the channel could have eroded slightly to this level during the 1966 flood. Finally, the present position of the channel and floodplain of North Fork were obtained by at least 1983.

In summary, the alluvial history of the Virgin River alternates between episodes of deposition and erosion. The sequence of terraces is the result of this progressive downcutting and backfilling. The erosional episodes were after A.D. 1100-1200, 1883 to 1926, 1937-1940, and 1980-1983. The effect of the first and second episodes was substantially larger than the third and fourth episode. Historic entrenchment and widening of the Virgin River between A.D. 1883-1940 coincides with regional arroyo cutting that deepened and widened the channel of almost every stream in the Southwest (Bryan, 1925). The aggradational episodes on the Virgin River were the prehistoric alluvium from before A.D. 800-1100 to 1100-1200, the settlement alluvium after A.D. 1200 until 1883, the early modern alluvium from 1926-1937, and the modern alluvium from 1940-1980.

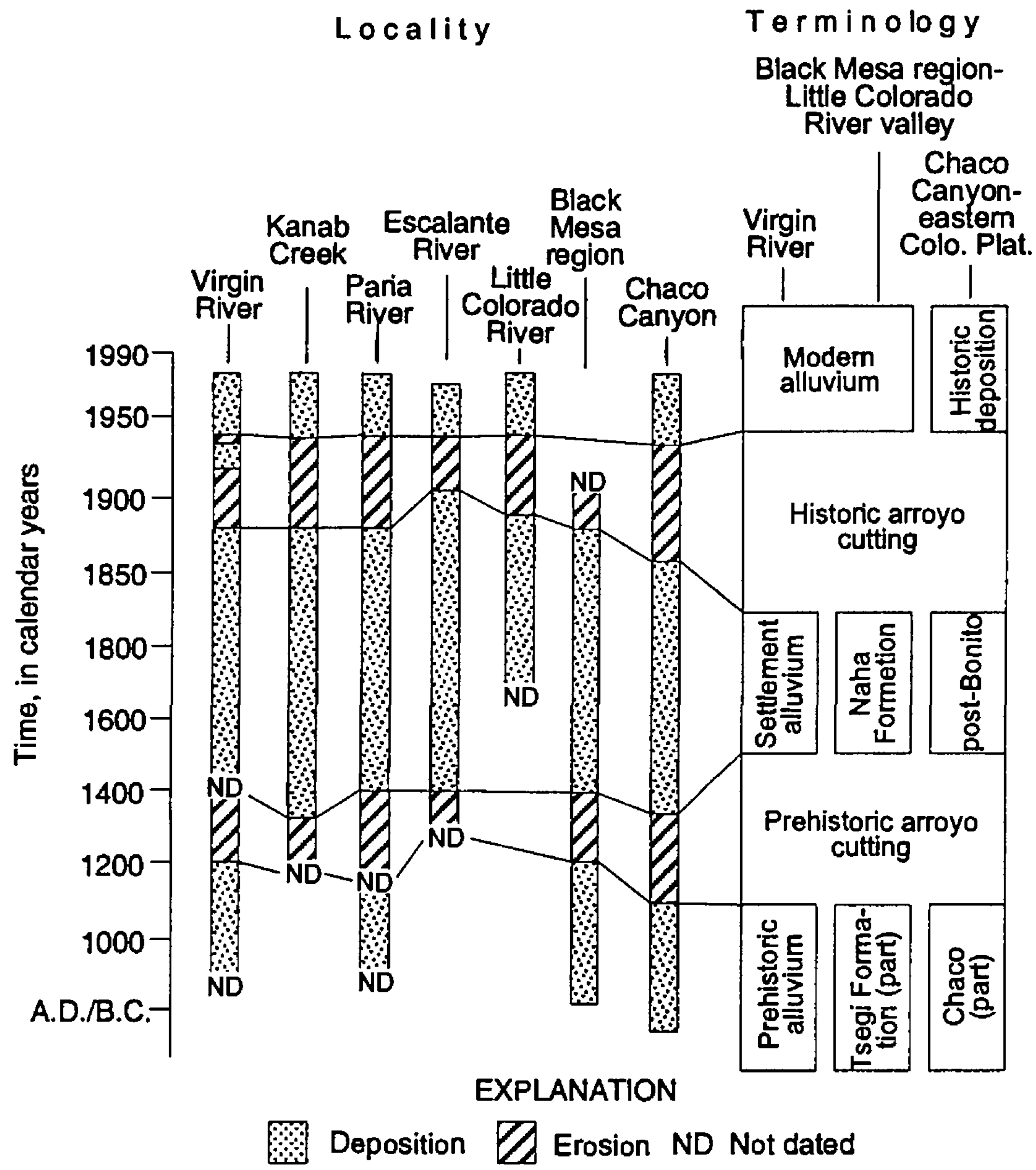
Regional Correlation of Alluvial Histories

Broadly speaking, the timing and number of erosional and depositional events of the upper Virgin River are similar to other streams on the southern Colorado Plateau. Figure 10 shows the regional correlation of upper Holocene fluvial stratigraphic units. The correlation chart was compiled and interpreted from recent or current work in the particular drainage or region. Details of the dating, stratigraphy, geomorphology, are in the cited references. For the most part, early work, summarized by Cooley (1962), showed that the depositional units are widespread and of roughly similar age throughout the southern Colorado Plateau.

The geomorphic relations among the depositional units varies from valley-to-valley as well as along individual valleys, as demonstrated by Karlstrom (1988, p. 46) in the Black Mesa region and illustrated in general by Leopold and others (1964, p. 460-461). Three geomorphic and stratigraphic relations prevail that effect the number and height of terraces; these are superposed, inset, and mixed superposed and inset. Alluvial valleys with a single terrace have superposed stratigraphy in which the terrace is the abandoned floodplain of the most recent deposition. This is similar to the arrangement of units shown on the correlation chart (fig. 10). Inset-terrace stratigraphy, or cut-and-fill stratigraphy, is perhaps the classic case of alluvial-valley geomorphology. This geomorphic relation is characterized by younger deposits at successively lower topographic positions in the valley. East Fork has inset-terrace stratigraphy (fig. 9, cross-section A-A'). The third type of stratigraphic and geomorphic relation is a combination of inset and superposed stratigraphy. In this situation, a younger sequence of superposed depositional units has an inset relation with an older sequence of superposed units. North Fork locally has elements of superposed and inset stratigraphy (fig. 9, cross-section A-A')

These geomorphic relations preclude correlation of the upper Holocene alluvial units based on the number and height of terraces, except in the case of inset terraces. Depositional history, therefore, does not necessarily correspond with the number and height of terraces. This geomorphic variability led Patton and Schumm (1981) and Patton and Boison (1985) to conclude that, in general, depositional histories need not be synchronous from basin-to-basin or within a basin. Thus, geologic dating is necessary to establish regional synchroneity of deposition and erosion.

Results of dating shown in figure 10 suggest a broad synchroneity of upper Holocene



Sources of information

Virgin River -- This study   Kanab Creek -- Webb and others (1991); Webb (personal commun., 1994)
Paria River -- Hereford (1986); (1987b)   Escalante River -- Webb (1985); Webb and Baker (1987);
Little Colorado River -- Hereford (1984)   Webb (personal commun., 1994)
Chaco Canyon -- Hall (1977); Love (1977)   Black Mesa region -- Dean (1988); Karlstrom (1988)

Figure 10. Correlation chart of upper Holocene fluvial erosion and deposition, southern Colorado Plateau region.

alluvial histories across the southern Colorado Plateau, although the timing of erosion and deposition varies across the region, particularly for the older deposits. However, some variability is expected for geologic reasons. Deposits are poorly preserved in the fluvial environment, and it is difficult to know if the youngest beds of a particular stratigraphic unit are present. Likewise, the vagaries of exposure make it difficult to identify the base of older deposits. Some uncertainty, therefore, pertains to dating either the base or top of alluvial units. Generally, it is not possible to date exactly the same stratigraphic horizon, because either it is not exposed, has been eroded, or cannot be identified due to sedimentologic differences caused by different source rocks and depositional environments. Uncertainties in the radiocarbon method of dating compounds the problem further. These dates have an analytical error that may span several centuries, dates younger than about A.D. 1400 have inherently poor resolution, and the relation of the dated material to the age of the alluvial deposit is usually not well understood (Taylor, 1987, p. 108-143). Finally, each drainage probably has a lag or threshold effect that delays the response of the channel system to the process causing change.

As shown in figure 10, the nomenclature applied to the deposits varies across the region. The prehistoric and settlement alluviums of the upper Virgin River correspond to the Tsegi and Naha Formations, respectively, of the Black Mesa region and the Little Colorado River valley (Karlstrom, 1988). Although in the Little Colorado River valley and Paria River basin, the Naha Formation was informally referred to as the cottonwood terrace (Hereford, 1984; 1986). In Chaco Canyon and the eastern Colorado Plateau, deposits of similar age are referred to as the Chaco and post-Bonito deposits (Hall, 1987), respectively.

Deposits equivalent to the modern alluvium of the upper Virgin River valley are present in most valleys of the southern Colorado Plateau (Hereford, 1987a; Graf, 1987). Because the alluvium was recognized only recently, it has not been formally named. In the Little Colorado River valley and Paria River basin, the modern alluvium was referred to as the floodplain alluvium (Hereford, 1984; 1986). At Chaco Canyon and the eastern Colorado Plateau, the alluvium is referred to as the historic deposits (Hall, 1977; Love, 1977). Similar deposits that mostly post-date 1940 are widespread in the channels of Southwest streams (Leopold, 1976).

Two erosional events or periods of nondeposition, referred to as the prehistoric and historic arroyo cutting, are widespread in the upper Holocene of the southern Colorado Plateau (fig. 10). Although detailed studies reveal a number of erosions during the upper Holocene, these were of short duration and had little geomorphic effect (Hall, 1977; Karlstrom, 1988). Prehistoric arroyo cutting was ongoing regionally around A.D. 1200-1400, if not somewhat earlier and later, and probably had severe environmental consequences. Major cultural adjustments affected the Anasazi population at about this time, including a general abandonment of the region. These adjustments were at least partly related to the environmental changes brought about by widespread arroyo cutting (Plog and others, 1988, p. 259). Historic arroyo cutting was widespread around A.D. 1900, except for the Escalante River. This erosion also affected the human population, causing widespread problems with erosion of farmland, disruption of irrigation structures, abandonment of pioneer settlements, and a redirection of economic activity from farming to livestock (Gregory, 1950; Graf, 1983; Webb, 1985). Although widely recognized and studied, the causes of this recent entrenchment are topics of debate (Graf, 1983).

The erosional episodes are characterized by a lack of deposits, the result of nondeposition and erosion. In the Escalante River (R.H. Webb, personal commun., 1994) and parts of the Paria River basin (Hereford, 1987b), the older erosion is marked by a subsurface contact having the shape of a channel incised deeply into the prehistoric alluvium. This channel-like feature was an arroyo cut into the prehistoric alluvium during prehistoric arroyo cutting. Deposition of the settlement alluvium eventually filled and overtopped this early arroyo.

The historic erosion also lacks significant sediment accumulation, although a thin, discontinuous deposit is present locally. This deposit has been identified at the base of the modern alluvium in several streams of the southern Colorado Plateau (Hereford, 1987a). Referred to as the older channel alluvium, these deposits were probably channel bars and other transient features that were reworked frequently (Hereford, 1986). The basal unit of the modern alluvium, the early modern terrace, and the historic terrace in the upper Virgin River are probably equivalent to the older channel alluvium.

This regional correlation (fig. 10) suggests a shared causal mechanism for erosion and deposition. Variations in climate are broadly similar across the region, and these variations probably altered rainfall and runoff regionally, which in turn altered long-term patterns of erosion and deposition. In short, the late Holocene alluvial history of the upper Virgin River and other southern Colorado Plateau streams probably results to some extent from climate variations that change rainfall and runoff patterns. In historic times, landuse has probably altered runoff, perhaps leading to increased erosion at least locally.

FLOODS AND HISTORIC CHANGES IN THE CHANNEL OF THE VIRGIN RIVER

This section of the report addresses the effect of floods on the geomorphology of the alluvial valleys as interpreted, for the most part, from the observations of pioneer settlers. The earliest description of the Virgin River downstream of the forks in the study area was September 1858. The alluvial valley has changed substantially since then, and the changes are contemporaneous with a run of large floods and high runoff in the latter part of the 1800s and early 1900s.

Historic Changes in the River Channel

Before settlement, the river flowed near the surface in a relatively narrow, shallow, and possibly meandering channel from Virgin to at least as far upstream as the confluence of East Fork and North Fork (fig. 1). The river valley was explored for farmland and the potential for settlement by Jesse N. Smith in September 1858 (Crampton, 1965, p. 84-90). Smith reported that the river meandered across a narrow valley, showed signs of large freshets, and that a minor flood would cover the bottomland extensively. A year later in 1859, the channel at Virgin was described as being narrow with banks covered by grass. The channel was evidently shallow, as a dam constructed in 1859 was merely a cottonwood log laid across the river anchored by two slots cut into each bank (Larson, 1961).

When Shunesburg was settled in the spring of 1862, the channel of East Fork was narrow and deep with farmland on both sides of the valley, according to DeMille (1977). In 1865 or 1866, exactly which year is uncertain, North Fork in Zion Canyon was described as flowing through a narrow, meandering channel with abundant brush, grass, and timber that made cultivation difficult (Wittwer, 1927). The reference to the deep channel of East Fork is inconsistent with the condition of North Fork in 1865-1866 and with a photograph taken in 1873 that shows an unentrenched tributary of East Fork at Shunesburg. It is possible that deep refers to the canyon rather than the channel of East Fork. Briefly, at the time of settlement in the early 1860s, the channels of Virgin River downstream of the forks, North Fork, and East Fork were quite likely meandering, narrow, and shallow with an expansive floodplain.

Floods and Settlement

Historically noted floods of the Virgin River and their effects as recorded by regional historians who cite church records, diaries, and newspaper accounts are listed in Table 1. A large flood in 1862 caused extensive damage only 1-3 years after settlement of the river valley. This flood, referred to locally as "The great flood" or the "The great storm" of 1862 (Reid, 1931; Larson, 1961; Crampton, 1965), was exceptional. Rain began on December 25, 1861 throughout the area and continued almost continuously for 40 days. The resulting flood literally destroyed the pioneer communities of Virgin, Duncan's Retreat (upstream from Virgin), Grafton, and Adventure (moved and renamed Rockville); the settlements were subsequently relocated to higher and safer ground. Loss of farmland and damage to other settlements in the river basin was just as thorough, forcing most of the new settlers to relocate houses and irrigation ditches (Larson, 1961). Other areas in the western United States were also hit hard by extreme floods and cold weather in winter of 1861-1862. Rivers from Oregon to the Mexican border were at flood stage and rainfall amounts in parts of California were 300-400 percent above normal (Roden, 1989).

The 1880s and early 1900s were characterized by unusually large floods (Table 1).

Table 1. Historic floods of the Virgin River

Date	Area and Effect	Source
January-February 1862	Extensive flood damage to all riverside settlements; channel of Virgin and Santa Clara Rivers deepened and widened for miles above junction; Grafton (early site) and Rockville (Adventure) destroyed; serious dislocations among most settlers	1, 3-4, 6
Winter 1867-68	Rockville and Grafton, considerable damage to farmland; Millersburg (near Littlefield on Beaver Dam Wash) destroyed	4, 7
June 1872	Shunesburg, crops destroyed, dam broken	7
June 28, 1880	Mesquite, small flood followed by two larger floods lasting 4-5 hours	10
August 1880	Orderville, community center inundated	4
1881	Orderville, homes inundated with muddy water	4
Spring 1883	Bunkerville, disastrous floods	4
1884	Bunkerville and St. George, dams washed out	4
August 1885	Orderville, farmland destroyed, deep gullies cut at various parts of valley; St. George, dams and irrigation ditches washed out; damage to fields and ditches from Shunesburg to Bunkerville	4
December 7, 1889	Bunkerville and St. George, dams destroyed; floodmark two feet higher than flood of 1862	4
December 15, 1889	ibid.	4
July 14, 1896	Springdale, canyon floor covered with water which reached bottom of windows in church	2
July 25, 1902	Bloomington, diversion dam partly destroyed, many washes running	8
August 24, 1905	St. George, largest flood in the history of St. George, cropland flooded, one dam swept away another partly destroyed	7
March 25, 1906	Springdale, bridge washed away, man drowned attempting to cross river near La Verkin	2
August 20, 1906	St. George, two dams damaged	8
October 1906	Mesquite, about the largest flood in 64 (?) years	11
August 13, 1909	Springdale and Northrup	2
September 1, 1909	St. George, largest flood in history of county, dam washed out farmland flooded, crops damaged by heavy rains; Virgin, farmland eroded, low parts of town flooded; Orderville, much farmland eroded, bridges and roads washed out, $3,000 damage	8, 9
1910	Mesquite, one of the largest floods with much property damage along the river	12
July 20, 1911	St. George, roads and canals damaged, rain damage to crops	8,12
October 29, 1912	St. George, dam constructed in 1874-75 washed out	4, 12
August 23, 1920	Floods in Virgin River and North Fork; Zion National Park, bridge and road washed out isolating park, considerable damage to land and ditches	3, 8, 9
September 1929	Zion National Park, flood with seven foot waves	3
March 1938	Zion National Park, flood following five inches of rain	3
December 6, 1966	St. George, extensive flood damage following four days of rain; road damage isolates Rockville and Springdale; Rockville, old riverbank overtopped, livestock killed	5, 9

(1) Crampton (1965)
(2)Crawford and Fairbanks (1972)
(3) Culpin, Mary S. (written commun., 1993)
(4) Larson (1961)
(5) Lewis (1982)
(6) Reid (1931)
(7) Stout (1972)
(8) Woolley (1946)
(9) *Washington County News*
August 19, 1909
September 2, 1909
August 26, 1920
December 8, 15, 29, 1966
Mesquite Historical Museum
(10) Francis Leavitt
(11) William Abbott
(12) J. Abbott

Two floods in December 1889 and the flood of September 1909 are noteworthy because they were probably as large or larger than the flood of 1862. Damage, however, was evidently not as widespread or extensive. This apparent lack of widespread damage suggests that people had gained experience with floods and had adjusted to the flood hazard by careful selection of construction sites and location of farmland.

Early settlement and economic development of the Virgin River basin were affected to a large extent by the floods of the late 1800s and early 1900s. Flood-related loss of farmland and damage to irrigation structures, dams, and dwellings were continuing problems for early settlers of the region (Larson, 1961). The cost of replacing and maintaining dams, irrigation ditches, and property was an economic burden on every community.

Population growth, moreover, was limited by the progressive loss of farmland after settlement. Unused land suitable for farming was simply unavailable for future, expanded agricultural development. From 1862-1886, 50 percent of the original bottomland at Virgin was lost to erosion (Slusser and Olson, 1992); at Rockville 50 percent was lost by 1890 (Larson, 1961). The population of Duncan's Retreat, Grafton, and Shunesburg was declining and the settlements were almost deserted in the 1890s. The remaining farmland could not support earlier population levels, and the economic base shifted from agriculture to livestock as farming could no longer provide subsistence and was unprofitable (Larson 1961; Crampton, 1965).

Springdale, interestingly, was not as seriously affected by flood-related problems. This is probably because much of the channel and the banks of North Fork near Springdale are relatively coarse gravel, and the settlers were able to successfully divert the river and control erosion (Larson, 1961). Nevertheless, floods have been troublesome at Springdale and are noted in local history (Crawford and Fairbanks, 1972).

The difficulty of controlling the Virgin River at Grafton was recalled by Russel (1982). In the early 1900s, he reports that the river shifted course and occupied a different channel after each flood, which was several times a year. A rise of only a few feet would necessitate repair of the dam; these difficulties explain the frequent complaints regarding maintenance of irrigation structures (Larson, 1961).

The erosional effects of this repeated shifting of the channel are illustrated by the remnant of an irrigation ditch west of Grafton. About 1 km (0.6 mi) of the ditch is preserved discontinuously on the south side of the river beginning 1.1 km (0.7 mi) west of Grafton. At the upstream point, the ditch was dug into the prehistoric terrace; the terrace and ditch are now truncated by a 6-7 m (20-23 ft) vertical cutbank of the active river channel. At the downstream point west of Grafton Wash, the ditch was excavated into a steep slope of Pleistocene gravel and the water was directed to the fields below. Presently, the ditch ends 5-6 m (16-20 ft) above historic-age deposits, which are younger than early-day farming. Erosion removed both the inlet of the ditch and the bottomland under irrigation.

Just east of Grafton Wash, the ditch was excavated into a steep slope of Moenkopi Formation that was subsequently eroded as the channel widened. A 70 m (230 ft) segment of the ditch was eroded from the slope and the bedrock was steepened into a nearly vertical scarp 10-15 m (33-49 ft) high. Historic-age alluvium is present at the base of the scarp 5-10 m (16-33 ft) inside the projected path of the ditch (fig. 11). At this locality, bedrock as well as alluvium were eroded as the river shifted course during arroyo cutting.

Historic Floods and the Beginning of Arroyo Cutting

Historic accounts interpreted by (Bailey, 1935) suggest that arroyo cutting began with the flood of 1862 and that the initial incision progressed headward into the upper basin by

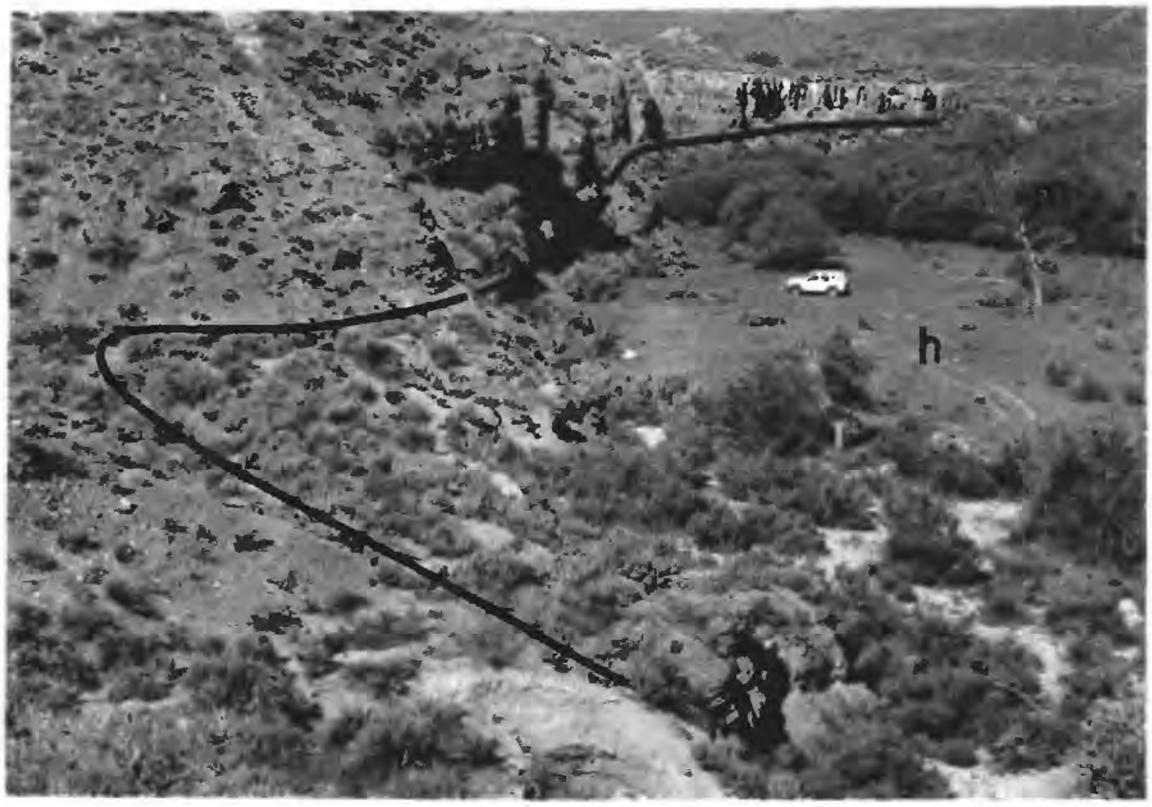


Figure 11. Photograph illustrating erosion of bedrock (Moenkopi Formation) associated with historic arroyo cutting west of Grafton. Line shows trace of irrigation ditch. Dashes show eroded ditch and bedrock. h = historic terrace; m = modern terrace.

1870 (Table 1). Previously discussed geomorphic evidence, however, indicates that arroyo cutting in the study area began after 1883. As they apply to the study area, historic accounts are somewhat ambiguous, because they reflect a set of circumstances that are probably unrelated to the beginning of arroyo cutting.

The 1862 flood is noted for its severe consequences, and it is probably one of the largest floods of the historic era, according to Enzel and others (1994), although four floods were as large or larger (Table 1). The severe problems caused by the flood of 1862 were probably exacerbated by the inexperience of the pioneer settlers. These people were recent immigrants from Europe and New England; the desert environment of the flood-prone Virgin River valley was unlike anything in their past experience (Larson, 1961, p. 90). Settling a narrow valley with a river subject to large floods and a shifting channel would present numerous problems under the best of conditions. Farmland and housing were probably established and built on or very near the active floodplain. After only 1-3 years in the area, the settlers had the misfortune of experiencing one of the largest floods in 130 years.

The loss of property and hardships caused by the flood were no doubt real. What seems less tangible is the extent to which the channel was widened and deepened, particularly in regard to arroyo cutting in the Zion National Park region. In the St. George area, the channels of the Virgin and Santa Clara Rivers were widened and deepened for several kilometers upstream of the junction (Table 1), although a large flood will cause erosion upstream of a major junction. At any rate, the channel in the study area was evidently not altered extensively. Samuel Wittwer's (Wittwer, 1927) description of North Fork in Zion Canyon indicates that the channel was not entrenched in 1865-1866 and photographs of North Fork and East Fork indicate the channels were not entrenched in 1873.

Farmland was lost in the upper valley in 1862, but this was probably flood-related shifting of the channel across the floodplain rather than erosional lowering of the channel and abandonment of the floodplain. Interestingly, there is no geomorphic evidence of this flood in the study area, either because evidence was not preserved or because the effect of the flood was not large. Likewise, the flood of December 1966, which ranks with the 1862 flood (Enzel and others, 1994), had negligible geomorphic effect, although roads and bridges were damaged (Table 1). It is possible that a single large flood isolated in time is incapable of triggering arroyo cutting on a basin-wide scale.

Nonetheless, loss of farmland was a continuing problem for every settlement in the study area except Springdale. Was this loss the result of arroyo cutting? Possibly, but again no evidence of entrenchment was found before 1883. Although it is clear that floods were a persistent problem for settlers in the valley (Larson, 1961, p. 357-375), it is less certain that early flood-related problems resulted from arroyo cutting. The loss of farmland from 1862 to the early 1880s probably resulted from normal shifting of the channel during aggradation of the settlement alluvium.

Historic accounts show that floods were particularly frequent and troublesome from 1880 through the early 1900s (Table 1). This corresponds with a time of unusually high streamflow that began in the early 1880s, based on dendrohydrological estimates. Between 1883-1892 or 1893, the channel was deepened at least several meters throughout the area to the extent that it no longer flooded at the level of the settlement floodplain. In short, arroyo cutting in the study area quite likely began around 1883 when the channel was demonstrably altered, as inferred from geomorphic evidence. Geomorphic studies are needed in the lower basin to determine whether the 1862 flood initiated arroyo cutting.

HISTORIC PHOTOGRAPHS OF THE VIRGIN RIVER

Relocation of early photographs provides a wealth of information about subtle changes in landscape that are otherwise difficult to describe, map, or interpret (Malde, 1973). In this section of the report, changes in the alluvial valley are interpreted by comparison of early images with contemporary photographs made at relocated camera stations. The date, location, and archival source of the photographs are listed in Table 2. Over the years, numerous photographs have been made of Zion Canyon, beginning with the early work of J.K. Hillers, who photographed the area in April or August of 1873 (Fowler, 1989, p. 39). Although most photographs illustrate the rugged walls of Zion Canyon, many of the photographs include the channel of North Fork. Landscape photographers were evidently less interested in East Fork and the Virgin River downstream of the forks, as only a few early photographs were found. The photographs are discussed by area and interpreted in terms of the previously discussed terraces. The photographs are on pages 34-53.

North Fork in Springdale and Zion Canyon Areas

The junction of Virgin River with East and North Fork is shown in figure 12 (Table 2). The early photograph (fig. 12a) was taken in 1873 by J.K. Hillers. In 1873, the river flowed at the level of the settlement terrace, and the river appeared to flood widely across the bottomland, as indicated by the streaks of high-albedo material parallel to the river (fig. 12a). The valley was relatively free of vegetation, probably the result of grazing and clearing for farming. The channel of East Fork in 1873 (fig. 12a) was located about where the dirt road crosses the settlement terrace in the contemporary photograph (fig. 12b). East Fork has shifted about 100 m (330 ft) south of its 1873 position, and the junction with North Fork shifted downstream. Although not visible in the contem-

Table 2. Date, location, subject, and source of historic photographs

Figure No.	Date	Location and Source of Place Names (1)	Source	Relocation Date
		North Fork in Springdale and Zion Canyon Areas		
12a, b	1873	500 m south of North and East Fork junction, SE¼ map 1	J.K. Hillers No. 80, USGS	April 1994
13a, b	1873	240 m north of West Rim trailhead, on river 20 m east of trail, SW¼ map 2	J.K. Hillers No. 73, USGS	April 1994
14a, c	1873	250 m south of Great White Throne turnout Floor of the Valley Road, ibid.	J.K. Hillers No. 78, USGS	April 1994
14b	8/12/1929	At turnout north side Floor of the Valley Road, ibid	National Archives 79-2-142	--
15a, c	1903	Observation Point, SE¼ map 2	W.T. Lee No. 2713, USGS	April 1993
15b	9/12/1929	ibid.	National Archives 79-2-101	--
16a, b	1909	780 m north of West Rim trailhead, 150 m west of trail, SW¼ map 2	R. Anderson No. 245, USGS	April 1994
17	1909	In saddle at The Pulpit, ibid.	R. Anderson No. 249, USGS	--
		Virgin River in Grafton and Rockville Areas		
18a, b	1917-1939	On cliff 1 km southwest of Grafton, SW¼ map 1	Gregory (1939, fig. 12)	September 1994
19a, b	1937	1.5 km east of Rockville and 100 m north of State Route 9, SE¼ map 1	H.E. Gregory No. 9-2455, Univ. Utah Special Collections	April 1994
		East Fork near Shunesburg		
20a, b	1873	300 m west-southwest of Shunesburg, SW¼ map 3	J.K. Hillers No. 520	September 1994
21a, b	1926	460 m east of Shunesburg, ibid.	H.E. Gregory No. 9-2242, Univ. Utah Special Collections	April 1994
22	1936	660 m east-northeast of Shunesburg at park boundary fence, ibid.	H.E. Gregory No. 9-2428, Univ. Utah Special Collections	--

(1) Place names from indicated quadrant of U.S. Geological Survey 1:24,000 scale topographic maps.
Map 1, Springdale West (1980); map 2, Temple of Sinawava (1980); map 3, Springdale East (1980)

porary photograph (fig. 12b), the river now flows 4 m (13 ft) below the adjacent settlement terrace. A woodland composed mainly of cottonwood is now well established along the river. At this locality, the width of the channel does not appear to have increased, but the channel has shifted position and deepened 4 m (13 ft).

Figure 13 is North Fork in Zion Canyon looking upstream to Angels Landing and The Organ (Table 2). In 1873, alluvium on the floor and banks of the channel appears to be sand with silt and mud (fig. 13a). The area in the mid-ground of the channel in the early photograph is probably the settlement-age floodplain. The contemporary photograph shows that the channel is mainly cobble to small-boulder gravel and only the modern terrace is present in this area now (fig. 13b). Riparian vegetation in the mid-ground of the early photograph appears to be willow and at least one cottonwood. Presently, the riparian vegetation is dominated by saltcedar, a non-native species that is widespread in many streams in the western United States below about 1,830 m (6,000 ft) elevation (Robinson, 1965).

North Fork in the vicinity of the Great White Throne is shown in figure 14 (Table 2). The camera station is 1.6 km (1 mi) upstream of the station in figure 13. In 1873, the channel in the vicinity of Great White Throne also appears to be composed of sand with silt and mud, similar to figure 13a. A low bank just below the right mid-ground (fig. 14a) is probably the settlement-age floodplain. The lower-right portion of figure 14b shows the foreground of figure 14a from a position several hundred meters north and about 10-15 m (33-49 ft) above the early location. By at least 1929, the channel had changed substantially; it is wider, the vegetation canopy is gone, and the channel and banks are gravelly. Figure 14c is the contemporary photograph taken from the camera position of figure 14a. The channel appears to be substantially wider than in 1873, although the discharge level is higher in the contemporary photograph. The modern terrace is present in the foreground, and deposits of the 1966 flood occupy most of the alluvial valley behind the camera station. The present vegetation is mainly saltcedar and cottonwood, whereas in 1873 it appears to be mainly willow and cottonwood (fig. 14a).

Zion Canyon and North Fork downstream from Big Bend are shown in figure 15, an oblique aerial view from Observation Point (Table 2). The foreground of figure 12 is visible in the mid-ground of figure 15. In the 1903 photograph, the active channel of North Fork is indicated by the high-albedo material on the floor of the alluvial valley (fig. 15a); the channel appears to occupy most of the valley floor. At least five meander scars are eroded into the settlement terrace downstream of the mid-ground of the photograph. The meander scars resemble the plan-form of the historic terrace at East Fork (fig. 5). A plowed field or orchard is present on the settlement terrace on the right side of the valley. This field is not present in the 1929 photograph (fig. 15b); the terrace and field were removed by a shift in the channel between 1903-1929. Vegetation had begun to occupy channel bars by 1929, these bars probably correspond with the early modern terrace mapped upstream at the North Fork study site (fig. 9). The contemporary photograph (fig. 15c) shows a substantial decrease of channel width since 1929. In addition, a woodland of cottonwood is well developed. Extensive channelization and realignment of North Fork were done in this reach to maintain the present all-weather road. Much of this conservation work was done in the 1930s, and the present position of the channel in many places is partly a consequence of this stabilization work.

The alluvial valley south of Big Bend is shown in figure 16 (Table 2). The early photograph (fig. 16a) shows the historic channel extending across most of the valley in 1909. The cutbank and relatively high terrace on the right side of the river is probably the settlement terrace. However, a terrace cannot be identified at this spot in the Observation Point photograph (fig. 15a) taken only six years earlier. It is possible that the cutbank and terrace are related to the historic terrace. Gravel is present in the channel on the right side of the photograph in the upper foreground. The contemporary photograph (fig. 16b) shows that the channel shifted south, placing the active channel against bedrock. This shift occurred by 1929, as shown in the Observation Point photograph (fig. 15b). The height and diameter of cottonwood on the left side of the river identify this surface as the early modern terrace. This reach is largely unaffected by channel stabilization, which was unnecessary because the Zion Canyon Road is on bedrock above the alluvial valley. The left bank downstream from the bedrock cliff has been stabilized, as shown by the linear feature in the lower right of figure 16b.

Figure 17 (Table 2) is North Fork downstream of The Pulpit in 1909. This area was not rephotographed because dense vegetation in the foreground blocks the view. The settlement terrace is present in the left foreground. The furrows show that the terrace was recently plowed for farming, as described in the photographers' notes. The channel is below the terrace, as shown by the dark, linear feature in the left foreground, which is probably the shadow of the terrace and cutbank cast on the channel.

Virgin River in the Grafton and Rockville Areas

An oblique aerial view of the Virgin River in the Grafton area taken from the cliffs of Shinarump Sandstone is shown in figure 18 (Table 2). The early photograph was quite likely taken before 1939, as it appeared in a publication of that date (Gregory, 1939, fig. 12). The earliest possible date for the photograph is suggested by the condition of the road (State Route 9) on the north side of the river. The roadbed is wide, unpaved, well graded, and is aligned differently than the existing paved highway (fig. 7b). The road is probably contemporaneous with relatively heavy automotive traffic, as the pioneer route followed the south side of the valley. In 1917, $15,000 of Federal funds were appropriated to construct 17 miles of an "---interstate wagon road or highway---" into Zion National Park (Larson, 1982). National Park Service brochures (U.S. Department of Interior, 1926) show that the road in the park was graded and improved as early in 1926 and the road was oiled in 1928 to reduce dust (*Deseret News*, June 4, 1928). This information suggests that the photograph was probably taken sometime after 1917 and before 1939; the date is assumed to be the mid-1920s, a time that includes the late historic-age terrace.

Grafton is on the settlement terrace (fig. 18), which has a steep terrace rise extending 2-3 m (6-10 ft) above the active channel. In the mid-1920s (fig. 18a), the river flooded freely across a channel extending from Grafton to the north side of the valley at State Route 9. The historic-age channel dominates the scene, extending from near the Grafton school to bedrock on the north side of the valley. The active channel was near the school building in the early 1900s, when a rock wall was constructed (Russel, 1982) to stabilize the cutbank of the settlement terrace. This wall is still present just east of the school building. The contemporary photograph (fig. 18b) shows that the channel narrowed substantially, shifted course, and a woodland of cottonwood developed.

A downstream view of the valley between Rockville and Springdale is shown in figure 19 (Table 2). The settlement terrace is present along the south and north margin of the channel in the early photograph. In 1937, a point bar extended north across the valley and the roadbed was the right bank of the river (fig. 19a). The point bar was lightly vegetated and appears to have been active recently. The point bar is equivalent to the early modern terrace of North Fork and the basal unit of the modern alluvium at East Fork. There is little evidence of channel stabilization work in this reach, except on the right bank just downstream of the roadbed. Between 1937-1994, the active channel shifted south 270 m (750 ft), and a mobile home was located near the center of the formerly active channel (fig. 19b). In addition, an open-canopy woodland of cottonwood developed on the point bar and in the earlier channel. The height and diameter of the cottonwood trees resemble those in East Fork associated with the modern terrace.

East Fork near Shunesburg

Although the river is not shown in figure 20 (Table 2), this early photograph of Johnson Mountain is important because of evidence that tributaries of East Fork and the channel of East Fork itself were not entrenched in 1873. The camera station is located on the settlement terrace at the junction with a small, entrenched tributary about 50 m (160 ft) north of the remains of a cut-stone dwelling at the west end of the former site of Shunesburg. The mid-ground on the right side of the early photograph shows that the tributary was only a shallow swale in 1873 (fig. 20a). In the contemporary photograph (fig. 20b), a well-formed arroyo with vertical walls 2-3 m (6-10 ft) high is present in this area. This modern channel is a first-order tributary of East Fork on the Springdale East 1:24,000 scale topographic map, and the arroyo extends about 800-900 m (2,620-2,950 ft) upstream from the junction. The west side of the arroyo is aligned north-south for 200-250 m (660-820 ft) upstream from the junction, suggesting that the arroyo was initiated along a fence line. A few meters east of the camera station, the river presently occupies a large meander scar entrenched 5-7 m (16-23 ft) below the settlement terrace. The settlement of Shunesburg was built on the terrace at the present location of the entrenched meander. The absence of an arroyo in 1873 suggests that East Fork was not entrenched at that time, otherwise the tributary would also be entrenched as the main channel is the baselevel control.

A downstream view of East Fork in 1926 near Shunesburg is shown in figure 21 (Table 2). The stone house of Oliver DeMille dating from around 1880 (DeMille, 1987) is present on the high terrace of Pleistocene gravel in the upper-right quadrant of the photograph. The prehistoric and settlement terraces are present in the foreground above a steep terrace rise that extends 3-4 m (10-13 ft) above the late historic-age channel. Gullies graded to river level are eroded into the terraces. In flood stage, the river flowed across the entire channel, and riparian vegetation was sparse. Figure 21b is an approximate relocation of the 1926 photograph. Presently, the steep terrace rise present in 1926 is subdued and is eroded farther into the valley margin. An open-canopy woodland and the modern terrace are present in the former channel.

The channel of East Fork in 1936 at the park boundary fence east of Shunesburg is shown in figure 22. The photographic station could not be relocated, because subsequent erosion removed the camera station which was on the settlement terrace at the terrace rise. In 1936, the early modern floodplain is present slightly above the active channel. The historic terrace is present in the right mid-ground just below a cottonwood tree on the settlement terrace. Presently, the channel is occupied almost entirely by the modern terrace and a dense woodland of cottonwood.

Discussion and Summary of Channel Conditions Inferred from Historic Photographs

Relocation of historic photographs reveals striking changes in the channel of Virgin River during the past 120 years. North Fork in Zion Canyon is the longest and most complete sequence of photographs that begins in 1873. A sand-bed channel was present in 1873 that varied in width from about the same to much narrower than the present channel (figs. 13 and 14). In addition, the banks were vegetated and appear stable. The artistic rendering of the 1873 (figs. 13a and 14a) photographs was probably intended to portray a sense of tranquility along the river, and the photographs are probably somewhat biased in their portrayal of channel conditions. Nevertheless, historic accounts indicate that in 1865-1866 the channel was heavily vegetated and the river flowed in a narrow, meandering channel (Wittwer, 1927). This description of the channel in 1865-1866 is consistent with the condition of the channel in the 1873 photographs.

By 1903, the channel had widened substantially and the settlement-age floodplain was incised and undergoing active erosion (fig. 15). This erosion and widening of the channel continued until at least 1929 (figs. 15a and 15b). Gravel was definitely present in the channel in 1929, although the change from a sand to gravel-bed stream probably occurred by at least 1909 (figs. 16 and 17). The change from sand to gravel bed suggests stream competency increased. The gravel is probably a lag deposit, resulting from selective removal of sand-size sediment during the large floods of the late 1800s and early 1900s.

The river appeared to flood freely across the channel in 1903 and 1909 with little evidence of an active floodplain. These photographs suggest that the historic-age channel lacked a clearly defined floodplain. By 1929, however, stabilized mid-channel bars were present in the channel that now form the early modern terrace. Since 1929, channel width decreased substantially and the deposits and riparian woodland of the modern terrace partly fill the former channel.

The photographic record of East Fork and the Virgin River downstream of the forks only begins in 1926 and the mid-1920s, respectively. These photographs show the late-historic and early modern channel. The earliest photographs (figs. 18a and 21a) show that the late-historic channel was relatively flat, largely unvegetated without a

FIGURES 12 TO 22 FOLLOW

Figure 12. View to northeast up North Fork showing junction of North Fork and East Fork west of Springdale, Towers of the Virgin on skyline. A) 1873 and B) 1994.

Figure 12b.

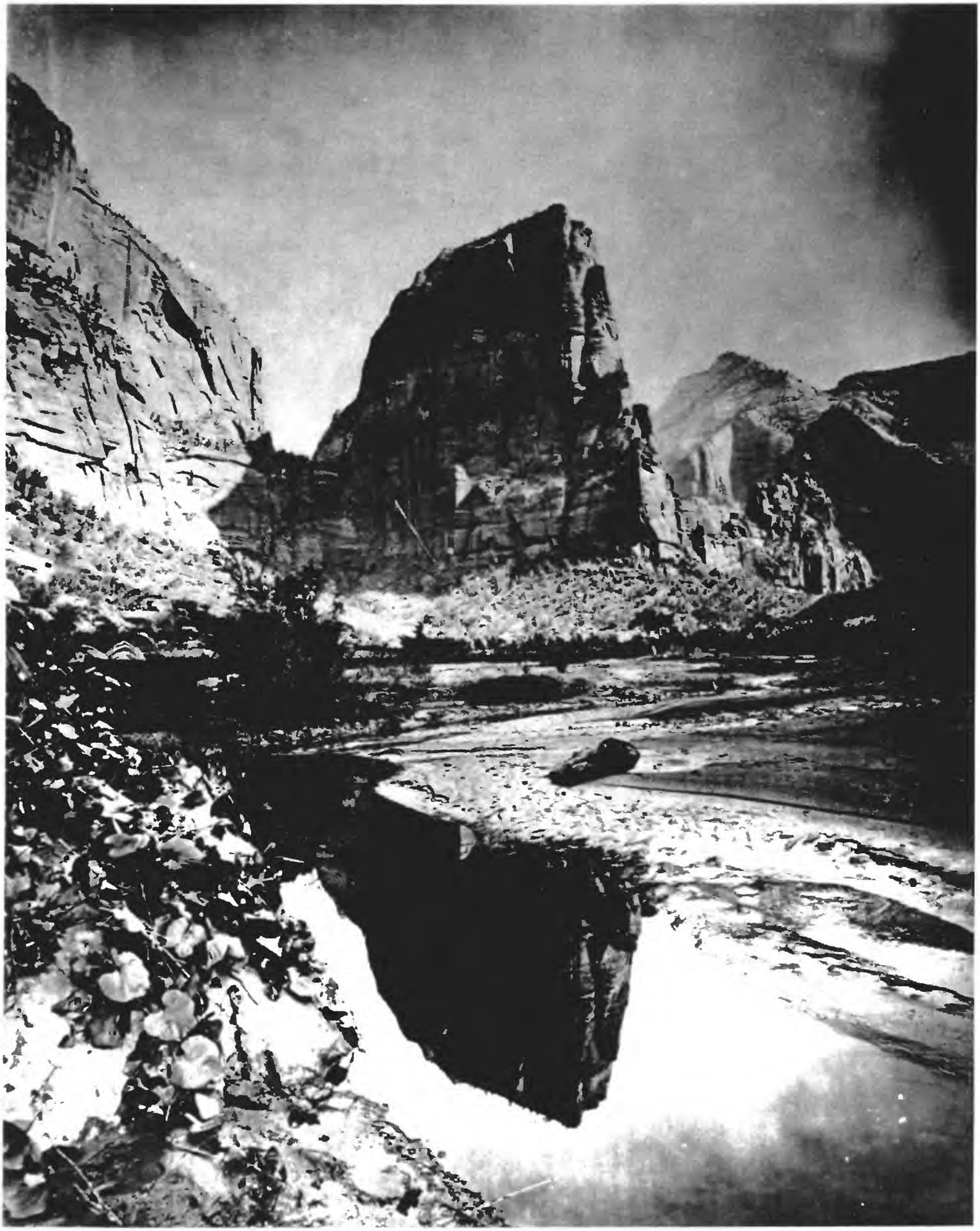


Figure 13. Upstream view of North Fork showing Angels Landing and The Organ. A) 1873 and B) 1994.

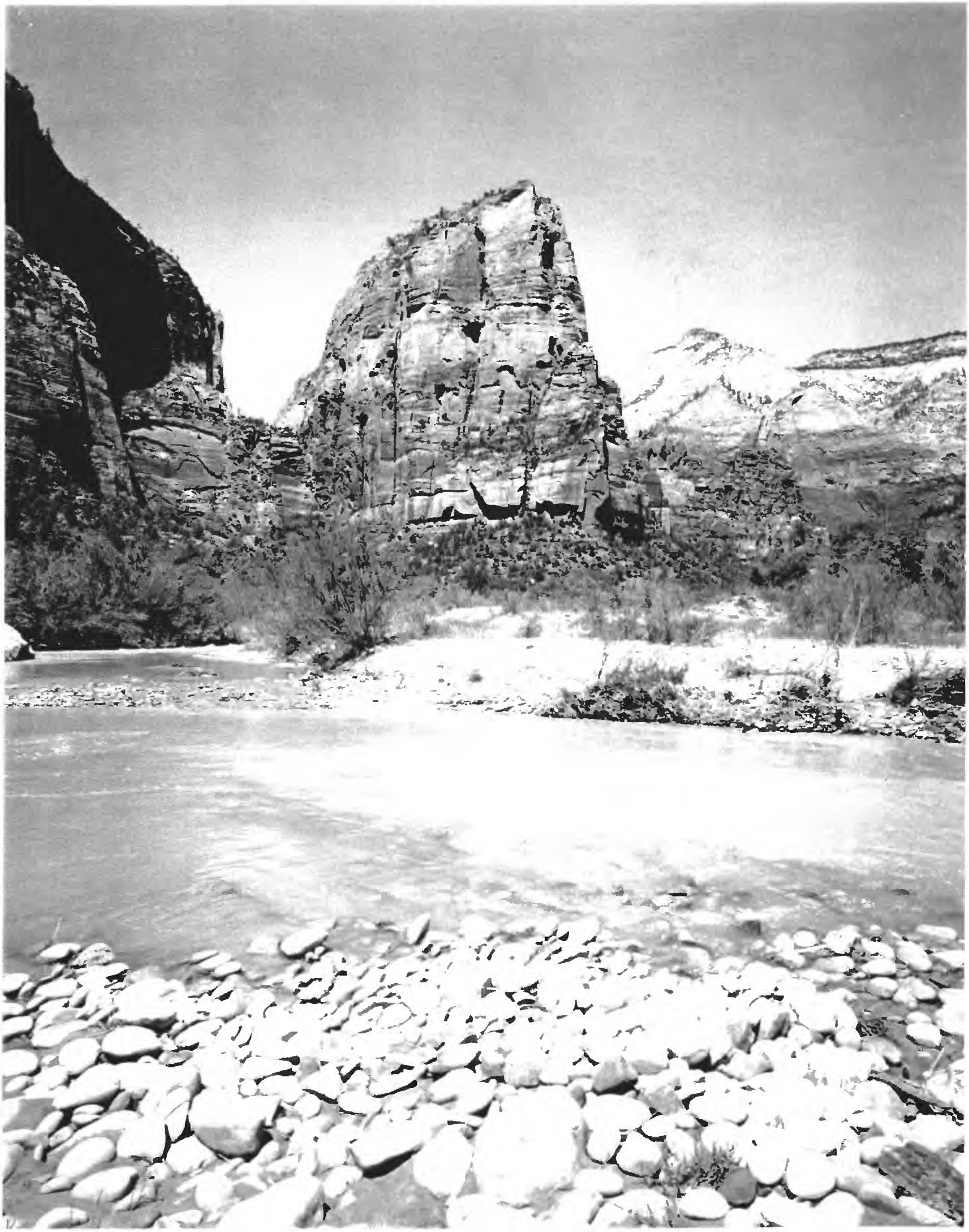


Figure 13b.

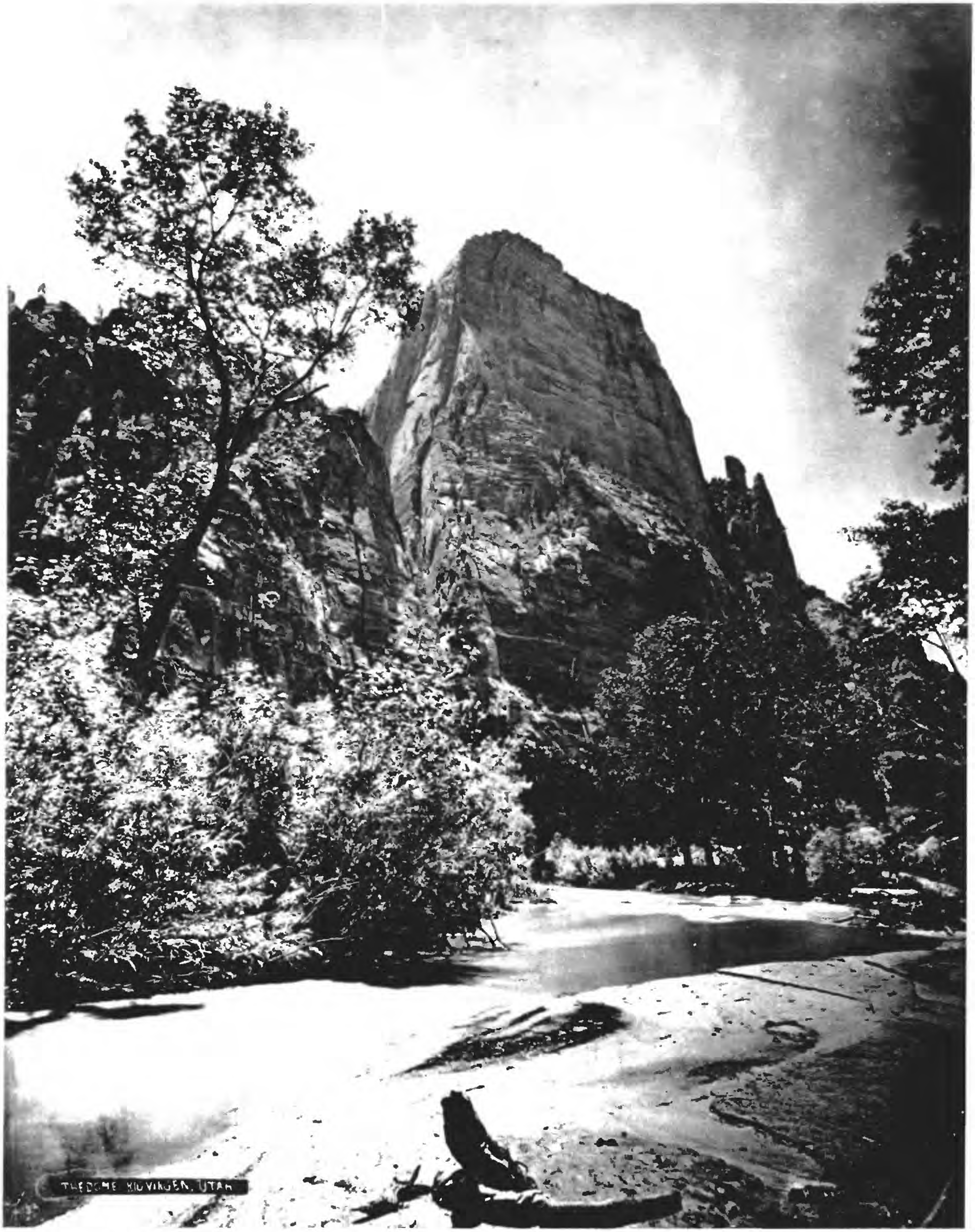


Figure 14. Downstream views of North Fork and Great White Throne. A) 1873, B) Foreground of figure A, 1929, and C) Relocated photograph of figure A, 1994.

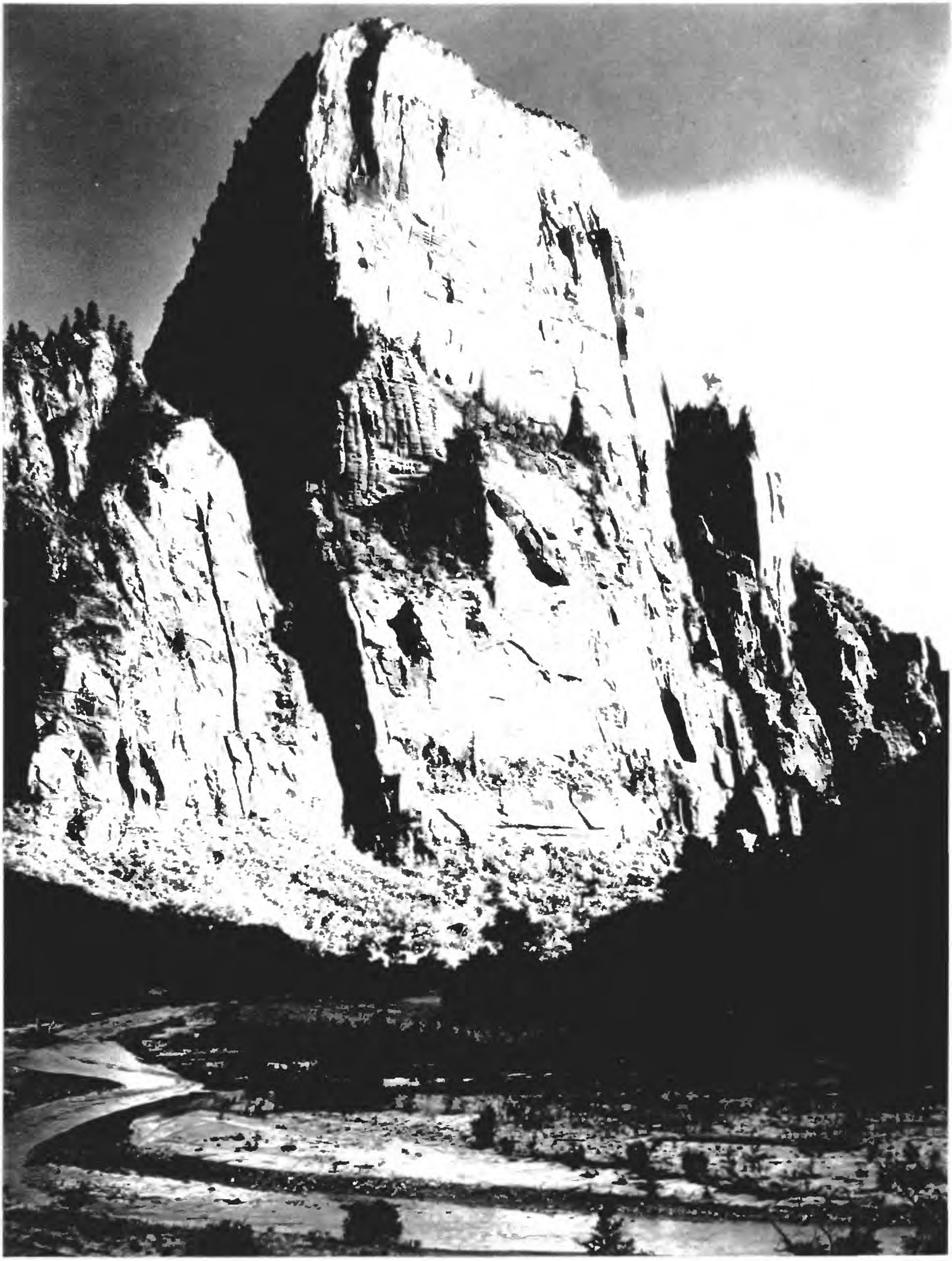


Figure 14b.

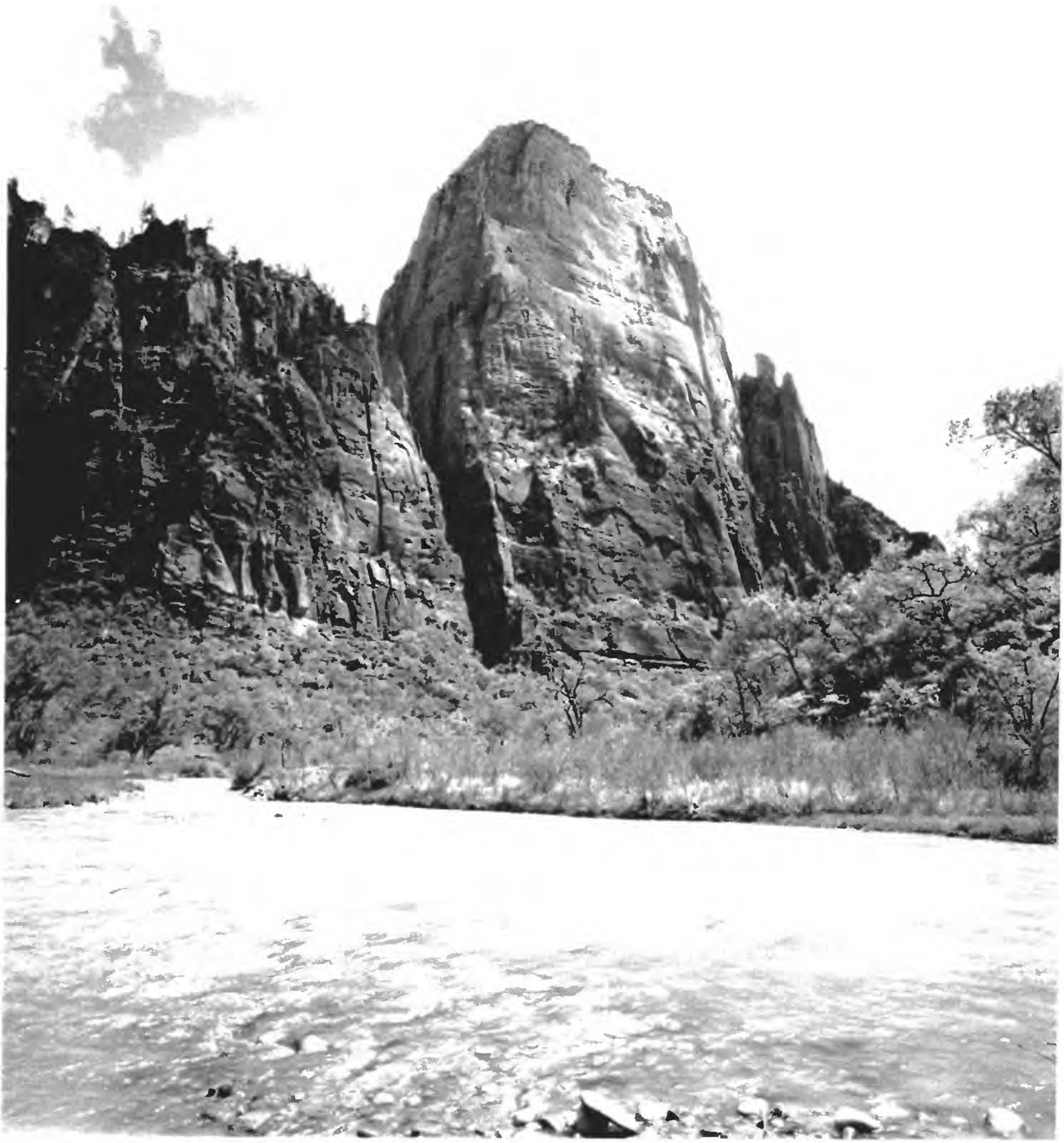


Figure 14c, Approximate relocation of 14a.

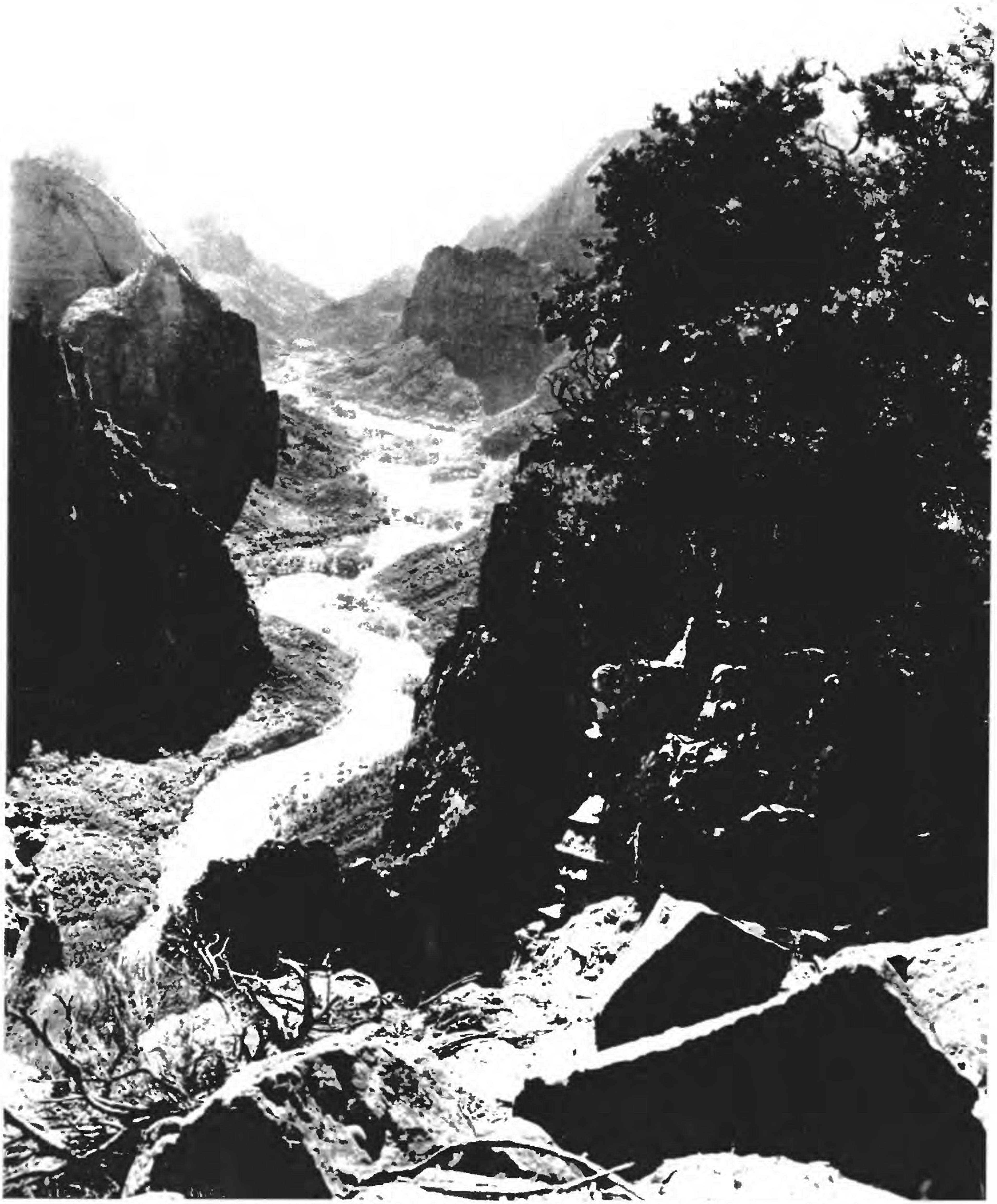


Figure 15. Zion Canyon and North Fork from Observation Point. A) 1903, B) 1929, and C) 1993.

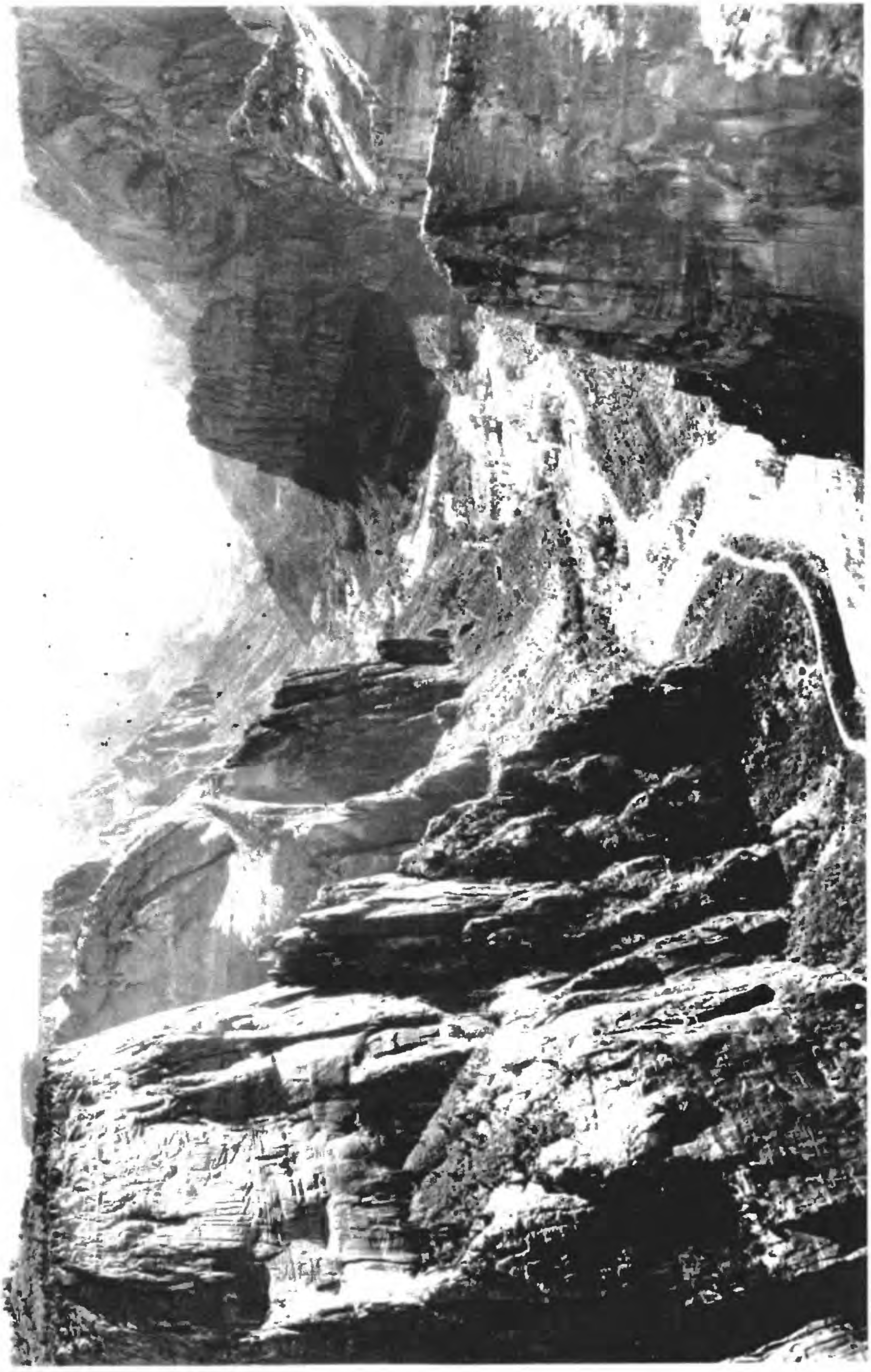


Figure 15b.

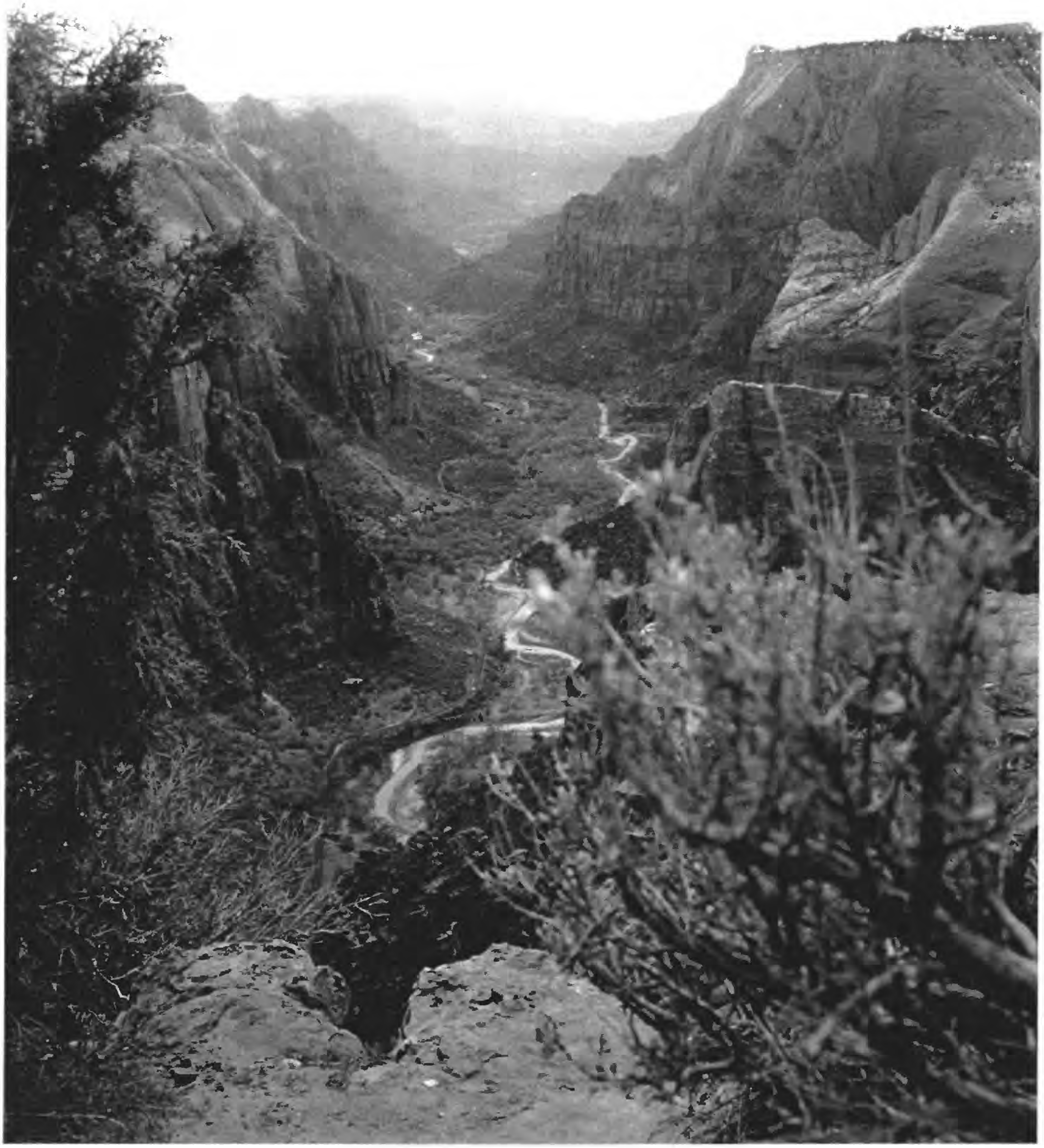


Figure 15c. Relocation of figure 15a.

Figure 16. Upstream view of North Fork and Cable Mountain. A) 1909 and B) 1994.

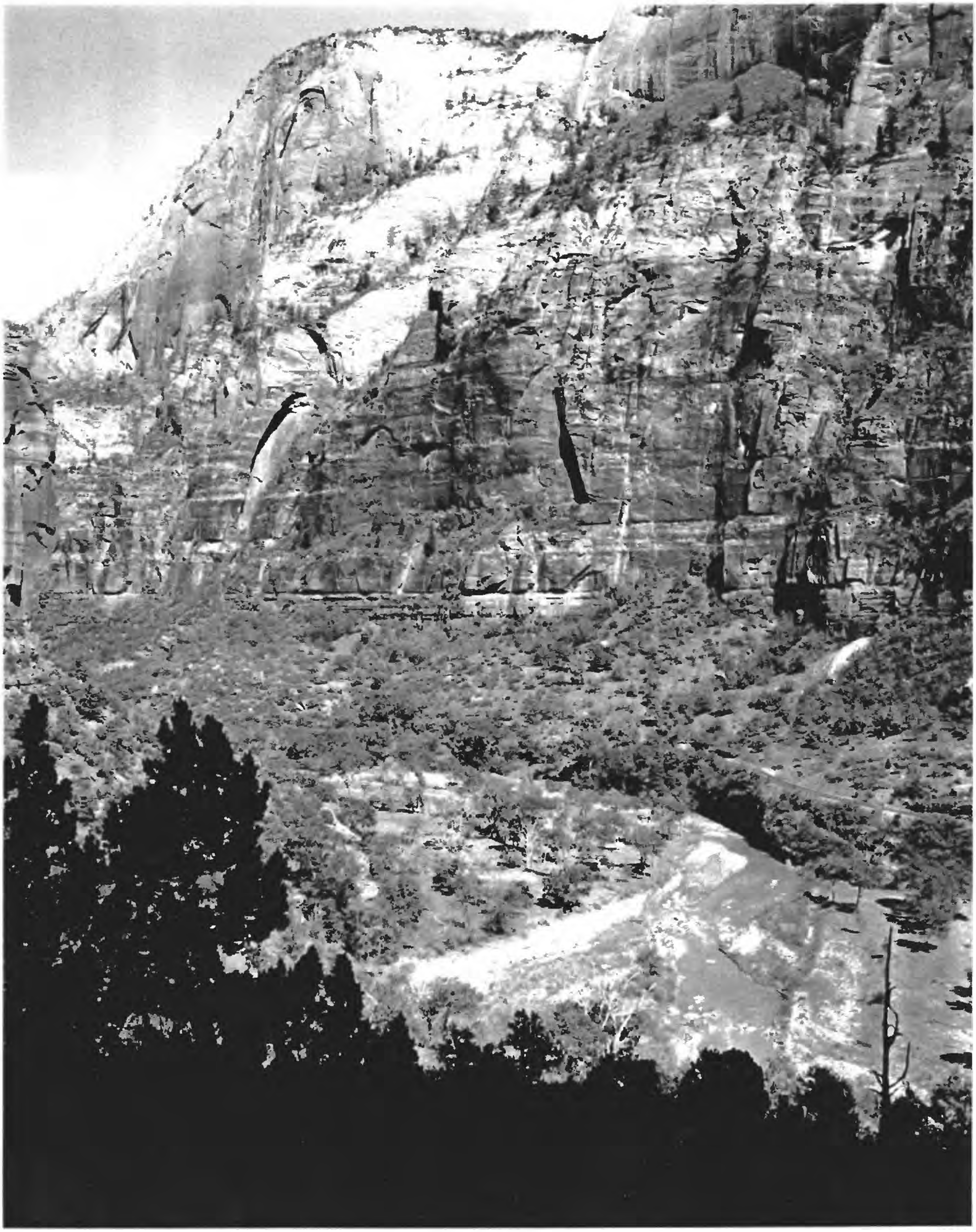
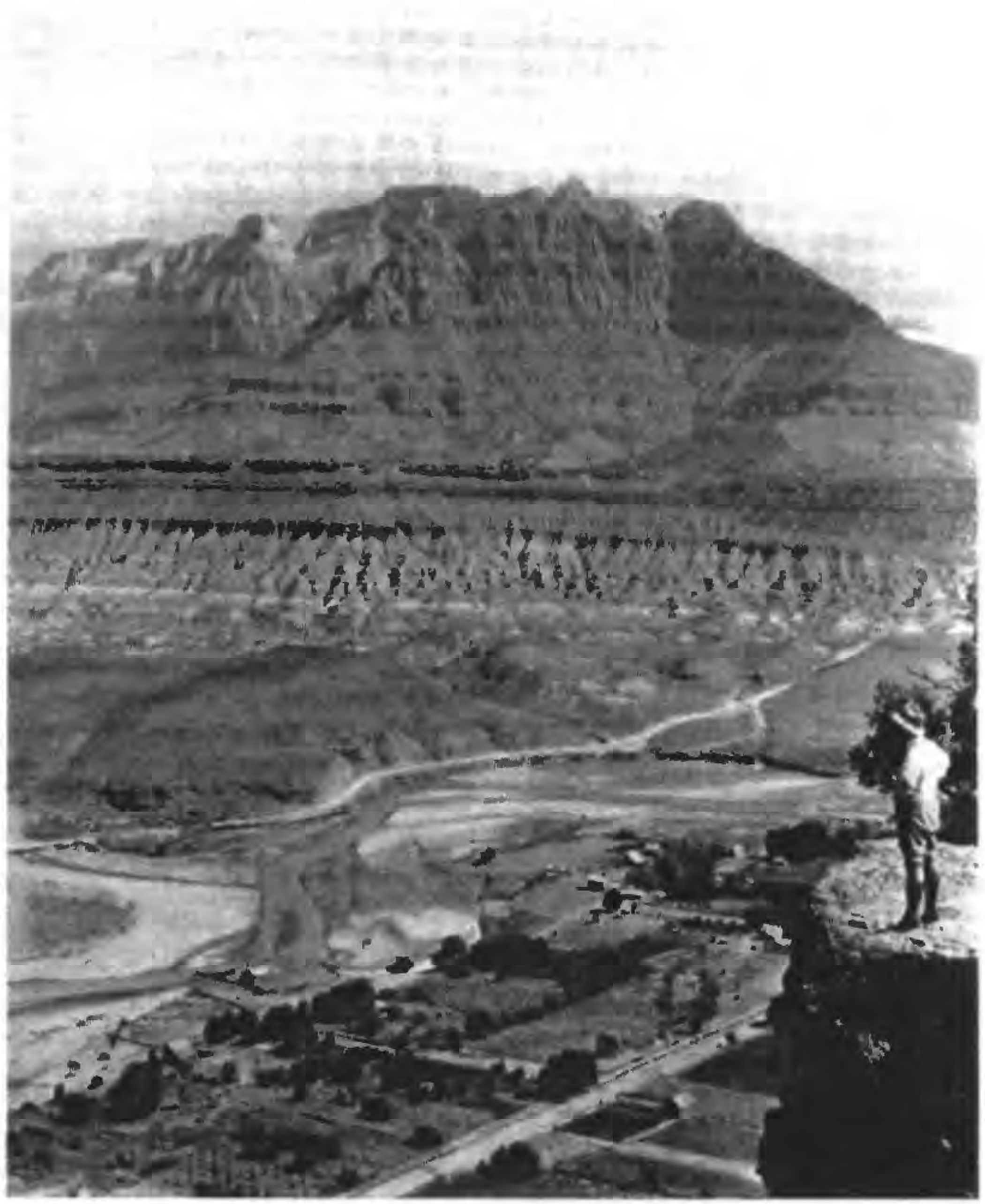
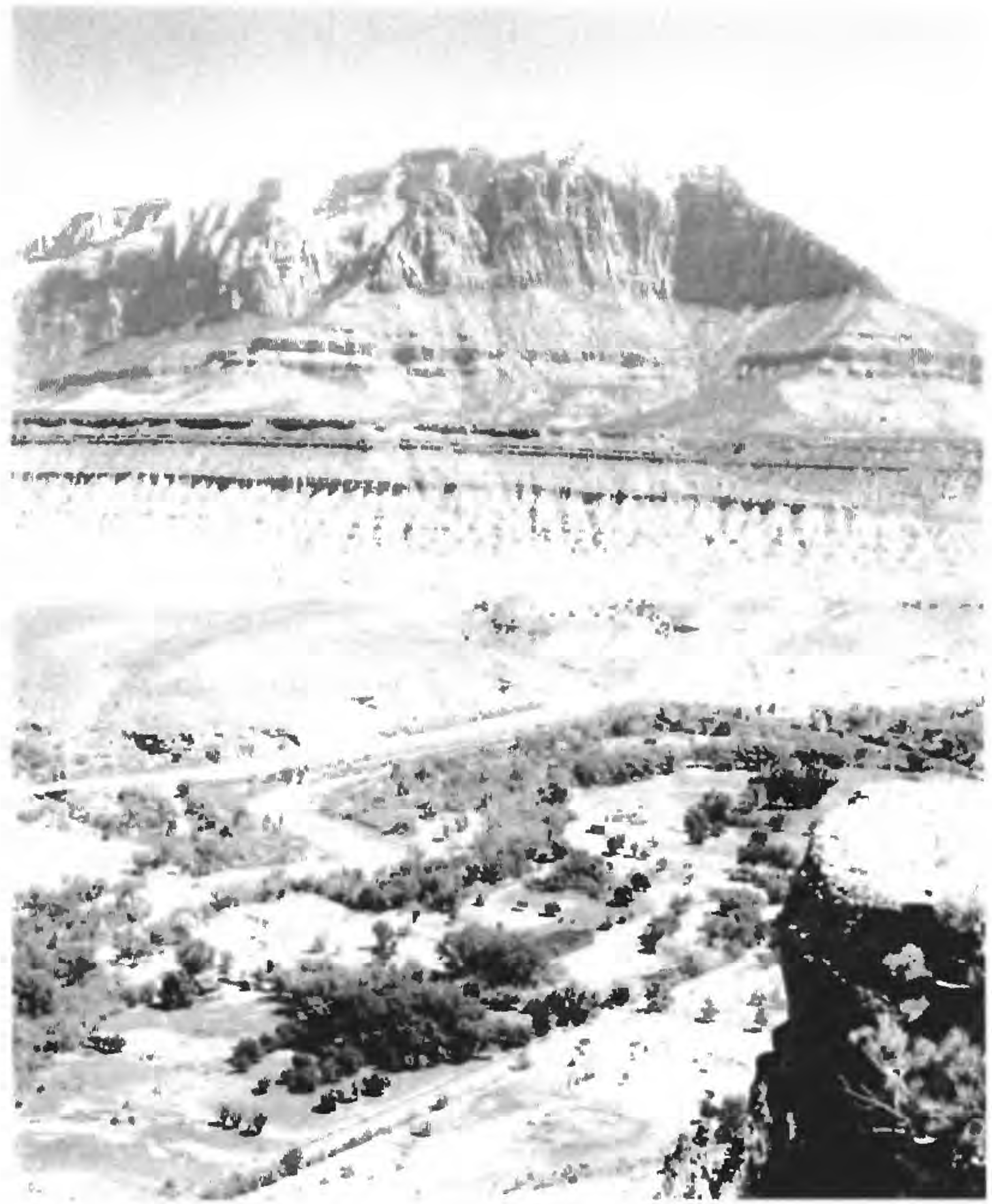


Figure 16 b.

Figure 17. Downstream view of North Fork from The Pulpit, 1909.



(A)



(B)

Figure 18. Upstream view of Virgin River showing Grafton and Coal Pits Wash. A) Mid-1920s and B) 1994

(A)

(B)

Figure 19. Downstream view of Virgin River between Springdale and Rockville. A) 1937 and B) 1994.

Figure 20. Johnson Mountain from site of Shunesburg. A) 1873 and B) 1994.

Figure 20b.

Figure 21. Downstream view of East Fork near Shunesburg. A) 1926 and B) 1994.

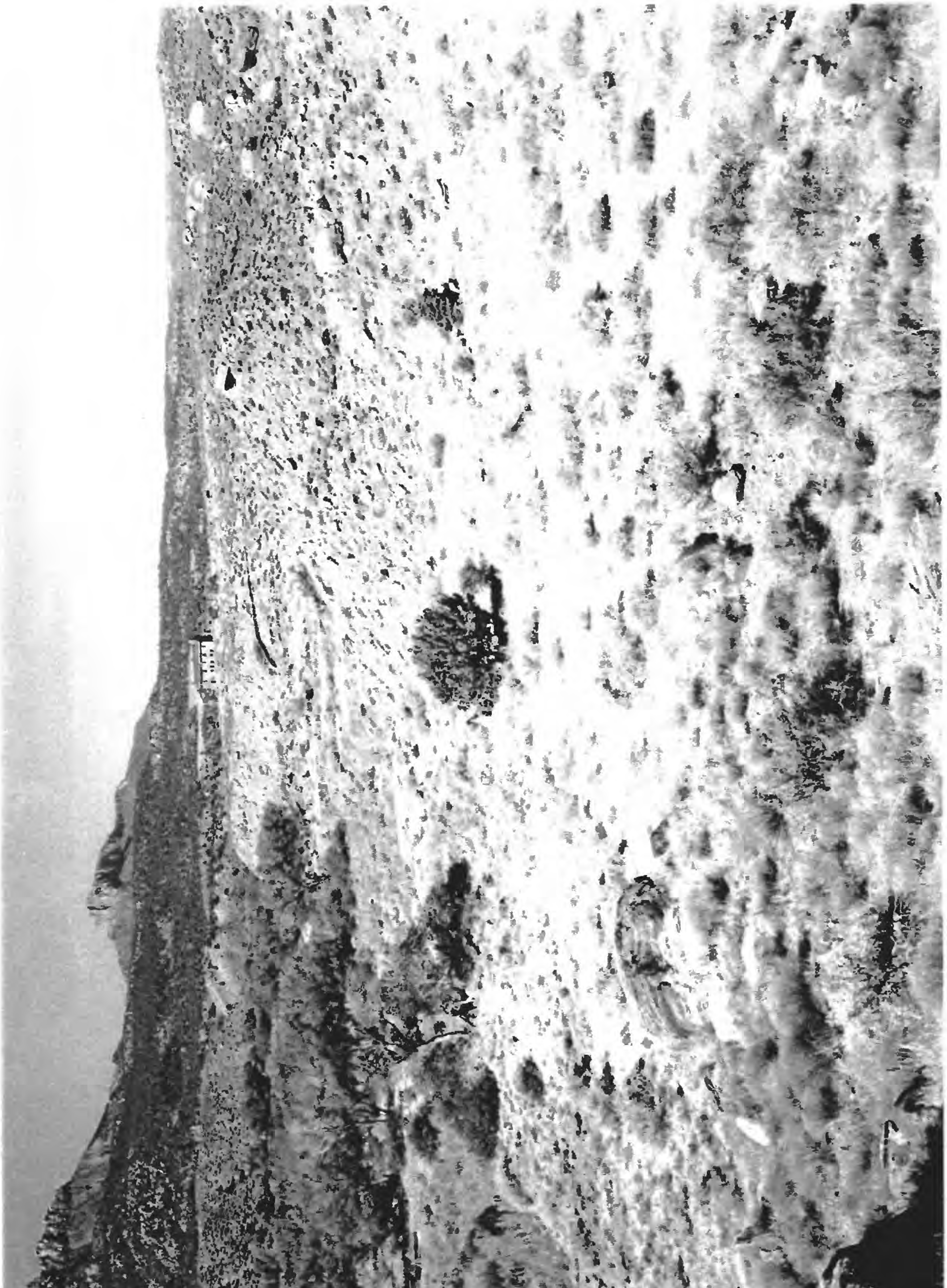


Figure 21b.

Figure 22. Upstream view of East Fork from prehistoric terrace at park boundary fence, 1936.

well-formed floodplain, and occupied most of the alluvial valley. The later photographs (figs. 19a and 22a) suggest that some relief had developed in the channel through point-bar and channel-margin deposition. These deposits are probably equivalent to the basal unit of the modern alluvium at the East Fork study site (figs. 5 and 8). Contemporary photographs show that channel width is decreased substantially, deposits of the modern terrace partly fill the former channel, and an open-canopy riparian woodland is present. Finally, first-order tributaries of East Fork were probably not entrenched in 1873, implying that the channel of East Fork was not entrenched either, as it is the baselevel control of the low-order tributaries.

STREAMFLOW HISTORY AND GEOMORPHIC CHANGE OF THE VIRGIN RIVER

In this section of the report, long-term variations of streamflow and the relation to geomorphic change are discussed. The purpose is to examine the temporal relations between variation of streamflow and dated geomorphic activity. The gaged record, which begins in 1910 at the gage near Virgin (fig. 1; gage 09406000), is used to develop a 303-year dendrohydrologic reconstruction of streamflow from A.D. 1690-1992. Dendrohydrological reconstruction is thought to be an effective and reliable means to study long-term variability of streamflow (Loaiciga and others, 1993). The reconstruction is done by calibrating ring width of pinyon growing on semiarid hillslopes to measured average flow rate on a year-by-year basis. Annual streamflow before 1910 was then estimated using the calibration function and ring width. This information is used to assess streamflow patterns during historic arroyo cutting and incision of the settlement terrace, geomorphic events that predate measured streamflow. Development of the historic, early modern, and modern terraces, are explained using the reconstructed and gaged discharge.

Calibration and Verification of Reconstructed Streamflow

The dendrohydrological model assumes that streamflow during the water year (October through September) is directly related to precipitation, which in turn controls to a large extent the ring width of trees growing in the river basin. Generally, precipitation from October through June accounts for about 80 percent of ring growth during the water year. Summer rainfall during the water year effects only about 6 percent of ring width variability (Fritts, 1976, p. 238, 412). Thus, calibration of ring width to measured streamflow establishes correlation between annual tree growth and October through June flow rates.

The analysis is done in two steps, calibration and verification. Calibration is done statistically by regression of standardized ring width against average daily discharge for water years 1910-1992. Verification tests the reconstructed streamflow against independent data such as historic accounts of floods and droughts and other dendrohydrologic studies in nearby areas.

The independent variable of the calibration regression is standardized ring width averaged between the two tree-ring study sites, and the dependent variable is log-transformed average daily discharge for the water year. Standardized ring widths, or ring-width indices, were calculated from the raw-width measurements to remove systematic changes of ring width related to the age of the sampled trees. The discharge data were transformed to reduce the positive skewness caused by large values. Water years 1972-1978 are missing from the gaged record; these missing data were estimated by using annual flow rates from the North Fork gage near Springdale (gage 09405501). Discharge of North Fork is highly correlated with the Virgin River downstream of the forks such that 95 percent of the annual variation of Virgin River discharge is explained by discharge of North Fork.

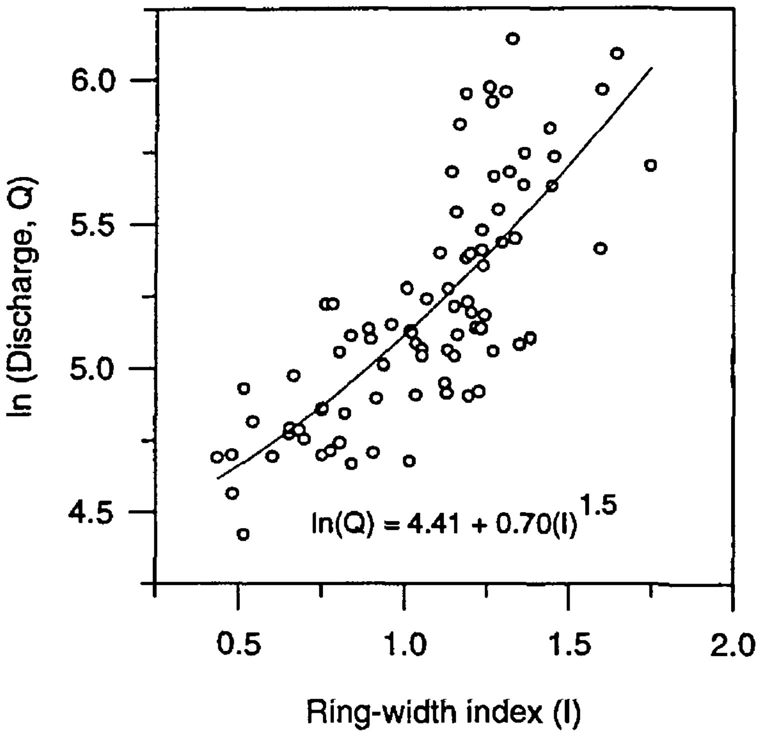


Figure 23. Natural logarithm of average-annual daily discharge (Q) as a function of ring-width index (I).

In the regression equation, the natural log of discharge (Q in ft^3/s) is a power function of the ring-width index (I).

$$\ln(Q) = 4.41 + 0.70(I)^{1.5} \quad (1)$$

The regression line and data are plotted in figure 23. The F-test for the significance of the regression gives F(1, 81) = 120.2; this is substantially larger than F = 7.0, which is the 0.01 significance level with 81 degrees of freedom. Thus, the probability that discharge is unrelated to ring width is much less than 0.01. Although far from perfect correlation, ring width accounts for 59 percent of the measured variability in annual streamflow.

A time series of the actual streamflow and streamflow estimated from equation (1) is shown in figure 24. For the most part, the estimated values track the measured data reasonably well; the peaks and troughs of the calibrated values are in phase with the data in 80 percent of the cases. The calibrated values are distinctly out of phase from 1927-1930 and in 1960. In addition, discharge above about 5 m^3/s (180 ft^3/s) is underestimated in many cases, the result of biologic limitations on tree growth. Water years 1922-1923, 1978-1980 and 1983 are examples of underestimation. Overestimation is less frequent, only 1914 and 1949 stand out.

Streamflow reconstructed with equation (1) from the full tree-ring chronology is shown in figure 25. This reconstruction is qualitatively verified from the flood history listed in Table 1, from an independently derived reconstruction in the lower Virgin River basin (Larson and Michaelsen, 1990), and from a tree-ring chronology in Kanab Creek basin (Webb and others, 1991).

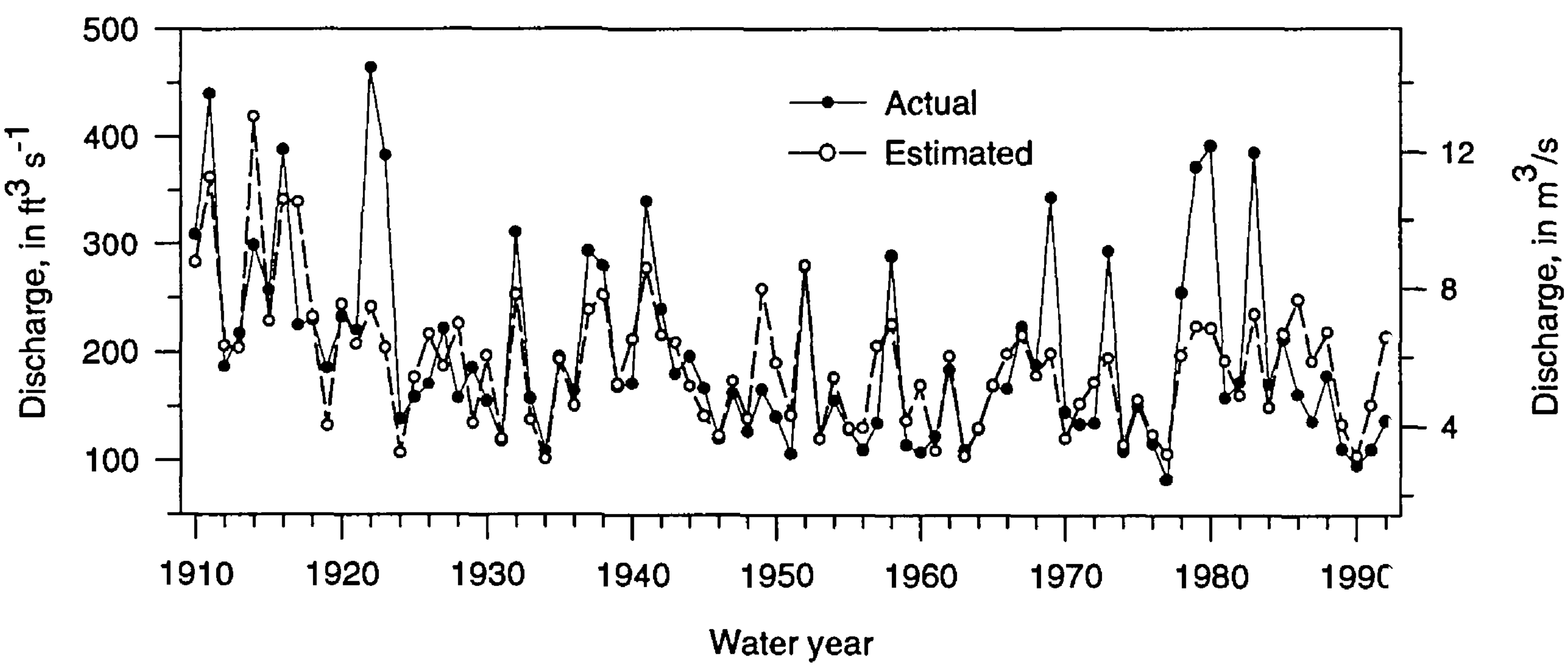


Figure 24. Time series of actual and estimated average daily discharge by water year of Virgin River near Virgin, Utah, 1910-1992.

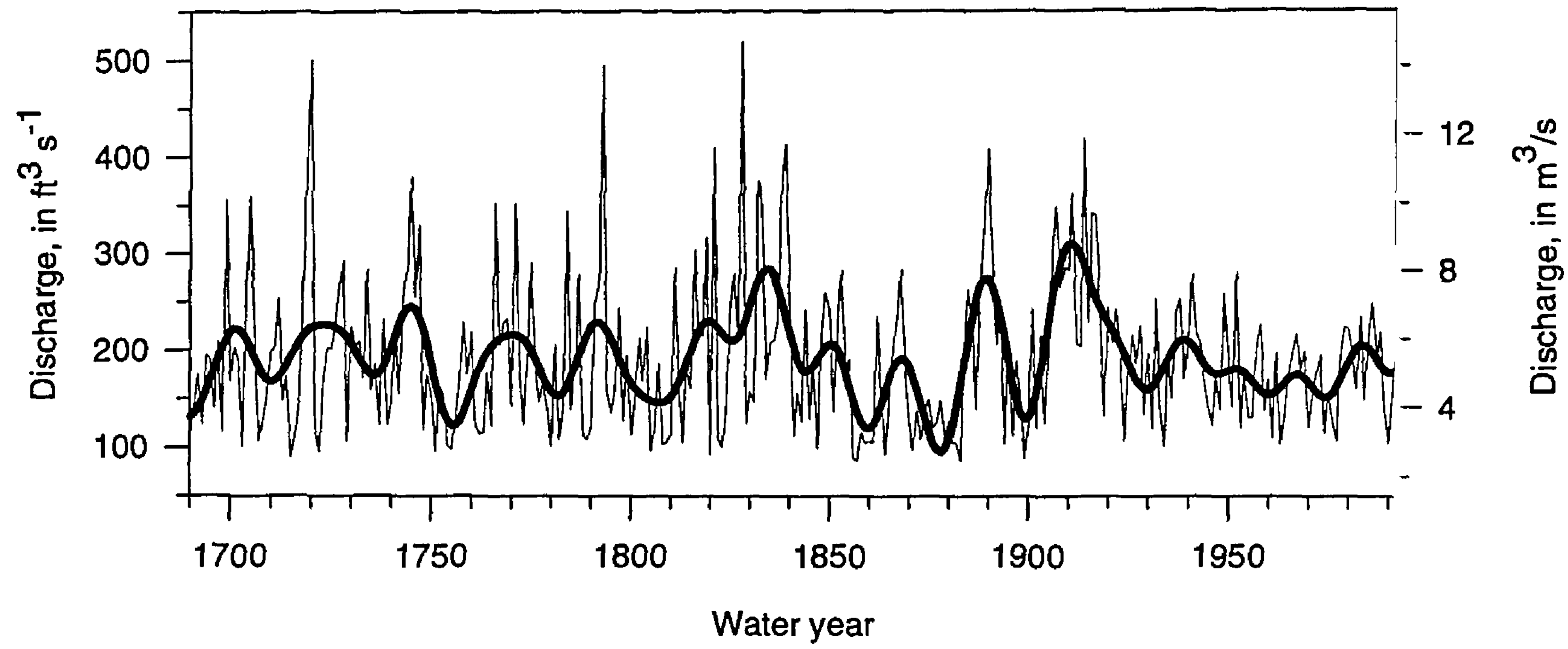


Figure 25. Reconstructed average daily discharge by water year, 1690-1992. Heavy line is discharge smoothed with fourier transform algorithm, smoothing level 35 percent.

Twenty-five floods of historic significance occurring in 21 years are listed in Table 1. Fourteen of the floods, or 67 percent (of 21), had estimated annual discharge significantly larger than the 95 percent confidence interval of the estimated long-term average discharge of 5.2-5.7 m^3/s (183-200 ft^3/s). Thus, in 67 percent of the cases, historically significant floods were associated with reconstructed discharge that was equal to or larger than the long-term average.

Streamflow of the lower Virgin River was reconstructed by Larson and Michaelsen (1990, figs. 8 and 9) from A.D. 966-1965. They used a tree-ring chronology from bristlecone pine on Charleston Peak in the Spring Mountains near Las Vegas, Nevada, 270-km southwest of the Virgin River gage. The data were calibrated to streamflow measured at the gage near Littlefield, Arizona (gage 09415000), which is south of St. George (fig. 1). The reconstruction of Larson and Michaelsen (1990) is broadly similar to figure 25 in the overlapping period, even though the distance between sites is large and the tree-ring chronology is from a different species growing outside the Virgin River basin.

The smoothed reconstructed streamflow has 21 peaks and troughs of about 5-10 years duration between A.D. 1700-1950 (fig. 25). These match 17 of the peaks and troughs in the Larson and Michaelsen (1990) reconstruction. In addition, they cite two historically recorded droughts, 1856-1857 and 1863-1864, that have discharge well below the long-term reconstructed average. Estimated average daily discharge in the study area for the four drought years is 2.5, 2.5, 4.3, and 2.6 m^3/s (88, 150, 92 ft^3/s), respectively. The earlier drought is among the driest 10 years in the 1,000-year reconstruction, although the later drought is overestimated substantially in the Larson and Michaelson (1990) reconstruction.

Finally, a tree-ring chronology in the Kanab Creek basin, which adjoins the Virgin River basin on the east (fig. 1), was developed from Ponderosa pine by Webb and others (1991, fig. 1-12). Although not calibrated to streamflow, the ring-width indices are similar to Virgin River reconstructed streamflow (fig. 25). The broad pattern of wet-and-dry years is well matched, and specific wet-and-dry years are matched in most cases. The high streamflow of the early 1880s to mid-1890s and from about 1910-1920 (fig. 25) is matched, respectively, by slightly above average to well-above average ring-width indices in the Kanab Creek chronology. In addition, a 5-year drought between 1896-1900 that seriously affected the cattle industry of the region (Gregory, 1950, p. 45) is well expressed in both chronologies, having the lowest ring-width indices in the two chronologies.

In short, verification shows that the reconstructed streamflow is consistent with historic accounts of heavy flood years in 67 percent of the cases. Moreover, the reconstruction is broadly consistent with the streamflow history of the lower Virgin River basin developed from tree-ring samples of different species growing outside the basin. Reconstructed streamflow of the upper Virgin River (fig. 25), therefore, is related to regional climate.

The Gaged Streamflow History, 1910-1992

Annual and Seasonal Streamflow

Streamflow of the Virgin River declined from 1910-1992. Figure 26 is a time series showing annual variation and long-term decline of average daily discharge. As estimated by the regression, average annual flow rates declined from about 7-4 m^3/s (250-140 ft^3/s) over the period of record. Streamflow was largest from 1910-1923, when even the driest years were wetter than most following years. After 1941, discharge was relatively low, except for 1952, 1958, 1969, 1973, 1980-1981, and 1983. This result is compatible with the reconstructed streamflow, which was consistently low after about 1940 relative to pre-1940 streamflow (fig. 25).

The decline of annual discharge results largely from variation of seasonal streamflow. Figure 27, shows average daily discharge by water year for fall (October-December), winter (January-March), spring (April-June), and summer (July-September). Spring is clearly the dominant streamflow season, having average daily discharge nearly twice as large as the other seasons. Over time, spring discharge has remained essentially constant, without a significant trend toward either higher or lower discharge (fig. 27c). Fall, winter, and summer discharge have decreased over time, however, and the trend is statistically significant (fig. 27a-b,d). The large annual streamflow from 1910-1923 (fig. 26) resulted from high streamflow during the latter three seasons combined with spring streamflow.

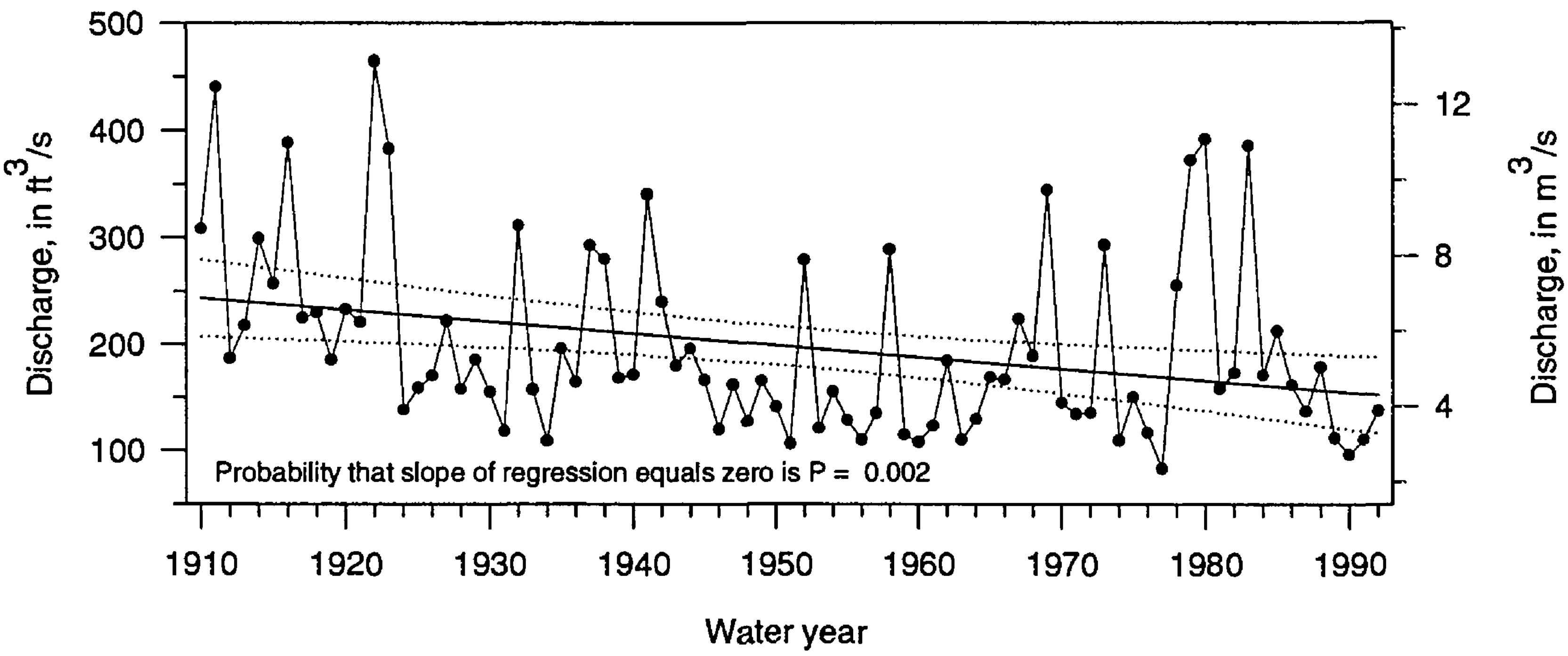


Figure 26. Time series of average daily discharge, 1910-1992. Regression line shows long-term, linear decline of annual discharge, dotted lines are 95 percent confidence interval of regression.

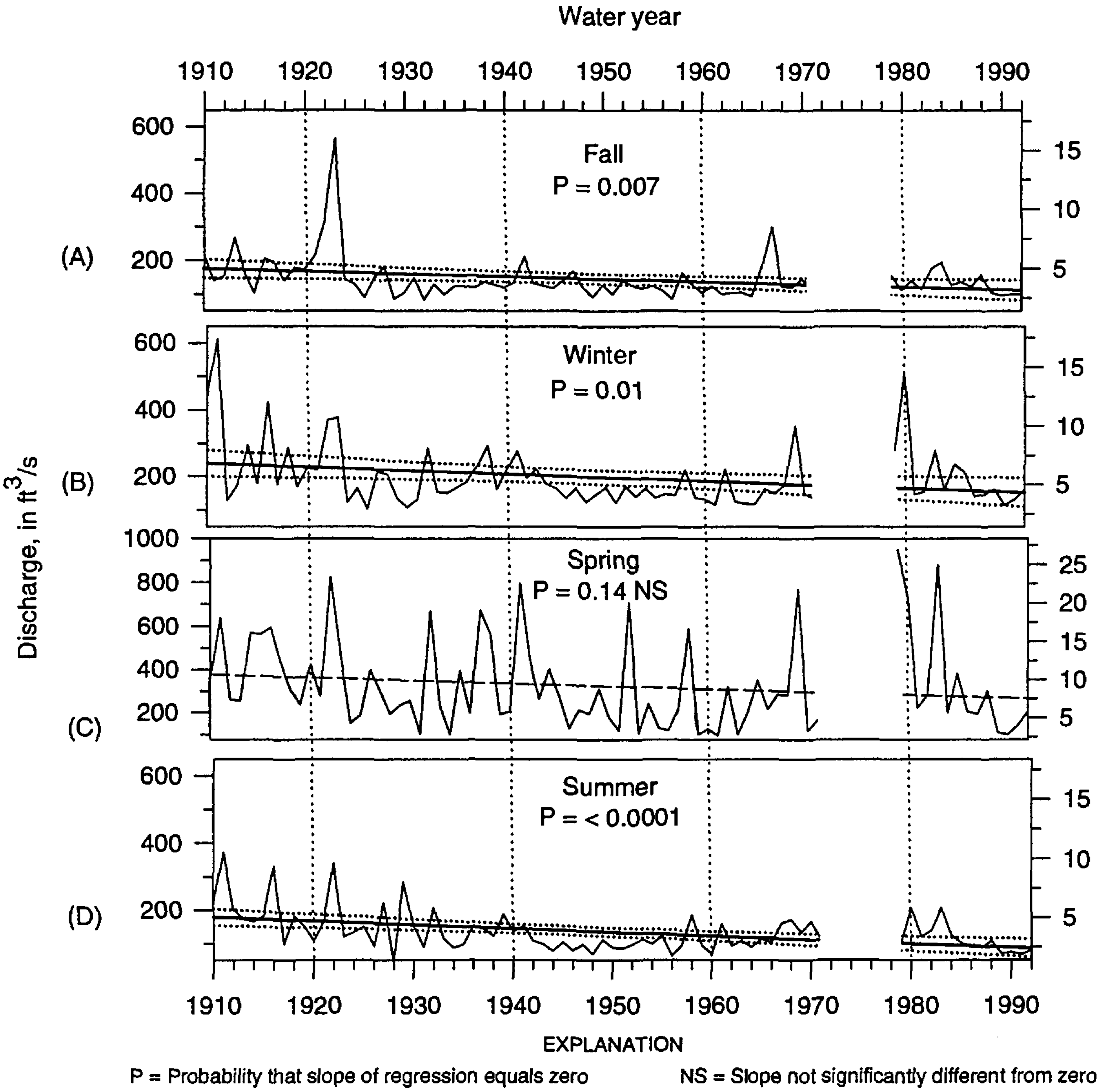


Figure 27. Time series of A) fall, B) winter, C) spring, and D) summer average daily discharge, 1910-1992. Data for 1972-1978 are missing. Regression line shows long-term, linear decline of discharge, which is not statistically significant for spring (dashed line), dotted lines are 95 percent confidence interval of regression.

Variation of seasonal streamflow is further illustrated in figure 28, a time series showing annual deviation in percent from the long-term seasonal average. Discharge of all four seasons was typically above or near the long-term seasonal average for most of 1910-1923 (fig. 28), and summer discharge remained at these elevated levels discontinuously until 1939 (fig. 28d). After about 1923-1930, fall and winter flow rates remained at or below the long-term average (fig. 28a-b). Spring streamflow was relatively constant, however, and this season has produced most of the annual streamflow since about 1930. Only one year, 1980, approached the earlier conditions of large spring, winter, and summer flow rates (fig. 28b-d).

Long-term decline of seasonal discharge of the Paria River is similar to the Virgin River, except the decline is in the fall and winter partial-duration flood series (Graf and others, 1991). Runoff in the Paria River basin is in fall, winter, and summer with only negligible spring runoff. During the period 1923-1986, winter, summer, and fall

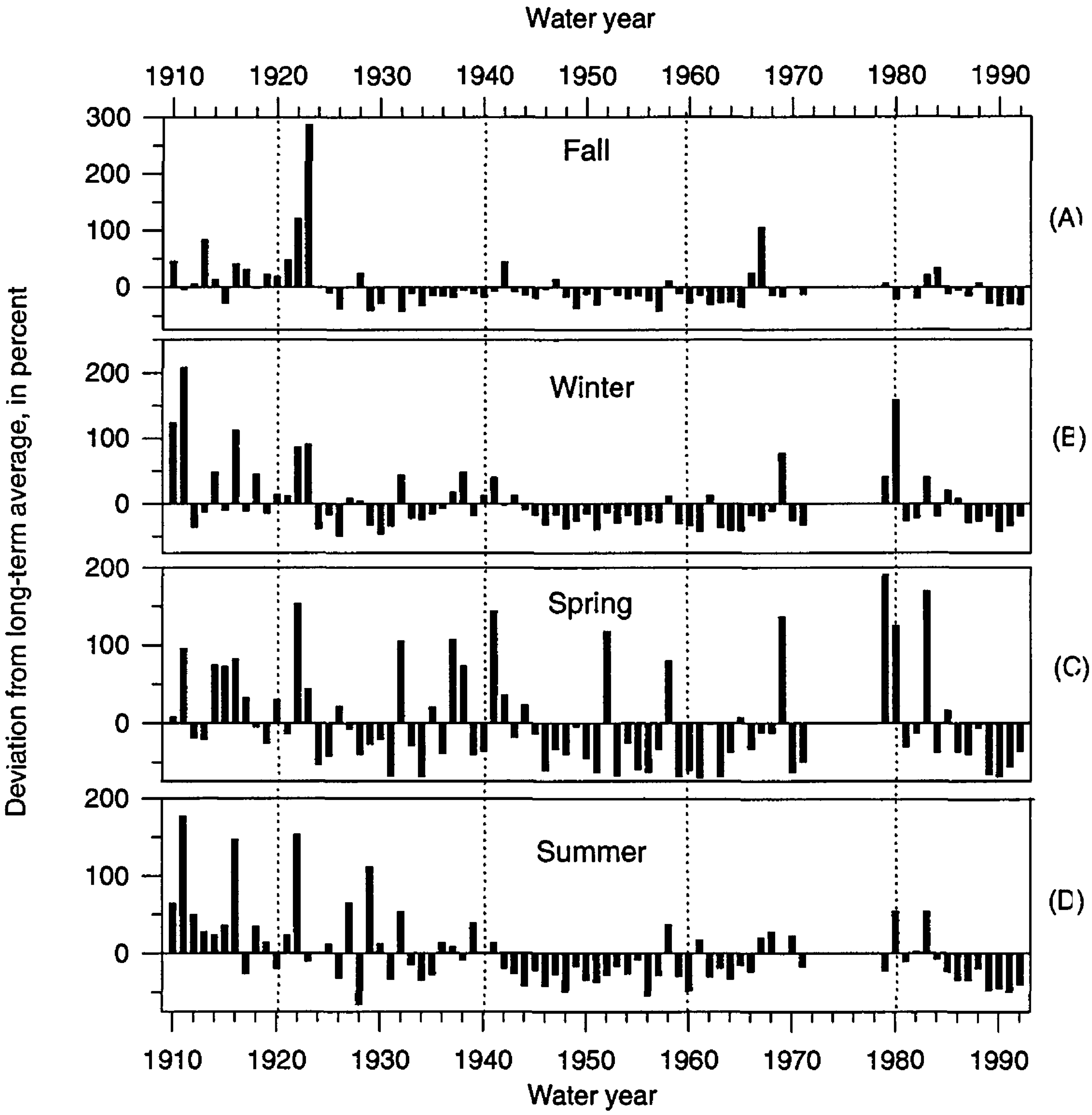


Figure 28. Time series of deviation in percent from long-term average flow rates, 1910-1992. A) fall, B) winter, C) spring, and D) summer. Data for 1972-1978 are missing.

constituted 42, 26, and 25 percent of the average annual flow volume, respectively. Summer and fall floods are evenly distributed in time and both decrease in magnitude. Winter floods are less frequent, unevenly distributed in time, and are without a long-term trend. Thus, the early period of large fall and summer runoff in the Virgin River basin (figs. 26-27) was also typical of the Paria River basin, as suggested by declining seasonal-flood magnitudes.

Annual Flood Series

Figure 29 shows the statistics of the annual peak flood by season (fig. 29a) and a time series of the annual flood classified by season (fig. 29b). The annual peak flood occurs in every season, but is most frequent in summer. These summer flood peaks have little affect on average summer streamflow because of short duration, which is substantially less than average spring streamflow (fig. 27). Annual flood peaks in spring are infrequent, although the largest spring flood is close to the largest winter and summer peak flood. The largest annual flood was in fall and was almost twice the size of the largest flood of the other seasons (fig. 29a).

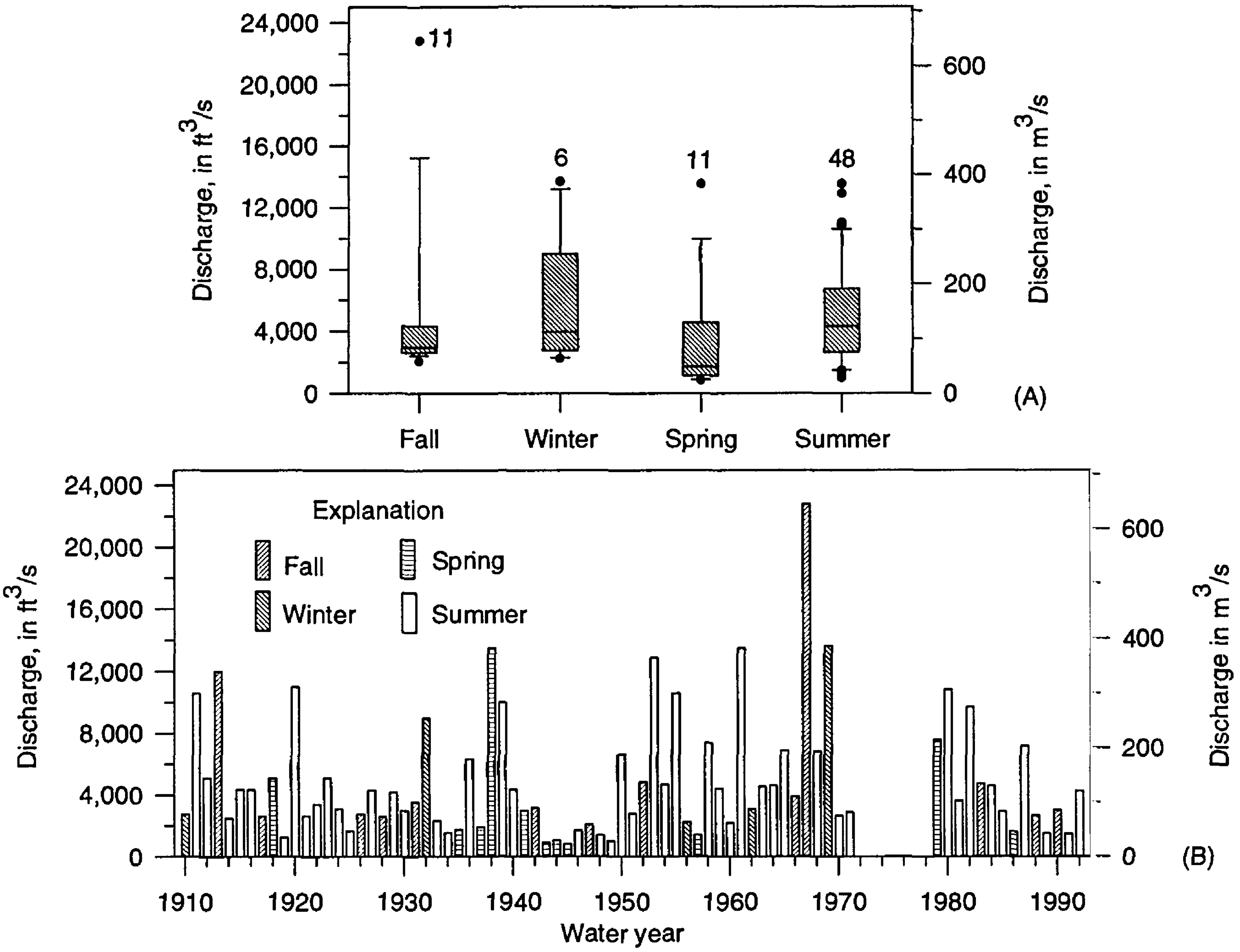


Figure 29. Discharge of the annual flood. A) Statistical summary of the annual flood by season; box shows median and 25-75th percentile, vertical line is range of 10-90th percentile, and solid circles are values less than 10th and greater than 90th percentiles, respectively. Number of floods shown at top of upper vertical line. B) Times series of annual flood, 1910-1992. Data for 1972-1978 are missing.

The time series of annual floods shows little if any change in either flood magnitude or seasonality (fig. 29b). The annual flood was in the summer from 1919-1925 and from 1979-1992, with the exception of 1986 and 1990. A mixed seasonality of low annual floods during spring, fall, and summer was typical of the period 1941-1949. The flood of record, with a flow rate of 646 m^3/s (22,800 ft^3/s), was on December 6, 1966. According to Enzel and others (1994), this flood may have been as large as the previously discussed flood of 1862 (Table 1). Although one of the largest floods since 1862, the geomorphic effects are negligible in East Fork and North Fork. Six of the floods in figure 29b--1911, 1912, 1920, 1929, 1938, and 1967 (calendar year 1966)--are among the historically noted floods listed in Table 1. Damage from these six floods was substantial, even though four floods of similar size (1953, 1955, 1961, and 1980) did not cause enough damage to warrant attention.

The annual flood series has little obvious relation to historic geomorphic change of the Virgin River. Changes in the morphology of the river channel, therefore, result mainly from variation of seasonal streamflow rather than long-term variation of the annual flood. This conclusion is supported by a study of sediment load and channel adjustment by E.D. Andrews (written commun., 1993).

Eighty percent of the average annual sediment load is transported during the 13 and 24 highest days of streamflow at the North Fork and East Fork study sites (fig. 1), respectively. These long-duration high flows transport large quantities of sediment and modify channel morphology. High-transport rates are typical during spring; however streamflow was also high during summer, fall, and winter during the early 1900s (fig. 27). Although high-magnitude streamflow has large instantaneous transport rates, the streamflow is of short duration and relatively infrequent. These large events typically carry only a small part of the long-term average sediment load.

Nevertheless, infrequent and large floods are clearly associated with channel erosion during the late 1800s and early 1900s (Table 1). The high-seasonal flow rates of this era probably destabilized the channel, enhancing erosion by infrequent, short-duration high-magnitude floods. Thus, at times of high-seasonal streamflow, these large floods are competent to modify the channel erosionally; conversely, when seasonal streamflow is low, floods of similar size are not particularly erosive.

Streamflow and Geomorphic Change

Geomorphic change in the alluvial valleys is broadly contemporaneous with discharge variations that result in deposition or erosion. The main depositional periods led to accumulation of the prehistoric, settlement, and modern alluviums. Erosional periods resulted in floodplain abandonment, downcutting to lower depositional levels, and formation of the prehistoric, settlement, historic, and modern terraces.

Streamflow during erosion of the prehistoric terrace is not known in the study area. In the lower Virgin River basin, however, streamflow in the period A.D. 1200-1400 was consistently higher than the unusually high levels around A.D. 1880-1920, as inferred from Larson and Michaelsen (1990, fig. 9). This early episode of consistently high streamflow probably coincides with entrenchment of the prehistoric alluvium (fig. 10). Conversely, a period of relatively low streamflow from about A.D. 1400-1880 coincides with deposition of at least the upper settlement alluvium, although dating is necessary to determine when deposition of the settlement alluvium began. Figure 25 shows that streamflow between A.D. 1700-1839 was at times larger than any subsequent streamflow. However, these were isolated, short-term occurrences that lasted only 1-3 years. In any case, geomorphic evidence suggesting that the settlement alluvium was eroded before A.D. 1883 was not found.

Reconstructed streamflow of the upper Virgin River and dated geomorphic events from 1850 1992 are shown in figure 30. The smoothed streamflow curve is used for interpretation because the large annual variability of reconstructed and actual streamflow obscures the general correspondence between streamflow and dated terraces. In addition, the smoothed curve has resolution that is roughly comparable with the uncertainties in dating the terraces. Entrenchment of the settlement terrace was between 1883-1892 or 1893, as suggested by dendrogeomorphic evidence (figs. 5, 9). This initial entrenchment coincides with about 12 years of unusually high streamflow between 1883-1895 that peaked in 1890 (fig. 30). A second episode of unusually high streamflow lasting 20-30 years was between the early 1900s and the mid-1920s to 1930; flow rates were largest from 1906-1917. The wide, flat-floored channel of this era (figs. 15, 21) now forms the historic terrace. Development of this terrace coincides with the latter part of the early high-flow episode as well as the second episode of high streamflow.

The early modern terrace and basal unit of the modern alluvium developed in the flow regimen of the mid-1920s to late-1930s. The terrace and deposits apparently record incipient deposition in the historic-age channel (figs. 19, 22) during a period of relatively low streamflow (fig. 26). This flow regimen developed after a drop in fall, winter, and summer

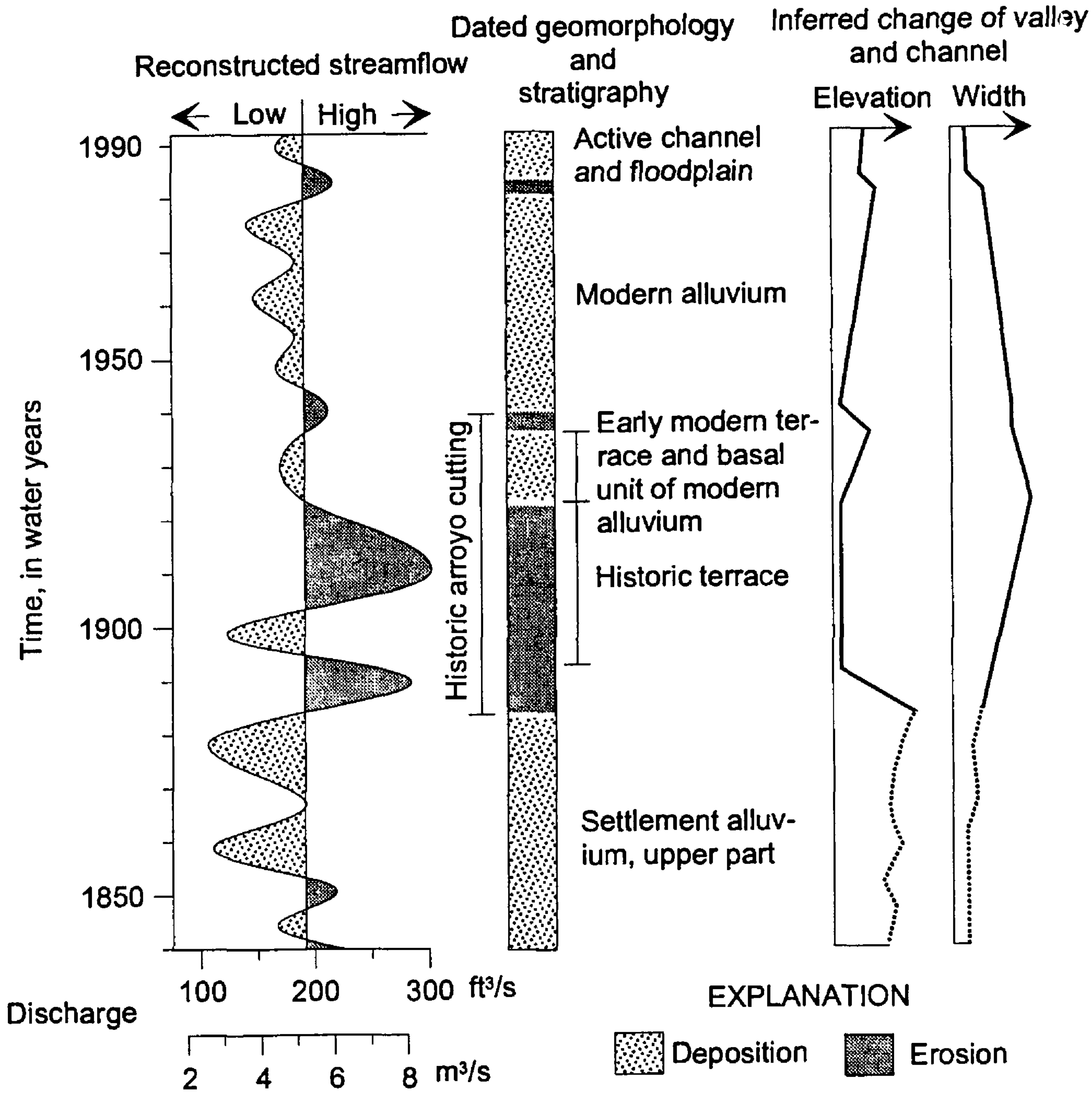


Figure 30. Reconstructed streamflow, dated geomorphology and stratigraphy, and inferred change in width and elevation of valley and channel, respectively, 1850-1992. Streamflow data smoothed with fast fourier transform algorithm, smoothing level 32 percent.

runoff (fig. 27). High streamflow during the late 1930s and early 1940s (fig. 26) evidently reestablished the channel below the historic and early modern terraces. Deposition of the modern alluvium beginning about 1940 was coincident with low-flow conditions from the early 1940s until the late 1970s. Most of the runoff during accumulation of the modern alluvium was during spring with little contribution from fall, winter, or summer runoff. Finally, during the early 1980s, minor channel adjustment during an episode of increased streamflow (fig. 26) eroded the modern alluvium, forming the active channel and floodplain.

In summary, historic channel instability as expressed by widening and deepening (fig. 30) was during two periods of high streamflow that lasted several decades in the case of historic arroyo cutting and perhaps several centuries in the case of prehistoric arroyo cutting. The gaged streamflow record indicates that discharge in the early part of the 20th century was above average during three of four seasons. This produced high-annual flow rates, which in turn increased sediment transport rates and destabilized the channel. Conversely, a decline of streamflow in fall, winter, and summer reduced sediment transport rates, leading to channel stability and floodplain accretion. These relations may apply to entrenchment of the prehistoric terrace and aggradation of the settlement alluvium, although the seasonal distribution of streamflow is unknown during this time. Entrenchment of the prehistoric terrace probably happened during a 200-year episode of high streamflow from about A.D. 1200-1400. Aggradation of the settlement alluvium was probably during relatively low streamflow between A.D. 1400-1880.

A generalized model of fluvial erosion and deposition for the Virgin River is suggested by the association of geomorphic activity with streamflow variations. Arroyo cutting is evidently linked to periods of increased streamflow lasting at least several decades. This increased streamflow supplies excess transport capacity that eventually destabilizes the channel resulting in widening and deepening. When the channel is unstable, large floods are particularly effective at eroding the channel margin. Increased streamflow results from above normal runoff during fall, winter, and summer that augments the normally high spring discharge. Conversely, deposition and relative channel stability are probably linked to periods dominated by spring runoff lasting several decades or even several centuries. As the channel stabilizes, large floods are relatively ineffective at modifying the channel erosionally; instead floods probably spread sediment across the floodplain, causing aggradation of the channel system. Streamflow during depositional episodes is relatively low because fall, winter, and summer runoff probably do not contribute substantially to annual or long-term streamflow.

Causes of Long-Term Streamflow Variation

Landuse

Precipitation variability and human activity, particularly grazing, were probably the main causes of streamflow variation and geomorphic change in the Zion National Park area. Landuse began to alter runoff to some extent beginning with settlement of southwest Utah around 1860 (Bailey, 1935). Extensive overgrazing alters the rainfall-runoff relation by soil compaction and destruction of vegetation, thereby reducing infiltration and increasing runoff. Overgrazing by large herds of sheep and cattle is believed by regional historians to have produced progressively larger floods, eventually leading to abandonment of Shunesburg (Stromberg, 1992) and other communities along the Virgin River. Erosion was contemporaneous with large-scale cattle and sheep ranching that reached a maximum around 1900-1914 (Gregory, 1950, p. 44-45), this coincidentally was a time of unusually high streamflow (figs. 25-26).

Likewise, conservation measures and grazing control brought about by establishment of the national forests and enactment of the Taylor Grazing Act of 1934 should result in channel stabilization and deposition of the modern alluvium. Overgrazing has been controlled or at least reduced by limiting the number of cattle and sheep allowed to graze on public lands. In addition, numerous stock tanks and small reservoirs have been constructed in the basin. These structures are designed to water cattle and distribute grazing use, but the structures also reduce peak-flow rates and sediment load. The descendants of pioneer families believe that restricted grazing and other conservation measures have resulted in fewer large floods (DeMille, 1982).

Nevertheless, landuse practices were quite likely not the single cause of historic arroyo cutting or channel stabilization, although the effects of overgrazing may have exacerbated the rate and extent of channel entrenchment and widening. The tree-ring chronology strongly suggests that during the mid-1850s to about 1920-1930 precipitation was extremely variable. This period was characterized by both the least and most precipitation in 300 years. This extreme variability is illustrated in figure 31, a time series of the smoothed tree-ring indices used in the streamflow reconstruction. Smoothing is necessary to remove the high year-to-year annual variability that is characteristic of ring-width data (Dean, 1988). For the 303-year record, the mid-1850s, mid-1870s, and late 1890s were the second, third, and fourth driest periods, respectively; whereas the wettest periods were the mid-1880s to mid-

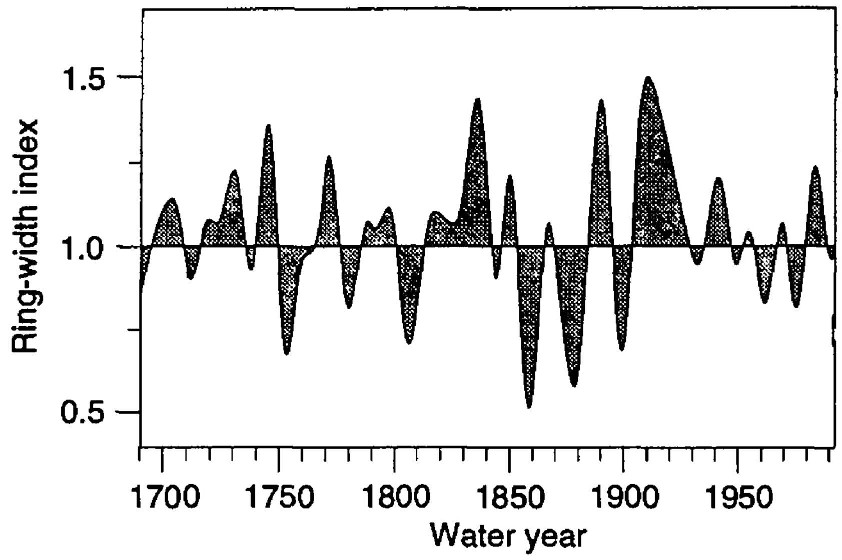


Figure 31. Time series of smoothed ring-width indices, 1690-1992. Pattern shows above and below normal growth indices. Smoothing done with fourier transform algorithm, smoothing level 32 percent.

1890s and early 1900s to about 1920-1930, which tie for second wettest and wettest, respectively. The latter wet period was the longest episode of high precipitation since about A.D. 1400, according to the streamflow reconstruction of Larson and Michaelsen (1990).

Historic arroyo cutting followed settlement of the region closely, but erosion was also contemporaneous with some of the wettest and driest climate since A.D. 1400. The combination of very dry conditions followed by extreme moisture between the mid-1850s to mid-1890s (fig. 31) was probably sufficient to initiate arroyo cutting, which was further enhanced during the second occurrence of high precipitation and streamflow from 1900 to about 1920-1930. The two dry periods that preceded widespread arroyo cutting probably weakened channel and hillslope vegetation, thereby increasing runoff during the unusually wet climate beginning in the mid-1880s. This information suggests that arroyo cutting resulted in part from the climate variations of the mid- to late 1800s. Settlement of the region, introduction of livestock, overgrazing, and removal of vegetation probably intensified erosion, but it seems unlikely that these were the only causes of arroyo cutting.

Deposition of the modern alluvium and related stabilization of the channel probably did not result entirely from control of grazing, increased water diversion, or construction of water-retention structures. Diversion of water for agricultural and domestic purposes accounts for only a small amount of annual streamflow. Grazing control and water-retention structures probably improved range conditions and reduced peak-flow rates locally. However, the effect of this activity was probably not large, because it is not apparent in the annual flood series, which has not declined over time (fig. 29). Indeed, annual peak floods after 1950 are among the largest of the measurement period. In short, historic arroyo cutting and subsequent channel stabilization resulted mainly from variation of precipitation that in turn controlled streamflow, although human activity probably intensified erosion and might have enhanced stabilization of the channel resulting in deposition.

Climate Variation

The late Holocene is a time of global climate variability, beginning with the Little Climatic Optimum, or Medieval Warm Period, from about A.D. 900-1300 (Lamb, 1977, p. 435-449), the Little Ice Age from about A.D. 1400 to the mid-1800s (Bradley, 1985, p. 239; Grove, 1988, p. 241-262), and global warming beginning in the late 1800s (Lamb, 1982, p. 247-251). The Medieval Warm Period is recognized in Europe and is noted for above average temperatures and generally favorable conditions. The Little Ice Age is defined largely on the basis of glacial advances in mountainous regions.

How or if Colorado Plateau climate was affected during the Medieval Warm Period and Little Ice Age is not well known. The warm interval is based on European history and the Little Ice Age is recognized from glacial activity that has no immediate corollary on the Colorado Plateau. Global warming, however, is evident in historic temperature records from the southern Colorado Plateau (Hereford, 1984, fig. 15).

Aggradation of the prehistoric and settlement alluviums was partly contemporaneous with the Medieval Warm Period and Little Ice Age, respectively. The effect of the warm interval on southern Colorado Plateau climate is poorly understood. Dean (1994) found little correspondence between the 400-year warm interval and temporal variations of human adaptive behavior and hydroclimatic indicators such as groundwater levels and floodplain deposition and erosion. He concluded that the Medieval Warm Period could not be viewed as an interval of consistent climate; rather it was an interval of environmental variability that differed little from the variability that is typical of the past 2,000 years.

A somewhat different conclusion was reached by Petersen (1994) for the eastern Colorado Plateau and the southern San Juan Mountains based on pollen studies of pinyon. Summer rainfall is important for establishment of pinyon. The abundance of pinyon determined from pollen studies, therefore, is an indicator of the long-term strength of the summer monsoon (Petersen, 1994). Pinyon were particularly abundant between A.D. 750-1150, suggesting that summer rainfall was at least comparable to present levels. In addition, during the height of the Medieval Warm Period from A.D. 1000-1100, the region was characterized by a more vigorous atmospheric circulation resulting in both wetter summers and winters than at present. Thus, the Medieval Warm Period could have produced anomalous precipitation and temperature patterns that effected deposition of the prehistoric alluvium of the study area as well as the Tsegi and Chaco formations. However, initial deposition of the latter two alluviums and probably the prehistoric alluvium as well predates this warm and wet interval. The relation between climate of the Medieval Warm Period and fluvial activity is evidently not clear, as Dean (1994) suggested.

During the Little Ice Age from about A.D. 1300-1850, as temporally placed by Petersen (1994), pinyon was relatively scarce at the eastern margin of the Colorado Plateau, which he attributes to relatively cool and dry conditions. These conditions resulted from less vigorous atmospheric circulation that decreased summer rainfall and presumably lowered temperatures. There may be some connection between deposition of the settlement alluvium and the Little Ice Age climate described by Petersen (1994). Relatively dry conditions in the Virgin River basin during this time are suggested by the reconstructed streamflow of Larson and Michaelsen (1990). Streamflow at this time was probably dominated by spring runoff with little contribution from fall, winter, or summer. These are the seasonal streamflow patterns associated with deposition of the modern alluvium, which could also pertain to deposition of the settlement alluvium if conditions persisted for at least several centuries. In short, there appears to be only a weak link to deposition of the prehistoric and equivalent alluviums with the climate of the Medieval Warm Period. However, deposition of the settlement alluvium during an interval of relatively low runoff is at least broadly consistent with Little Ice Age conditions.

Generally, the erosion around A.D. 1200-1400 and 1900 ensued during the transition from one climate regimen to another. The early erosional episode was between the end of the Medieval Warm Period and the beginning of the Little Ice Age, and historic arroyo cutting happened near the end of the Little Ice Age. Little is known about climate during the early entrenchment, although streamflow of the Virgin River was unusually high, implying that precipitation conditions enhanced runoff, thereby increasing erosion and channel instability.

Climate during historic arroyo cutting is somewhat better understood. The anomalous climate beginning in the mid-1850s to mid-1860s (figs. 25, 31) may arise from the strong and frequent warm ENSO (El Niño Southern Oscillation) conditions that prevailed from 1864-1891 (Quinn and others, 1987). A complex system of global climate fluctuations, ENSO typically increases rainfall in the Southwest from April through

October (Ropelewski and Halpert, 1986), although weather at other times of the year is also affected. During ENSO conditions, a warm pool of water is present in the eastern Pacific Ocean near the equator that is a source of precipitable moisture for advection into the Southwest (Cayan and Webb, 1992). In addition, the strength of the jet stream increases during ENSO conditions, guiding weather disturbances into the Southwest.

Generally, runoff producing precipitation in the Southwest results from four storm types--frontal systems, monsoonal storms, dissipating tropical cyclones, and cut-off low pressure systems (Webb and Betancourt, 1992, p. 6-10). ENSO conditions tend to increase the severity and frequency of these storm systems, although the affect is complex, variable from one ENSO to another, and poorly understood in most cases. The amount of precipitation and severity of frontal-type winter storms increases during ENSO, leading to large floods in high-elevation basins such as the Virgin River (Cayan and Webb, 1992). Dissipating tropical cyclones tend to occur during ENSO, and precipitation is extremely high in some cases. However, monsoonal rainfall is apparently little affected by ENSO (Hereford and Webb, 1992). Cut off-low pressure systems probably increase in number during ENSO, leading to flooding in the fall months. The unusual ENSO activity from 1864-1891 evidently increased precipitation year-around, resulting in frequent heavy floods and high runoff.

The ENSO activity that increased precipitation evidently continued in some form through about 1930-1940. Michaelsen (1989) found that 1917-1941 was a high-amplitude ENSO phase, a pattern recurring every 80-100 years on average that is dominated by strong to moderate ENSO activity. This pattern was also associated with a dominance of meridional atmospheric circulation from at least 1899 to about 1930. This circulation involves large north-south excursions of the polar jet stream that increase the number and severity of Pacific storms in fall and winter particularly during ENSO conditions (Webb and others, 1991).

Meridional circulation and the high-amplitude ENSO phase of the early 1900s affected climate of the southern Colorado Plateau and Virgin River basin. The reconstructed streamflow and tree-ring chronology (figs. 25, 31) show that annual precipitation and runoff were unusually high from 1900 to about 1920-1930. The gaged record shows that seasonal runoff from 1910 to about 1920-1930 was unusually high, except for spring (fig. 27). Warm-season rainfall over the southern Colorado Plateau was above normal from 1900 (when widespread instrumentation began) until about 1930-1940, this is the longest interval of above normal warm-season rainfall during the 20th century (Hereford and Webb, 1992). Similar results were obtained by Balling and Wells (1990) in the Zuni River basin of New Mexico.

The relatively low discharge levels of the post-1940 era that led to deposition of the modern alluvium resulted in part from a breakdown of the previous ENSO pattern and a decrease of meridional circulation. The earlier high-amplitude ENSO phase decreased into a low-amplitude phase dominated by weak ENSO after the early 1940s (Michaelsen, 1989). Weakened and reduced ENSO would alter precipitation patterns through less frequent tropical cyclones and less vigorous atmospheric circulation. In addition, around 1930, circulation of the upper atmospheric shifted from meridional to dominantly zonal, a west-to-east upper level wind that generally produces dry weather in the Southwest.

Regulated Streamflow and Geomorphic Change

The recent alluvial history of the Virgin River indicates that alluvial valleys in the Zion National Park region change frequently and rapidly. Regulation of streamflow will almost certainly alter this evolutionary pattern. In the past 1,000 years, the channel has widened, deepened, and partly refilled several times. Much of this change was only in the past 100-120 years. Moreover, detectable bedrock erosion occurred at least locally during historic arroyo cutting, as illustrated in figure 11. In time, the cumulative effect of this short-term bedrock erosion might contribute substantially to canyon cutting.

The alluvial history also indicates that channel deepening and widening were associated with periods of high streamflow. In contrast, deposition resulting in buildup of the channel and alluvial valley was during periods of relatively low streamflow. The normal pattern of channel evolution evidently requires streamflow that varies from high to relatively low with an adequate supply of sediment.

Elimination of high-flow rates reduces the scale of channel widening and deepening. Short-term erosion of the bedrock channel will also be curtailed, erosion that is a small-scale version of canyon cutting. Likewise, deposition will be limited by reduced sediment loads and peak-flow rates, depending on the relative magnitude of change between unregulated and regulated streamflow. In short, the pattern of alternating erosion and deposition will be altered by regulated streamflow, reducing the magnitude of geomorphic change in the alluvial valleys.

The balance between tributary sediment input and its removal by mainstem streamflow will be altered by regulated streamflow. This balance is important in maintaining the channel in Parunuweap Canyon below the narrows and to a lesser extent in Zion Canyon. Tributary sediment is transported to the alluvial valley by streamflow and debris flow, and the deposits form alluvial fans in the river channel. These deposits are readily removed by the river, and they are preserved only as eroded remnants along the valley margin. Reduced streamflow will increase preservation of alluvial fans at the mouths of tributaries, leading to low-gradient channel reaches and partial ponding of the river. Thus, the relatively straight, uniform-gradient channel would likely become a series of pools in the flat stretches upstream of tributaries separated by steep reaches where the river crosses the alluvial fans.

SUMMARY AND CONCLUSIONS

Alluvial valleys of the study area are the latest development in the geologic history of the Virgin River. Extensive erosion of Mesozoic strata during the Quaternary established the present course and elevation of the river. Termed canyon cutting, this erosion produced the major canyons in the Zion National Park area. Canyon cutting was controlled by movement along the Hurricane fault, a north-trending fault west of the study area that forms the physiographic boundary between the Basin and Range province to the west and the Colorado Plateau province to the east. The eastern block or footwall of the fault moved up episodically 600-850 m (2,000-2,800 ft) while the western block remained stationary. This uplift steepened the gradient of the ancestral Virgin River, increasing its erosive power, eventually cutting the canyons of Zion National Park. The Hurricane fault has not been active in the late Holocene, thus the recent alluvial history of the Virgin River described in this report is quite likely unrelated to tectonic activity.

Deposits of the alluvial valleys accumulated during the late Holocene, or the past 1,000 years. Although older Holocene deposits are probably present, they have not been identified on or below the surface of the valley. The deposits are derived from upstream sources as well as from nearby adjacent hillslopes and tributary streams. Mainstem deposits are transported by the Virgin River from distant sources. The mainstem deposits are primarily light-colored very fine to medium-grained sand and minor subrounded to rounded pebble to cobble gravel; the fine-grained alluvium accumulated by lateral and vertical floodplain accretion. Tributary deposits are transported to the alluvial valleys mainly by fluvial and debris-flow processes. Relative to mainstem deposits, tributary deposits are typically darker colored, coarser grained, and less rounded. Near the margin of the valley mainstem and tributary deposits are interbedded.

A study of the alluvial valleys of North Fork and East Fork (figs. 5, 9) shows that the two streams have similar alluvial and geomorphic histories. Moreover, the mapped sequence of terraces and deposits are present downstream of the forks at least to Virgin. Four terraces and the active channel and floodplain are present in the alluvial valleys. From oldest to youngest, the terraces are referred to as the prehistoric, settlement, historic, and modern terraces. The terraces typically have inset relations with one another such that the oldest terrace is topographically the highest and closest to the valley margin. Except for the historic terrace, the insets are the result of cut-and-fill stratigraphy in which the alluvial channel is repeatedly cut or eroded and then partly refilled with alluvium.

The main processes are erosion and deposition at the scale of this investigation. Erosion deepens and widens the channel, causing abandonment of the floodplain and truncation of earlier deposits; whereas deposition partly refills the channel to a lower topographic level than the preceding deposition. Two erosional events during the late Holocene removed most of the previously deposited sediment and locally eroded bedrock as well. This prehistoric and historic erosion entails substantial widening of the channel that in places includes the entire width of the alluvial valley.

The prehistoric terrace is the oldest unit identified in the study area. The terrace is present at the margins of the alluvial valley where it ranges from 6-10 m (20-33 ft) above the active channel on East Fork and 3-4 m (10-13 ft) above the channel on North Fork. Near the top of the unit at East Fork, the deposits locally contain archeologic material of the Virgin branch of the Kayenta Anasazi. This material dates to A.D. 800-1200, and the stratigraphic context suggests that deposition of the alluvium was concurrent with occupation. The end of prehistoric deposition was after A.D. 1100-1200, as suggested by the age and stratigraphic position of the archeologic material (fig. 10).

The settlement terrace is named for historic archeologic material and evidence of Anglo agricultural activity on the surface. Historic accounts suggest that the terrace and related alluvium were the active channel and floodplain of the Virgin River when the area was settled in the late 1850s and early 1860s. The terrace is situated 2-4m (7-13 ft) below the prehistoric terrace on East Fork and less than 2 m (6 ft) below the terrace on North Fork. The age of the terrace could not be determined directly due to the lack of dateable material. The inset relation indicates that the settlement terrace is younger than the prehistoric terrace; the absence of Anasazi remains in the settlement alluvium indicates that it post-dates abandonment of the area by the Anasazi, which was around A.D. 1200. The alluvium is younger than A.D. 1200, and deposition could have begun around A.D. 1400, based on correlation with alluvial deposits of the Escalante River and Paria River basin (fig. 10). Tree-ring dates from cottonwood growing on the surface of the alluvium at North Fork indicate that the settlement alluvium probably pre-dates A.D. 1883 (fig. 9).

The historic terrace is mainly an erosional feature that is not associated with aggradation. The terrace is situated 3 m (10 ft) below the settlement terrace on East Fork and less than 1 m (3 ft) below the terrace on North Fork. Typically, the historic terrace occupies meander scars cut into the settlement terrace. The historic terrace probably represents an abandoned channel that was active during incision of the settlement terrace and during subsequent channel widening. Ring-counts of cottonwood growing on or just below the surface were used to date the terrace. The oldest dates indicate that the historic-age channel formed in 1892 and 1893 at North Fork and East Fork, respectively (figs. 5, 9). This channel was active until about 1926 when sediment began to accumulate on point bars and along the channel margin in straight reaches.

Alluvium of the modern terrace is relatively thin, although the surface area of the terrace is large, as it occupies a substantial portion of the earlier historic-age channel (figs. 5, 9). The terrace forms point bars (fig. 7) in wide reaches of East Fork and Virgin River downstream of the forks and floodplain-like surfaces on both sides of the channel in relatively narrow reaches. The alluvium consists of two units: a basal, subsurface unit of largely unstratified sand present at East Fork (fig. 8) and a terrace, referred to as the early modern terrace, on North Fork. The basal unit quite likely predates 1940 and the early modern terrace formed between 1926-1937. Deposition of the upper unit began in 1940, based on tree-ring dating of cottonwood partly buried in the alluvium, and continued until at least the late 1970s or early 1980s, when minor adjustment of the channel caused abandonment of the modern-age floodplain.

The active channel and floodplain lie 1-2 m (3-7 ft) and 0.5-1 m (1.6-3 ft) below the modern terrace at East Fork and North Fork, respectively. This topographic separation is defined by steep cutbanks at most localities. The floodplain and channel are too small to show separately on the 1:2,000 scale maps used to compile the surficial geology. Dating of vegetation associated with the floodplain suggest that it began to form by at least 1983 if not a few years earlier. Two periods of erosion, referred to as the prehistoric and historic arroyo cutting, separate the principal depositional units. These erosions were widespread, affecting the entire drainage basin of the Virgin River as well as many other streams in the Southwest. Prehistoric arroyo cutting, which ended deposition of the prehistoric alluvium, occurred after A.D. 1100-1200 and between A.D. 1200-1400, as suggested by regional relations. Historic arroyo cutting ensued between 1883-1940 and ended deposition of the settlement alluvium.

These erosional changes had severe environmental consequences for the region. Prehistoric arroyo cutting was probably one of the main factors leading to abandonment of southern Utah and northern Arizona by the Anasazi. Likewise, historic arroyo cutting caused major dislocations, loss of property, and economic problems for early settlers in the Zion National Park area and elsewhere in the southern Colorado Plateau.

Historic accounts and relocation of early photographs document the condition of the alluvial channel shortly before, during, and after historic arroyo cutting. In 1859-1862, when the Zion National Park area was first settled, the Virgin River downstream of the forks flowed at the surface of the alluvial valley in a narrow, shallow, and possibly meandering channel. The valley was not entrenched and the wide floodplain was overtopped with only a slight rise of water level. An unusual storm in the winter of 1862 caused one of the five largest floods of the historic period (Table 1). The flood caused major dislocations among the settlers, who had virtually no experience with alluvial-channel rivers. Farmland and housing were likely established and built on the active floodplain, a situation that probably continued to some extent after the flood.

Photographs of the river suggest that the channels of East Fork and North Fork were unentrenched in 1873 (figs. 12-14, 20). North Fork had a sand-bed channel without gravel and a floodplain vegetated with cottonwood and willow. This condition of the channel contrasts sharply with the historic-age channel in 1903 and 1909 (figs. 15-17), only 20-26 years after arroyo cutting began. In 1903-1909, the historic-age channel was entrenched below the settlement terrace, gravel was present in the channel, and a steep terrace rise with meander scars was cut into the settlement terrace. These conditions suggest that the channel had deepened and was then widening, removing portions of the settlement terrace.

East Fork near Shunesburg and the Virgin River near Grafton were photographed in 1926 and 1917-1939 (figs. 18, 21), respectively. The exact year of the latter photograph is uncertain, although it probably dates to the mid-1920s. The channel in the mid-1920s was flat floored,vegetation was sparse, and sites of overbank deposition were largely absent. Photographs taken in the late 1930s (figs. 19, 22) indicate that some relief had developed in the channel through deposition of channel bars and other mostly transient depositional features. These were the incipient deposits of the modern alluvium. Contemporary photographs show that the channel has stabilized relative to early conditions. The braid-like pattern of the historic-age channel was replaced by a locally meandering channel having a recently active floodplain, which is the modern terrace along with a well-developed woodland of cottonwood and other riparian vegetation.

These changes in the channel and alluvial valley of the Virgin River were contemporaneous with variations of annual streamflow. Long-term streamflow was estimated by tree-ring chronologies from two sites in the study area. Ring width of pinyon growing on semiarid hillslopes is largely a function of October through June precipitation, which in turn is related to streamflow. Measured streamflow for 1910-1992 was calibrated to ring width using regression analysis; ring width explains 59 percent of annual streamflow variability. In addition, estimated annual streamflow is in phase with actual streamflow in 80 percent of the cases (figs. 23-24). A 303-year record of streamflow from 1690-1992 was developed from the full tree-ring chronology (fig. 25), this was used along with the gaged record to interpret historic geomorphic activity. Prehistoric geomorphology was interpreted using a streamflow reconstruction from the lower Virgin River that begins in A.D. 966 (Larson and Michaelsen, 1990).

Prehistoric arroyo cutting was probably contemporaneous with a period of high streamflow between about A.D. 1200-1400. Streamflow during this time was the largest since A.D. 1400. Conversely, a period of relatively low streamflow following A.D. 1400 until about 1880 coincides with deposition of the settlement alluvium. This interval of low streamflow was punctuated by brief episodes of very high streamflow in the upper basin that had no discernible geomorphic effect.

Historic arroyo cutting was preceded by and concurrent with extremely variable precipitation, including the driest and wettest climate in 300 years. The second, third, and fourth driest intervals in at least 300 years were the mid-1850s, mid-1870s, and late 1890s; the wettest intervals were the mid-1880s to mid-1890s and early 1900s to about 1920-1930, which tie for second wettest and wettest, respectively (figs. 30-31). Drought conditions that preceded arroyo cutting may have weakened hillslope and valley-floor vegetation. This and, to some extent, the introduction of livestock increased runoff. The first wet episode from the early 1880s to the mid-1890s caused the initial entrenchment and widening of the Virgin River; the second episode from around the early 1900s to the mid-1920s widened the channel further. The end of arroyo cutting, which may only be temporary, began with deposition of the modern alluvium in 1940, following a brief resurgence of relatively high streamflow in the late 1930s.

The gaged streamflow record shows that the high annual runoff of the early 1900s (fig. 26) resulted from mostly above average streamflow during fall, winter, and summer that augmented normally high spring runoff (figs. 27-28). The early episode of high streamflow during the late 1800s could also result from increased seasonal runoff, although the early episode predates streamflow measurements. These runoff variations are presumably related to climate; human activity in historic times possibly increased runoff, but arroyo cutting would probably-have occurred without human interference.

In short, the recent alluvial history of the Virgin River in the Zion National Park region indicates that the geomorphic development of the alluvial valley and channel are linked to variations of streamflow (fig. 30).

Regulation of streamflow by upstream reservoirs will alter the geomorphic development of the Virgin River valley. In the recent past, geomorphic development was rapid, and changes in the alluvial valley are expected during the next several hundred years. For example, in the late 20th century, two periods of increased streamflow lasting less than five years caused readily detectable adjustment of channel width and depth. Longer periods of unusually high streamflow, lasting several decades in historic times and several centuries in prehistoric times, caused major changes of width and depth of the channel and alluvial valley. Conversely, periods of relatively low streamflow resulted in aggradation of the channel and increased the elevation of the alluvial valley. Upstream reservoirs and regulated streamflow will quite likely change the magnitude and pattern of channel development, unless existing flow conditions can be maintained.

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