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FINAL CONTRACTOR'S REPORT

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
SOLAR SYSTEM EXPLORATION DIVISION
PLANETARY GEOLOGY AND GEOPHYSICS PROGRAM

N.A.S.A. GRANT - NAGW 707
(FEBRUARY 1, 1985 - JANUARY 31, 1988)

GROUNDWATER SAPPING VALLEYS: EXPERIMENTAL STUDIES, GEOLOGICAL CONTROLS, AND IMPLICATIONS TO THE INTERPRETATION OF VALLEY NETWORKS ON MARS

PRINCIPAL INVESTIGATOR:

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May 15, 1988

(NASA-CR-182718) GROUNDWATER SAPPING VALLEYS: EXPERIMENTAL STUDIES, GEOLOGICAL CONTROLS AND IMPLICATIONS TO THE INTERPRETATION OF VALLEY NETWORKS ON MARS Final Contractor's Report, 1 Feb. (University   N88-22847

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ABSTRACT

An integrated approach using experimental laboratory models, field studies of terrestrial analogs, and remote studies of terrestrial field sites were applied to the goals of understanding the nature and morphology of valley networks formed by groundwater sapping. In spite of problems with scaling, the experimental studies provided valuable insights into concepts relating to the initiation, development, and evolution of valleys by groundwater sapping. These investigations were also aimed at developing geomorphic criteria for distinguishing valleys formed dominantly by surface runoff from those formed dominantly by groundwater sapping processes. Channels that were field classified as sapping vs. runoff were successfully distinguished using statistical analysis of their respective morphologies, therefore, it may be possible to use similar techniques to interpret channel genesis on Mars. The terrestrial and flume studies provide the ground-truth dataset which can be used (and will be during the present year) to help interpret the genesis of valley networks on Mars.

Our studies provided a conceptual model of how sapping dominated valleys evolve, and elucidated our understanding of the geologic controls affecting valley morphology. Better understanding of these controls may enable us to make reliable interpretations about the underlying geologic structure and composition of selected areas on Mars. Many of the results from this project have been published or are currently in press, therefore, they will only be summarized here.

ACKNOWLEDGEMENTS

This research was funded by N.A.S.A. Grant NAGW-707 over three years between February 1, 1985 to January 31, 1988, with experimental research continuing into late March, 1988. I wish to thank the three technical monitors at NASA headquarters for their help in facilitating the research - initially Dr. Joe Boyce, followed by Dr. David Scott, and currently Dr. James Underwood, Jr. Research assistants during the first half of this project deserve special thanks for working in difficult conditions - Mr. Jay Piper and Mr. Dave Simmons. Mike Phillips helped in the field and lab research during the last year.

Many other SIU graduate students freely contributed their time to the labor intensive task of obtaining changing, and evacuating sediment from the experimental fluvial laboratory. The Department of Geology frequently covered expenses associated with the logistics of running the experiments and obtaining sediment for the experiments.

INTRODUCTION

CHANNELS ON MARS

Studies of the Viking images of Mars have resulted in the identification of at least four major classes of Martian channels (Figure 1) (See reviews by Baker, 1982 and Mars Channel Working Group, 1983). Enormous channels hundreds of kilometers long and tens of kilometers wide were extensively mapped and interpreted as having formed by cataclysmic flooding (Baker and Milton, 1974; Baker and Kochel, 1978a, 1978b, 1979; Masursky and others; 1979; Grant, 1987). Termed outflow channels, these large Martian channels contain an assemblage of depositional and erosional features analogous to the largest known terrestrial cataclysmic floods which coursed through the Channeled Scablands of eastern Washington numerous times during the Pleistocene (Baker, 1973; Baker and Nummedal, 1978; Baker, 1978).

Recently, the focus of attention in Martian channel studies has turned to an intriguing array of smaller-scale channel features generally integrated into drainage network patterns (See review in Baker, 1982). Mars valley networks can be divided into three general styles (Figure 1): 1) dry valley networks which have distinctly dendritic tributary patterns formed generally on ancient hilly and cratered terrain; 2) longitudinal valley networks which have short, stubby tributaries with amphitheater heads; and 3) slope valley networks which have short, amphitheater-headed tributaries formed along major escarpments such as Valles Marineris and on the slopes of major volcanic cones.

MARTIAN VALLEY TYPES

	SIZE	MORPHOLOGY	DISTRIBUTION
OUTFLOW CHANNELS	10's km long 10's km wide	anastomosis, grooves, streamlined hills, massive flood features, distinct chaos sources, lack tributaries	mostly equatorial regions
*** VALLEY NETWORKS ***			
DRY VALLEYS	10's km long < few km wide	dendritic pattern w/ numerous tributaries, fresh & weathered	ancient hilly & cratered terrain
LONGI-TUDINAL VALLEYS	100's km long few km wide	flat-floored main channel, short & stubby tributaries, amphitheater heads	mostly equatorial regions
SLOPE VALLEYS	10's km long few km wide	flat-floored & V-shaped cross-sections, amphitheater heads, stubby tribs. w/ high junction <'s	equatorial along Valles Marineris chasma

Figure 1. Classification of Martian channels visible in Viking images. Valley networks and some margins of outflow channels are the focus of studies related to sapping

Theories explaining the origin of Martian valley networks exhibit considerably less agreement than models suggested for the outflow channels on Mars. The occurrence of dry valley networks on very ancient terrains contemporaneous with the late stages of planetary accretion (Baker and Partridge, 1986) place their origin during a period of Martian history that many speculate was characterized by a climate capable of sustaining significant precipitation. The superficial resemblence of dry valley networks to terrestrial dendritic valley networks formed by precipitation and runoff led to suggestions that the Martian valley networks were formed in the same manner (Milton, 1973, Sagan and others, 1973; Sharp and Malin, 1975). Although there is support for a more volatile rich early Martian atmosphere (Pollack, 1979; Toon and others, 1980) with considerable volumes of initial water (Squyres, 1984), there are enough conflicting ideas and models of early conditions to warrant caution to be exercised in using the presence of valley networks as independent evidence of a former warmer climate capable of the kind of intense precipitation that would be necessary to develop valleys of the dimensions present on Mars.

During the past few years, investigators of Martian channel networks realized these valleys had peculiarities in their morphologic expression compared to terrestrial runoff systems. In particular, attention was called to the amphitheater-heads, apparent low drainage density, stubby tributaries, and structural control of Mars valley networks which led to suggestions that perhaps the process of groundwater sapping played a significant role in creating these networks (Baker, 1982; Baker and Kochel, 1979; Higgins, 1982; 1984; 1988; Kochel and others, 1983; Kochel, Howard, and McLane, 1985; Laity and Malin, 1985; Howard and McLane, 1981; Howard and others, 1988). Additional studies of slope degradation on Mars have also invoked groundwater sapping as a major process which may have contributed to backwasting and downwasting of Martian landforms (Sharp, 1973; Baker and Kochel, 1979; Kochel and Baker, 1981; Kochel and Burgess, 1983; Kochel and Capar, 1983; Kochel and others, 1983; Kochel, 1984; Kochel and Peake, 1984). Groundwater sapping is presumed to be a reasonable process which may have operated on Mars due to its ability to operate in permeable materials by recharge with low intensity precipitation. Alternatively, sapping could even operate in the absence of precipitation by the thermal decay of ground-ice due to a host of triggering mechanisms unrelated to precipitation.

GROUNDWATER SAPPING

Most terrestrial channels are probably formed and maintained by a combination of runoff and groundwater sapping processes, therefore, are best referred to as composite channels (Schumm and Phillips, 1986). Prior to the late 1970's most models of channel formation focused upon erosional processes associated with Hortonian overland flow. Recently, geomorphologists and hydrologists have begun to recognize the importance of subsurface flow processes on the initiation and maintenance of surface channels. Groundwater sapping is a rather broad term which refers to the weathering and erosion of sediments and rocks by emerging groundwater by some combination of intergranualr flow and channelized flow (referred to as piping). Groundwater sapping discharge typically emerges as distinct springs, referred to as spring sapping or along laterally extensive planar zones where it is referred to as seepage erosion (Higgins, 1984, 1988).

Dunne (1980) provided an excellent review of channel initiation processes by sapping and runoff and illustrated clearly how effective sapping can be in creating and extending terrestrial channel networks. Dunne (1980) depicted the random emergence of a spring along an escarpment and showed how it is rapidly followed by groundwater flow convergence into the spring head as it retreats headwardly (Figure 2). This flowline convergence operates as a positive feedback process which favors continued expansion of the selected springhead and valley at the expense of neighboring regions of the escarpment which have large portions of their groundwater recharge diverted into the favored channel by subsurface piracy. Through competition, selected channels are enlarged while neighboring channels become less active or relict.

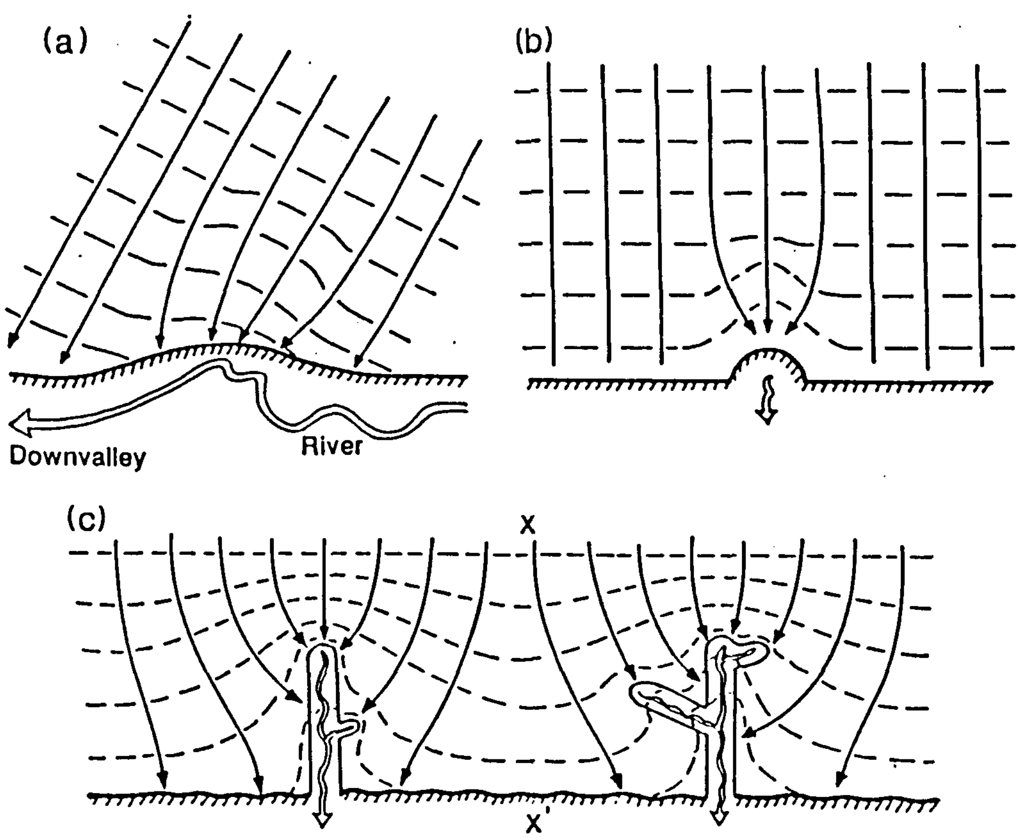

Figure 2. Scenario model of the development of channel networks by groundwater sapping. Erosion by rivers or landslides results in an irregularity along the escarpment. The cut will favor headward channel extension because of favored flow convergence of groundwater. The favoring is progressive. (from Dunne, 1988).

Since the suggestion that sapping processes may be important in Martian channel formation, the importance of sapping processes as a geomorphic agent of erosion has become increasingly evident in many terrestrial physiographic settings, on a variety of scales, and in a variety of unconsolidated and consolidated geologic materials (Higgins, 1982; 1984; Baker; 1982; Kochel and others, 1985; Laity and Malin, 1985; Pillans, 1985; Kochel and Piper; 1986; Schumm and Phillips, 1986). Table 1 provides a review of significant recent studies involving groundwater sapping in terrestrial and planetary settings.

OUTLINE OF THE REPORT

The results of our three-year investigation of groundwater sapping studies, summarized in the following report, represent the integration of a four-phased research approach. Much of the research reported here has been done in collaboration as a coordinated effort with Alan Howard of the University of Virginia. First, the report will summarize the results of a series of experiments in sapping tanks designed to provide a conceptual framework for understanding the development and evolution of valley networks formed by groundwater sapping. These experiments also contribute to models for comparing sapping and runoff valleys. Second, we will summarize a series of studies of terrestrial analog sites where sapping processes dominate channel evolution using a combination of field reconnaisance observations and aerial photographic studies to develop a suite of geomorphic criteria useful in distinguishing between sapping and runoff valley networks. Third, we will summarize field and experimental studies aimed at determining the important geological controls on sapping processes and how these controls may be reflected in valley network morphometry and channel morphology. The compliment to this aspect of our research is an attempt to show how morphologic expression of sapping-dominated valleys can be used to interpret the nature of geological materials on which they are developed.

The last phase of the research described in this report leads directly into the research currently underway to apply the experimental and terrestrial analog results to the interpretation of the genesis of Martian valley networks. The intent of the current research effort is to develop a global map of Mars channels classified by genesis. In addition, we plan to use to results of the studies summarized in this report to make interpretations about the underlying geology for selected valley network regions of Mars.

Table 1. Recent Major Published Groundwater Sapping Studies

Author	Date	Focus of the Contribution
R.P. Sharp	1973	Suggested sapping processes to explain some Mars terrains
V.R. Baker, R.C. Kochel	1979	Sapping suggested to explain channel walls on Mars
T. Dunne	1980	Formation of terrestrial channel networks & theory
V.R. Baker	1982	Review of Mars channels and valley networks - book
C. Higgins	1982	Analogy of beach sapping tidal channels (micro) to Mars
Mars Channel Group	1983	Review of Mars channels and networks
R.C. Kochel, A.D. Howard	1985	Experimental sapping valleys and Mars analogies
J. Laity, M. Malin	1985	Sapping processes and Colorado Plateau
Howard, Kochel, Holt	1985 1988	Groundwater sapping field conference - NASA - 11/85 publication of guidebook
R.C. Kochel, J. Piper	1986	Distinguish Hawaiian sapping & runoff valleys - Mars
V.R. Baker, J. Partridge	1986	Dry Mars valleys, degraded and pristine and sapping
S.A. Schumm, L. Phillips	1986	Discuss composite origin of terrestrial channels
R.C. Kochel and others	1988	Summary of expeimental sapping studies in sediments
R.C. Kochel, G. Riley	1988	Sedimentary controls sapping Colorado Plateau
A.D. Howard	1988	Theoretical review of sapping processes & experiments
C. Higgins	1988	Review book on groundwater sapping - many authors

Table 2 provides a summary of the publications and manuscripts in press which have resulted to date from this contracted research. Numerous additional manuscripts are currently in preparation and planning related to this research both jointly and separately between our efforts at SIU and UVa.

EXPERIMENTAL SAPPING VALLEYS

OBJECTIVES

The primary purpose for the experimental phase of this research was to design a laboratory system which would be conducive to the development of surface valley networks by groundwater sapping processes. Experimental study of small-scale sapping networks allows direct observation of valley evolution and provides data on basin morphometry and channel morphology of these systems which can be compared to terrestrial runoff valley networks and used in interpretation of genesis of Martian valleys networks.

The major objective of the sapping experiments was to provide a database for testing conceptual and theoretical models of the development of valley networks by groundwater sapping. In particular the secondary objectives included: 1) characterization of the morphology of sapping valleys and morphometry of sapping valley networks formed in a variety of unconsolidated and weakly consolidated sedimentary materials; 2) characterization of the differences in sapping networks developed in uniform, multi-layered strata, and in experiments simulating numerous structural perturbations such as joints, dikes, and folding; 3) development and description of the evolution of sapping valley networks; 4) morphometric comparison of experimental sapping and runoff valley networks; and 5) comparison of experimental sapping networks to selected valley networks on Mars. A pimary factor in the selection of variations to the experimental design was the attempt to simulate certain aspects of the geologic setting of the areas where we were conducting terrestrial analog studies of sapping-dominated valleys. Finally, the experimental data will provide valuable calibration data for the theoretical modeling of sapping valley systems being conducted simultaneously by Alan Howard at University of Virginia.

PRELIMINARY EXPERIMENTAL STUDIES

The combination of simultaneous experiments using a two-dimensional sapping tank by Howard (Univ. Virginia) and a small 3-dimensional experimental tank less and 0.8 cubic meter in size by Kochel (then at SUNY Fredonia) showed that channel networks could be developed by groundwater sapping processes in the absence of surficial runoff in unconsolidated sediments. These early experiments provided the impetus for the elaboration and design of a new, larger sapping tank having dimensions of about 1 cubic meter at University of Virginia by Howard and Kochel in 1983. Finally, the contracted research reported on here was conducted in a larger flume modified for sapping experiments to extend over an area 2.5 m wide by 5 m or more long, and slightly less than 1 meter deep at Southern Illinois University.

Table 2. BIBLIOGRAPHY OF PUBLICATIONS SUPPORTED BY THIS CONTRACT by R. Craig Kochel

1985

Kochel, R. C., 1985, Martian fretted terrain morphometry interpreted using principal components analysis: *NASA Technical Memorandum No. 87563*, p. 352-354.

Kochel, R. C., and Howard, A. D., 1985, Groundwater sapping and ancient valley networks on Mars: *Lunar and Planetary Science Institute Technical Report No. 85-03*, p. 48-50.

Kochel, R. C., Howard, A. D., and McLane, C., 1985, Channel networks developed by groundwater sapping in fine-grained sediments: analogs to some Martian valleys: *in*, Woldenberg, M. (Ed.), *Models in Geomorphology*: Boston, Allen & Unwin, p. 313-341.

Kochel, R. C., 1985, Role of groundwater sapping in development of large valley networks on Hawaii: *in*, Howard, A. D., Kochel, R. C., and Holt, H., (eds.) *Field Guide and Program for NASA Groundwater Sapping Conference - Preliminary Draft*, November, Flagstaff, p. 14-16.

Howard, A. D., Kochel, R. C., and Holt, H., 1985, *Field Guide and Program for NASA Groundwater Sapping Conference - preliminary draft*, Flagstaff, 76p.

1986

Kochel, R. C., and Piper, J. F., 1986, Morphology of large valleys on Hawaii: Implications for groundwater sapping and comparisons to Martian valleys: *Abstracts, 17th Lunar and Planetary Science Conf.*, p. 424-425.

Kochel, R. C., and Piper, J. F., 1986, Morphology of large valleys on Hawaii: Evidence for groundwater sapping and comparisons with Martian valleys: *Journal of Geophysical Research*, v. 91, p. E175-E192.

1987

Kochel, R. C., 1987, Valley morphology on Hawaii and Mars: Arguments for their origin by groundwater sapping processes: *Geological Society of America, Abstracts with Programs*, v. 19, no. 6, p. 395-396.

Kochel, R. C., and Phillips, M. A., 1987, Geological controls on the morphology of valleys influenced by groundwater sapping on the Colorado Plateau: *Geological Society of America Abstracts with Programs*, v. 19, no. 7, p. 731.

Kochel, R. C., and Simmons, D. W., 1987, Groundwater sapping channels: Summary of effects of experiments with varied stratigraphy: *NASA Technical Memorandum No. 89810*, p. 291-293.

1988

Kochel, R. C., and Phillips, M. A., 1988, Preliminary investigation of geological controls on valleys influenced by groundwater sapping, southern Colorado Plateau, Arizona and Utah: *Abstracts, 19th Lunar and Planetary Science Conference*, p. 615-616.

In press for 1988:

Howard, A. D., Kochel, R. C., and Holt, H., 1988, *Proceedings and Field Guide for the NASA Groundwater Sapping Conference*, Washington, NASA, 208pp.

Howard, A. D., and Kochel, R. C., 1988, Introduction to Cuesta Landforms and Sapping Processes on the Colorado Plateau: *in*, Howard, A.D., Kochel, R. C., and Holt, H., (editors)*Proceedings and Field Guide for the NASA Groundwater Sapping Conference*, Washington, NASA, p. 1-91.

Kochel, R. C., Simmons, D. W., and Piper, J. F., 1988, Groundwater sapping experiments in weakly consolidated layered sediments: A qualitative summary: *in*, Howard, A.D., Kochel, R.C., and Holt, H., (editors) *Proceedings and Field Guide for the NASA Groundwater Sapping Conference*, Washington, NASA, p. 161-183.

Kochel, R. C., and Riley, G. W., 1988, Sedimentologic and stratigraphic variations in sandstones of the Colorado Plateau and their implications for groundwater sapping: *in*, Howard, A.D., Kochel, R.C., and Holt, H., (editors) *Proceedings and Field Guide for the NASA Groundwater Sapping Conference*, Washington, NASA, p. 102-115.

Kochel, R. C., and Baker, V. R., 1988, Case Study: Groundwater sapping and the development of large Hawaiian valleys: in, Spring Sapping and Valley Network Development, Chapter 10, in, Higgins, C.G., and Coates, D.R., (editors) Groundwater Geomorphology, Geological Society of America Special Paper, in press.

Design of Early Experiments

Experiments in the Fredonia sapping box were confined to homogeneous sediments composed of a mixture of 90% 2.25 phi fine sand and 10% clay-sized coal fly ash which helped provide cosheion for channel walls (Kochel, Howard, and McLane, 1985). The purpose of these experiments was to determine if surface channels could be created by groundwater sapping processes in the total absence of runoff. Constant head was maintained throughout a series of 23 runs of less than 3 hours duration. Sapping channels evolved through a processes of rapid headward extension following toe scarp slumping at the onset of saturation of the sediments from the rear reservoir. Tributary extension was extensive only along headward reaches of the valley networks where supplies of groundwater were plentiful. Downstream reaches were unable to develop new tributaries during latter stages of the runs because available groundwater was being intercepted or pirated by upslope, rapidly-extending valley networks (Figure 3). Insignificant changes occurred in drainage density and channel length following a period of rapid adjustment, in contrast to the abstraction of tributaries observed by Schumm and others (1987) in experiments with valleys formed by runoff (Figure 4). Table 3 summarizes that final basin morpmetric data for the 69 networks developed in the small sapping box.

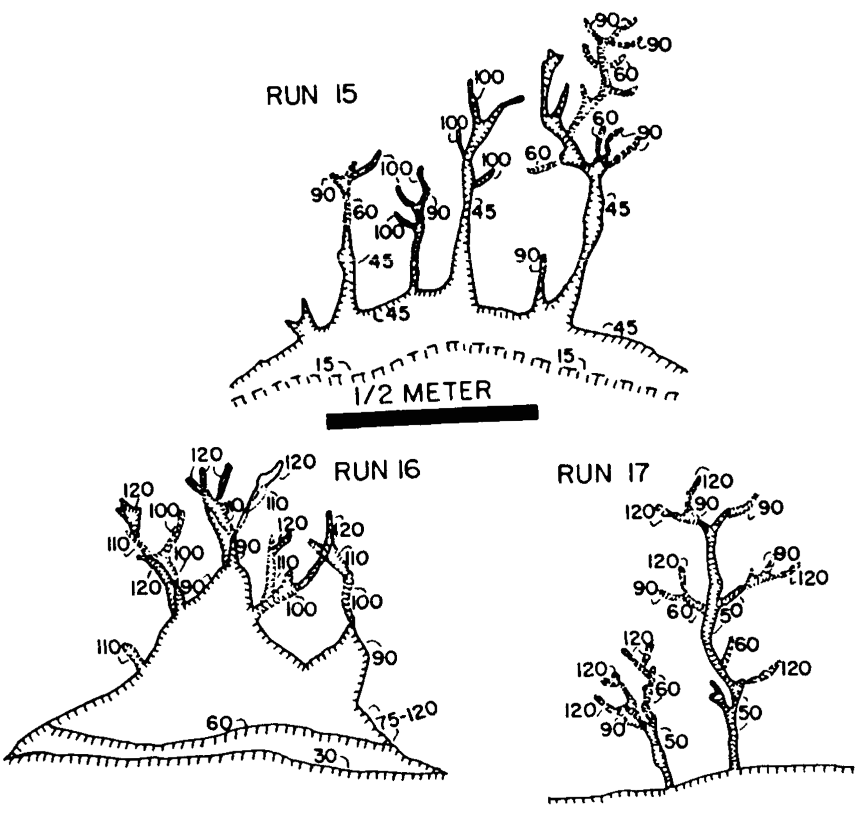

Figure 3. Example of channel networks form Fredonia sapping box (See Kochel, Howard, and McLane 1985 for discussion).

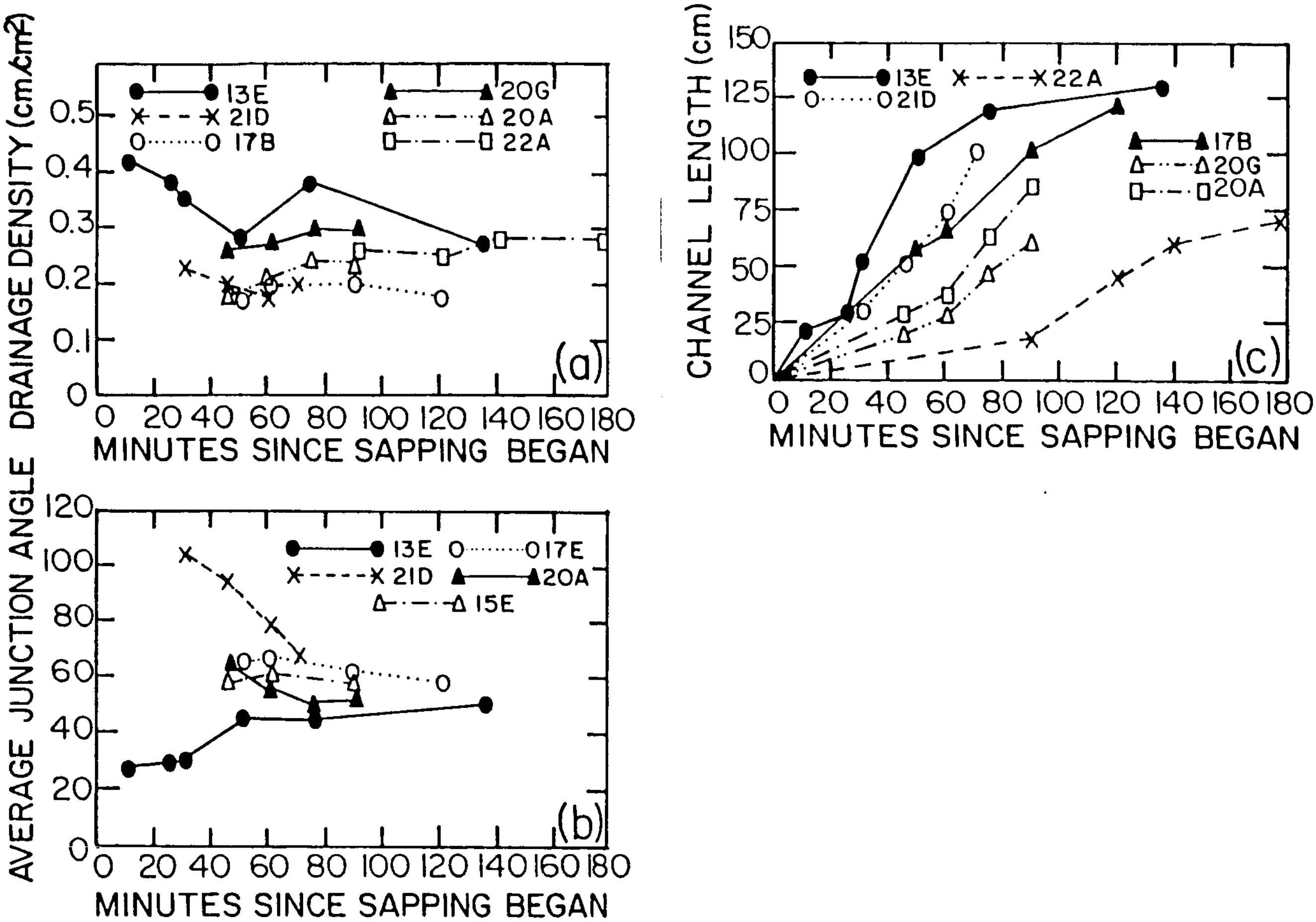

Figure 4. Examples of channel evolution in Fredonia sapping box. Note tendency to approach equilibrium after 100 minutes (from Kochel, Howard, and McLane, 1985).

Table 3. Morphometry of Sapping Valleys Formed in Fredonia Sapping Box (from Kochel, Howard, and McLane, 1985)

Parameter	n	Mean	Standard deviation
basin area (cm²)	69	101.00	120.00
basin shape			
lemniscate k	69	2.83	1.20
length/width	69	2.43	0.77
junction angles	221		
θ_1		35.00	17.00
$\theta_1+\theta_2$		44.00	18.00
dimensionless			
drainage density	69	9.10	6.61
bifurcation ratio	56	2.93	1.01
length main channel/ length first order tributaries	23	4.50	1.10
Shreve magnitude	69	4.45	3.28
Strahler order	69	1.94	0.89
channel length ratios			
1:2	55	1.09	0.45
1:3	27	1.37	0.53
2:3	27	1.20	0.52
basin area/channel area	69	6.70	2.72
interchannel spacing	57	9.20	2.80

Experimental Morphometry and Comparisons to Mars

Channels formed along the escarpment in the early experiments occurred with rather uniform lateral spacing which averaged about 9 cm. This spacing was presumed to reflect the scale of local subsurface catchment area for each of the growing sapping valleys (Kochel, Howard, and McLane, 1985). Strahler orders for the sapping valleys never exceeded 3.0. Similar, low order valley networks were studied along the Valles Marineris escarpment on Mars (Figure 5) and compared to the valleys formed by these early sapping experiments (Kochel, Howard, and McLane, 1985). Table 4 summarizes the morphometric data collected from 70 slope valley networks along Valles Marineris for comparison with Table 3.

The morphometric characteristics of the sapping valleys were similar to the slope networks on Mars. In particular, these similarities included: 1) elongate basins with tendency for rapid widening toward basin heads; 2) an abundance of short, stubby tributaries of Strahler order 1.0; 3) high ratios of channel length to tributary length; 4) low dimensionless drainage density compared to terrestrial runoff valley networks; 5) regular interbasin spacing along the escarpments; 6) a lack of regularity in junction angles throughout the network; 7) considerably low stream order for the size of the basins; 8) channels with steep walls and amphitheater heads; 9) valleys with broad U-shaped cross-sections; 10) abundant valley segments with right-angle bends; and 11) large channel width to total basin area compared to terrestrial runoff valleys. For more elaboration on the results of the early research and theory, see Kochel, Howard, and McLane (1985).

Table 4. Morphometry of Sapping Valleys Along Valles Marineris, Mars (from Kochel, Howard, and McLane, 1985)

Parameter	n	Mean	Standard Deviation
basin area (km^2)	70	603.00	627.00
basin shape			
lemniscate k	70	2.33	0.75
length/width	70	2.06	0.64
junction angles	275		
θ_1		42.00	20.00
$\theta_1+\theta_2$		49.00	21.00
dimensionless			
drainage density[1]	70	12.61	9.53
length main channel/			
length first order			
channels	27	3.89	0.85
bifurcation ratio	55	3.53	1.46
Shreve magnitude (M)	70	5.01	3.85
Strahler order	70	1.74	0.85
channel length ratios			
1:2	54	1.39	0.42
1:3	24	1.69	0.38
2:3	24	1.23	0.29
basin area/channel			
area	70	3.40	1.85
interchannel			
spacing	54	20.50	5.70

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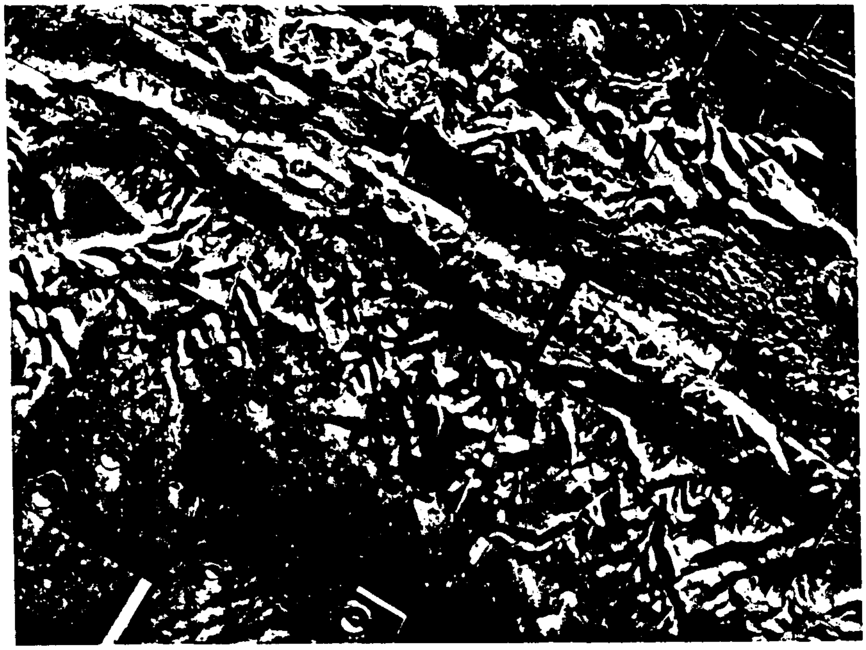

Figure 5. Low order slope valleys along Valles Marineris, Mars. Note that Strahler orders are less than 3.0

EXPERIMENTAL SAPPING STUDIES AT SIU (Feb. 1985 - Mar. 1988)

Over a period of three years between Spring 1985 and Spring 1988 a series of 56 experiments were designed to investigate the morphology and evolution of valleys formed by groundwater sapping in unconsolidated and slightly cemented sediments. The major tasks investigated in the research included the following:

1) geomorphologic characterization of sapping valleys formed in uniform, homogeneous sediments and their evolution
2) comparison of sapping valley morphology with experimental and terrestrial valleys formed by runoff processes - part of the dataset used to develop a suite of geomorphic criteria useful in distinguishing valley types
3) investigation of the effects of varying geology on the development and evolution of sapping valleys - in particular, variations in stratigraphy, cohesion, and the effects of various structural features
4) simulation of selected field situations where terrestrial analog studies of sapping phenomena were being conducted
5) the development of an experimental dataset to be used in theoretical modelling studies of sapping valley evolution being developed by Howard at Virginia

Although experimental studies inevitably suffer from problems of scale and other difficulties that will be discussed later, they served as invaluable devices for helping to build conceptual models for the development and evolution of valleys by sapping processes. Natural sapping processes occur with extreme slowness and are typically not conducive to the collection of process-oriented observations over the lifespan of most research projects. Schumm and others (1987) discussed the advantages and disadvantages of experimental geomorphic research at length and concluded that in spite of the scaling problems and difficulties in modelling field boundary conditions in the lab, there are major advantages to these kinds of experiments. Foremost of these advantages are the identification, direct observation, and measurement of processes under controlled conditions that can not be investigated in the field. In addition, Schumm and others (1987) underscore the utility of experiments for permitting studies of the evolution of physical systems and allowing the study of the reaction of the systems to controlled perturbations in the boundary conditions or process variables. They further note that careful observation of these systems may reveal processes or concepts previously unrecognized from field and theoretical study. Our experiences with sapping experiments underscore the conclusions made by Schumm and others (1987) and have provided us with a much better conceptual framework to apply to field and theoretical situations involving sapping processes.

SIU Sapping Flume

The 12m x 2.5m SIU recirculating flume was modified for groundwater sapping experiments by installing a perforated, screened headwall near the rear of the flume which permitted the development of a constant head reservoir (volume = 10 cubic meters) for purposes of recharging a groundwater table established in a sediment wedge downflume from the headboard (Figure 6). Although the sediment wedge could have extended for some 10m downflume, experiments were typically limited to sediment wedges between 3m and 5m in length. The large size of this flume provided several advantages over earlier experimental designs. Wall effects were minimized and there were no downflume barriers to interfere with fluvial transport of material away from the seepage or sapping face. This system is capable of modeling processes acting in a variety of natural settings by varying sediment characteristics such as permeability, porosity, cohesion, stratigraphy, and structure. Control on the reservoir head was maintained by an overflow pipe which was variable in elevation. Runs requiring rainfall were accomplished with the use of irrigation spriklers installed on the lab roof.

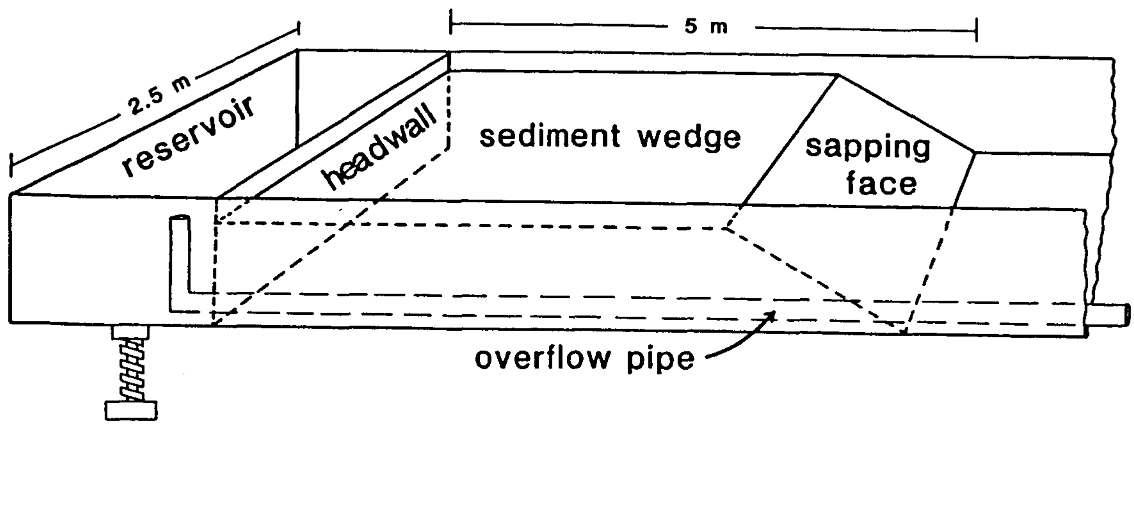

Figure 6. Sketch of SIU flume modified for sapping.
Downstream sapping face can extend unimpeded for 8 meters farther if necessary.

Data collected for each of the successful sapping run is summarized in Table 5. The frequency of data collection depended upon the length of the run and the rate at which changes were occurring. Most successful runs contain data on the rates of channel evolution measured by changes in channel width, channel head extension, and channel gradient. Morphologic data was collected using a 3-dimensions system based on a cart mounted on steel rails to the top of the flume capable of 1 millimeter accuracy. Overhead and oblique photographs were also taken to record each experiment and for use in digitization of planimetric changes in the channels. Figure 7 provides a general summary in chronologic order of the 56 runs made between January 1985 and March 1988. Later discussions of the results will treat the runs in groups categorized by experimental design objectives.

Our experimental studies were partly transport limited because of scaling problems inherent in the relative size of the sand compared to the dimensions of the channels produced and their associated discharges. A series of runs showed that due to scaling problems inherent in the ability of small discharges to remove sand grains by seepage erosion and transport them downstream, slopes on the sediment wedge had to exceed a threshold which was material dependent. Most of the experiments involved fine sand on which slopes had to exceed 6^{o} for sapping channels to form. Variations in sediment wedge slope were installed during each run setup and could also be adjusted through a range of 1.5^{o} using the hydraulic system enabling the entire flume to be tilted. We also realize that there are problems involved with chemical reactions between the groundwater and cement used in some of the runs. We were unable to effectively simulate the effects of chemical weathering processes along the seepage faces which probably play a large role in the erosion of sapping valleys in many environments.

All runs with the exception of Runs 39-44,46,48, and 50-54 were designed for purposes of constructing channel and valley networks. The excepted runs were designed to investigate alcoving processes and will be discussed under a separate heading.

Table 5. Summary Matrix for All Experimental Setups

RUN	sapping	rainfall	layered	coarse aquifer	fine sand	coarse sand	loess	sand & loess	weak cement	strong cement	dikes	joints
1	x				x							
2	x				x							
3	x				x							
4		x			x							
5		x			x							
6	x				x							
7	x			x	x							
8	x		x		x							x
9	x		x	x	x	x						x
10	x		x	x	x	x						x
11		x	x	x	x	x						x
12	x					x		x				
13	x							x				
14	x							x				
15	x		x		x	x	x					
16	x		x		x		x					
17	x			x				x				
18	x				x						x	
19	x				x						x	
20	x				x				x			
21	x								x		x	
22		x										
23	x								x			
24	x			x					x			
25	x		x		x	x						
26	x		x	x					x	x		
27	x		x	x					x	x		
28	x		x						x	x		
29		x										
30	x								x			
31	x								x			x
32	x										x	
33	x		x						x	x		
34	x								x			
35	x								x			
36	x								x			
37	x		x	x					x			
38	x		*	x					x	x		
39	x		x	x					x	x		
40	x		x	x					x	x		
41	x		x	x					x	x		
42	x		x	x					x	x		
43		x	x						x	x	x	
44		x	x						x	x		
45	x		*						x	x		
46		x	x						x	x		
47	x		*						x	x		
48		x	x						x	x		
49	x		*						x	x		
50		x	x						x	x		
51	x		x						x	x		
52	x		x						x	x		
53	x		x	x					x	x		
54	x		x	x					x	x		
55	x		*						x	x		
56	x		*							x		
			* = 5% base									

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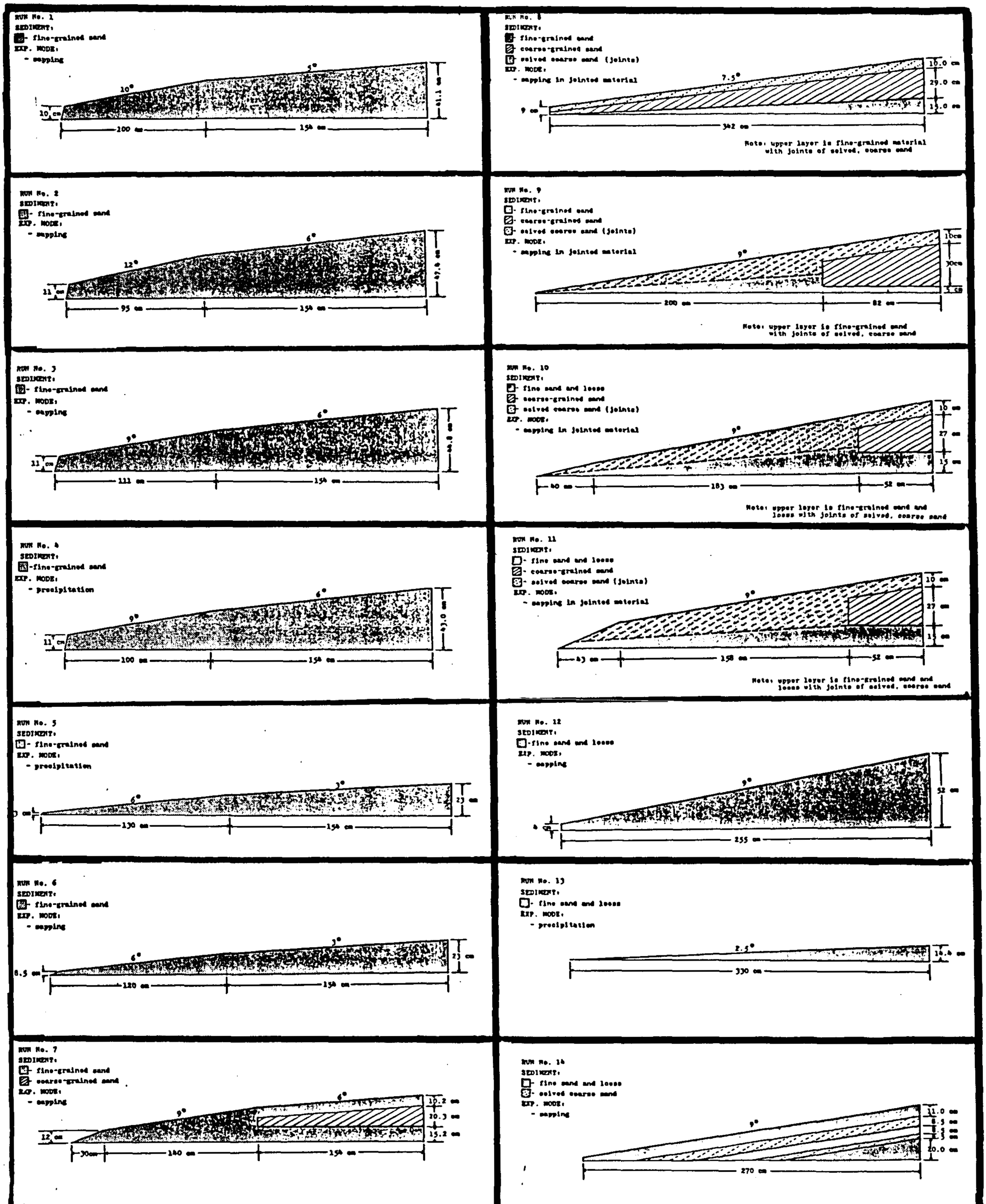
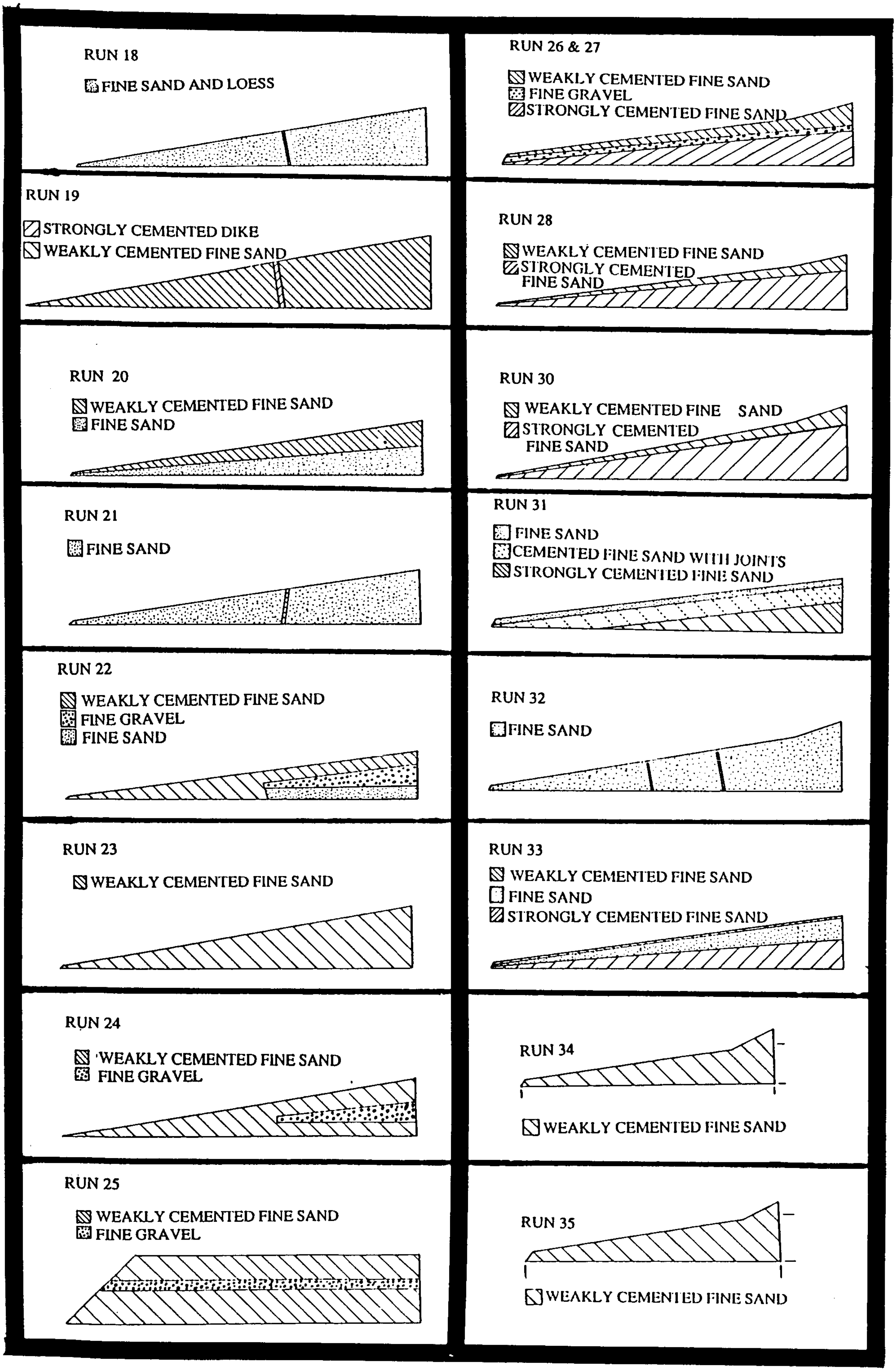


Figure 7. Summary design set-up for Runs 1-56 (in 3 parts).


RUN 18
FINE SAND AND LOESS
RUN 19
STRONGLY CEMENTED DIKE
WEAKLY CEMENTED FINE SAND
RUN 20
WEAKLY CEMENTED FINE SAND
FINE SAND
RUN 21
FINE SAND
RUN 22
WEAKLY CEMENTED FINE SAND
FINE GRAVEL
FINE SAND
RUN 23
WEAKLY CEMENTED FINE SAND
RUN 24
WEAKLY CEMENTED FINE SAND
FINE GRAVEL
RUN 25
WEAKLY CEMENTED FINE SAND
FINE GRAVEL
RUN 26 & 27
WEAKLY CEMENTED FINE SAND
FINE GRAVEL
STRONGLY CEMENTED FINE SAND
RUN 28
WEAKLY CEMENTED FINE SAND
STRONGLY CEMENTED FINE SAND
RUN 30
WEAKLY CEMENTED FINE SAND
STRONGLY CEMENTED FINE SAND
RUN 31
FINE SAND
CEMENTED FINE SAND WITH JOINTS
STRONGLY CEMENTED FINE SAND
RUN 32
FINE SAND
RUN 33
WEAKLY CEMENTED FINE SAND
FINE SAND
STRONGLY CEMENTED FINE SAND
RUN 34
WEAKLY CEMENTED FINE SAND
RUN 35
WEAKLY CEMENTED FINE SAND

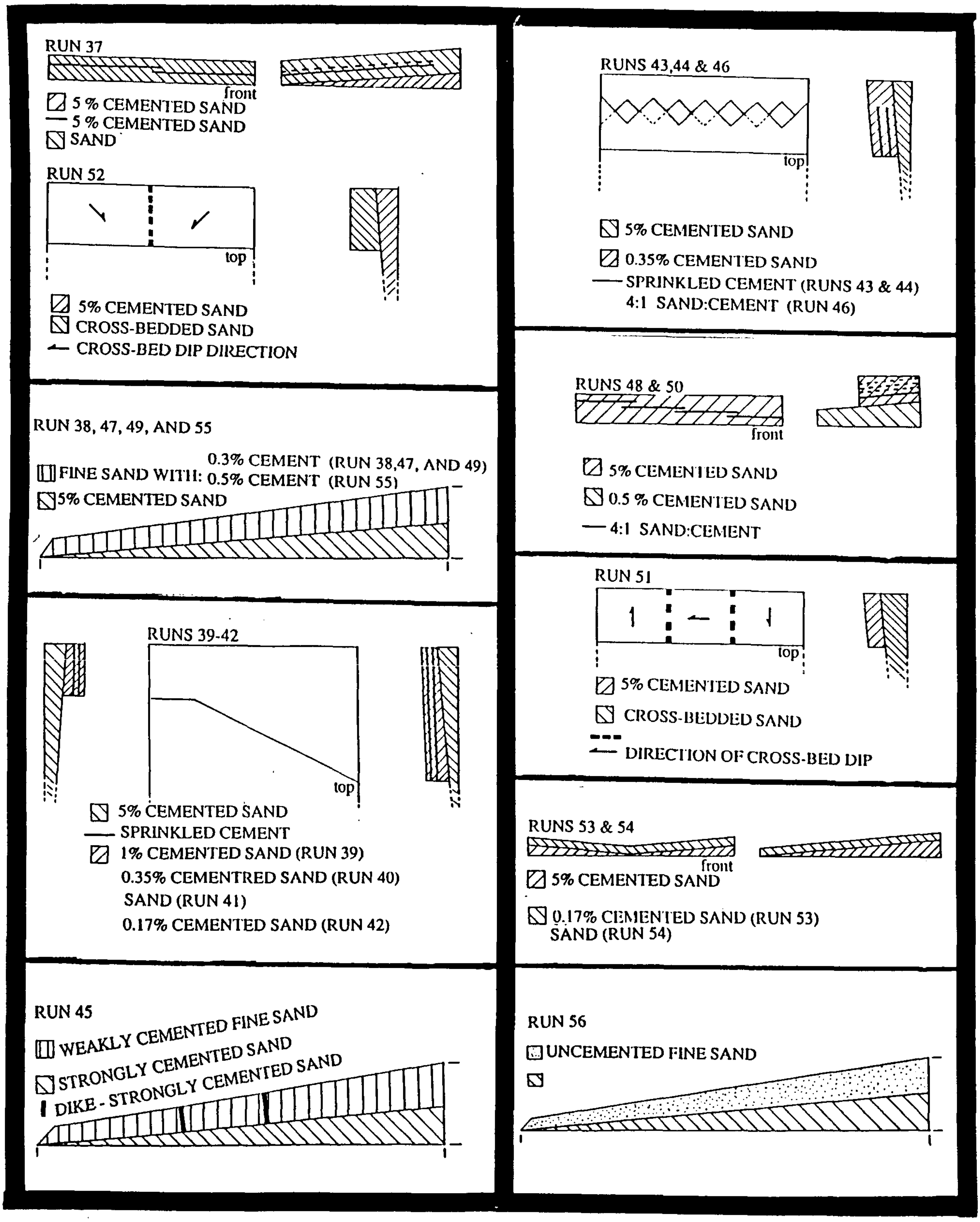


Figure 7, part 3.

Experiments in Homogeneous Materials

Several sapping runs were conducted in homogeneous sediments for purposes of establishing a set of controls to be used for comparison with experiments using layered stratigraphy and structural variations. Figure 8 summarizes the design for each of the runs done with uniform sediments, which included Runs 1,2,3,23,34, and 35. Runs 1,2, and 3 all used fine-grained sand extracted from a point bar on the Mississippi River at Grand Tower, Illinois. Table 6 provides a summary of the grain-size characteristics of the Mississippi River sand as well as the other sediments used in later experiments. Run 23 used fine sand that was weakly cemented. Runs indicating cemented sand were prepared by mixing small concentrations of portland cement (typically < 1%) with the sand while dry in order to provide cohesion and to decrease permeability. The mixture was then wetted to just below saturation and allowed to set up for 24 hours prior to the experiment.

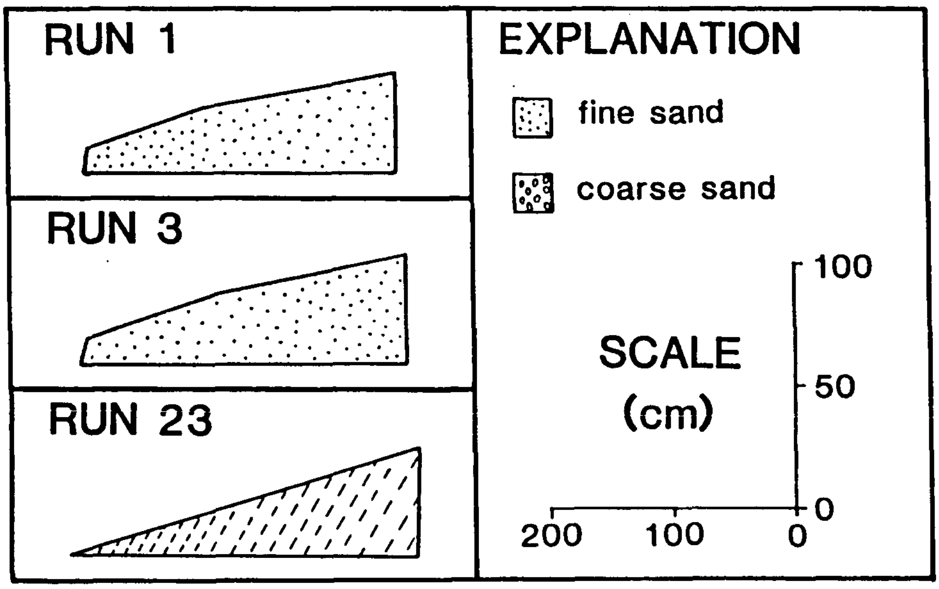


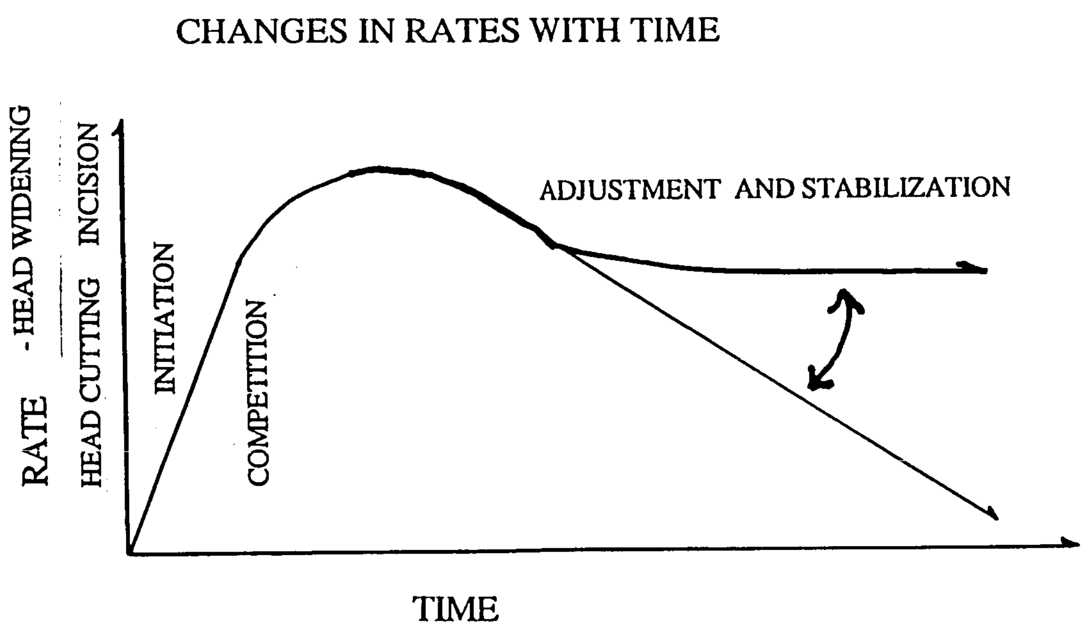
Figure 8. Generalized setup for rus using homogeneous sediment.

Table 6. Grain Size Data for Flume Sediments

Size Fraction	Fine Sand & Loess	Fine Sand	Sieved Coarse Sand	Coarse Sand
Clay	9.03%			
Fine Silt	12.89%	0.54%	1.90%	2.34%
Coarse Silt	25.85%			
Fine Sand	28.19%	52.81%	25.20%	23.62%
Medium Sand	22.54%	45.08%	34.68%	34.41%
Coarse Sand	0.45%	0.89%	36.96%	26.38%
Pebble	0	0	0.84%	12.45%

Channel Evolution

Following establishment of the reservoir head, the saturated zone migrated downflume through the sediment wedge during each run until the water table intersected either the escarpment at the base of the wedge or the mid-slope region of the wedge, whereupon sapping began. In most runs a rather steep hydraulic gradient was observed from the reservoir surface to the intersection of the water table and the sediment wedge. Although there were slight differences in the rates of valley establishment between runs depending upon initial slope and material variations, a general sequence of sapping valley evolution was common to each run. The channel evolution sequence was characterized by four distinct phases shown schematicaly in Figure 8: 1) Channel initiation; 2) rapid adjustment and competition between adjacent channels for available groundwater; 3) channel extension (headcutting) and accelerated groundwater flow convergence; and 4) channel stabilization.



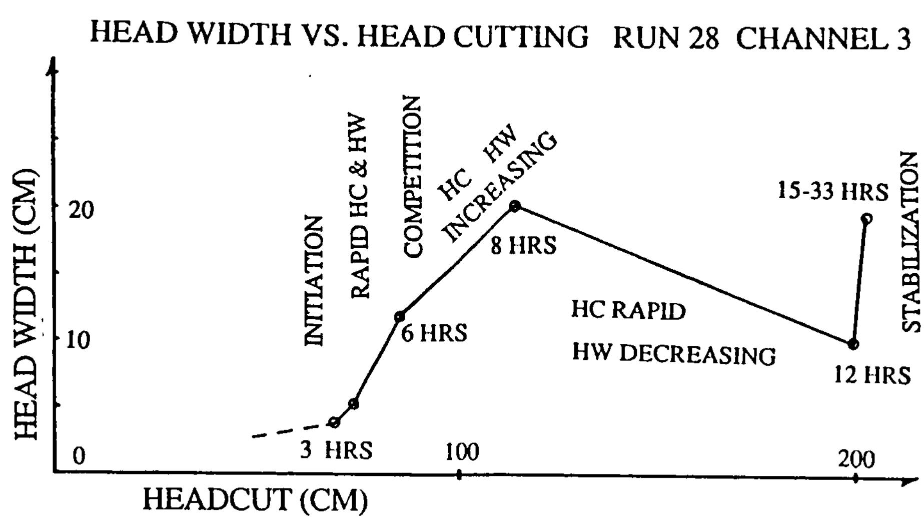


Figure 9. (top) Idealized channel evolution phases observed in the flume. (bottom) Example of sequence from Run 3.

Channel initiation occurred by one of two processes depending upon the location of the intersection of the water table and the downflume surface of the sediment wedge. In most runs, the water table intersected the sediment wedge along its mid-slope region, resulting in the development of a linear saturated seepage face or zone that extended across the entire width of the wedge and was typically between 5-10 cm in thickness parallel to the flume axis. Immediately downslope of the seepage face, emergent water began to form numerous micro-rills. Within minutes, several of these rills would become the preferred loci of groundwater flow convergence and ultimate locations of sapping valleys within a few tens of minutes. Between two and four equally-spaced channels were established during the channel initiation phase of each experiment. Between-channel spacing is determined by the extent of subsurface recharge feeding each channel consistent with the model developed by Dunne (Figure 2). The constancy of spacing between initial channels probably reflected an equilibrium adjusted to boundary conditions established by the thickness of the wedge, the width of the flume, and the permeability of the sediments. During this initiation phase, the dominant rills rapidly downcut and began to extend headwardly as groundwater seepage forces lifted grains off the bed and from the base of headscarps in the channels, inducing mass wasting of overlying channel walls. Once removed from the walls, sediments continued downslope by fluvial processes downstream of the sapping zone.

An alternative mode of channel initiation occurred when the water table intersected the nearly-vertical escarpment near the base of the wedge. The height of this escarpment varied with the slope of the wedge surface. Excessive pore pressures along this seepage zone promoted extensive slumping of the wedge. Initially, slumping resulted in parallel slope retreat, but within a few tens of minutes, accelerated slumping at several locations across the wedge (near the sites where dominant channels formed when sapping valeys were initiated by mid-slope seepage zones) resulted in the establishment of three or four dominant channels. Channels spaced about 1m apart seemed to reflect equilibrium spacing for valleys formed in unconsolidated sediments in the flume. Continued seepage through the slump debris removed sediments until incipient sapping channels were formed. Local steepening of the hydraulic gradients in the areas of accelerated slumping promoted groundwater flow convergence into the channel, resulting in predominant channels.

Sediment wedges with slopes in excess of 12^{o} typically failed by extensive slumping and resulted in the termination of the run. Sapping valleys failed to become initiated in runs with initial slopes less than 6^{o} because these slopes were below the threshold needed to transport sapped debris from the seepage face by fluvial processes in the small channels.

The second phase of channel evolution was characterized by *rapid channel adjustment and competition* for groundwater between neighboring initial channels. The initial channels immediately began to downcut and extend headwardly as groundwater flow converged at the channel head accelerating the sapping processes in the manner described by Dunne (1980). In every case, at least one of the three or four initial channels had its groundwater supply pirated in the subsurface by competition of neighboring channels. Ultimately, the pirated channel became inactive and remained unchanged throughout the remainder of the run. Successful channels rapidly evolved from narrow V-shaped rills to broad U-shaped channels with flat valley floors and amphitheater heads typical of the Martian valleys proposed for sapping origin. This phase of development was generally complete within one or two hours after channel initiation.

The third phase of channel evolution was characterized by continued groundwater flow convergence and *rapid channel extension and enlargement.* During the extension phase, the active channels enlarged rapidly by incision and headward extension. Incision generally proceeded at a linear rate until the channel head reached a zone of equilibrium equivalent to the location of the intersection of the water table on the upper reaches of the wedge. During the enlargement phase, no tributaries ever formed along downslope reaches of the channels. In addition, springs and seepage zones were noticeably absent along lower reaches of the channels (Figure 10). All of the active sapping was confined to the headward 25% of the channel areas. Some bifurcation was common along the channel heads, but rarely persisted to the extent that integrated networks developed. Development of integrated networks was inhibited by the relatively low cohesion of the sediments necessary to promote effective removal in the scale of our experiments. Slumping of the promontories between extending channel branches rapidly destroyed interfluves in most of the runs at the heads of any given channel attempting to bifurcate. Theoretical modelling by Howard (1988) illustrates how the network would probably have developed, provided scaling parameters had not interfered with the experiment.

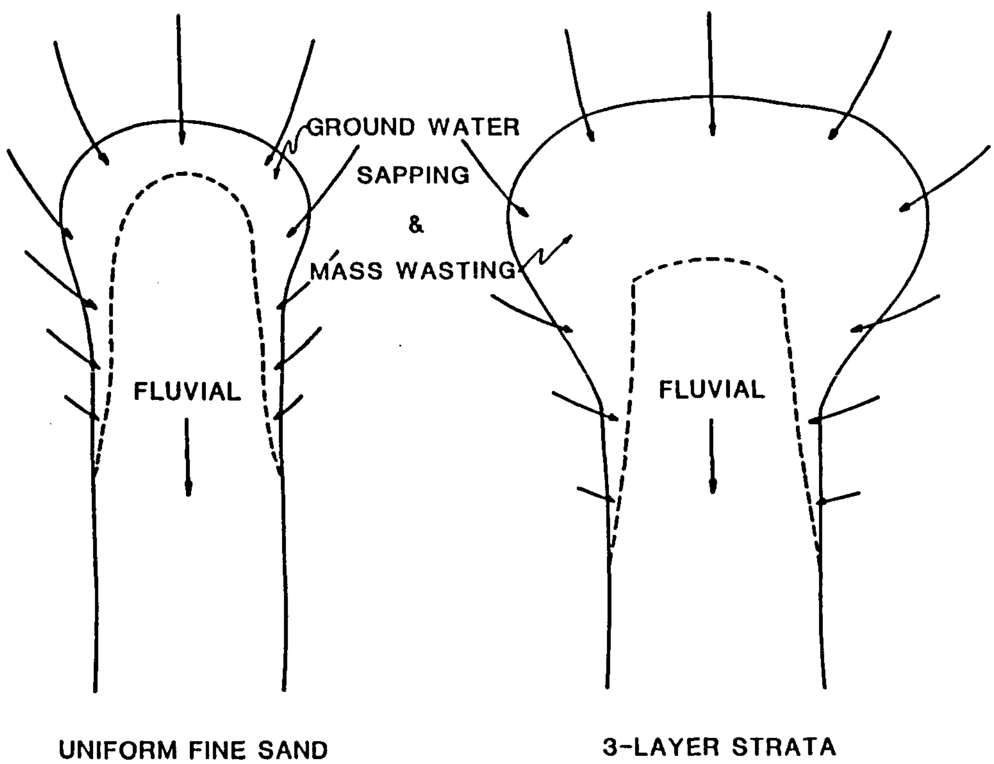


Figure 10. Sapping valleys form from a combination of sapping-mass wasting processes operative in a zone near the seepage face. Fluvial processes dominate downstream.

In the active seepage zone, granular removal of sediment grains was visible as well as extensive small-scale slumps. Channel walls remained nearly vertical but were extensively scalloped by slumping processes. Slumps were preceeded by the formation of small-scale alcoves in upstream channel walls and channel headwalls in the sapping zone. Channel extension was episodic. Therefore, in micro-time scales, valley extension was likewise episodic. Periods of catastrophic change were follwed by longer periods of slow adjustment and material removal. Periods of relative quiesence and granular removal were interrupted by catastrophic slumps whose debris would fill channel floors until it could be removed by continued seepage and downstream fluvial processes. Howard and McLane (1981) described a similar episodic nature to the evolution of sapping escarpments in their two-dimensional experiments. During this period of rapid extension and incision, channel widening did occur, but it was not prominent.

Simultaneously, extensive alluvial fans were prograding at the mouths of the sapping channels. Although the fans were not specific targets of our investigation, their dynamics were intimately invovled with sapping processes operating in upstream reaches of the channels. During periods of rapid channel enlargement and high rates of sediment production, fans actively prograded. During periods of relative channel stability, fans were trenched reflecting diminshed sediment supply from upstream. An interesting footnote related to the fans was that the stability of fan surfaces was also observed to be directly tied into fluctuations in the reservoir head. Therefore, this indicates that fluctuations in water tables, perhaps due to cyclic climatic variations, can ultimately cause thresholds in fan incision and accretion to be crossed. This observation has interesting implications to the interpretion of downstream sedimentary sequences in sapping-dominated channels and even to environmental problems on terrestrial alluvial fans. A special run (Run 56) was included at the end of the experiments to document the response of sapping fans to temporal flucuations in the water table.

The final phase of channel evolution is termed *channel stabilization*.. Stabilization is actually a misnomer, however, the rate of channel growth eventually became exceedingly slow compared to early phases (See Figure 9) so that it could be considered relatively stable. Fanhead trenching typically coincided with the onset of this phase of channel growth. Stabilization occurred when channels had extended headward to the point of coincidence with the intersection of the slope and the water table. Then, channel incision continued, but at a slower pace, while headcutting typically ceased. At the same time, the rate of head widening often increased dramatically during this latter phase. Head widening was now promoted by the stability of the seepage zone across the wedge. Valleys typically developed enlarged amphitheaters at their heads for a period of time. Finalley, even the rate of headcutting diminished in runs with uniform sediment.

Examples from Homogeneous Sediments

Run 3 best typifies the control runs using homogeneous fine sand and is illustrate in Figures 11 and 12. Run 3 had a surface slope of 10^{o} and used a constant head of 35 cm in the reservoir for 46 hours. Figure 11 shows oblique photographs taken at hours 15 and 46. Four channels formed during the channel initiation phase during the first two hours. Channel incision and rapid headward extension during hours 1-5 was followed by gradual incision and enlargement during the stabilization phase between hours 6-46 (Figure 12). Abandonment of the third channel from the left occurred between at hour 10. The resulting final form was three prominent channels having amphitheater heads and relatively uniform channel width along their axes. Valley walls showed prominent slumps and scalloped margins indicative of the importance of mass wasting processes triggered by groundwater sapping. This run provided a good control for contrasting with later runs in varied geologic settings.

Run 23 provides a comparison of the effects of increased cohesion and decreased permeability with the unconsolidated sand used in Run 3. A 0.3% mixture of cement was added to the fine sand in Run 23 for greater cohesion. One prominent channel and two smaller ones once were formed by groundwater sapping in Run 23, but the general characteristics of these channels differed significantly from those formed in Run 3.

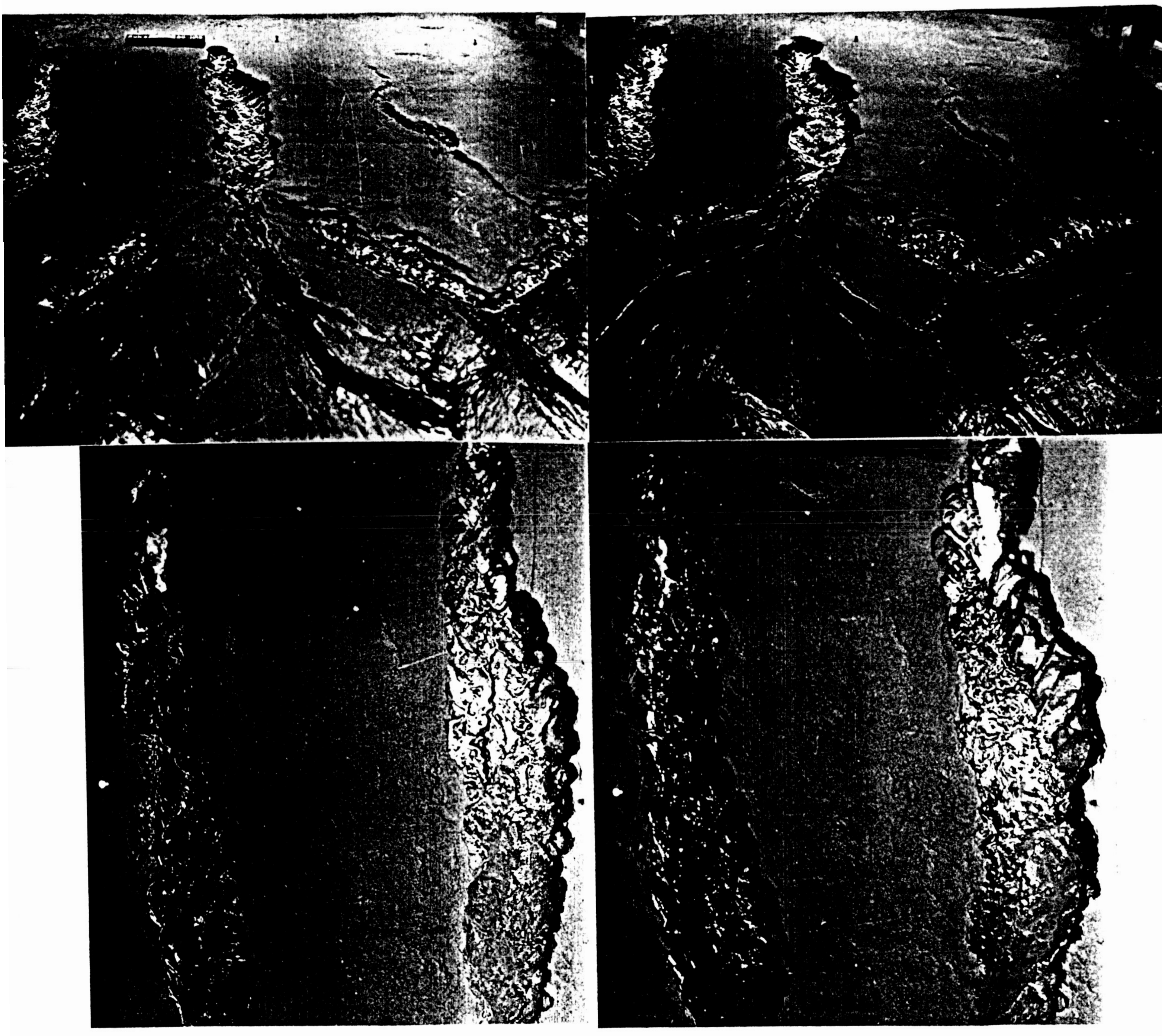


Figure 11. Oblique and overhead photos of Run 3.
Clockwise from upper left: 1) 20 hrs, 2) 46 hrs, 3) 46 hrs, 4) 20 hrs.

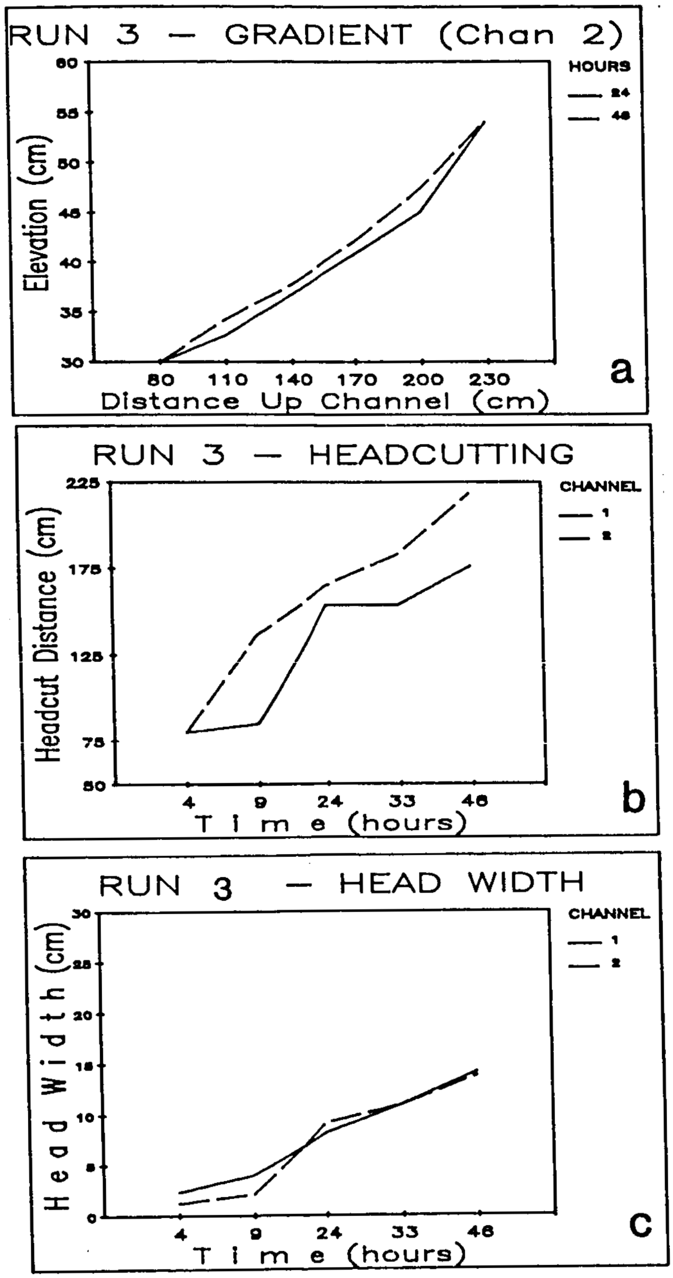


Figure 12. Morphodynamics of Run 3 in homogeneous sediments.

Modifications Using Uniform Sand

Run 33 provides interesting observations from an experiment done in weakly-cemented sand similar to the mixture described for Run 23. These runs were designed to see how preformed channels with predetermined junctions would be modified by groundwater sapping processes. This scenario may be useful in providing ideas about what the effects might be of a climatic change which would cause a runoff-dominated valley network to become dominantly affected by sapping processes. A single dendritic channel network was carved by hand into the sediment surface as illustrated in Figure 13 which had three upstream bifurcations established with junction angles commonly found in terrestrial runoff networks. Following the construction of the channels, the overhead sprayer was used to produce runoff for 2 hours. Runoff had no apparent effects on the channels except to continue to enlarge them without significantly altering the junction angles. After the episode of rain, sapping commenced and was permitted to occur for 194 hours. Early in the sapping run, minor extension occurred along the upper reaches of the first order branches. Meanwhile, small seepage rills began to develop at locations independent from the precut channels by seepage erosion. These seepage channels subsequently progressed through the normal sequence of channel development until a dominant one between the two pre-cut upper channels joined the trunk of the pre-cut system. During the remainder of the run, the sapping valley continued to enlarge and remained independent of the network initially cut into the wedge.

Run 33 illustrated that sapping processes can be significant enough to cause significant alterations in the morphology of pre-existing channels and may become useful in making interpretations about paleoclimatic flucuations in terrestrial and Martian valleys. Baker and Partridge (1986) observed two distinct styles of valleys in dry valley networks, termed degraded and pristine. Pristine valleys commonly occupied downstream reaches of the same networks that contained degraded valleys, causing Baker and Partridge to speculate that the pristine segments may record a rejuvenation of channel incision. It is possible that the pristine valleys, which are typically more sapping-like in appearance, may record an alteration in channel morphology caused by the onset of groundwater sapping.

Run 35 looked at the effects of sapping upon previously established channel networks. In this case, two networks were cut into the wedge with parallel drainage patterns composed of only two branches (Figure 14). The use of parallel networks removes some of the suspicion that the changes observed in Run 33 were due simply to the shift from dendritic to parallel drainage that would be expected for any channel on steep slopes such as these regardless of the formation by sapping or runoff. The run was allowed to proceed for 77 hours and resulted in significant alterations to the original channel patterns. This time, no new channels were created, but substantial modifications did occur to junction angles and symmetry of the original valley networks as a result of sapping. The channels originally oriented such that they could most efficiently capture the subsurface water entering from the reservoir became the two prominent channels while pirating supplies of groundwater from their adjacent channels. In contrast, the channel oriented almost parallel to slope enlarged in a regular manner consistent with the style observed in Run 3. The channel on the left, oriented more obliquely to slope, developed a distinct asymmetry.

Sapping modifications caused the oblique channel to extend directly up the dip slope toward the reservoir in the direction of preferred hydraulic gradient. This asymmetry of channel pattern seems especially common in valley networks influenced stongly by sapping due to the strong preference for valleys to extend up dip slopes along preferred hydraulic gradients. In virtually all sapping runs, channels showed accelerated slumping along the wall oriented up the dip slope, reflecting the uneven entrance of groundwater flow into the channels. The direction of asymmetrical extension was controlled by structural dip and by groundwater flow net interferences caused by competing valleys. Many of the Martian slope valleys along Valles Marineris, for example (Figure 15), have a distinct asymmetry which may be related to slope. Studies by Laity and Malin (1985) and our studies on the Colorado Plateau also contain numerous examples of asymmetrical valley networks in areas of dipping strata strongly influenced by sapping processes.

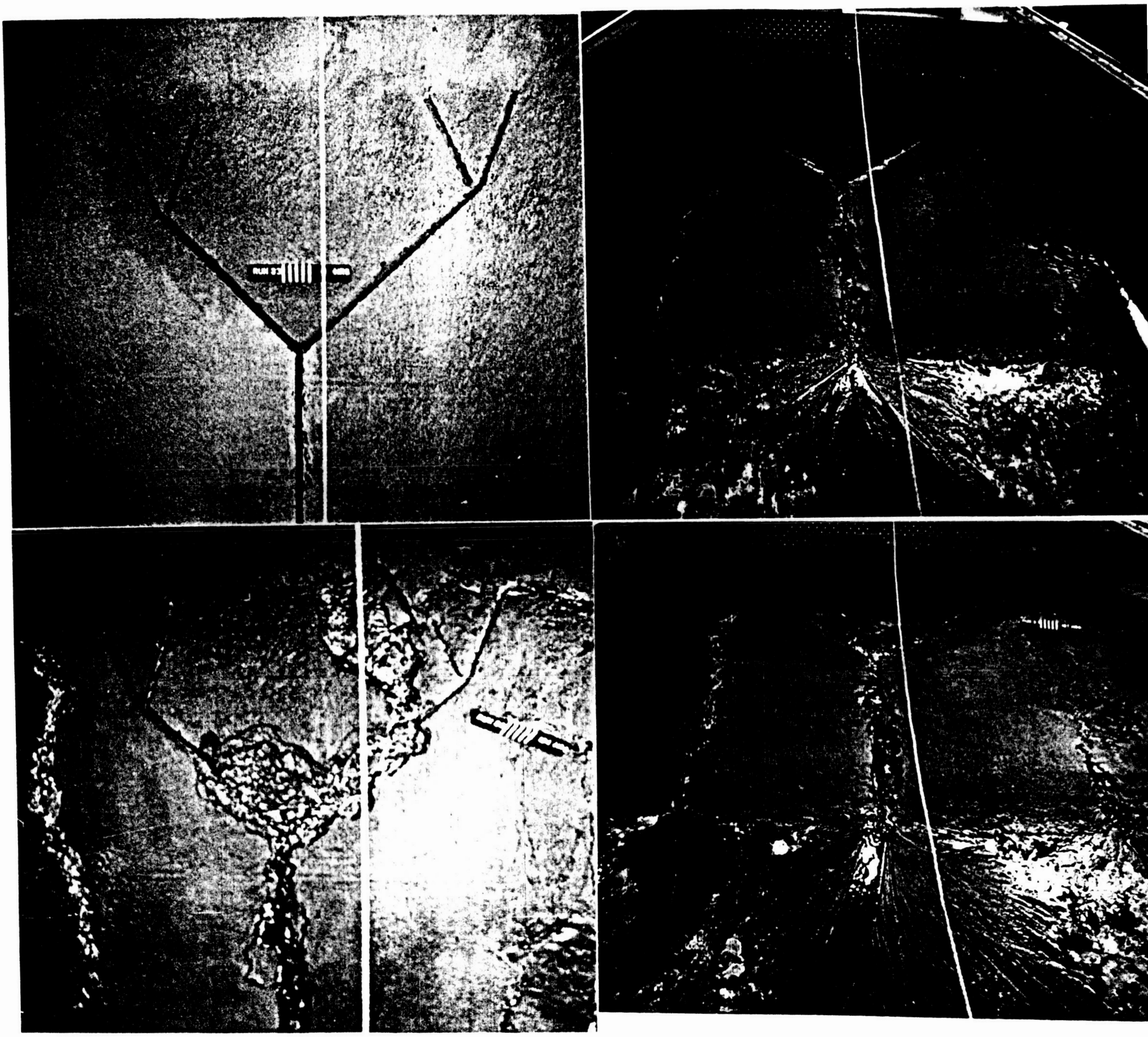


Figure 13. Photos from Run 33.
Clockwise from upper left: 1) initial setup, 2) 40 hrs, 3) 157 hrs, 4) 194 hrs.

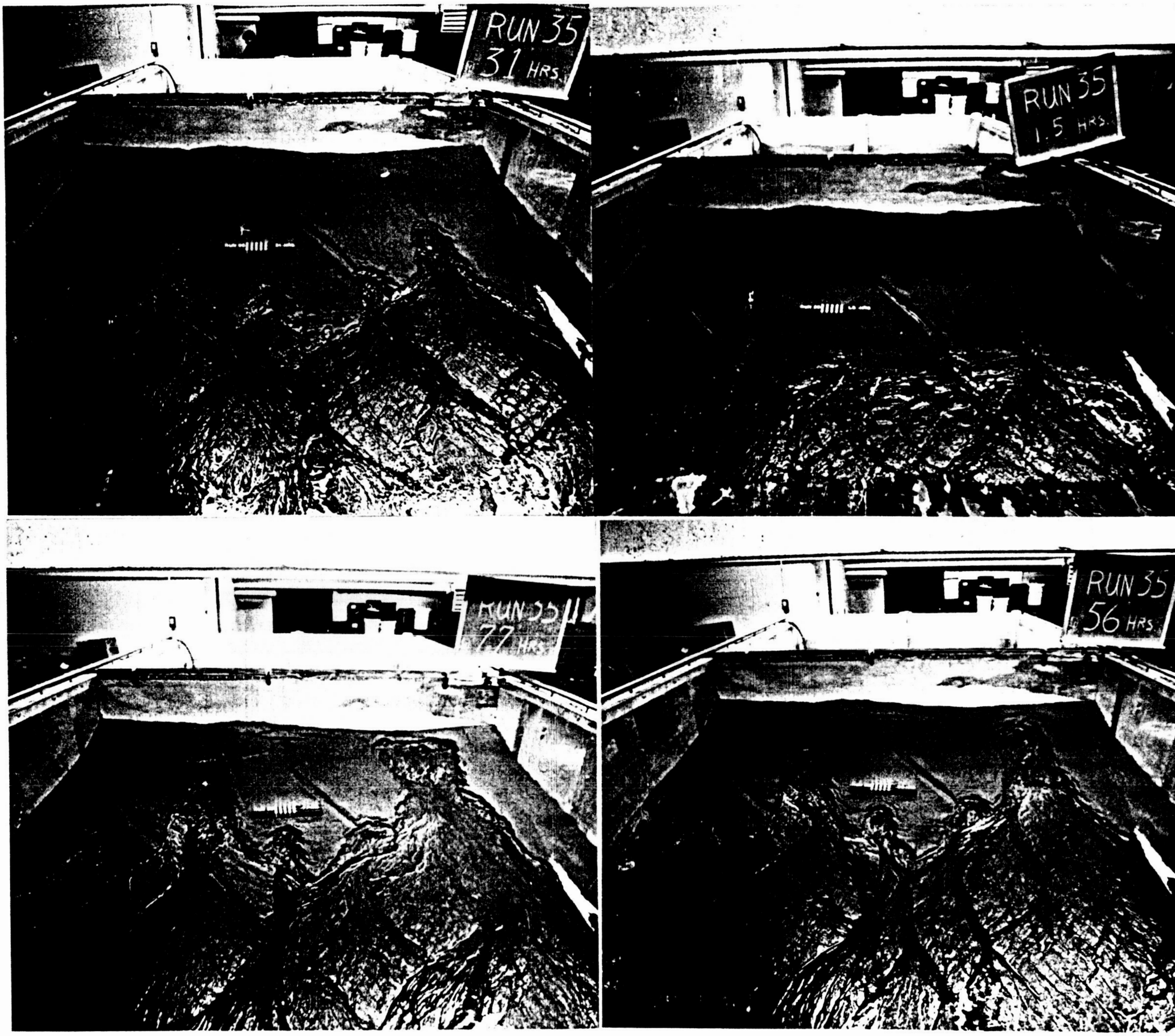


Figure 14. Photos from Run 35. Clockwise from top leftp: 1)1.5 hrs - initially following joints, 2) 31 hrs - developing up-dip sapping; 3) - 56 hrs - up-dip sapping deviates from joint trends, 4) 77 hrs - continues up-dip sapping.

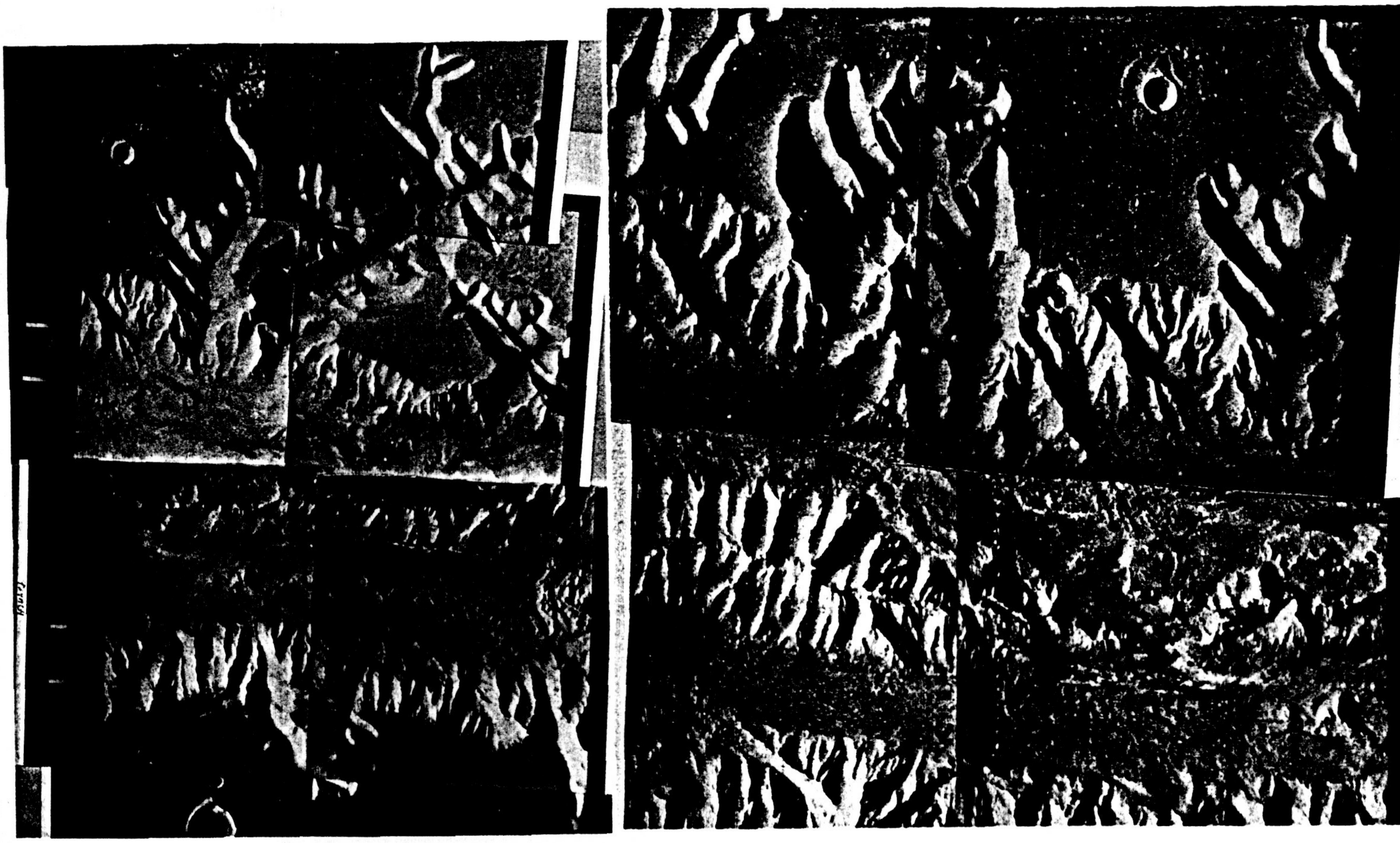


Figure 15. Examples of asymmetry common in Mars slope valleys along Valles Marineris. Note the pronounced extension of channels toward the upper left.

Rainfall Runoff Networks in Uniform Sediments

In several runs, rainfall was applied to the sediment wedges in an attempt to create channel networks for comparison to sapping valleys. Rainfall channels typically developed wide, straight valleys parallel to slope with little channel identification. Head areas of rainfall channels were indistinct and blended into the wedge slope in sharp contrast to the deeply-incised amphitheater heads characteristics of the valleys formed by sapping in the same sediments.

Phillips and Schumm (1987) performed a series of experiments creating drainage networks in unconsolidated sediments by runoff processes. They showed that runoff networks on a wedge of similar size to ours developed well-integrated branching networks with substantially high drainage densities. In addition they found that with increasing slope, the drainage pattern shifted from dendritic to parallel at slopes less than 2^{o} concurrent with a decrease in junction angles from approximately 60^{o} to approximately 40^{o}. Therefore, we would expect runoff channels on our wedges with significantly higher slopes to be parallel and have even lower junction angles than those reported by Phillips and Schumm (1987). These observations argue strongly that the higher junction angles sometimes observed in our sapping runs were due to groundwater influence and extension along inhomogeneities in the sediments. Likewise, the high junction angles of the Hawaiian valleys and the Colorado Plateau valleys assumed to be influenced by sapping (see later summary sections) reflect structural control under the influence of groundwater sapping.

Experiments With Layered Stratigraphy

A series of experiments were designed using dipping layers with varying permeability to simulate the kind of geological setting that occurs in the gently-dipping strata of the southern Colorado Plateau. Earlier research by Laity and Malin (1985) and the recent field conference on groundwater spping (Howard, Kochel, and Holt, 1988) held in the Colorado Plateau have shown that an abundance of sapping phenomena have been involved with the evolution of channels in that region. The effects of slope in our experiments with layered stratigraphy appeared to be complex. Figure 16 shows a summary of the types of experimental setups used in the layered runs. Run 3 can be used as the homogeneous control to be compared to Runs 8,9,11,25,26,27,28,30, and 33.

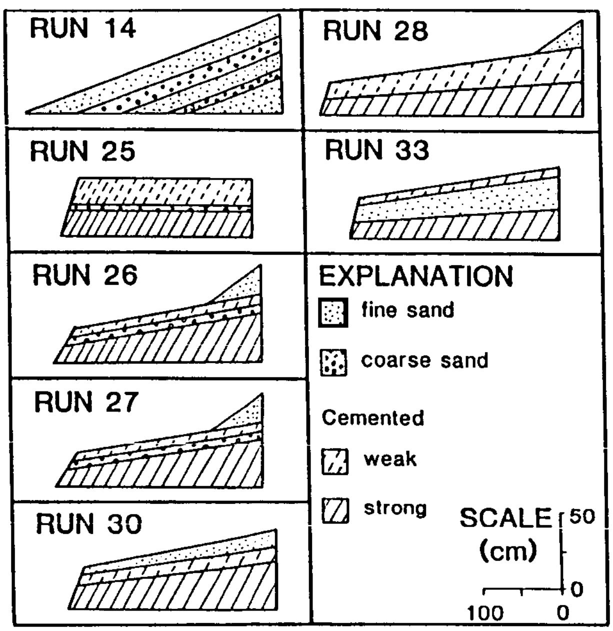


Figure 16. Summary of design set-ups for runs using layered stratigraphy.

Channels produced in runs with layered stratigraphy followed the regular scenario of channel evolution outlined in the section on homogeneous sediments. However, layered runs exhibited channels with considerably less development during equivalent time periods than either the experiments with uniform stratigraphy or the set of runs to be discussed later using high-level aquifers. This indicates the important effect that changing hydraulic characteristics of the host sediments can have upon the morphology of the resulting sapping valleys. In most of the runs with layered sediments, channel width did not increase appreciably in the upchannel direction, but remained relatively constant or even tapered slightly. Part of the explanation for the lower rate of head widening may be the limiting recharge area available to the growing sapping channel heads imposed by the two-dimensional nature of permeable units. The added recharge from below the sapping head was reduced in these runs by the presence of relative aquicludes below permeable units in contrast to the uninhibited three-dimensional recharge areas around the heads of valleys formed in homogeneous sediments. In the latter case, the only limiting factor would have been the thickness of the entire sediment wedge, rather than the thickness of a given permeable stratum during the experimetns with layered sedments.

The depth of sapping canyons appears to have been directly controlled by the thickness of the sediment in the upper layers of the runs. In situations where there is a more permeable upper layer (weakly cemented) over a less permeable base (strong cement or loess mixture), the basal layer acts as a base level control on incision. Thick, cemented upper layers prevented good channel development in the experiments because channels were clogged by massive slumps eroded from valley walls. Coarse slump block debris from the resistant caprock in some of the runs could not be transported and formed boulders of cemented sand which armored sapping channels. This limited channel development in some cases. Less cemented upper strata were readily eroded by fluvial processes downstream from the sapping face.

The width of sapping channels varied considerably with the thickness of the strata and with cohesion (Compare Figure 11 (Run 3) with Figure 17 (Runs 14 and 27)). Channels were considerably wider in less cohesive sediments (Run 3) where lateral migration of streams downslope from the active sapping face was extensive. Cohesion limited the rate of lateral cutting by retarding the rate of channel wall slumping, resulting in narrower valleys.

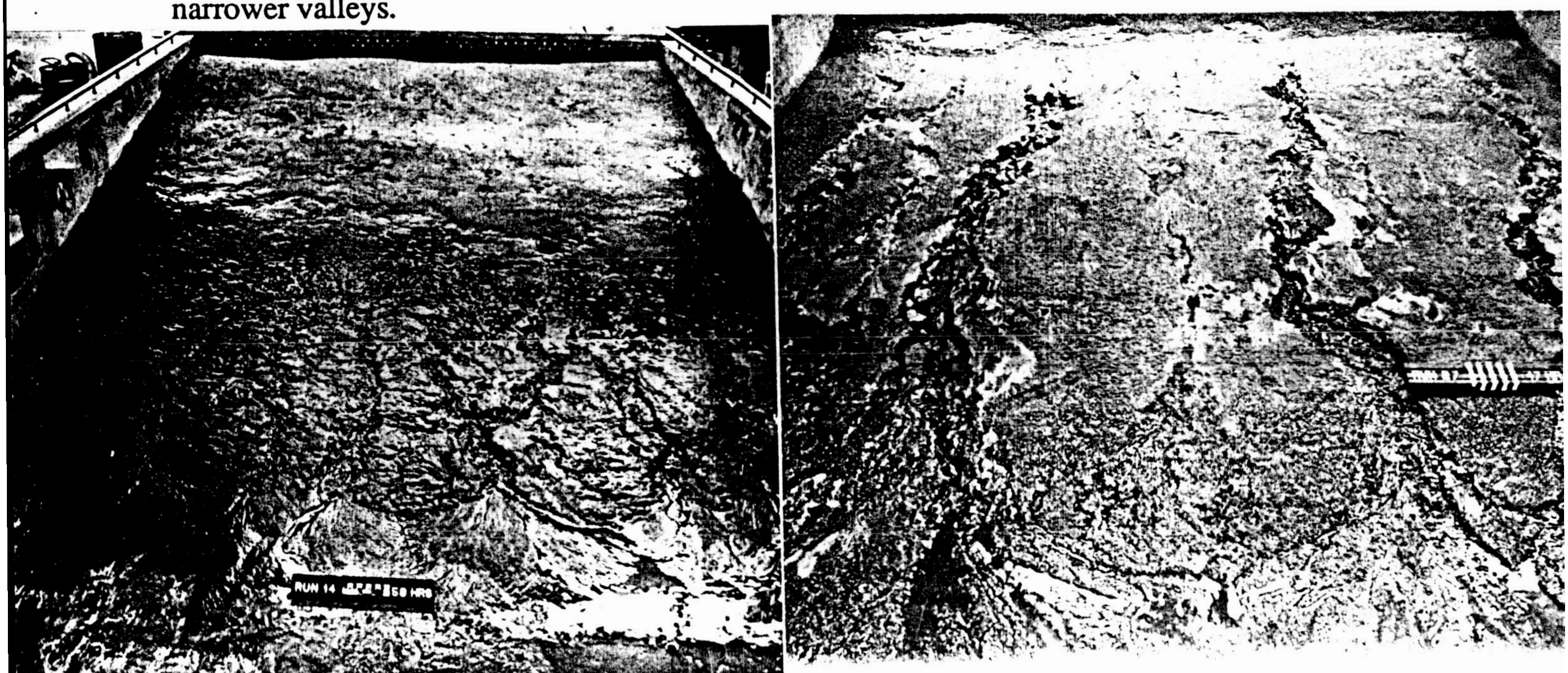


Figure 17. Variations in channel development depending on intersection of permeable strata with wedge slope. Left) Run 14, 58 hrs - shows minor channels because permeable layer did not intersect surface. Right) Run 27, 47 hrs - shows deep channels because permeable beds intersected slope surface.

Variations in the dip of the strata appeared to be more important in affecting channel development than surface slope. Runs 14 and 27 contained layered strata with markedly different surface and dip slopes. The 9° slope in Run 14 should have resulted in rapid channel formation. However, only small channels formed directly above the toe of the coarse layer. Slumping occurred downslope from the zone of seepage (Figure 17). The stratigraphy in Run 14 was parallel to the surface slope and no layering was exposed on the seepage face. Most of the groundwater discharge through the coarse layer either flowed along the flume floor to induce slumping or emerged directly above the toe of the coarse layer, taking the shortest route through the fine layer.

The surface slope of Run 27 was only 3°, well below the threshold of transport observed for the homogeneous sand runs, but this run experienced significant channel development. Channels developed because the coarse, permeable layer was exposed on the face of the low scarp at the wedge toeslope. Sapping rapidly produced small slumps which extended headward into channels (Figure 17). The coarse sand used in the more permeable bed armored the channels, which inhibited incision as the run continued. Therefore, these channels were not incised as deeply as those in homogeneous sediments. The plot of headcutting shows (Figure 18) where channel 1 quickly developed while other channels failed to undergo the rapid extension phase due to piracy until channel 1 approached the stabilization phase.

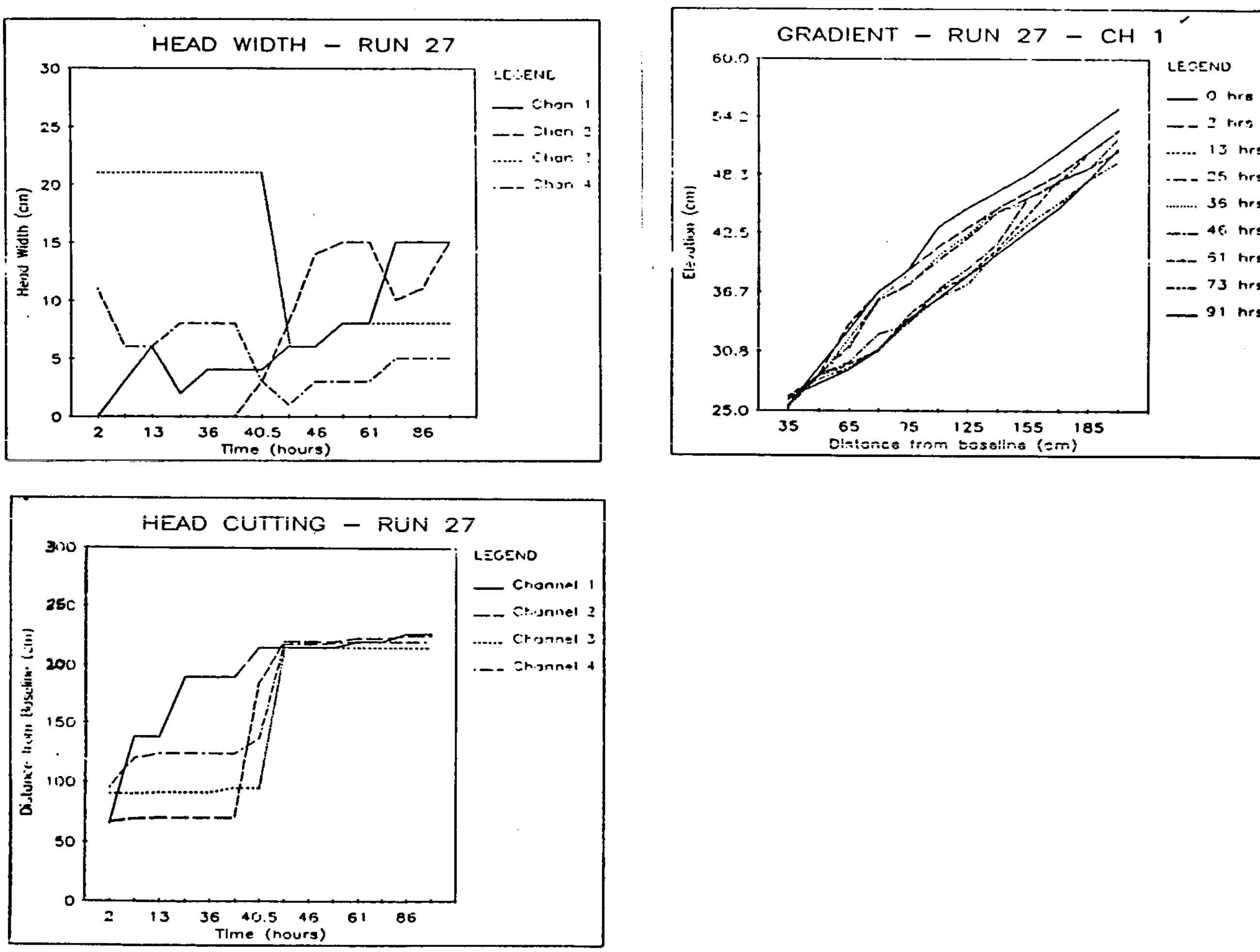


Figure 18. Channel morphodynamics for Run 27.
Note how channel (lower left graph) developed before other channels. After left channel stabilized, the other channels then permitted discharge to channels 2-4.

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Tributary Asymmetry and Dip Slopes in Layered Sediments

As was shown in the modified homogeneous sediment experiment in Figures 11 and 12 (Runs 34,35), tributaries developed preferentially along the sides of channels oriented oblique to wedge surface slopes in a manner extending directly up-dip toward the reservoir. This created a pronounced asymmetry to the overall drainage network. Laity and Malin (1985) drew attention to the role of structure in controlling the pattern of channel networks developed by sapping in the Navajo Sandstone of the Colorado Plateau. They noted that on a regional scale the tributaries to the Escalante River in southern Utah were asymmetrically distributed about the main channel. Tributaries were more frequent and more incised on the up-dip sides of the channel, reflecting the importance of groundwater flow parallel to dip in channel development influenced by sapping processes.

Run 18 also provided an example of the preferential asymmetry of channels developed in sapping systems along regional dip-slopes (Figure 19). Note that the right (up-dip) walls of the channel indicated by the arrow are scalloped by sapping alcoves while the down-dip slopes (left) are smooth. Similar asymmetry is also visible along valleys formed on slopes of Kohala volcano (Kochel and Piper, 1986) and in areas of the Colorado Plateau where sapping processes are active along dip slopes (Kochel and Phillips, 1987,1988). Asymmetrical valleys are also common along Martian slopes as exemplified along Valles Marineris in Figure 15.

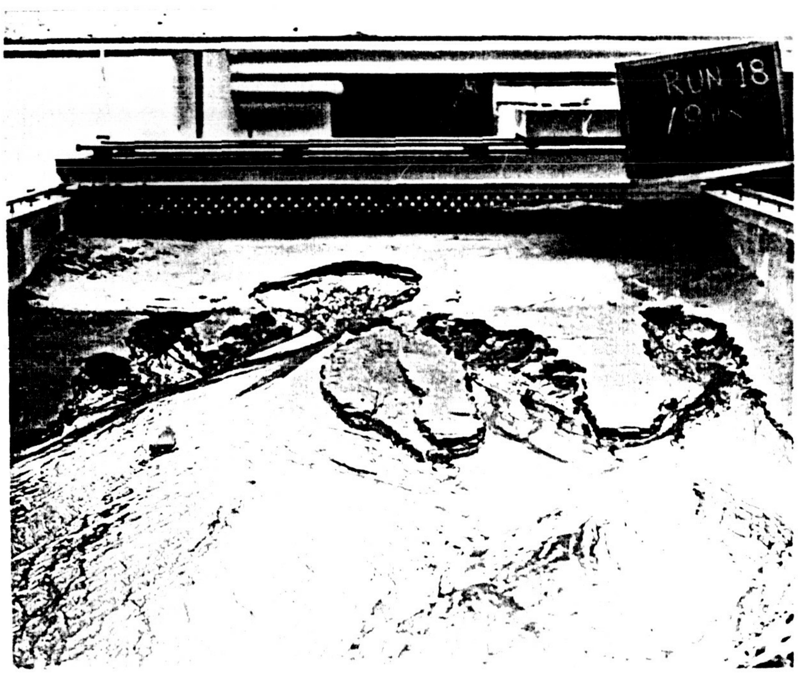

Figure 19. Run 18, 19 hrs. Note the example of asymmetric channel development. Second channel from right is extending headward along its right side. Left side of this channel is inactive due to upslope groundwater piracy by the large channel on the left which was first to tap into the perched high-level aquifer.

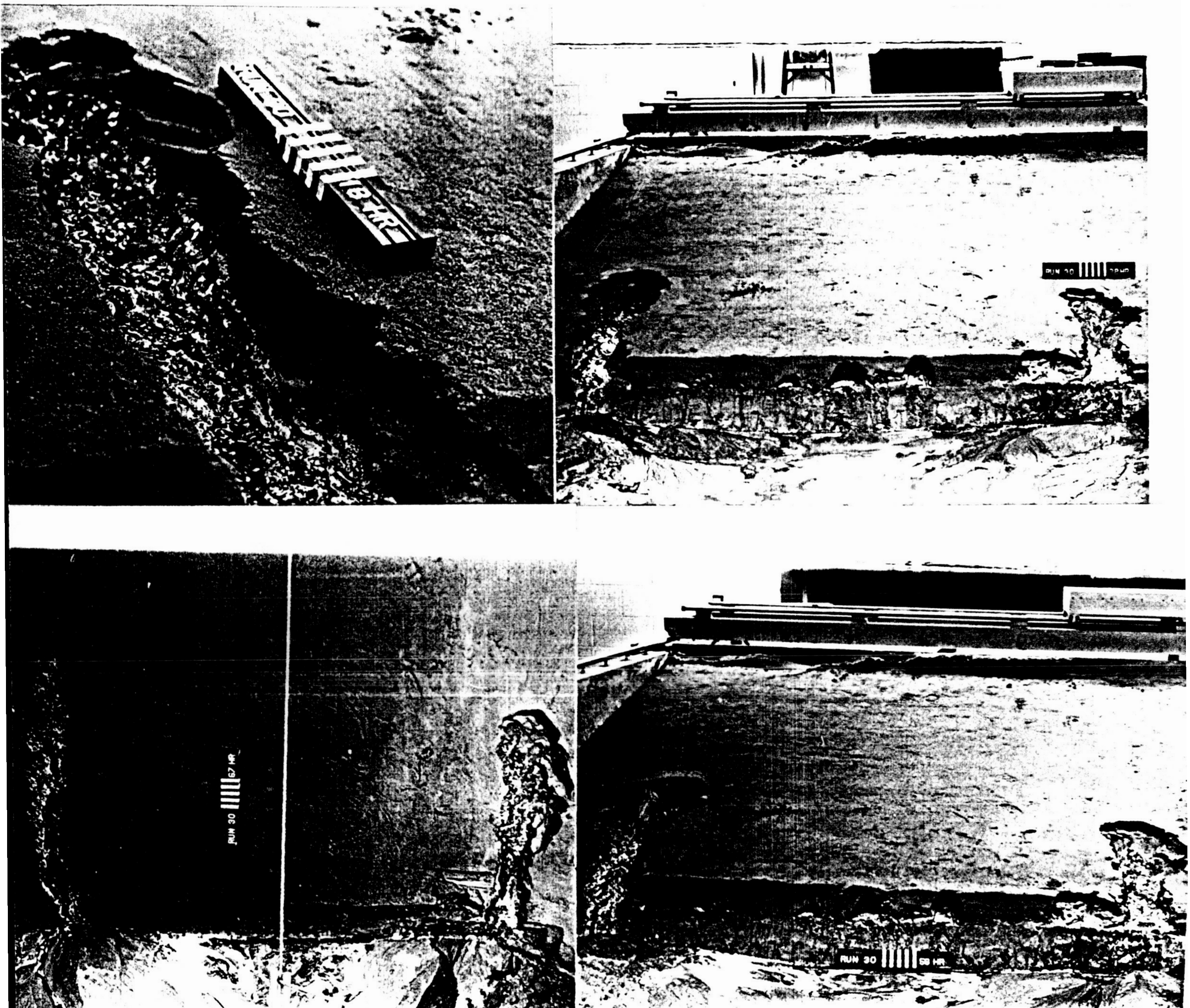

Figure 20. Photos from Run 30.
Clockwise from upper left: 1) 18 hrs - mass wasting along sapping channel walls, 2) 32 hrs - note limited channel development compared to Run 3, 3) 56 hrs, 4) overhead view showing amphitheater head with slump-dominated morphology

Example Using Layered Stratigraphy

Run 30 exemplified a successful run using layered stratigraphy (Figures 20,21). In contrast to Run 3 (uniform sand), it required about 4 hours to complete the phase of channel initiation in layered sediments, which was followed by a lengthy phase of channel adjustment which extended for 32-48 hours, depending upon which channel was being observed. Channel stabilization was reached after 48 hours and continued until the run was terminated at hour 78. Note the considerable irregularity in channel form compared to previous runs in less consolidated sediment as well as the abundance of channel wall alcoves in Run 30. Alcoves seemed to be preferentially developed in layered sediments with varying permeability. The marked contrasts in vertical permeability apparently permit groundwater to become localized along contacts between the units and concentrated flow occurs laterally, provided the contact is within the saturated zone. This situation is similar to the observations discussed later in the summary of field studies in the Colorado Plateau and in the section describing alcoving experiments.

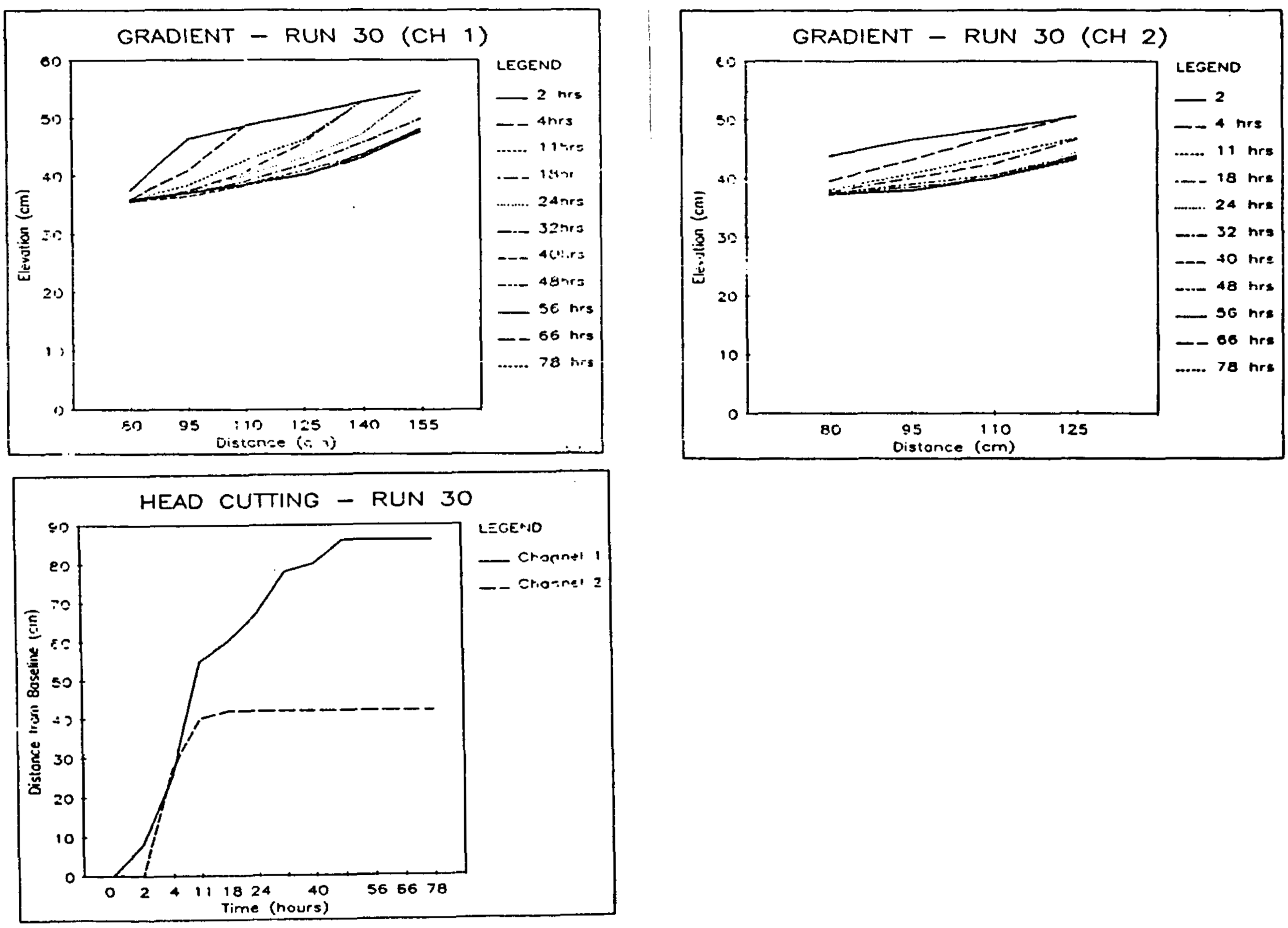

Figure 21. Channel morphodynamics for Run 30.

Figure 21 shows that headcutting was most rapid followed by incision during the early phases of Run 30. In the late hours of the run, the dominant changes were head widening as the channels cut down to a coarse, permeable layer. Channel 1 cut further upslope than channel 2, but both were rapidly extending until hour 18. After hour 18, the dominant process was head widening facilitated by slumping above the sapping faces. Photographs (Figure 20) show repeated slump blocks appearing in the channels and their removal by seepage flows and downstream fluvial activity. Alcoves remained a prominent morphologic feature of valley walls in the areas of active sapping and persisted along the walls even after the zone of active sapping migrated upslope with channel headcutting. The persistence of relict alcoves on downstream valley walls argues for the relative minor influence of lateral migration and fluvial activity in widening downstream areas of sapping valleys.

Experiments Using Joints

A series of five runs, Runs 8,9,10,11, and 31, tested the effects of joint patterns installed into layered stratigraphy on the evolution of channels by groundwater sapping. There is considerable evidence from field studies in the Colorado Plateau that groundwater movement in consolidated rocks is often preferred and accelerated along zones of structural weakness such as faults and joints. The objective of these experiements was to create linear avenues of increased permeability with respect to the host strata in order to mimick joints.

In general, main channel trends followed joint patterns and their tributaries formed along secondary joints. Channels in Run 11 followed the joints exclusively (Figure 22). During the first few hours, seepage occurred along the slope over a large range of elevations, but exclusively within the joints. Two main channels formed and elnlarged headward along the joint pattern. The left channel (Figure 22) was favored during the latter hours of the run because it reached an intersection of joints first and pirated water from the neighboring channel. In all of the runs, the predominant effects of the joints were observed in the upper reaches of the channel networks. In many cases, excessive fluvial activity in downstream reaches masked any influence of joints during later phases of the runs. Observations in the Colorado Plateau and on Mars images indicate that most of the effects of jointing are also best observed in the channel head regions.

In Runs 8,9, and 10, the channels did not follow the joints exclusively, but were strongly influenced by their presence. Run 8 began with a period of parallel scarp retreat by slumping at the toe of the slope. An indentation appeared along the scarp at the right by hour 30 (Figure 22) which extended to a joint intersection. By hour 9, this had grown into a large channel with a bifurcated head. Bifurcation was attributed to groundwater inflow from the two diverging joints upslope from the intersection. Early development in Run 9 followed the joint pattern (Figure 22) until major joint intersections were encountered. Then, the left channel widened rapidly along a major joint creating the diagonal channel. The right channel bifurcated at a joint intersection and followed two diverging joints as it cut headwardly, which is well illustrated in Figure 22. The rate of headcutting in the left channel (Channel 2) was rapid during the first 19 hours as the diagonal channel was forming. The rate of growth of Channel 2 then slowed as Channels 4 and 5 enlarged (right bifurcation). Apparently, Channels 4 and 5 pirated more water from the neighboring channels after reaching the joint intersection on the right.

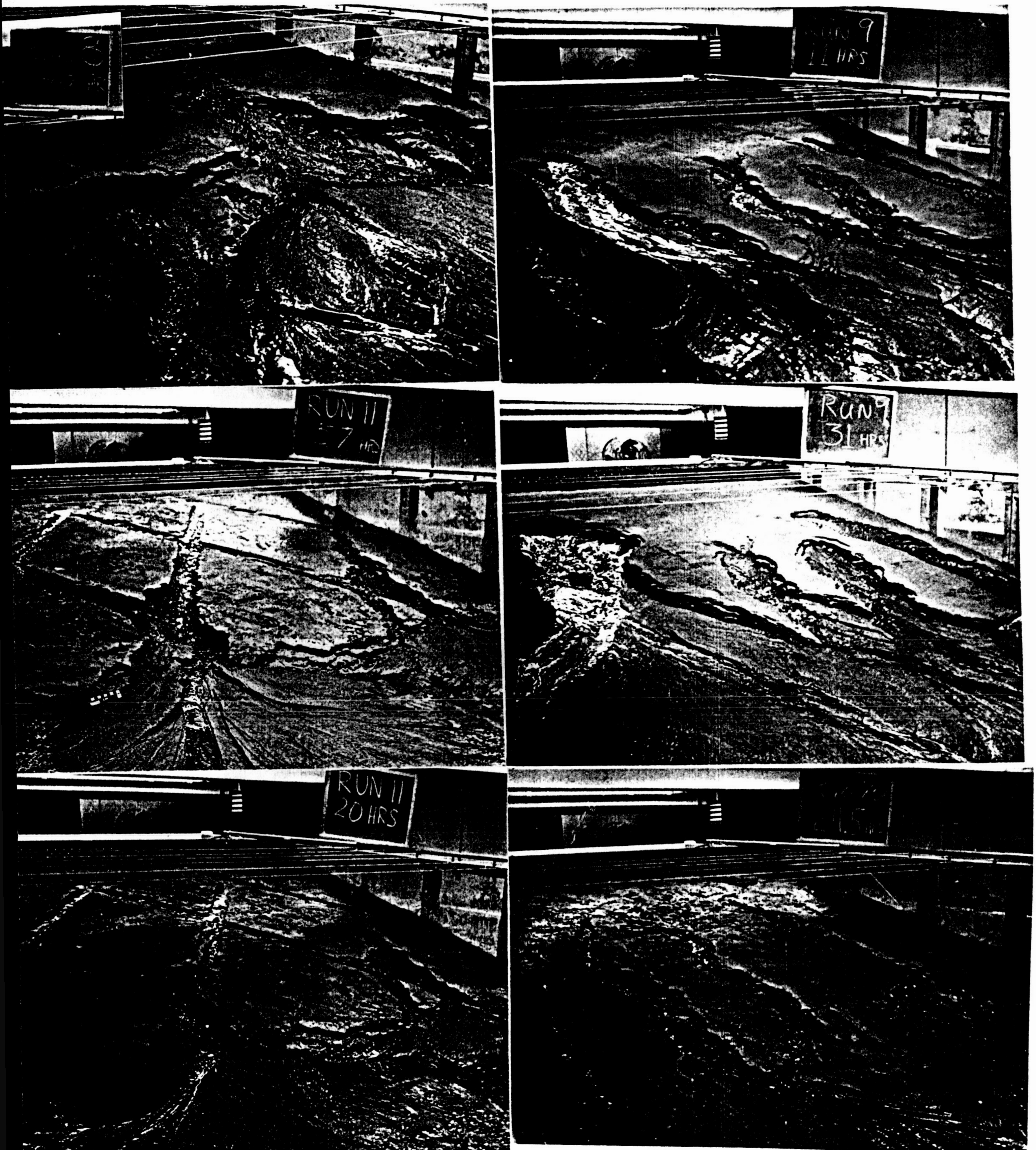

Figure 22. Photos from several joint runs.
Clockwise from upper left: 1) Run 8 - 4 hrs, 2) Run 9 - 11 hrs, 3) Run 9 - 31 hrs, 4) Run 10 - 24.5 hrs, 5) Run 11 - 20 hrs, 6) Run 11 - 57 hrs.

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Figure 23. Effects of structural control at the heads of slope valleys along Valles Marineris, Mars. Valleys are preferentially extending headward along grabens.

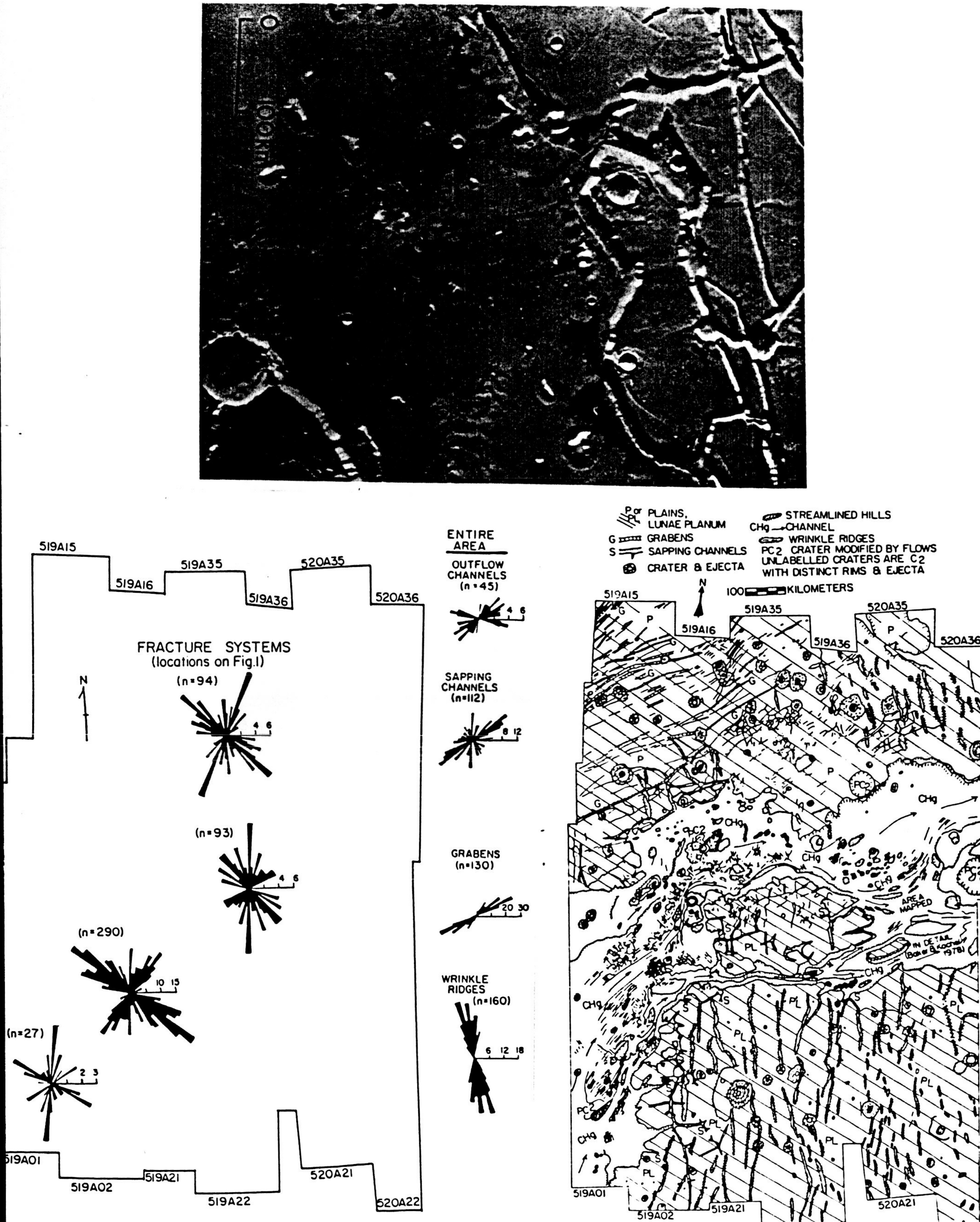


Figure 24. Sapping modified margins of western Kasei Vallis, outflow channel on Mars. Sapping has extended channel widths considerably by following structural trends. Note correspondence of structural features with channels (from Kochel and Burgess, 1983).

In summary, experiments with linear zones of increased permeability suggest that if significant joints are present, sapping valleys will preferentially extend along these avenues of increased groundwater discharge. The degree of influence that joints will have upon channel location and morphology probably depends upon the relative differences between permeabilities of the joints and the host rock. As this difference increases, the influence of jointing should become more pronounced. Runs 11 and 31 had the greatest permeability contrasts between the joints and the layers and channels in those runs exhibited the greatest adherence to the joint patterns. Channels in Runs 8, 9 and 10 exhibited some joint control, but channels still developed independent of the joints in several areas because the permeability of the sediments was still fairly high relative to the joints.

Rainfall was applied to some of the joint runs after sapping experiments were terminated to observe the influence of runoff on patterns adjusted to joint patterns. The onset of runoff resulted in significant adjustments to the sapping valleys. Runoff channels tended to adhere to the controls of the surface topographic slope, which in many cases was unrelated to the orientation of channels developed oblique to slope by sapping along the joints. The most important effect of rainfall was to increase discharge through the former sapping valleys which helped to remove slump debris which had accumulated in the channels from sapping erosion. Hence, in terrestrial composite channels, the processes of sapping and runoff may work in concert to erode channels. Only in areas where sapping is exceedingly prominent with respect to runoff will the channels probably acquire characteristics distinctive of sapping valleys.

Martian sapping valleys display numerous examples of structural control in their valley patterns. Figure 23 shows headward extension of slope valleys along Valles Marineris controlled by the influence of major grabens. Kochel and Capar (1983) showed close correspondence of structural features and sapping channels throughout the Valles Marineris region of Mars. Kochel and Burgess (1983) observed similar features along the walls of major Martian outflow channels that have been modified by post-flood widening processes (Figure 24).

Experiments With Structurally Controlled Perched High-Level Aquifers

Our field investigations in large, amphitheater-headed valleys on Hawaii provided evidence that they are influenced by large volumes of groundwater fed into their heads from dike-impounded aquifers perched near the summits of volcanoes (Kochel and Piper, 1986). Neighboring valleys which fail to intersect these aquifers are considerably less incised and show characteristics typical of parallel drainage networks formed by runoff. A series of experiments were designed to observe the effects of discharge from high-level aquifers into sapping valley systems and to contrast this with rates of valley formation in the same sediments formed exclusively by runoff. Runs 7,18,22,24,32,45, and 49 were designed to view the effects of high-level aquifers (Figure 25). Several of these runs used a coarse-grained wedge (i.e. Run 7) in the upper slope as a surrogate for a high-level aquifer, while other runs used cemented sand dikes (i.e. Run 18) to perch water in the upper slope region until dikes were breached.

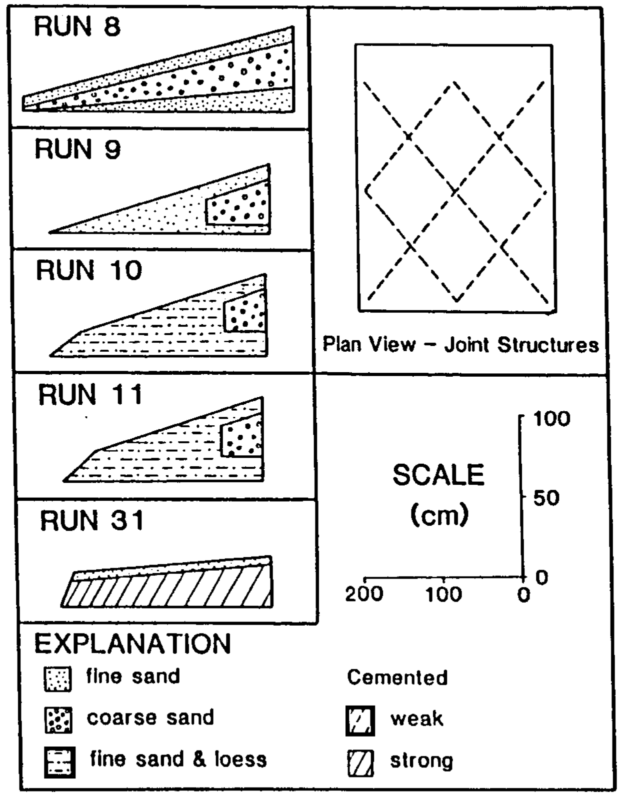


Figure 25. Summary of set-ups for stratigraphic high-level aquifer runs.

High-level Gravel Aquifer Runs

The results of **Run 7** typify the experiments with high-level aquifers (Figures 26,27). Run 7 contained a wedge of coarse, more permeable sand in the rear of the sapping wedge sandwiched between two layers of fine sand of the type used in Run 3. The coarse wedge extended down-flume only 1.5m from the headboard and did not intersect the sediment surface. The effects of the accelerated discharge through this aquifer became increasingly apparent as incision and channel development progressed through the run. Once channels incised deeply enough to tap into the perched aquifer, their rates of growth accelerated. Figure 26 shows that piracy of one channel occurred and its lower reaches were eroded during expansion of the neighboring channels to the extent that the inactive channel appears to be a tributary to one of the major valleys. Compare the final stage of the channels with that from Run 3 in homogeneous sediments. The channel head for the third channel from the left (channel 2) is almost three times as wide as the head area in Run 3. Figure 27 illustrates that head width increased dramatically between hours 12-18, corresponding to the time when channel incision intersected the buried aquifer. The rate of headcutting slowed markedly during this same period as the channel concentrated on lateral widening along the seepage face of the aquifer. Downcutting and headcutting rates were significantly reduced after the aquifer was tapped. The lateral growth of valley head regions resulted in the near merger of two channels which caused the intervening channel to be abandoned due to subsurface piracy. This situation is very similar to the scenario we proposed to explain the merger of Waipio and Honokane Valleys on Kohala volcano on Hawaii and the intervening piracy of channels (Kochel and Piper, 1986).

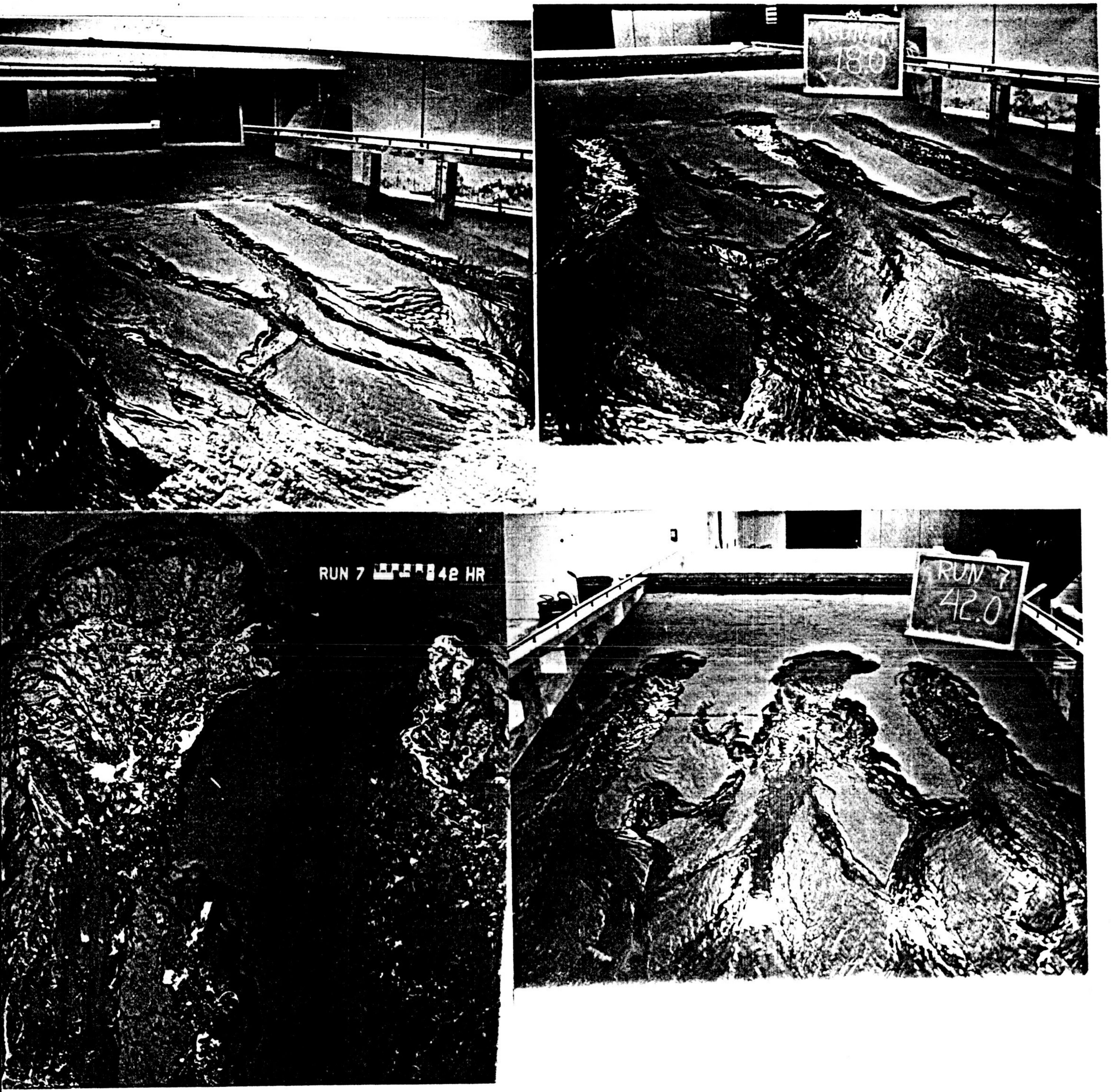


Figure 26. Photos for Run 7 with high-level stratigraphic aquifer.
Clockwise from top left: 1) 5 hrs - aquifer is untapped, 2) 18 hrs - 2 channels tap aquifer, 3) 42 hrs - extensive head widening at aquifer face, 4) 42 hrs - overhead view. See also Figure 19 for 19 hrs.

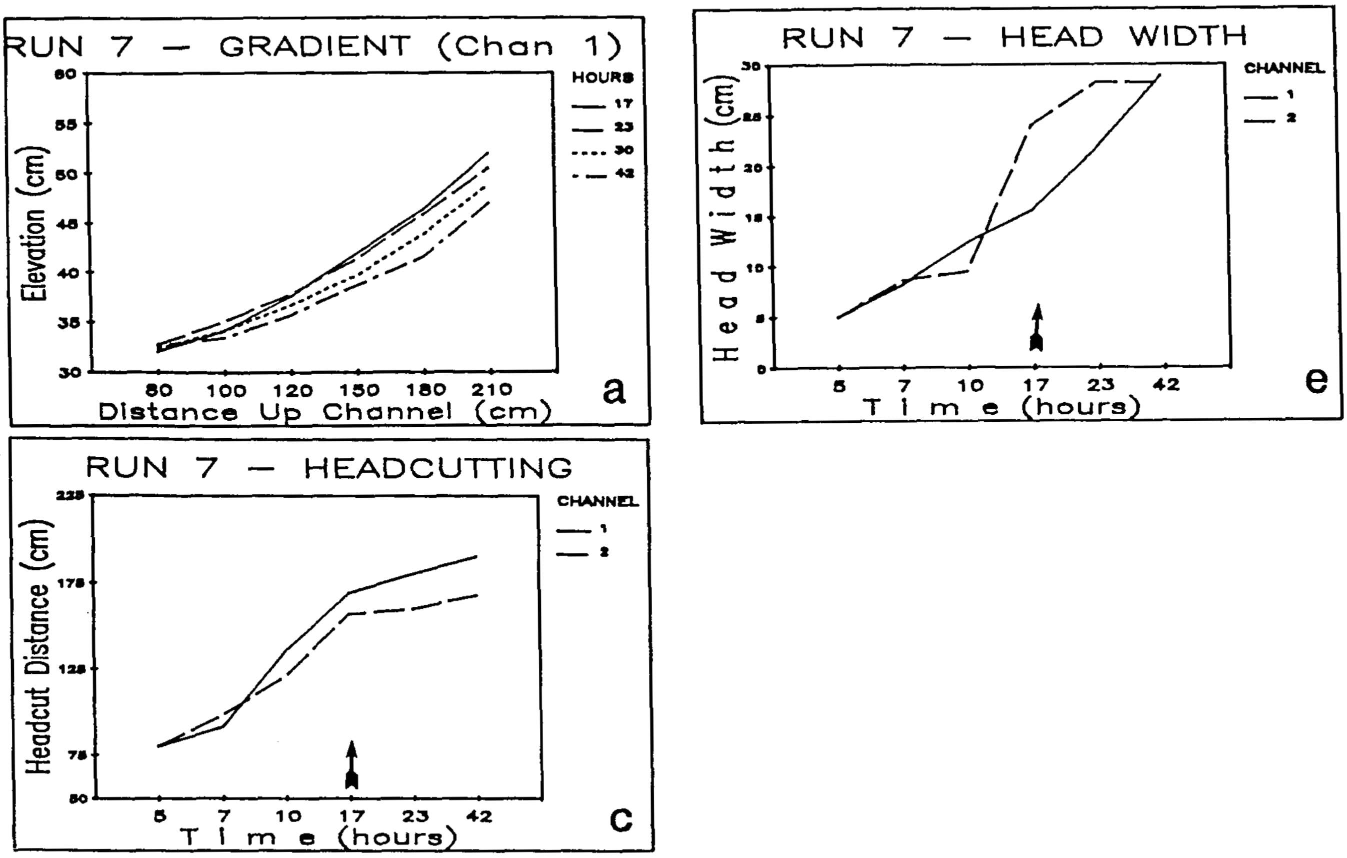


Figure 27. Channel morphodynamics for Run 7. Note accelerated growth after perched aquifer is tapped at hour 17 (from Kochel and Piper, 1986).

High-Level Aquifers Impounded by Dikes

Run 18 (Figure 28,29) provides a good example of the experiment using cemented dikes to trap high-level aquifers in a manner similar to the dike-impounded aquifers in Hawaiian volcanoes. Homogeneous fine sand was used throughout the sapping wedge. A relatively impermeable dike was placed midway through the wedge, dipping toward the headboard at about 70^{o}. Five channels initially formed within the first three hours of Run 18, four of which remained active throughout the remainder of the run. Channels incised and enlarged steadily, but more slowly than typical for runs in fine sand during the first 18 hours due to the decreased groundwater discharge downslope from the dike. Between hours 18-25 channel 3 incised through the dike, permitting additional groundwater to enter the channel. Rates of head widening then increased dramatically following the breach of the dike for channel 3. Rapid head widening in channel 3 soon pirated groundwater from neighboring channels (completed by hour 50), resulting in their abandonment. At hour 68, abandonment is well illustrated in Figure 28. Channel 6 also breached the dike at hour 62 and then rapidly widened its headward region as well.

The results of Runs 7 and 18 illustrate how sapping channels respond to the effects of structural or stratigraphic inhomogeneities in the subsurface which provide sudden increases in groundwater discharge into the channels. Tapping the high-level aquifers acted to rejuvenate the channels and they shifted from a stabilized condition into a new phase of rapid adjustment and enlargement (Figure 30). The final channel form was a much enlarged valley with a bulbous upper reach and well-developed amphitheater head.

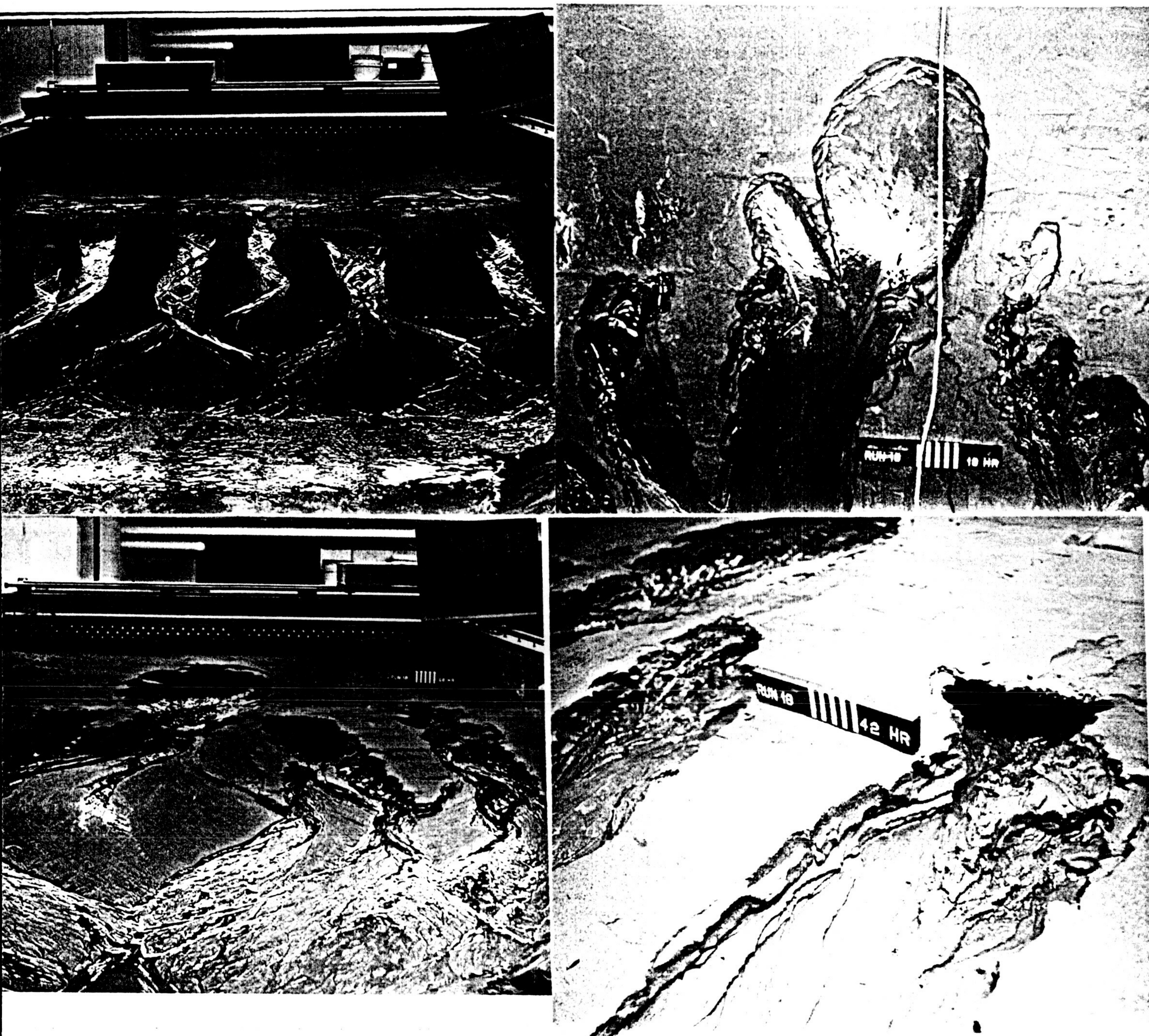


Figure 28. Photos from Run 18 with dike perched aquifer. Clockwise from upper left: 1) 4 hrs - dike is untapped, channel development is slow, 2) 18 hrs - dike is tapped by central channel which rapidly expands, 3) 42 hrs - left (central) channel has rapidly expanded while channel in foreground is still attempting to cut through dike, 4) 68 hrs - central channel is very enlarged, right channel has just tapped aquifer and begins to enlarge.

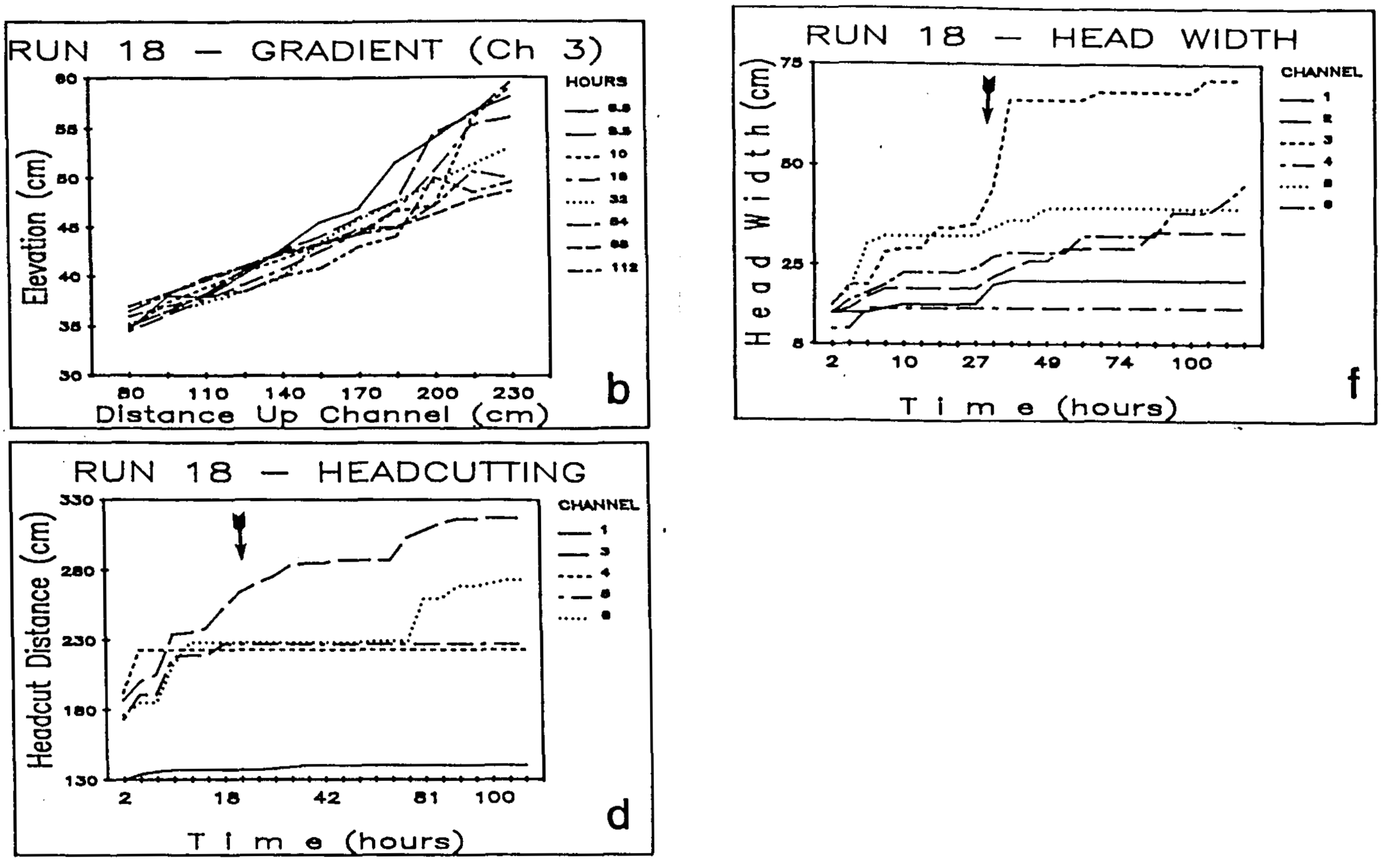
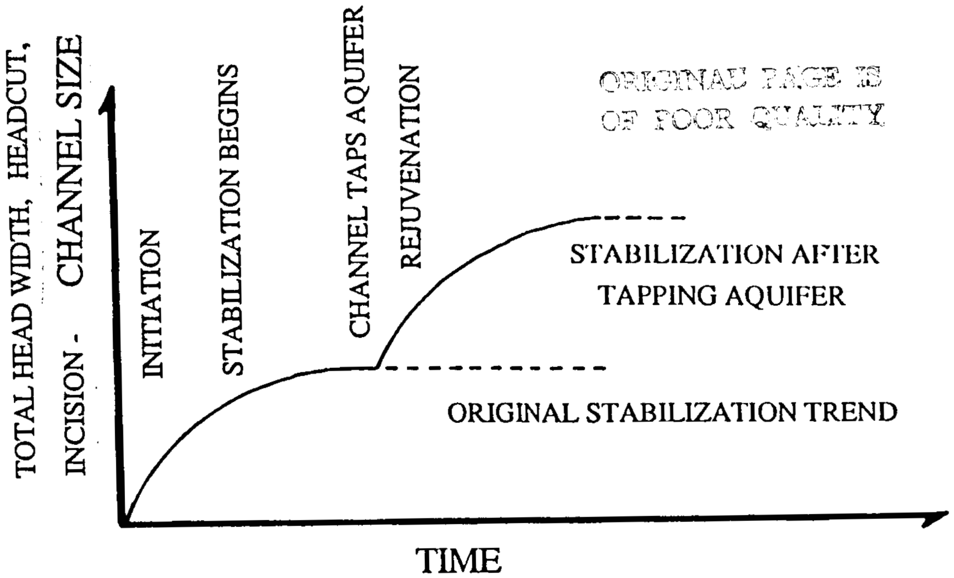


Figure 29. Channel morphodynamics for Run 18. Note rapid growth of channels once the diked aquifer is tapped at 18 hrs (from Kochel and Piper, 1986).

Runs that used two dikes (such as Run 45) had similar results to Run 18 except that the channel experienced two distinct episodes of channel rejuvenation in a manner consistent with that described for Run 18. The end result was a planform for the valleys that had distinct buldges in valley width immediately upstream from both of the dikes (Figure 31=photo).

Finally, several dike runs were made using a split flume design which permitted the introduction of surface runoff to both sides of the flume while restricting groundwater sapping to only one side. Run 49 serves as a good example of this experimental design. During the first 5 hours channels developed solely from runoff introduced by a trickling pipe placed at the upper end of the sediment wedge on both sides of the wood divider between the two flume halves. Following the initial period of channel development, the reservoir was raised and one side was allowed to experience sapping while both sides continued to receive runoff from the pipes. The channel on the sapping half rapidly enlarged following the introduction of sapping flow and downcut while the runoff valley continued to grow at an exceedingly slow rate. The limited discharge into the runoff channel caused this system to remain transport-limited and the valley terminated in a narrow, tapered upstream end, not much changed from its configuration established near the outset of the run. In contrast, the sapping channel enlarged by significant headcutting, developed a broad, flat-floored valley, and terminated upslope in a broad, amphitheater head. These experiments provide conceptual support for the model we proposed to explain the large Hawaiian valleys as being strongly influenced by sapping from the dike-impounded aquifers while their neighboring smaller valleys develop only in response to runoff.



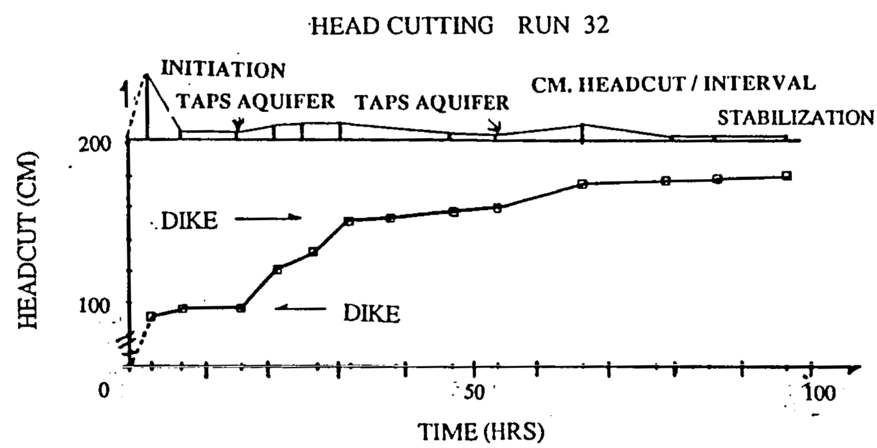


Figure 30. (top) Idealized channel evolution showing adjustment to new equilibrium conditions after threshold is crossed when aquifer is tapped. (bottom) Example of situation from Run 32 which had two dike-trapped aquifers.

Figure 31. Overhead photo from Run 45 showing bulges of channels immediately upslope of two dikes whose outline can be seen running east-west across photo.

Alcoving Experiments

Runs 39-44,46,48, and 50-54 were designed to determine if alcoves, like those that are ubiquituous throughout the walls of canyons in the Colorado Plateau in permeable sandstones, could be developed in an experimental setting. The goals of this work were to try to determine the influence of variables such as stratum thickness, dip, and joints upon the development of alcoves by groundwater sapping. The results of these experiments had mixed success. Water was introduced into the system by a spraying system of perforated hoses mounted to a board above the flume to mimick precipitation-recharged systems on the Colorado Plateau. Stratified wedges were set up having a vertical cliff at the down-flume edge which exposed the internal stratigraphy. Alcoves were formed in the flume experiments using layers of weakly cemented sand dipping about 2^{o} alternating with thin interbeds of heavily cemented sand which served as barriers to groundwater flow. These alcoves had morphologies very similar to those formed in the Navajo Sanstone of the Colorado Plateau. However, most of the alcoves formed only at the basal contact between a permeable unit and impermeable base stratum because of the difficulty in establishing lateral groundwater flow above the saturated zone.

Seepage did occur immediately above higher aquicludes, but its discharge was too insignificant to overcome the resisting forces of surface tension and cohesion in the grains to effectively erode material from the escarpments. Experiments with stacked impermeable units to mimick interdune aquicludes found in the Navajo Sandstone showed progressive wetting of the beds immediately above the aquicludes during experiments even in the absence of significant alcove production.

SUMMARY OF FLUME EXPERIMENTS

Experimental modelling provided a convenient way of making direct observations of the process and morphology of valleys formed by groundwater sapping. It is very difficult to resolve questions relating to the formative processes of valleys in the field many times because of the complexity of terrestrial channels. Terrestrial channels are usually composite channels, but may be dominated by sapping or runoff processes. In the lab, we can evaluate the evolution of valleys by each process by controlling the conditions of the experiment. Controlled laboratory settings are also required to observe evolutionary processes over short periods of time. We could not mimic all of the attributes of field settings due to scaling problems such as: 1) the important role of chemical weathering and removal of sapped debris; 2) actual rock strength; and 3) sediment size scaling. However, the observations made in the flume provided an excellent conceptual framework for us to apply to the interpetation of terrestrial analog examples and the interpretation of Martian valley networks.

These experiments proved extremely useful in constructing conceptual models of how sapping-dominated valleys evolve. In particular, the experiments point to the episodic nature of changes at the sapping head related to slumping. Similar importance of slumping has been observed in terrestrial settings such as the Hawaiian valleys (Scott and Street, 1976) which will be discussed in the next section. In addition, the experiment demonstrated the overwhelming role groundwater piracy has upon valley development and form. Piracy was shown to be directly controlled by the structure of the underlying geologic materials.

Our experiments sucessfully demonstrated the following features which have been suggested to be important in the evolution of channels on the Colorado Plateau: 1) joint control of groundwater flow and subsequent orientation of channels with predominant effects seen in the headward reaches of the channels; 2) the importance of groundwatrer piracy; 3) the importance of stratigraphy in controlling the location of seepage faces in layered rocks; and 4) has shown how impermeable strata can interact with the geometry of permeable strata as important controls on the dimensions of channels developed by groundwater sapping.

These kinds of modelling experiments are particularly good for: 1) testing concepts; 2) developing a suite of distinctive morphologies and morphometries indicative of sapping; 3) helping to relate processes to morphology; and 4) providing data necessary to assess the relative importance of runoff, sapping, and mass wasting processes on channel development.

The results of these experiments, concluded in late March 1988, are being assembled and will be prepared for publication in the near future. In addition, we hope to collaborate with Alan Howard at Virginia on some of the publication efforts.

TERRESTRIAL ANALOG STUDIES OF VALLEYS INFLUENCED BY SAPPING

Before reliable interpretations can be made concerning the genesis of Martian valley networks by assigning them to sapping or runoff systems, an integrated comparative investigation of sapping and runoff dominated terrestrial analogs must be completed to construct models for distinguishing between the channel types. This was the primary objective of the second phase of our research - to develop a suite of geomorphic crtiteria from terrestrial environments that could be used in remote sensing obsrvations of Mars to distinguish between channels formed by runoff or sapping.

The areas selected for this phase of terrestrial analog studies were: 1) large valleys on several Hawaiian Islands; and 2) selected portions of the Colorado Plateau based on reconnaissance studies during the NASA Field Conference (Howard, Kochel, and Holt, 1988).

HAWAIIAN VALLEYS

The islands of Hawaii, Maui, and Molokai contain many examples of extremely large, deep, flat-floored valleys having amphitheater heads which are markedly different than their neighboring valleys. The large Hawaiian valleys occupy wet, windward slopes of Hawaiian Islands and pose a stark contrast to the insignificant valleys which occur on the dry, leeward volcanic slopes. However, the differences between the valleys can not be fully ascribed to climatic variations because there are small, less-incised valleys are also found on windward slopes nestled in among the large valleys. We used a combination of field reconnaisance studies and morphometric analyses of basin characteristics made from aerial photographs and topographic maps to comare these valley types on the windward slopes of Kohala (Hawaii), Maui, and Molokai. The results of this investigation are summarized in detail by Kochel and Piper (1986) and by a forthcoming thesis by Piper (1988). Therefore, we will only present a summary in this report.

Field Reconnaissance

Field reconnaissance was used to determine the influence of sapping on the small and large valleys along the windward slopes of Kohala (Hawaii), Maui, and Molokai (Figure 32). Large springs emerging from the base of the amphitheater headwalls of the large valleys were observed, even in the absence of surface runoff over the headwalls. Further inspection revealed the presence of numerous dikes, as mapped by Stearns (1946) in valley head areas. These observations, and the lack of basal springs in the smaller valleys, led us to conclude that the large valleys were strongly dominated by groundwater sapping while the smaller valleys were formed by runoff processes alone in accord with a similar model proposed by Stearns (1966) and summarized in Figure 33. Additional field observations showed that the sapping-dominated valleys (See Figure 34 were typified by: 1) abrupt valley wall and floor junctions; 2) abundant evidence of mass wasting along valley walls; and by 3) large springs emerging from alcoves at the base of valley-head amphitheaters. In areas where waterfalls plunged over valley walls, insignificant plunge pools were observed, indicating that the dominant mode of headward retreat was from sapping erosion undercutting valley headwalls and subsequent mass wasting of the overhanging basalt. Hawaiian sapping-dominated valleys typically widen toward their heads in contrast to the runoff-dominated valleys which taper upslope (Figure 35). Sapping valleys have incised to sea level and enter the ocean with broad mouths while runoff valleys enter the sea as spectacular waterfalls from hanging valleys (Figure 35). The enlarged sapping valley heads at the elevation of the dike swarms which contain the high-level aquifers have widened to the point that merger of Waipio and Honokane valleys on Kohala has effectively pirated groundwater previous bound for intervening valleys. The experiments discussed previously using dikes and stratigraphic high-level aquifers produced final morphologies very similar to the basins observed along the eastern slopes of Kohala volcano (See for example, Runs 7 and 18).

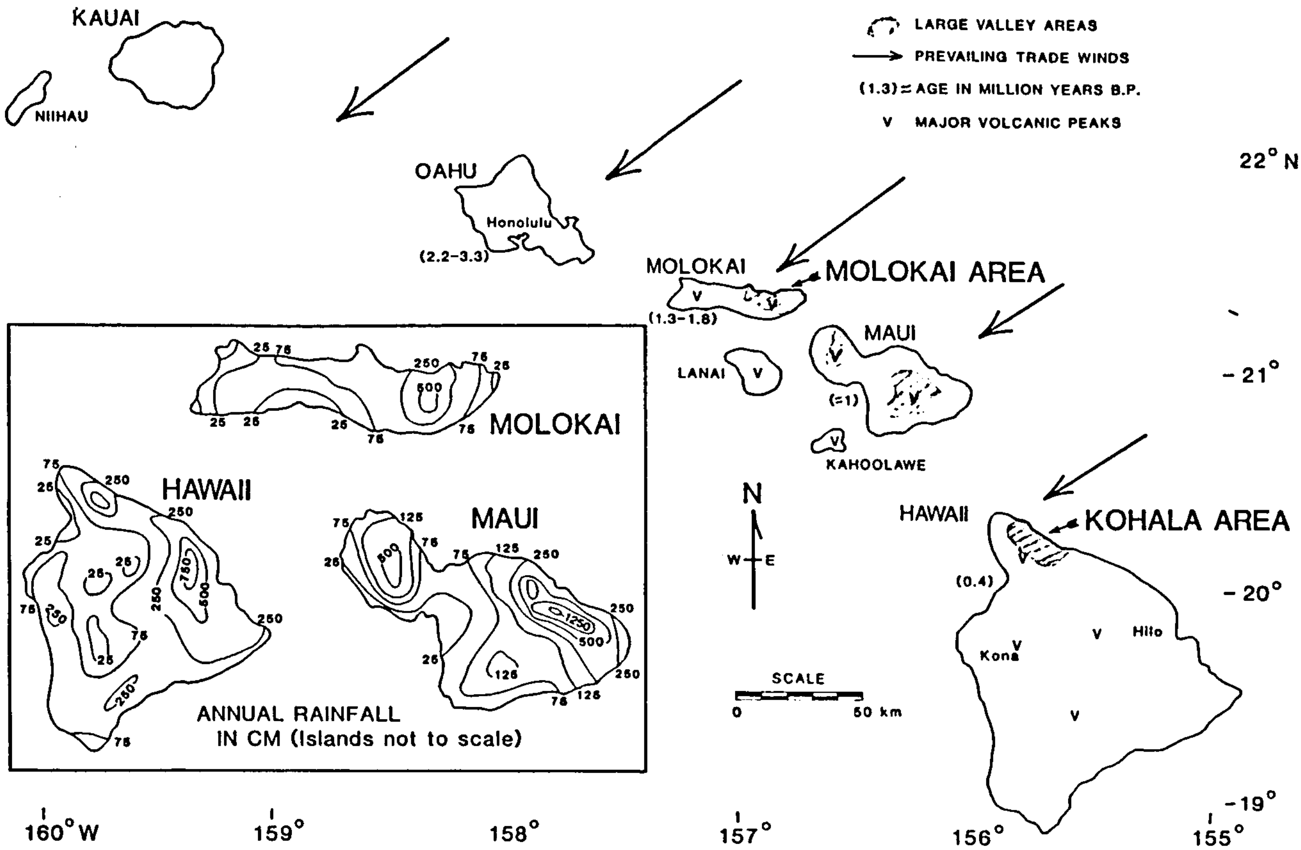


Figure 32. Index map and climate data for Hawaiian analog study sites.

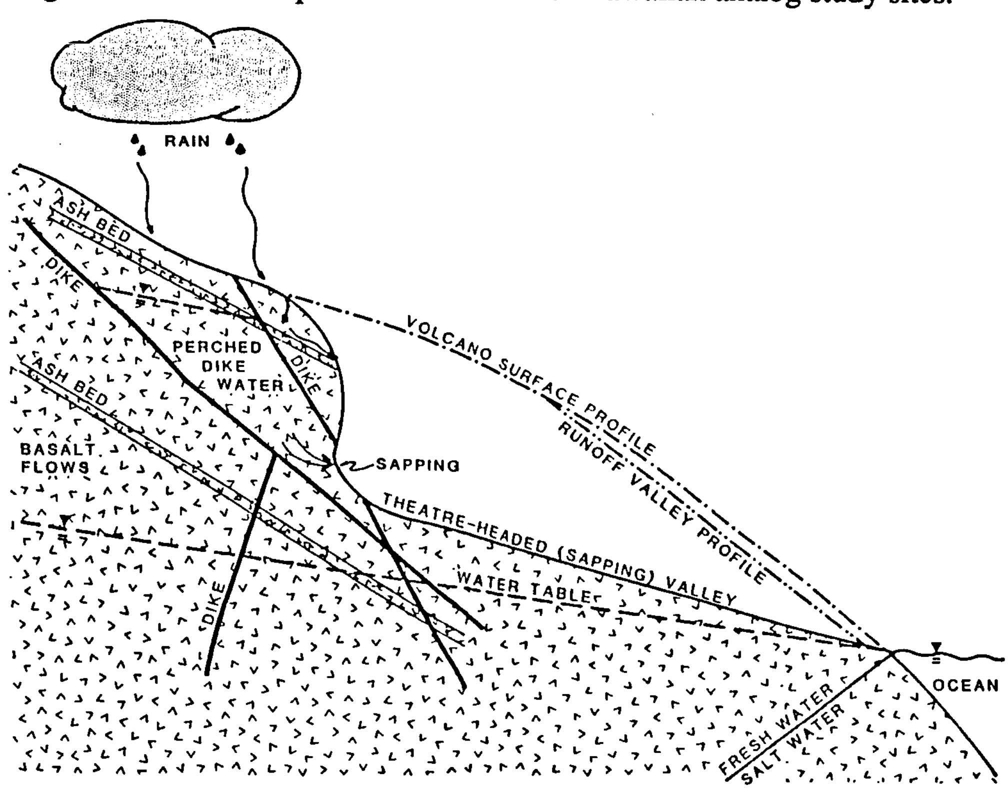


Figure 33. Model for high-level aquifers trapped by central volcanic dike swarms. Runoff channels successful in tapping dikes will enlarge rapidly due to sapping influence .

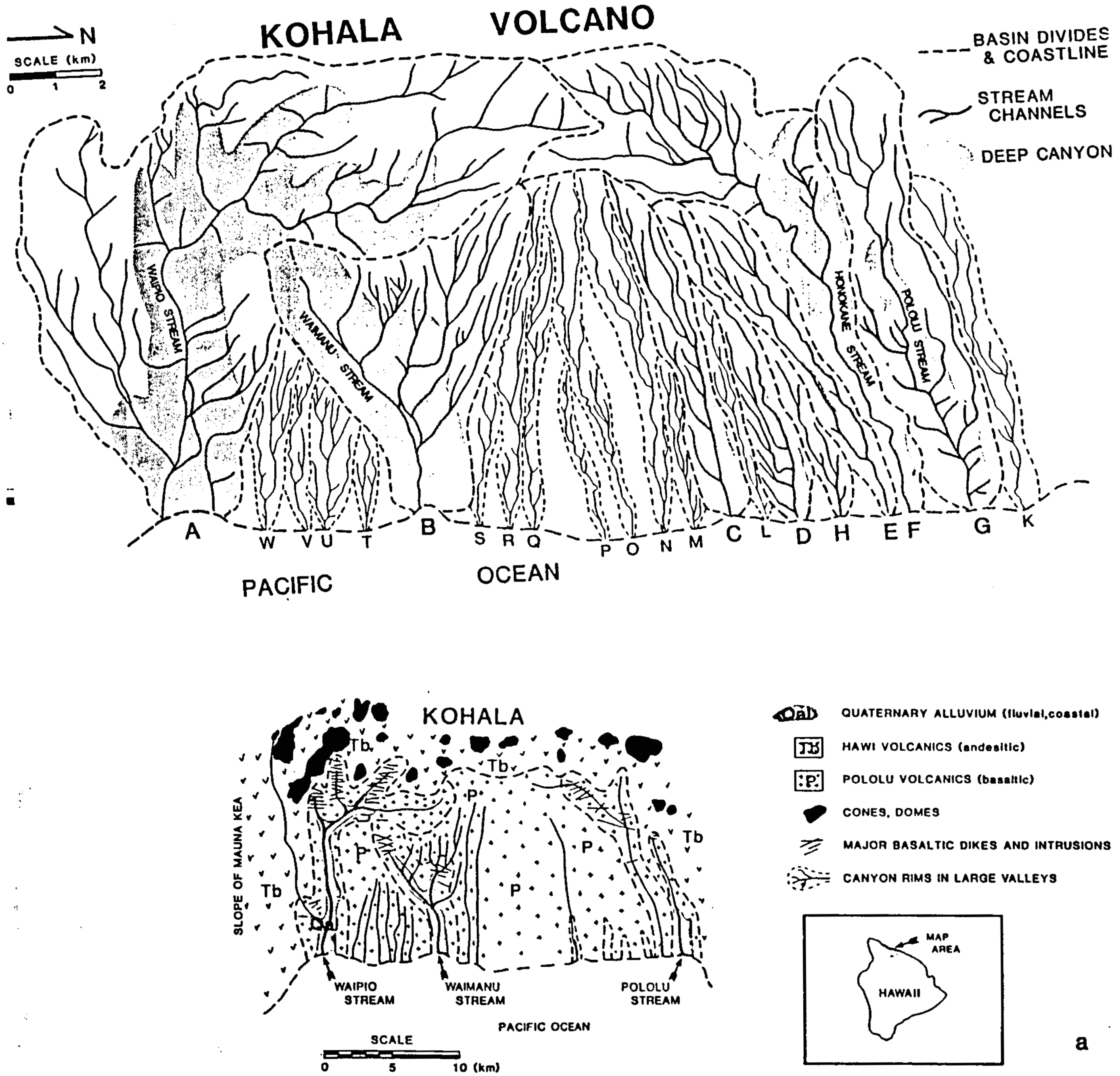


Figure 34. Drainage and geologic map for Kohala Volcano on Hawaii. Note enlarged valleys affected by sapping and the coincidence of their heads with exposure of dikes.

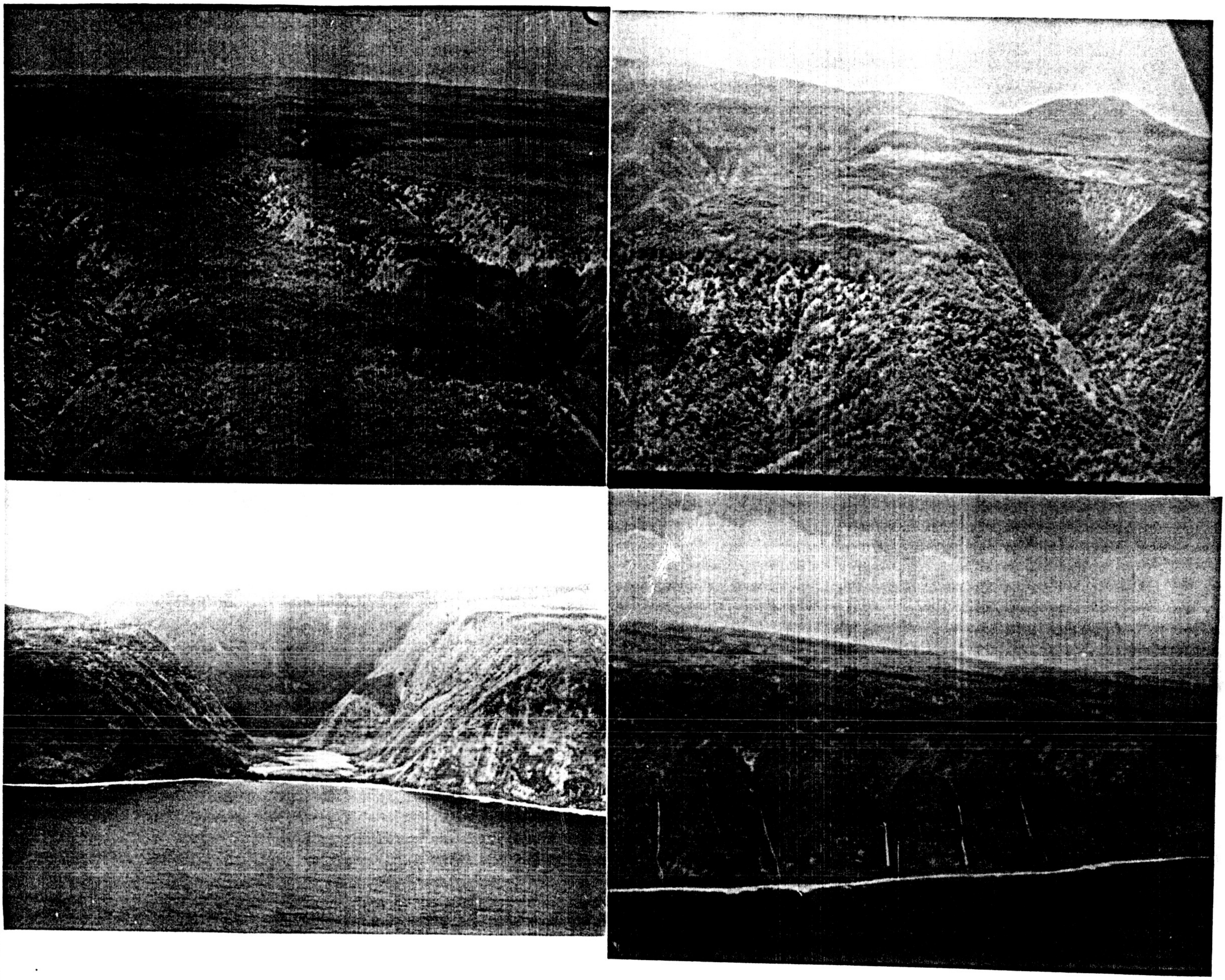


Figure 35. Photos showing contrasting morphology of sapping and runoff valleys on Kohala. Clockwise from upper left: 1) tapered heads on runoff valleys (Fig. 34, valleys R,Q), 2) amphitheater heads of tributaries to sapping valley b in Fig. 34, 3) hanging mouths of runoff valleys, 4) enormous mouths of sapping valleys cut to sea level.

Remote Studies and Comparative Analysis

Following the categorization of valleys as sapping-dominated vs. runoff-dominated from the field work, we gathered data on the morphometric characteristics of the valleys from analysis of aerial photographs and topographic maps. Six parameters included in the analysis proved to be statistically significant in distinguishing the valley types using principal components analysis (PCA) (Table 7). Figure 36 shows that PCA was successful in statistically distinguishing sapping and runoff valleys on the basis of morphometric parameters visible in remote imagery.

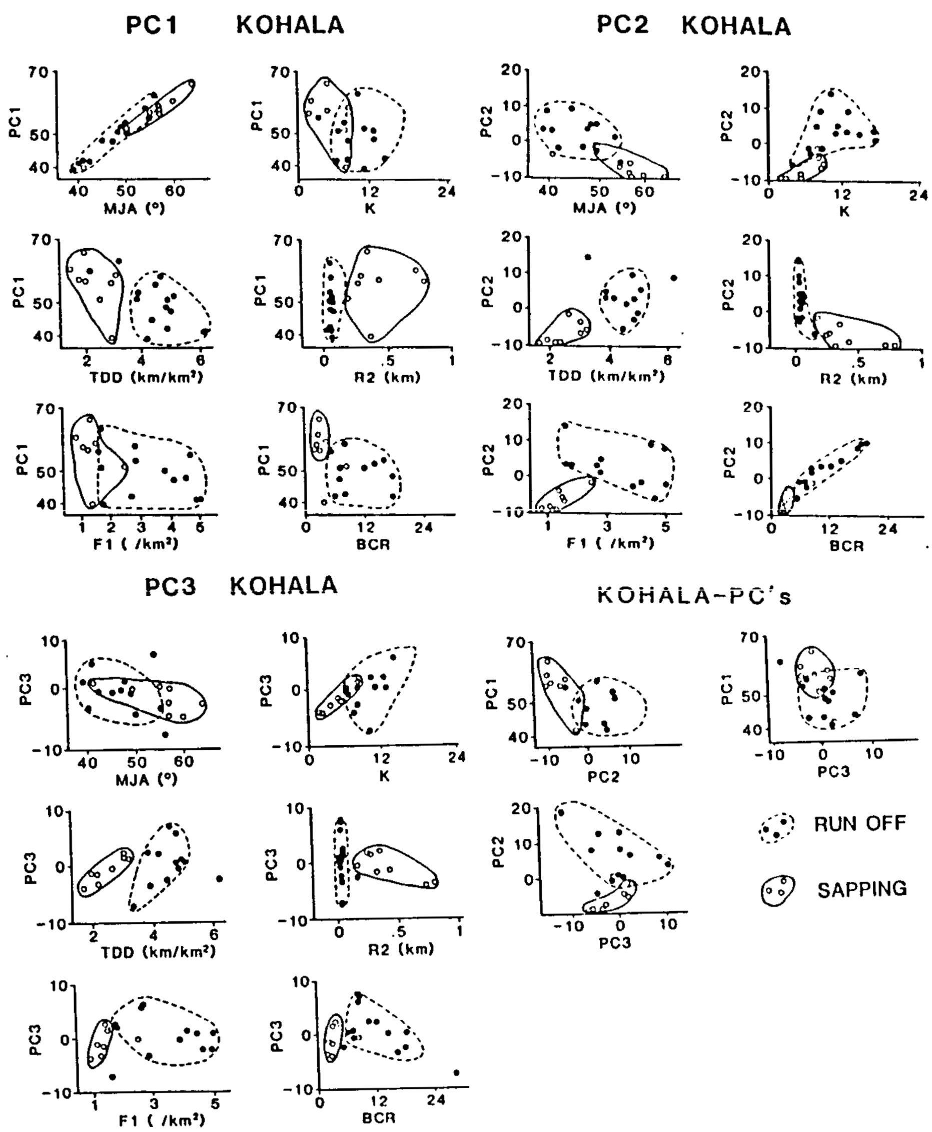


Figure 36. Examples of PCA from Kohala showing clear separation of sapping and runoff valleys (from Kochel and Piper, 1986).

Table 7. Geomorphic Parameters Used in PCA

Parameter	Explanation
K	basin shape using lemniscate
TDD	total drainage density
MJA	mean junction angle for basin
F1	first order stream frequency
R2	cross-axial relief at mid basin
BCR	basin area/canyon area

Table 8. Comparison of Sapping and Runoff Valleys in Hawaii (from Kochel and Piper, 1986)

RUNOFF vs. SAPPING VALLEYS in HAWAII

(from Kochel & Piper 1986)

PARAMETER	RUNOFF-DOMINATED	SAPPING-DOMINATED
basin shape	very elongate	light-bulb shape (wide head)
head termination	tapered, gradual	amphitheater, abrupt
channel trend	uniform	variable
pattern	parallel	dendritic
junction angle	low (30^{o}-45^{o})	higher (55^{o}-65^{o})
downstream tributaries	frequent	rare
relief	low	high
drainage density	high	low
drainage symmetry	symmetrical	asymmetrical
basin area/ canyon area	very high	low

Table 8 summarizes the morphologic and morphometric differences between sapping-dominated and runoff-dominated valleys on Molokai and Hawaii. The major distinguishing characteristics of mature sapping valleys are their blunt amphitheater heads, the increasing valley width usptream, the lack of parallel drainage, the small basin area/canyon area, and the asymmetry of drainage observed in tributary patterns. The degree of valley widening depends on structure, stratigraphy, and time as shown by the sapping box experiments. This study also demonstrated that there are a number of morphometric criteria of the type that can be identified from remote imagery which can be used to statistically distinguish between process origin of valley types within a selected area of relatively consistent geologic conditions. These kinds of parameters will be applied to the analysis of Martian channels in ongoing research to help interpret channels genesis.

Valley Evolution on Hawaii

Many of the Kohala valleys exhibit characteristics of both valley styles in different portions of their drainage basin. Sapping canyons extend in a headward direction after beginning at midslope at the major dike swarms. Drainage characteristics upstream from the sapping headwall exhibit characteristics of runoff valleys, i.e., parallel drainage, shallow incision, and tapered heads. Eventually, headward retreat of the sapping face results in channel extension to basin divides. This "mature" morphology is visible in the older sapping valleys that characterize the north side of Molokai (Figure 37). Figure 38 summarizes an evolutionary scheme proposed for the Hawaiian sapping valleys. Hawaiian valleys originate from runoff processes as elongated valleys with high drainage density and parallel drainage (Stage 1). Slope valleys on Mauna Loa, Mauna Kea, and the west side of Kohala typify this "youthful" stage on Hawaii. Continued valley incision eventually taps into perched dike water (Stage 2) which marks the initiation of the dominance of groundwater sapping processes in these valleys. Subsequent development (Stage 3) is characterized by headward extension of the sapping face and deep valley incision. Honokane Valley on Hawaii and Halawa Valley on Molokai are examples of Stage 3.

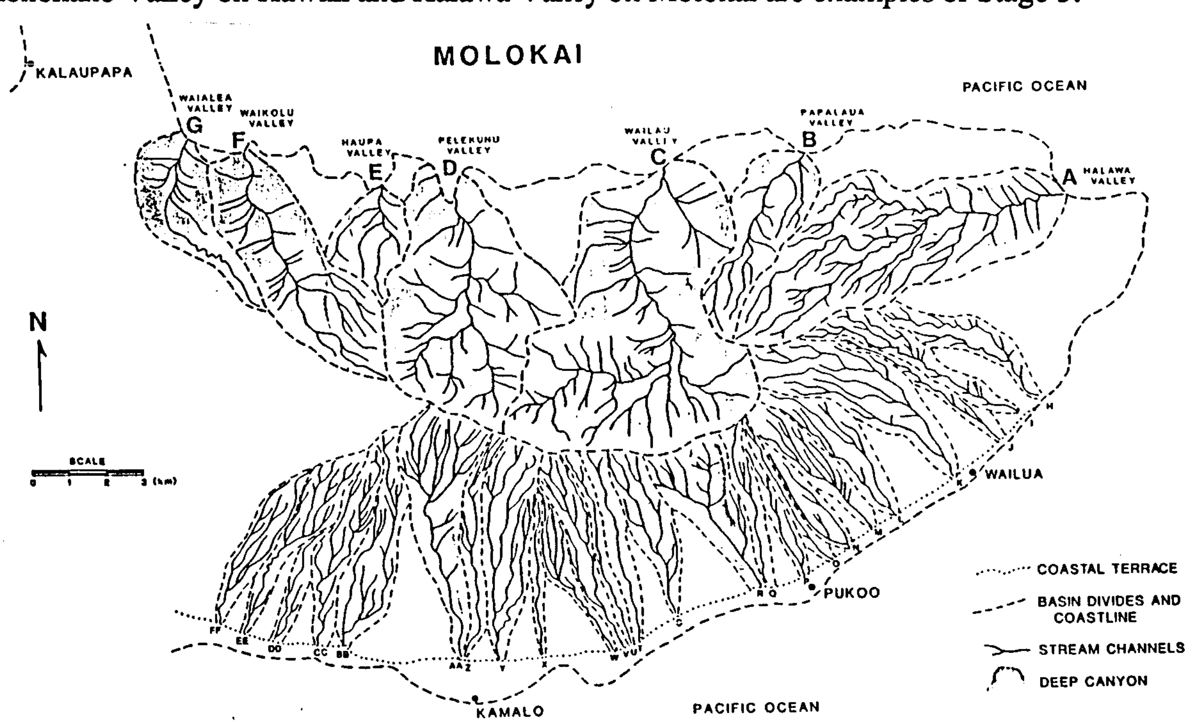


Figure 37. Drainage map of eastern Molokai. Extensive sapping valleys are shaded.

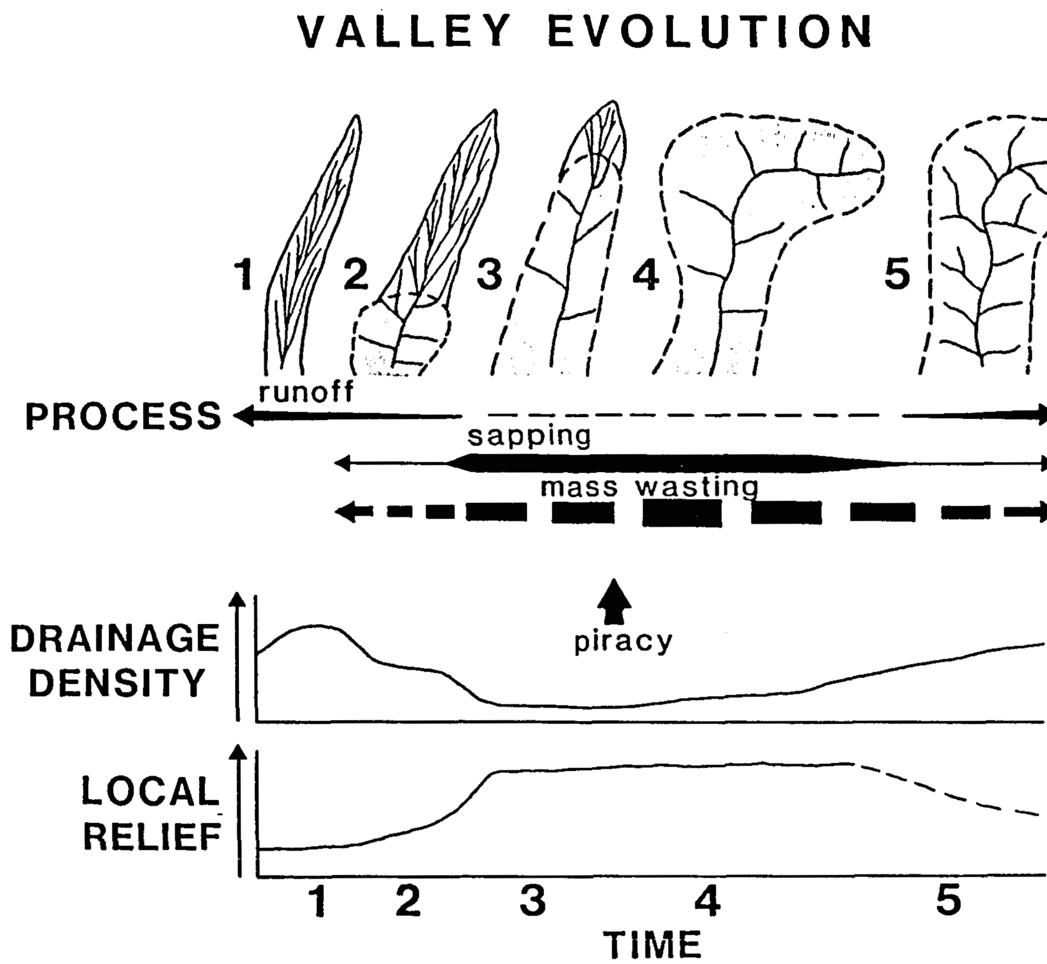


Figure 38. Evolution of sapping valleys and changing dominance of runoff and sapping processes (from Kochel and Piper, 1986).

Continued headward growth and valley widening results in a transition from runoff-dominance to sapping-dominance concurrent with downstream decrease in drainage density, abstraction of downstream tributaries due to subsurface piracy, and a shift toward dendritic or rectangular drainage patterns. Valley extension by sapping eventually proceeds to the basin divides (Stage 4). At this point, subsurface piracy causes extensive head widening, and "mature" sapping valleys are created, which many times behead subsurface and surface drainage to neighboring valleys. Waipio and Honokane Valleys on Hawaii have merged on Kohala and the effect has been a marked reduction in flow and valley growth to the valleys in between these two.

Many sapping valleys on Molokai have proceeded to stages 4 and 5. These valleys are increasingly beingly influenced by surface processes, which produces a greater drainage density and more dendritic drainage pattern. Generally, in terrestrial runoff systems, drainage density is a measure of erodibility and climate in a watershed. On Hawaii, drainage density is more controlled by the predominance of sapping or runoff processes during basin evolution. As more precipitation is delivered to the mainstream by groundwater discharge, drainage density decreases. In late stage valley evolution, precipitation is again dominantly delivered to the channels by runoff, hence, drainage density again starts to increase. Valley evolution ultimately proceeds until adjacent valleys merge as divides are breached. The resulting degraded and complex drainage system is characterized by the basins seen on the older islands of Oahu and Kauai. More refinement of this evolutionary model will be presented in a master's thesis by Piper (1988). This evolution described for Hawaiian sapping valleys has many parallels to the channel evolutionary sequence described for the flume studies done with uniform sediments, layered sediments, and experiments with high-level aquifers.

SAPPING VALLEYS ON THE COLORADO PLATEAU

During the past year we began to study potential sapping valleys as terestrial analogs in the Colorado Plateau, following in the lead of Laity and Malin (1985) and the suggestions of our Field Conference in 1985 (Howard and Kochel, 1988; Howard, Kochel, and Holt, 1988). Again, a combination of field reconnaisance for purposes of establishing sapping or runoff dominance (as well as collecting other related data on the morphology of sapping-related features) and remote studies was used as a framework of study with two major objectives in mind: 1) to continue to refine the construction of a suite of geomorphic criteria useful in distinguishing sapping-dominated from runoff-dominated valleys with the addition of data from sedimentary layered terrain; and 2) determining the hierarchy of geologic controls on sapping valley development with the goal of being able to use valley morphology as a means of interpreting underlying geological conditions.

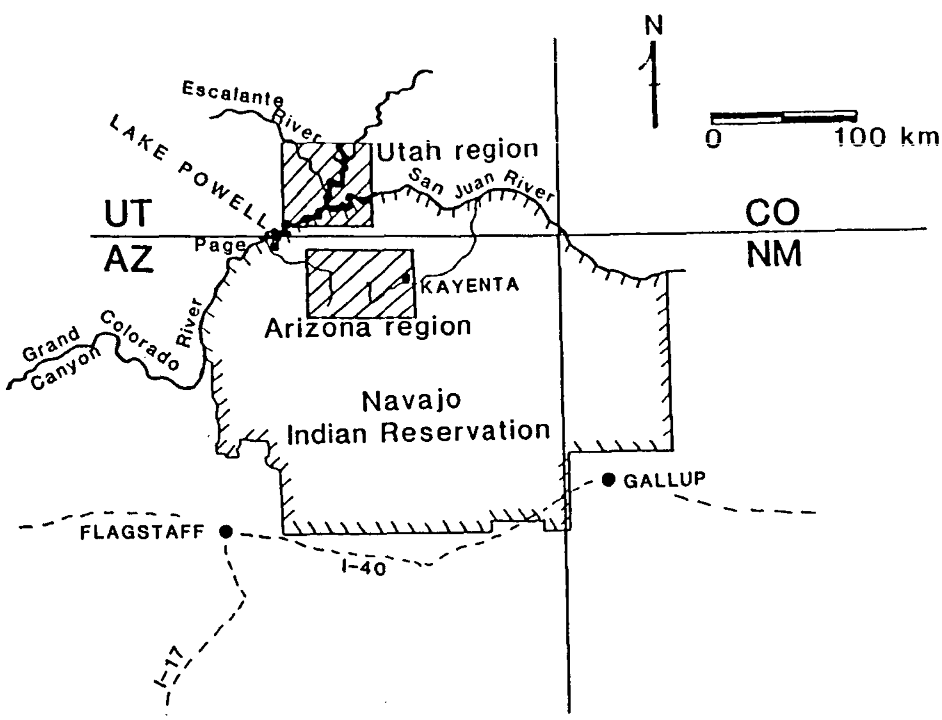


Figure 39. Index map of study areas on the Colorado Plateau.

The focus of the Colorado Plateau investigations was in two areas that contained prolific examples of sapping valleys interspersed with examples of runoff valleys in similar and different lithologies. The areas chosen were the Tsegi Canyon-Shonto Plateau region of northern Arizona and the lower portion of Lake Powell in Utah (Figure 39). The attention was focused upon valleys incised into the porous and permeable Navajo Sanstone. The Navajo Formation has ideal characteristics for the interception, transmission, and discharge of groundwater. Precipitation rapidly infiltrates into the unit from abundant surface potholes and moves downward until it reaches a less permeable barrier (Figure 40). Concentration of groundwater flow along impermeable barriers results in lateral flow that produces zonal seeps and results in the erosion of the poorly-cemented sandstone along canyon walls (Figure 41). This sapping process eventually undermines the material above, causing collapse and the production of alcoves along with eventual valley extension.

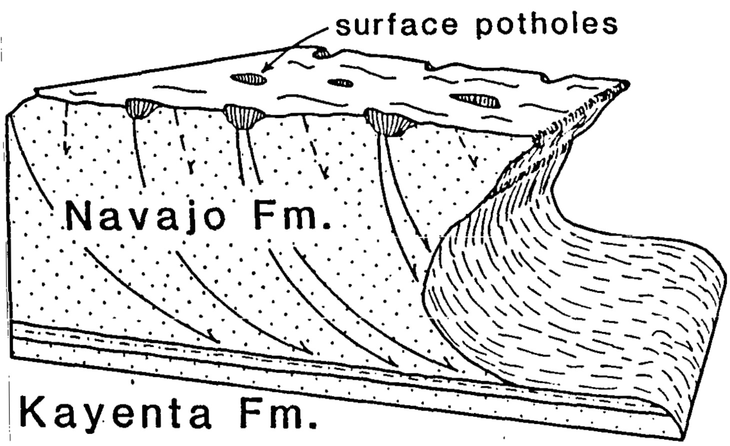


Figure 40. Schematic of infiltrating precipitation through potholes into Navajo Sandstone. At the boundary flow begins to move laterally down dip.

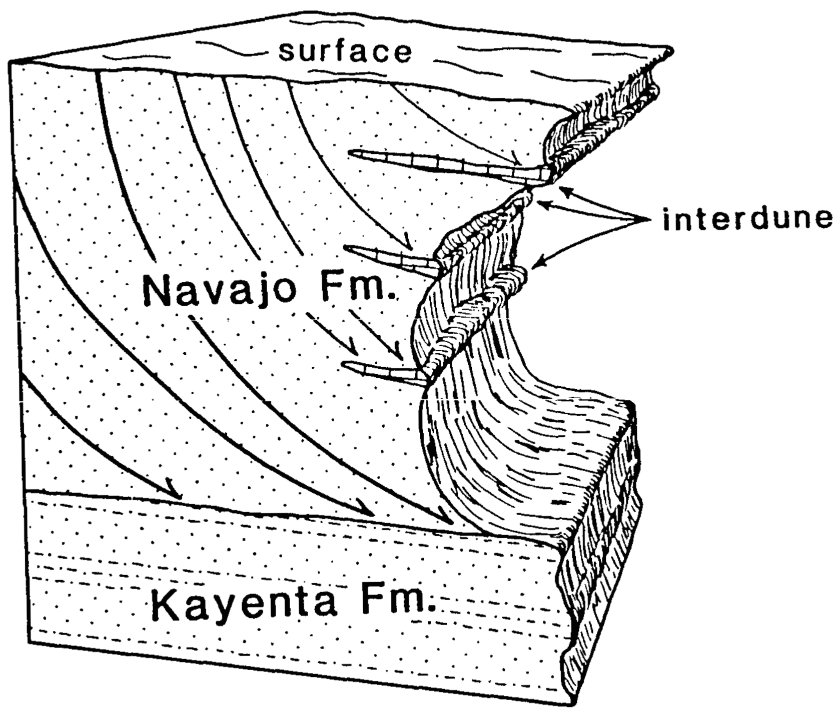


Figure 41. Schematic showing the localization of groundwater flow along impermeable boundaries. Seepage erosion results in extensive alcove production.

Distinguishing Between Sapping and Runoff Valleys

The dominance of sapping vs. runoff processes was determined from field reconnaissance. Sapping dominated valleys were observed to have large numbers of active seeps and associated alcoves in their headward regions and along tributaries. Runoff valleys had a paucity of these features and were presumed to be affected only by intermittent runoff events. A subset of 19 basins were selected from a variety of lithologies in the area of Shonto Arizona (Figure 42) for morphometric analyses based on the measurements from aerial photographs and topographic maps. Figure 43 shows the variety of drainage networks developed across the region which reflect both the differences in underlying lithology. The significant parameters and comparisons between sapping and runoff valleys are shown in Table 9. Sapping dominated valleys have higher junction angles, are more elongate, have lower drainage densities, have higher relief, and have greater basin area in canyon than their neighboring runoff dominated counterparts. The same comparisons hold true whether basins in similar or different lithologies are considered.

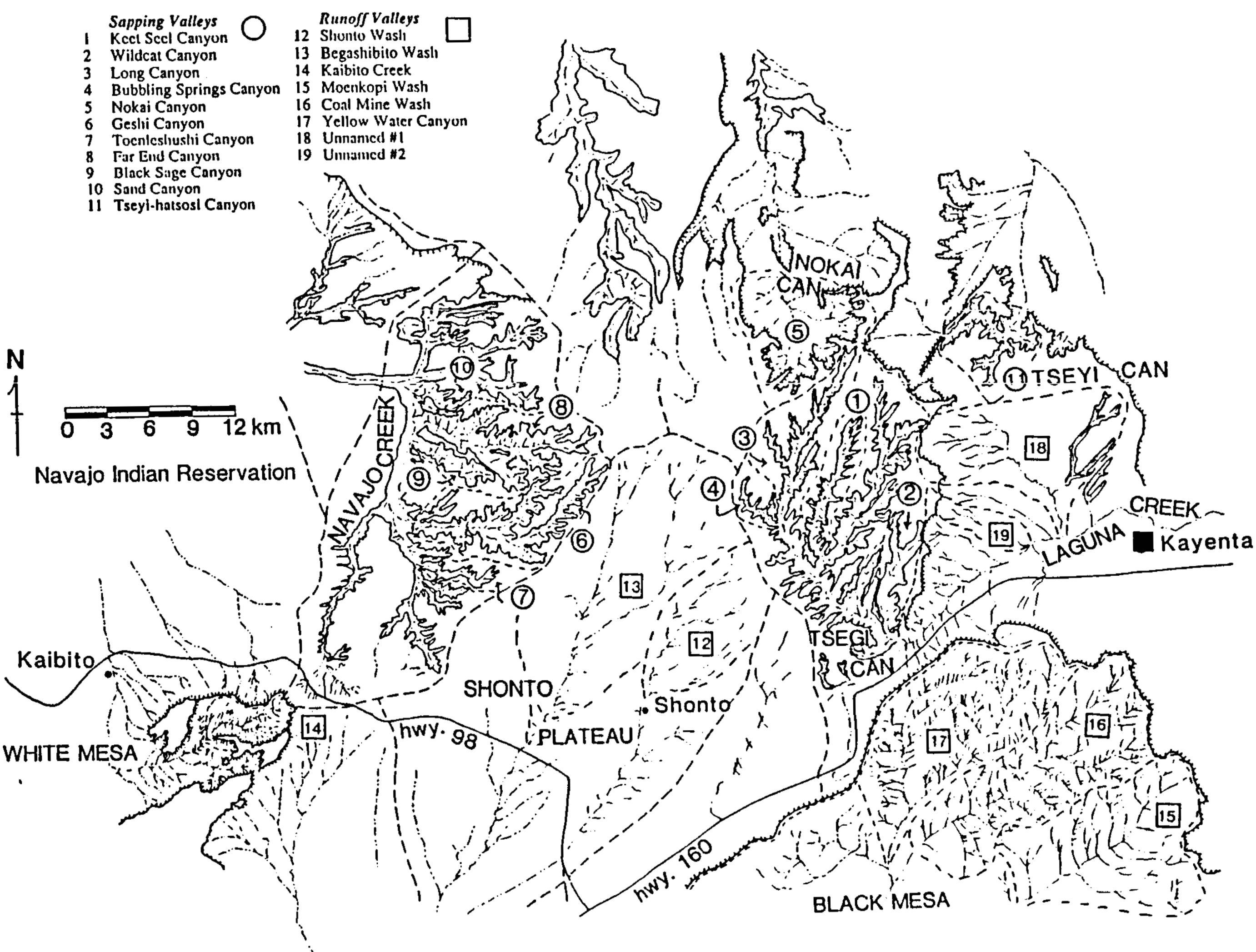


Figure 42. Index map showing basins used in morphometric analyses reported in Table 9.

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Table 9. Comparison of Sapping and Runoff Valleys in Shonto Area of Arizona
(from Kochel and Phillips, 1987)

DRAINAGE BASIN COMPARISONS

	AREA (km^2)	JCT < (o)	SHAPE (k)	CAN.% (%)	DD (km) km^2	F1 ($/km^2$)	RELIEF (m)
SAPPING BASINS (n = 11)							
mean	27.7	73.2	24.9	45.8	9.9	4.2	297
std dev	17.8	3.4	12.8	12.4	1.4	0.7	79
RUNOFF BASINS (n = 8)							
mean	48.5	52.1	17.4	17.0	12.2	5.7	150
std dev	38.1	6.9	8.1	12.6	5.3	4.4	38.6

JCT = junction angle CAN = % basin in canyon
DD = drainage density F1 = first order stream frequency

Figure 43. Aerial photo of Shonto study area. Tsegi Canyon and Navao Creek Canyon sapping valley systems are deeply incised. Other areas contain runoff valleys. Note the view of a portion of Black Mesa at lower right which is underlain by other rock types.

Additional differences between sapping and runoff dominated valleys can be seen in the comparison of longitudinal valley profiles (figure 44). Sapping valleys have abrupt head terminations and are generally more gentle throughout the remainder of their profiles downstream from the sapping face. Runoff valleys display smooth, concave-upward profiles typical of rivers in rocks with relatively uniform resistance.

Table 10 shows an inventory of the kinds of parameters found to be significant in distinquishing between sapping and runoff valleys from the combined field and experimental studies. The parameters which appear in the imagery category can be directly applied to the interpretation of valley networks visible in Viking imagery on Mars in attempts to interpret valley genesis. For areas of Mars where adequate topographic data becomes available, some of the topographic variables can be added into the analysis. This will be the topic of our research effort during the current year.

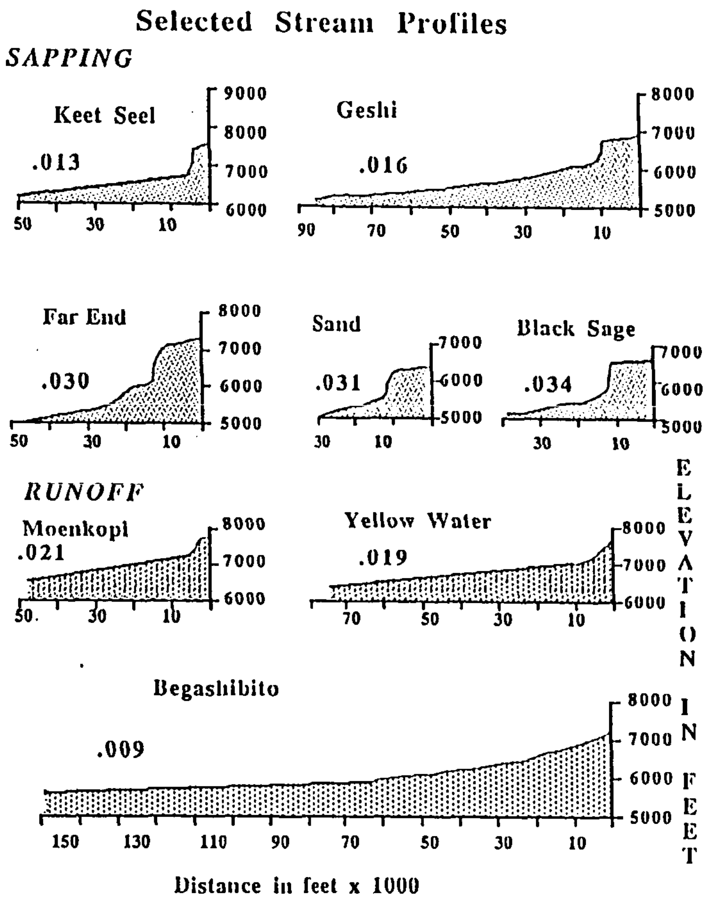

Figure 44. Comparison of the longitudinal profiles of sapping and runoff valleys on the Colorado Plateau.

Table 10. Geomorphic Criteria for Distinguishing Valley Origins

PARAMETER	SAPPING	RUNOFF	Field Observation	Topographic Map	Aerial Imagery
Lithology & Structure					
lithology	permeable	variable	x	x	x
facies variations			x		
directional permeability	will orient	variable	x		
sedimentary structures	major effect	variable	x		
joints, faults - orientation	major effect	variable	x		x
Headscarp Morphology					
channel head density	low	high	x	x	x
degree of extension	to aquifer	variable	x	x	x
rim/perimeter/valley area	high	low		x	x
Valley Morphology					
drainage density	low	high		x	x
basin area/canyon area	low	high		x	x
channel, valley x-section	abrupt, U	smooth, V	x	x	x
axial valley gradient	abrupt	smooth	x	x	
valley length, width	bulb shape	tapered		x	x
Hydrology					
seep discharge	high	low	x		
alluvial deposits	complex	fluvial seds	x		
downstream discharge	decreases	increases	x		
Mass Wasting & Walls					
freq., distrib. rockfalls	near seeps	random	x		x
relative age of deposits	cyclic clim.	cyclic clim.	x		
interaction with alluvium	complex		x		

Geological Controls on Sapping-Dominated Valleys

Apart from distinguishing between sapping and runoff valleys, the second goal of our research on the Colorado Plateau was to extend the investigations of Laity and Malin (1985) to develop a better understanding of the geological controls on sapping valley development and how these controls are reflected in the morphologic expression of the valleys. Various geological parameters were investigated to determine their effect upon valleys and develop a hierarchy of importance of these controls (Kochel and Phillips, 1987; 1988). Additional research is currently in progress on this topic which will be summarized in future publications and in a nearly completed master's thesis by Phillips (1988).

First Order Controls - Dip

Many factors influence groundwater sapping processes in sedimentary rocks. These can be organized into a hierarchy based upon their scale of influence on valley geometry (Figure 45). Major canyons and intermediate-sized tributary systems appear to be dominantly influenced by the dip of the strata because of preferred access to groundwater flowing down-dip. The experiments in layered strata nicely illustrated the preference of channels to extend directly up the dip of the strata regardless of the orginial configuration of the channel network. Sapping dominated valleys on the Colorado Pateau are typically asymmetrical, with their longest tributaries occurring along their up-dip sides of the master channel (Figure 46). In contrast, short valleys on the down-dip sides of the main channel will probably remain small because they receive only localized groundwater recharge (Figure 47). A survey of active seeps in alcoves around the Shonto field area and the Lake Powell area demonstrated that most of the active seeps are located in alcoves oriented down-dip (Figure 48). In areas of constant dip, active alcoves are uniformly oriented in that direction. In contrast, in areas of complex and variable dip, active seeps are likewise oriented in a multitude of directions. Therefore, on a limited basis, the orientation of active alcoves can be used to infer structure.

Controls on Sapping Valley Morphology

First Order

DIP

-dominant valley axes

Second Order

JOINTS

- major tributary axes
- minor tributary axes
- valley head extension
- dominant valley axes?

Third Order

SEDIMENTARY STRUCTURES

- local alcove dev. and activity
- 2ndary alcoves
  - interdune deps.
  - bedset boundary
  - cross-bedding & directional permeability

- primary alcoving at Navajo/Kayenta boundary

Figure 45. Hierarchy of geological controls on valleys influenced by groundwater sapping in the Colorado Plateau.

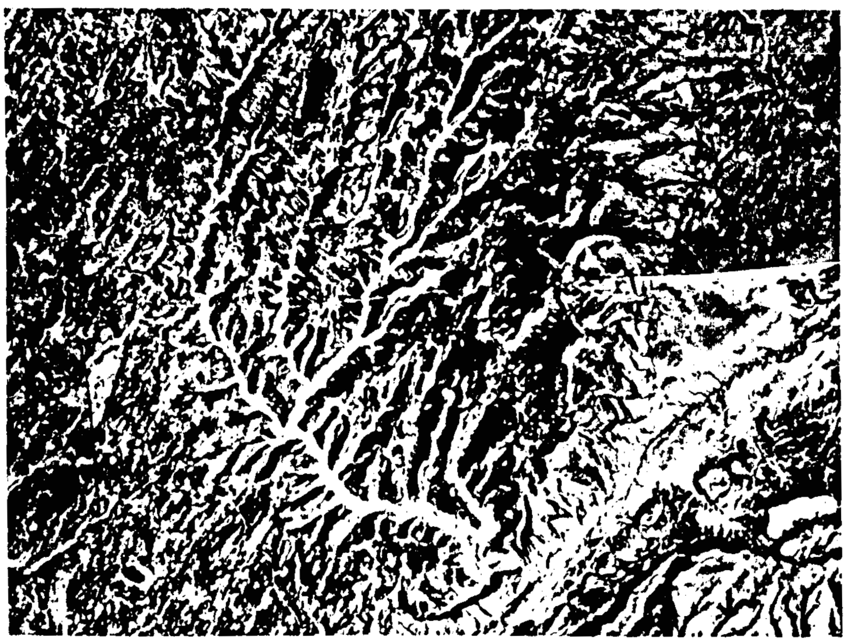

Figure 46. Aerial photo illustrating asymmetrical sapping valleys in Tsegi Canyon. Note the extension up-dip (to upper right). Down-dip tributaries are much smaller.

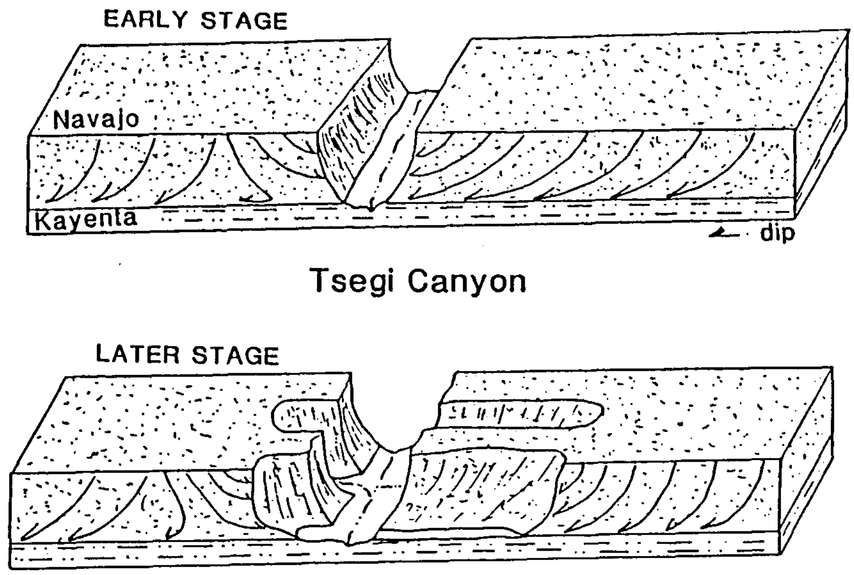

Figure 47. Schematic of groundwater recharge and asymmetrical valley development for Tsegi channels seen in Figure 46.

Laity and Malin (1985) showed that the asymmetry of valleys on opposite sides of the Escalante River in Utah was due to variations in dip. Large, sapping channels formed on up-dip sides of the valley, while smaller, less-developed runoff valleys formed on the opposite side in opposition to the regional dip of the strata. Figure 49 shows symmetrical sapping valleys disposed about a major channel tributary to the San Juan River. This pattern is indicative of a syncline with the main channel along the fold axis, which happens to be the case. Therefore, in many cases, the asymmetry of sapping valley networks can be used to infer geologic structure, chiefly dip, underlying the valley.

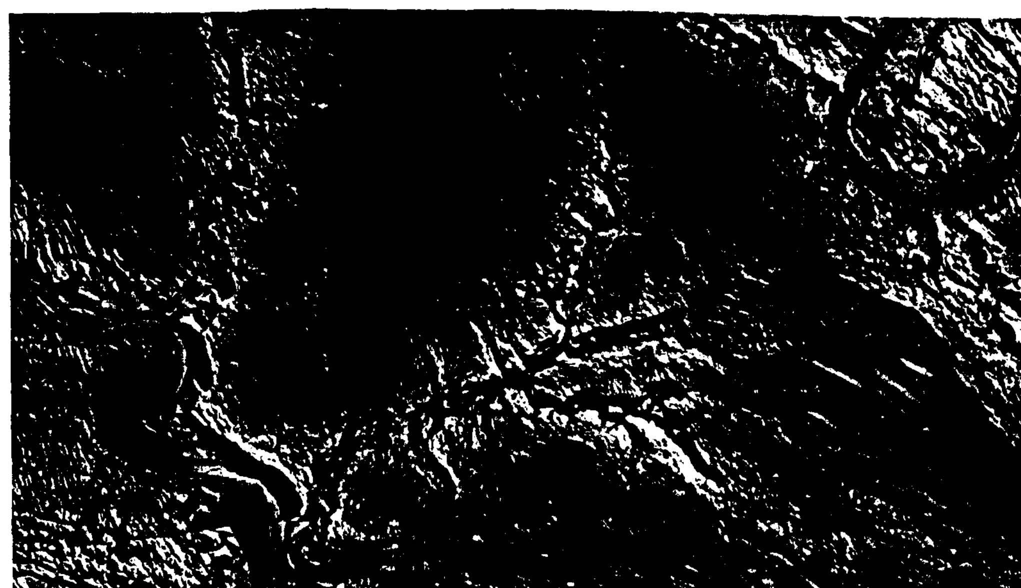

Figure 49. Synclinal axis running down axis of the main channel of the large sapping valley shows doubly extending sapping tributaries up each flank of the fold.

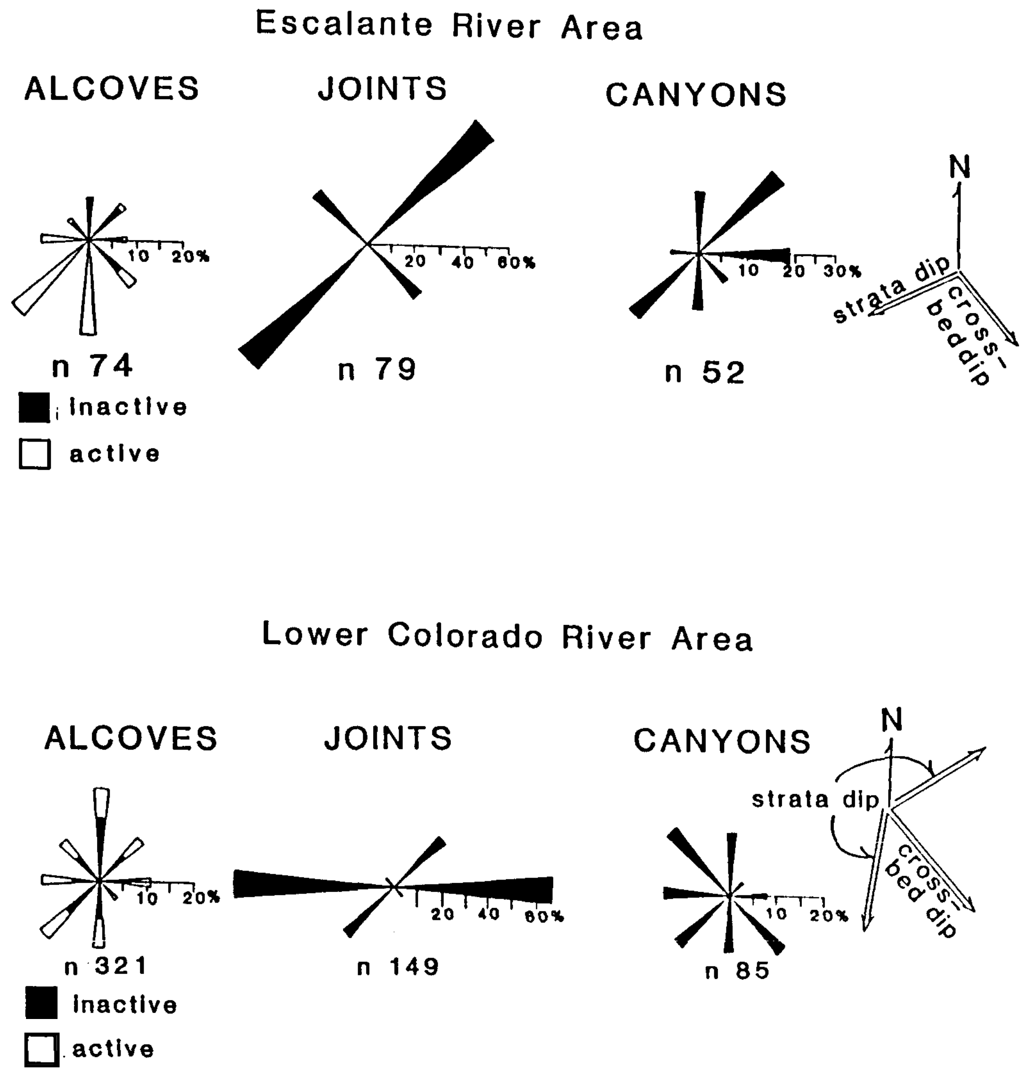

Figure 48. Relation of strata dip and orientation of active seeps and alcoves. top) Constant dip with focused active alcoves in same orientation. bottom) Variable dip and similar variability in orientation of active seeps and alcoves.

Second Order Controls - Joints and Faults

Our experiments with joint simulations demonstrated a strong preference for the localization of groundwater flow in layered sediments along joints. The influence of joints in the experimental systems was particularly prominent along the upper reaches of the valley network where actvie sapping was occurring. Joints provide local zones of increased permeability, localizing groundwater flow in consolidated rocks and helping to accelerate sapping processes. These effects are particularly pronounced in the Colorado Plateau (Figure 50) valleys underlain by the Navajo Sandstone. Effects of joints are particularly prominent along valley heads and tributaries (Figure 50). Note the remarkable similarity to valley heads on Mars along Valles Marineris that are extending along grabens parallel to the main canyon (Figure 51). The prominence of joints helps to explain the high junction angles characteristic of valley networks strongly influenced by sapping processes.

In Tsegi Canyon, the combination of joint orientation and strata dip can explain most of the variation in valley orientation. One of the prominent joint directions coincides with the dip orientation which is parallel to the major tributaries, while the other prominent joint trend is parallel to the major Tsegi valley (See Figure 46).

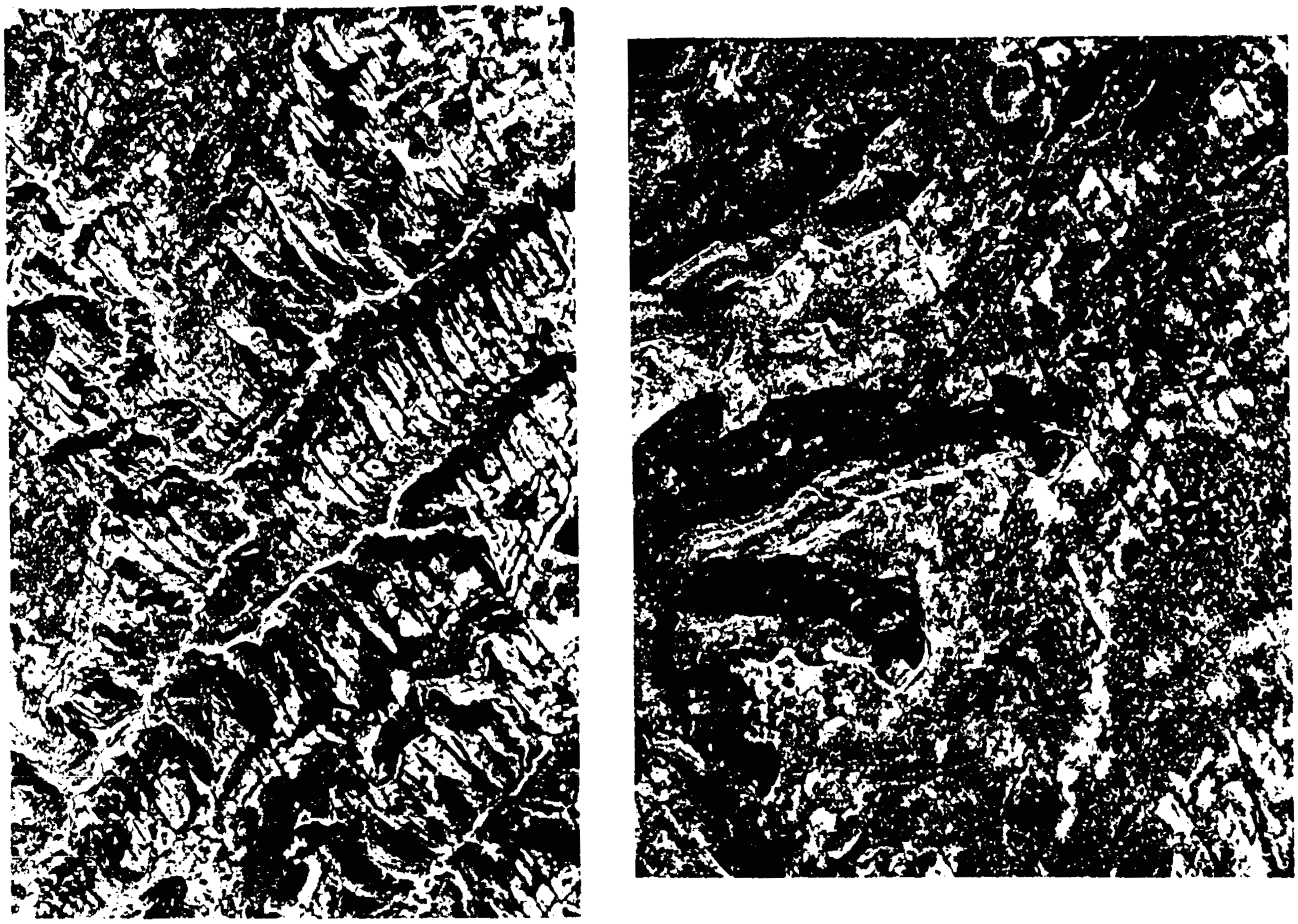

Figure 50. Influence of joints on valley head areas of sapping channels in Tsegi Canyon (left) and Nokai Canyon (right).

Figure 51. Joint influence on valley heads (right) along Valles Marineris, Mars. Compare with Figure 50.

Third Order Controls - Sedimentary Structures

Variations in the internal sedimentological charcteristics of rocks such as the Navajo Sandstone also affect the morphology of sapping-dominated valleys, but on more localized scales (Kochel and Riley, 1988). Aeolianites such as the Navajo have numerous internal bounding surfaces across which there are major permeability contrasts that strongly influence the pattern of valley development by groundwater sapping (Figure 52).

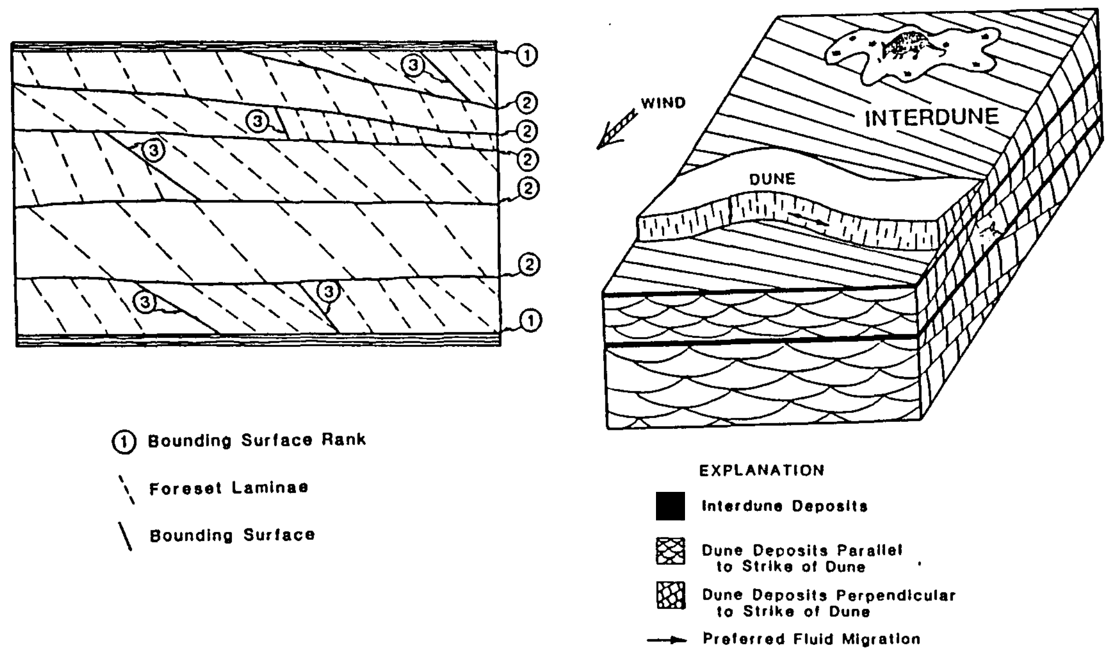

Figure 52. Schematic of major bounding surfaces in aeolianites like the Navajo Sanstone along which groundwater can be concentrated.

Interdune facies are one example of these variations (Figure 53). Interdune deposits are typically formed of impermeable carbonate which forms major ledges along canyon walls cut into the Navajo. Major seeps and alcoves are localized above these interdune deposits, resulting in the formation of multi-level or tiered alcoves. Laity and Malin (1985) observed that the largest alcoves in the Navajo are located along the boundary between it and the underlying Kayenta Formation. However, many regions have very large alcoves developed at many levels controlled by the stratigraphic location of interdune deposits (Figure 55). The limited lateral extent of interdune facies also acts as a major control on the lateral dimensions of alcoves. Alcoves have been observed to totally pinch out at the edge of interdune layers becaue there is no longer an impermeable boundary along which to localize and concentrate seepage. Petrographic studies are underway to document differences in relative permeability of the Navajo Sandstone at various locations with respect to alcoves.

Another locally important permeability contrast in aeolian sandstones like the Navajo are the boundaries of major coss-bed sets, which are typically several tens of meters thick. Fine-grained sediments often occur at these boundaries and localize seepage along their margins.

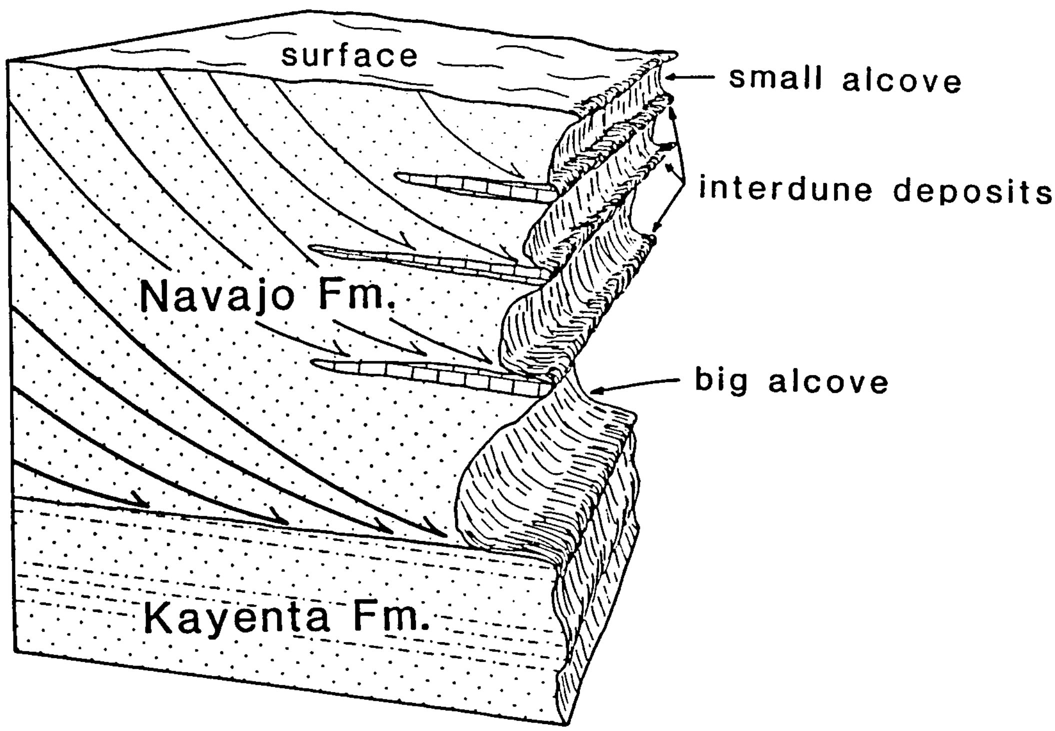

Figure 53. Schematic of localization of seeps above interdune deposits. This results in multi-level alcoves in the Navajo Sandstone.

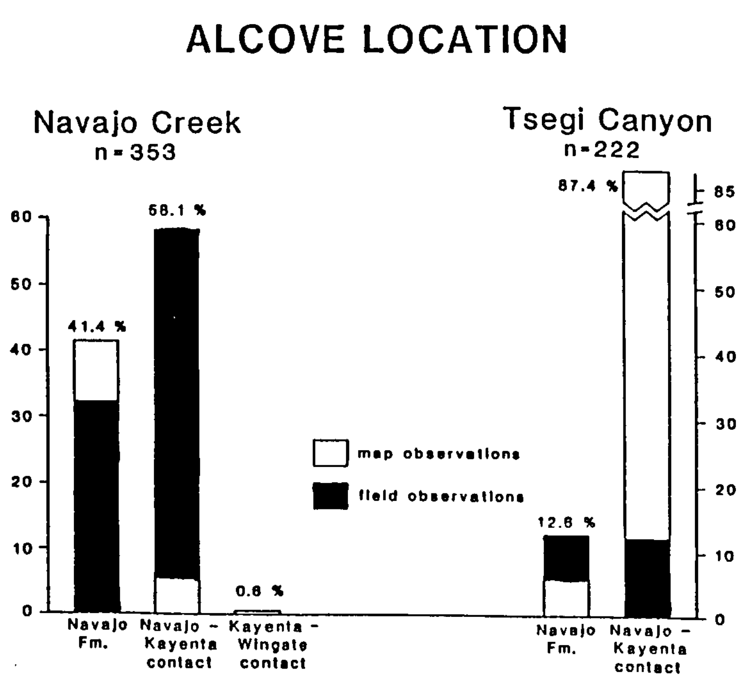

Figure 54. Stratigraphic location of alcoves surveyed in Shonto area. Many occur within the Navajo due to sedimentological controls.

Finally, the dip directions of major cross-beds can influence groundwater flow. Lateral permeabilities are much higher than vertical permeabilities across cross-bed laminations (Figure 55). Studies of directional permeability for petroleum reservoirs have shown drastic variations dependent upon cross-bed orientation (Lindquist, 1983). This directional permeability can be important as a major control when there is regional consistency of cross-bed direction which does occur in the Navajo outcrop region of the study area (Figure 56) (Marzolf, 1983). We recently completed several experiments in the sapping flume designed to observe the effect of cross-bed orientation on groundwater flow. The results of these runs indicated that groundwater discharge was significantly greater parallel to the cross-bedding as opposed to across the cross-beds. Numerous examples of seeps were observed in the field which also supported the model represented in Figure 57.

Sedimentary features appear to locally important in modifying sapping valley orientation and morphology, provided the features are large enough and of great enough regional extent. Most of the features described here would apply to most rocks originally formed in aeolian depositional environments and probably to many other rocks having sedimentary origin.

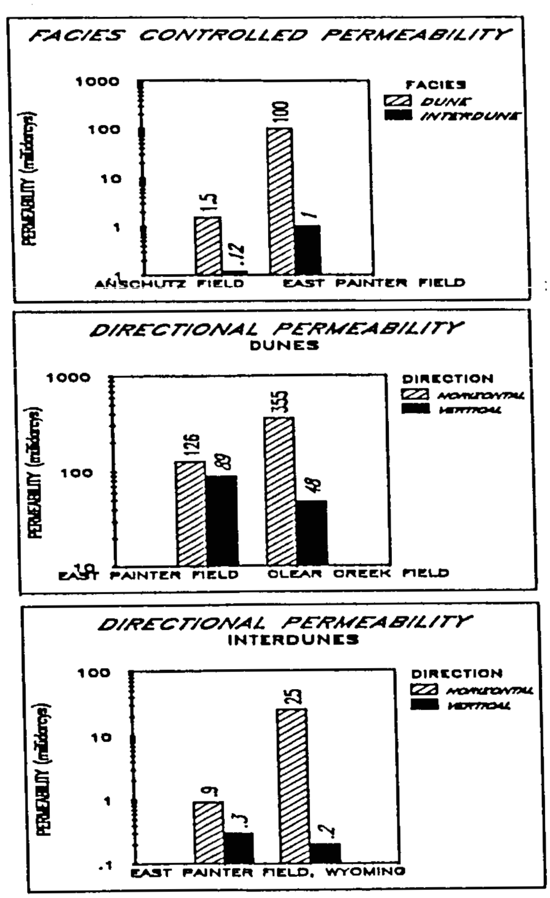

Figure 55. Variation in directional permeability in aeolianites due to facies variations and cross-bed orientations (from Lindquist, 1983).

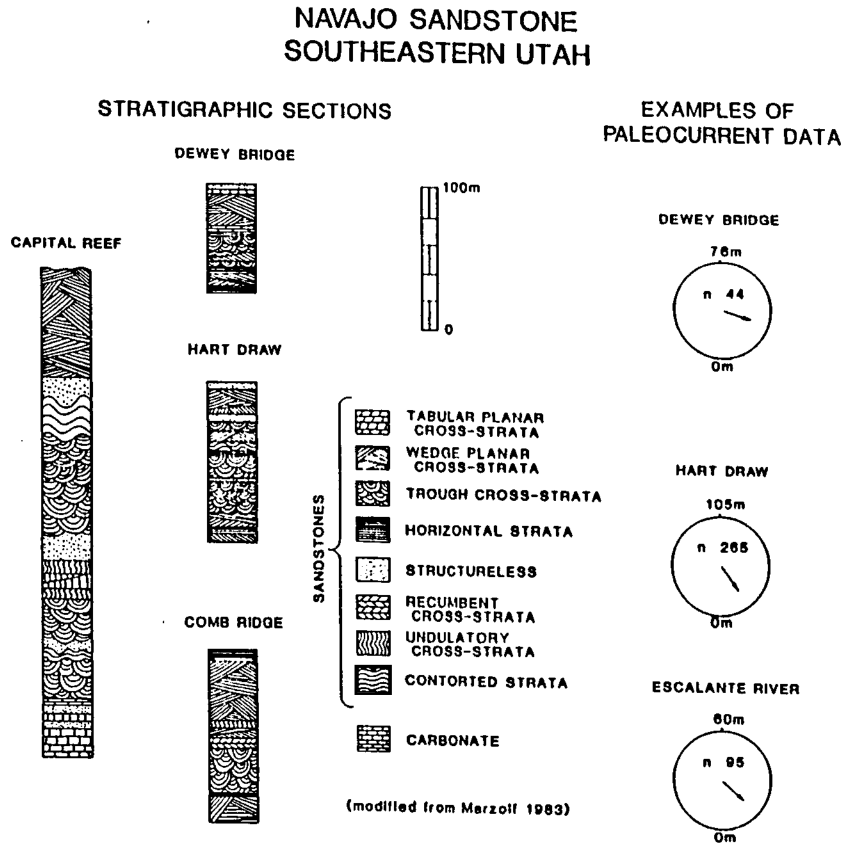

Figure 56. Regional constancy in dip of major cross-bedded sets within the Navajo Sandstone in the southern Colorado Plateau.

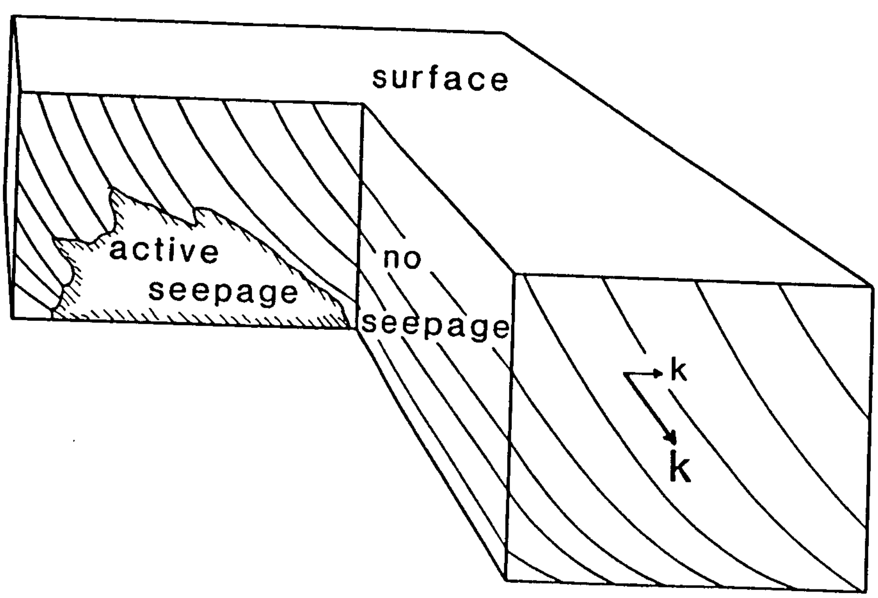

Figure 57. Directional permeability observed in the field sites by active seeps when three-dimensional outcrops with dune cross-bedding were located.

SUMMARY OF TERRESTRIAL ANALOG STUDIES AND APPLICATIONS TO MARS

Studies from diverse geological terrains hosting sapping-dominated valleys on Earth provide essential ground truth information necessary for constructing models for interpreting channel and valley network genesis on Mars. Figure 58 shows the how the various kinds of data discussed in our research report will provide a data base for interpeting Martian channel networks during the following year. The integration of the flume studies, the field observations, and the remote studies of terrestrial field sites has provided a set of geomorphic criteria visible in remote photographic imagery which will calibrate morphometric studies and interpretation of Martian valleys genesis.

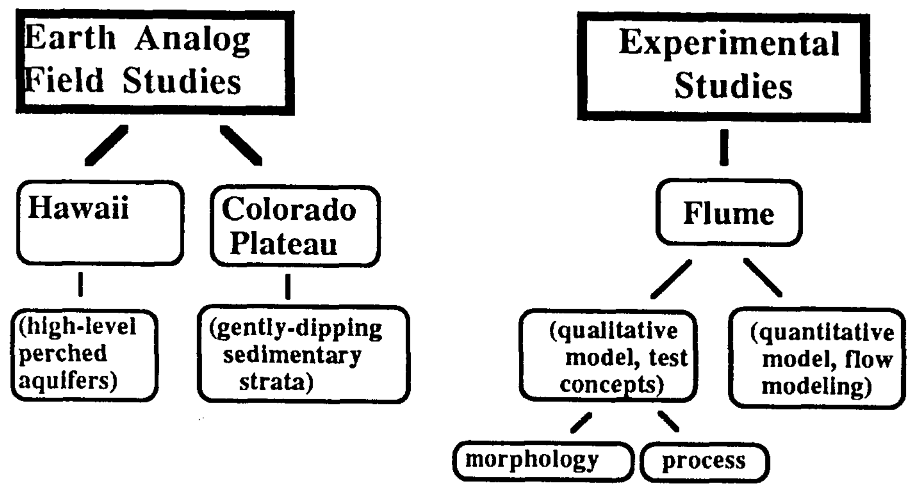

Figure 58. Schematic showing the flow of thought used in the combined terrestrial analog and flume experiments toward building a model for application to the interpretation of Mars valley networks.

The experimental studies provide a base of observations that have been exceedingly useful in understanding how channels are initiated, how they develop, and how they evolve under the dominance of groundwater sapping processes. Unlike runoff channels, sapping valleys can be distinctly separated into two systems on the basis of process dominance. Headward reaches undergoing active sapping are dominated by groundwater emergence and granular removal by seepage forces as well as catastrophic mass movements of an episodic nature. As a result, wall and channel head morphologies become amphitheater-shaped, scalloped, and very steep. Downstream reaches are dominated by fluvial processes, but they often retain relict sapping features for considerable time periods.

The specific size and extent of sapping valleys is controlled by the complex interaction of stratigraphy which controls the access of groundwater supplies available for flow convergence in channel heads. Valley form typically shows complicated patterns of asymmetry influenced by structure and examples of groundwater piracy are numerous.

Most of the features and processes observed directly in the experiments could be applied to field situations in the terrestrial analog studies. Together, these studies enable us to construct a set of geomorphic criteria which can be recognized on aerial imagery, and, is useful in distinguishing sapping and runoff channels. These data will be used in mapping channels on Mars and will help interpret the nature of underlying materials.

In addition, these studies suggest that in some cases, significant interpretations may be possible about the nature of underlying geologic structure and lithology, if not in an absolute manner, perhaps in a relative contrast to adjacent regions of Mars. In particular, attention will be given to the classification of Martian valley types according to genesis as sapping vs. runoff dominated. Additional attention this year will be given to regions with abundant channels such as some of the highland regions of great antiquity, the Valles Marineris area, and some of the volcanic slope channels to investigate what inferences can be made about the underlying geologic features.

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