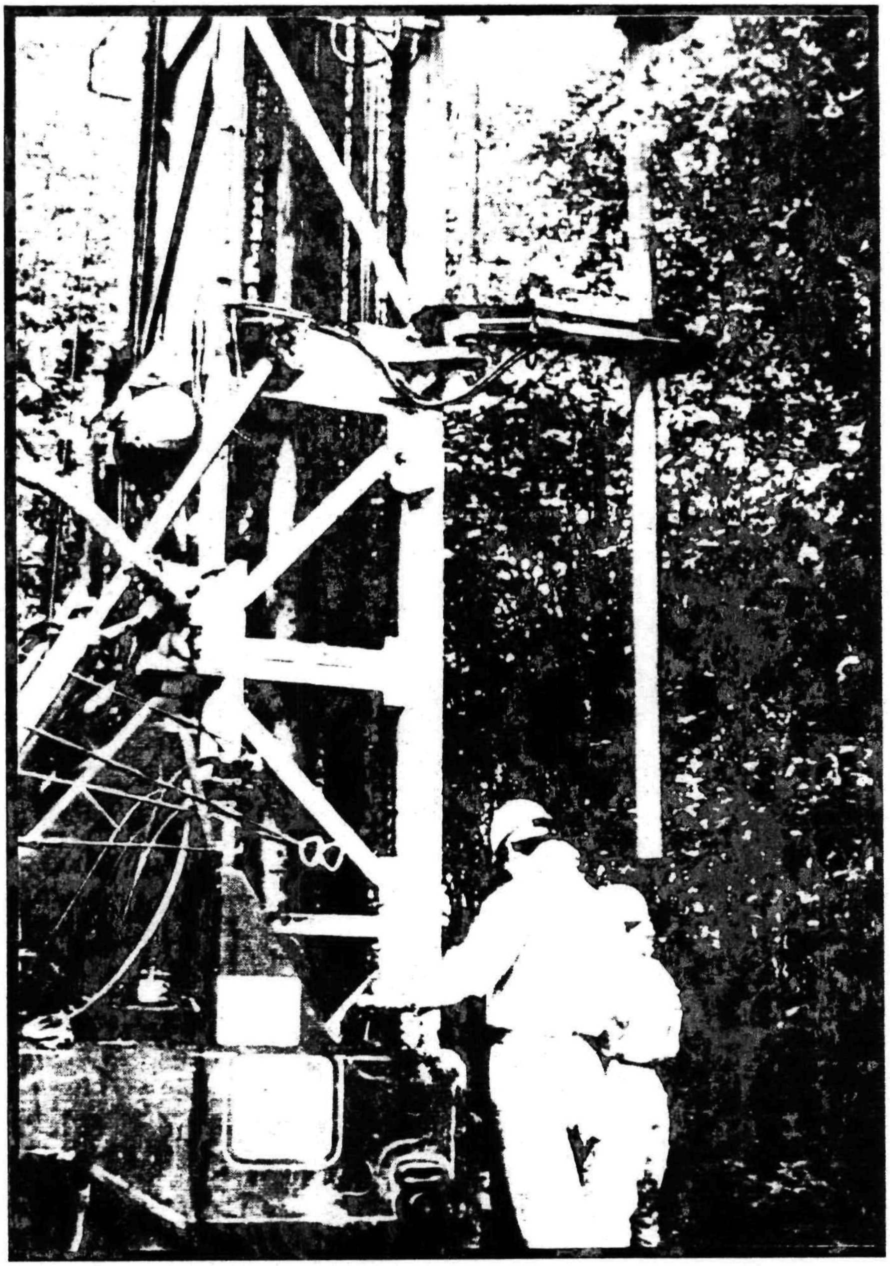
United States Environmental Protection Agency
Office of Emergency and Remedial Response
Emergency Response Division
Environmental Response Team

EPA

Introduction to Groundwater Investigations

Environmental Response Training Program



FOREWORD

This manual is for reference use of students enrolled in scheduled training courses of the U.S. Environmental Protection Agency (EPA). While it will be useful to anyone who needs information on the subjects covered, it will have its greatest value as an adjunct to classroom presentations involving discussions among the students and the instructional staff.

This manual has been developed with a goal of providing the best available current information; however, individual instructors may provide additional material to cover special aspects of their presentations.

Because of the limited availability of the manual, it should not be cited in bibliographies or other publications.

References to products and manufacturers are for illustration only; they do not imply endorsement by EPA.

Constructive suggestions for improvement of the content and format of the manual are welcome.

INTRODUCTION TO GROUNDWATER INVESTIGATIONS

(165.7)

3 Days

This introductory course is designed to provide participants with information concerning hydrogeological processes and the necessary elements of a sound groundwater site investigation. It is intended for personnel who are involved in groundwater contamination investigations but have **little prior hydrogeological experience**. This course is **not** designed for geologists or hydrogeologists.

Topics that are discussed include hydrogeological definitions and concepts; basic geology and geochemistry; drilling, construction, and placement of monitoring wells; groundwater sampling considerations; groundwater flow rates; and groundwater modeling.

Instructional methods include lectures, group discussions, case studies, and class problem-solving exercises.

After completing the course, participants will be able to:

- Identify the components of a groundwater system.
- List the primary hydrogeological factors to be considered in a site investigation.
- Construct a flow net and calculate the hydraulic gradient of a simple system.
- Discuss the primary advantages and disadvantages of the most common geophysical survey methods.
- Identify the different types of pumping tests and the information that can be obtained from each.
- Describe monitoring well drilling and sampling techniques.

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CONTENTS

ACRONYMS AND ABBREVIATIONS

ACS	American Chemical Society
AGI	American Geological Institute
ARAR	applicable or relevant and appropriate requirement
ASTM	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
atm	atmosphere
BDAT	best demonstrated available technology
BM	Bureau of Mines
BNA	base/neutral/acid extractables
BOD	biochemical oxygen demand
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAA	Clean Air Act
CDC	Centers for Disease Control
CE	current electrode
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act of 1980
CERCLIS	CERCLA Information System
CERI	Center for Environmental Research Information
CFR	Code of Federal Regulations
CLP	Contract Laboratory Program
CFA	continuous flight auger
COC	chain of custody
COD	chemical oxygen demand
COE	U.S. Army Corps of Engineers
CWA	Clean Water Act
DO	dissolved oxygen
DOJ	U.S. Department of Justice
DOT	U.S. Department of Transportation
DQO	data quality objectives
DRI	direct-reading instruments
DNAPL	dense, nonaqueous phase liquid
Eh	oxygen-reduction potential
EM	electromagnetic
EMSL-LV	Environmental Monitoring Systems Laboratory - Las Vegas
$\mathbf{EP_{tox}}$	toxicity-extraction procedure toxicity
EPA	U.S. Environmental Protection Agency
EPIC	Environmental Photographic Interpretation Center
ER	electrical resistivity
ERP	Emergency Response Plan

ERT	EPA Emergency Response Team
ERTS	Earth Resources Technology Satellite
EROS	Earth Resources Observation Systems
ESB	EPA Environmental Services Branch
ESD	Environmental Services Division
eV	electron volt
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
FIT	field investigation team
FRP	fiberglass reinforced plastic
FS	feasibility study
FSP	field sampling plan
GAC	granular activated carbon
GC	gas chromatograph
GC/MS	gas chromatography/mass spectrometry
gpm	gallons per minute
GPR	ground-penetrating radar
GWA	Ground Water Act of 1987
HASP	health and safety plan (see also site safety plan)
HAZMAT	hazardous materials team
HRS	hazard ranking system
HSL	hazardous substance list (previous term for target compound list)
HSA	hollow-stem auger
HSO	health and safety officer (see also SSC, SSHO, and SSO)
HSWA	Hazardous and Solid Waste Amendments (to RCRA, 1984)
HWS	hazardous waste site
ICS	incident command system
IDL	instrument detection limit
IDLH	immediately dangerous to life and health
IP	ionization potential
IR	infrared (spectroscopy)
K	hydraulic conductivity
LEL	lower explosive limit
LNAPL	light, nonaqueous phase liquid
LUST	leaking underground storage tank
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
MDL	method detection limit
MSL	mean sea level
m/sec	meters per second
MHz	megahertz

MS/MS	mass spectrometry/mass spectrometry
NBAR	nonbinding preliminary allocation of responsibility
NCIC	National Cartographic Information Center
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NEIC	National Enforcement Investigation Center
NIOSH	National Institute of Occupational Safety and Health
NIPDWR	National Interim Primary Drinking Water Regulations
NOAA	National Oceanic and Atmospheric Administration
n.o.s.	not otherwise specified (used in shipping hazardous material)
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NRC	Nuclear Regulatory Commission
NSF	National Sanitation Foundation
NTIS	National Technical Information Service
NWS	National Weather Service
OERR	EPA Office of Emergency and Remedial Response
OHMTADS	Oil and Hazardous Materials Technical Assistance Data System
OSHA	Occupational Safety and Health Administration
OSWER	EPA Office of Solid Waste and Emergency Response
OVA	organic vapor analyzer (onsite organic vapor monitoring device)
OWPE	EPA Office of Waste Programs Enforcement
PAC	powdered activated carbon
PAH	polycyclic aromatic hydrocarbons
PCB	polychlorinated biphenyls
PCDD	polychlorinated dibenzo-*p*-dioxin
PCDF	polychlorinated dibenzofuran
PCP	pentachlorophenol
PE	potential electrode
PEL	permissible exposure limit
PID	photoionization detector
PO	project officer (EPA)
POHC	principle organic hazardous constituent
POM	polycyclic organic matter
POTWs	publicly owned treatment works
ppb	parts per billion

PPE	personal protective equipment
ppm	parts per million
PRP	potentially responsible party
psig	pounds per square inch gauge
PVC	polyvinyl chloride
QA	quality assurance
QA/QC	quality assurance and quality control
QAMS	quality assurance management staff
QC	quality control
RA	remedial action
RAS	routine analytical services
RCRA	Resource Conservation and Recovery Act of 1978
RD	remedial design
REM	remedial planning
REM/FIT	remedial planning/field investigation team
RI/FS	remedial investigation and feasibility study
ROD	record of decision
RPM	EPA remedial project manager
RQ	reportable quantity
RSPO	remedial site project officer
RSCC	Regional Sample Control Center
SARA	Superfund Amendments and Reauthorization Act of 1986
SAS	special analytical services
SCBA	self-contained breathing apparatus
SCS	Soil Conservation Service
SDL	sample detection limit
SDWA	Safe Drinking Water Act
SI	site inspection
SITE	Superfund Innovative Technology Evaluation
SM	site manager
SOP	standard operating procedure
SP	spontaneous potential
SQG	small quantity generator
SSC	site safety coordinator
SVOC	semivolatile organic compound
SWDA	Solid Waste Disposal Act
TAT	technical assistance team
TCLP	toxicity characteristic leaching procedure
TEGD	Technical Enforcement Guidance Document
TDS	total dissolved solids
TLV	threshold limit value
TOC	total organic carbon

TOH	total organic halogen
TOX	total organic halides
TSCA	Toxic Substances Control Act
TSDF	treatment, storage, and disposal facility
TUHC	total unburned hydrocarbons
UEL	upper explosive limit
UMTRCA	Uranium Mill Tailing Radiation Control Act
USCG	United States Coast Guard
USCS	Unified Soil Classification System
USDI	U.S. Department of the Interior
USGS	U.S. Geological Survey
UST	underground storage tank
UV	ultraviolet
VOA	volatile organic analysis
VOC	volatile organic compound

GLOSSARY

acre-foot	enough water to cover 1 acre to a depth of 1 foot; equal to 43,560 cubic feet or 325,851 gallons
adsorption	the attraction and adhesion of a layer of ions from an aqueous solution to the solid mineral surfaces with which it is in contact
advection	the process by which solutes are transported by the bulk motion of the flowing groundwater
alluvium	a general term for clay, silt, sand, gravel, or similar unconsolidated material deposited during comparatively recent geologic time by a stream or other body of running water as a sorted or semisorted sediment in the bed of the stream or on its floodplain or delta, or as a cone or fan at the base of a mountain slope
anisotropic	*hydraulic conductivity* ("K"), differing with direction
aquifer	a geologic formation, group of formations, or a part of a formation that contains sufficient permeable material to yield significant quantities of groundwater to wells and springs. Use of the term should be restricted to classifying water bodies in accordance with stratigraphy or rock types. In describing hydraulic characteristics such as transmissivity and storage coefficient, be careful to refer those parameters to the saturated part of the aquifer only.
aquifer test	a test involving the withdrawal of measured quantities of water from, or the addition of water to, a well (or wells) and the measurement of resulting changes in *head* (water level) in the aquifer both during and after the period of discharge or addition
aquitard	a saturated, but poorly permeable bed, formation, or group of formations that does not yield water freely to a well or spring
artesian	confined; under pressure sufficient to raise the water level in a well above the top of the aquifer
artificial recharge	recharge at a rate greater than natural, resulting from deliberate or incidental actions of man
artesian aquifer	see *confined aquifer*
bedload	the part of the total stream load that is moved on or immediately above the stream bed, such as the larger or heavier particles (boulders, pebbles, gravel) transported by traction or saltation along the bottom; the part of the load that is not continuously in suspension or solution

capillary zone — negative pressure zone just above the water table where water is drawn up from saturated zone into soil pores due to cohesion of water molecules and adhesion of these molecules to soil particles. Zone thickness may be several inches to several feet depending on porosity and pore size.

capture — the decrease in water discharge naturally from a *ground-water reservoir* plus any increase in water recharged to the reservoir resulting from pumping

coefficient of storage — the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head

cone of depression — depression of heads surrounding a well caused by withdrawal of water (larger cone for confined aquifer than for unconfined)

confined — under pressure significantly greater than atmospheric throughout and its upper limit is the bottom of a bed of distinctly lower hydraulic conductivity than that of the material in which the confined water occurs

confined aquifer — geological formation capable of storing and transmitting water in usable quantities overlain by a less permeable or impermeable formation (confining layer) placing the aquifer under pressure

confining bed — a body of "impermeable" material stratigraphically adjacent to one or more aquifers

diffusion — the process whereby particles of liquids, gases, or solids intermingle as a result of their spontaneous movement caused by thermal agitation

discharge area — an area in which subsurface water, including both groundwater and water in the *unsaturated zone*, is discharged to the land surface, to surface water, or to the atmosphere

discharge velocity — an apparent velocity, calculated from Darcy's law, which represents the flow rate at which water would move through the aquifer if it were an open conduit (also called specific discharge)

dispersion — the spreading and mixing of chemical constituents in groundwater caused by diffusion and by mixing due to microscopic variations in velocities within and between pores

drawdown — the vertical distance through which the water level in a well is lowered by pumping from the well or a nearby well

effective porosity — the amount of interconnected pore space through which fluids can pass, expressed as a percent of bulk volume. Part of the total porosity will be occupied by static fluid being held to the mineral surface by surface tension, so effective porosity will be less than total porosity.

evapotranspiration — the combined loss of water from direct evaporation and through the use of water by vegetation (transpiration)

flow line — the path that a particle of water follows in its movement through saturated, permeable rocks (synonym: *streamline*)

fluid potential — the mechanical energy per unit mass of water or other fluid at any given point in space and time, with respect to an arbitrary state of datum

gaining stream — a stream or reach of a stream whose flow is being increased by inflow of groundwater (also called an effluent stream)

groundwater — water in the zone of saturation

groundwater divide — a ridge in the *water table* or other *potentiometric surface* from which groundwater moves away in both directions normal to the ridge line

groundwater model — simulated representation of a groundwater system to aid definition of behavior and decision-making

groundwater reservoir — all rocks in the *zone of saturation* (see also *aquifer*)

groundwater system — a groundwater reservoir and its contained water; includes hydraulic and geochemical features

head — combination of elevation above datum and pressure energy imparted to a column of water (velocity energy is ignored because of low velocities of groundwater). Measured in length units (i.e., feet or meters).

heterogeneous/geological formation — characteristics varying aerially or vertically in a given system

homogeneous — geology of the aquifer is consistent; not changing with direction or depth

hydraulic conductivity "K" — volume flow through a unit cross-section area per unit decline in head (measured in velocity units and dependent on formation characteristics and fluid characteristics)

hydraulic gradient — change of head values over a distance

$$\frac{H_1 - H_2}{L}$$

where:

H = head
L = distance between head measurement points

hydrograph — graph that shows some property of groundwater or surface water as a function of time

impermeable — having a texture that does not permit water to move through it perceptibly under the head difference that commonly occurs in nature

infiltration — the flow or movement of water through the land surface into the ground

interface — in hydrology, the contact zone between two different fluids

intrinsic permeability — pertaining to the relative ease with which a porous medium can transmit a liquid under a hydrostatic or potential gradient. It is a property of the porous medium and is independent of the nature of the liquid or the potential field.

isotropic — *hydraulic conductivity ("K")* is the same regardless of direction

laminar flow — low velocity flow with no mixing (i.e., no turbulence)

losing stream — a stream or reach of a stream that is losing water to the subsurface (also called an influent stream)

mining — in reference to groundwater, withdrawals in excess of natural replenishment and capture. Commonly applied to heavily pumped areas in semiarid and arid regions, where opportunity for natural replenishment and capture is small. The term is hydrologic and excludes any connotation of unsatisfactory water-management practice (see, however, *overdraft*).

nonsteady state-nonsteady shape — (also called unsteady state-nonsteady shape) the condition when the rate of flow through the aquifer is changing and water levels are declining. It exists during the early stage of withdrawal when the water level throughout the cone of depression is declining and the shape of the cone is changing at a relatively rapid rate.

nonsteady state-steady shape	is the condition that exists during the intermediate stage of withdrawals when the water level is still declining but the shape of the central part of the cone is essentially constant
optimum yield	the best use of groundwater that can be made under the circumstances; a use dependent not only on hydrologic factors but also on legal, social, and economic factors
overdraft	withdrawals of groundwater at rates perceived to be excessive and, therefore, an unsatisfactory water-management practice (see also mining)
pellicular water	water adhering as films to the surfaces of openings and occurring as wedge-shaped bodies at junctures of interstices in the zone of aeration above the capillary fringe
perched	unconfined groundwater separated from an underlying body of groundwater by an unsaturated zone
permeability	the property of the aquifer allowing for transmission of fluid through pores (i.e., connection of pores)
permeameter	a laboratory device used to measure the intrinsic permeability and hydraulic conductivity of a soil or rock sample
piezometer	a nonpumping well, generally of small diameter, that is used to measure the elevation of the water table or potentiometric surface. A piezometer generally has a short well screen through which water can enter.
porosity	the ratio of the volume of the interstices or voids in a rock or soil to the total volume
potentiometric surface	imaginary saturated surface (potential head of confined aquifer); a surface that represents the static head; the levels to which water will rise in tightly cased wells
recharge	the processes of addition of water to the *zone of saturation*
recharge area	an area in which water that is absorbed eventually reaches the *zone of saturation*
safe yield	magnitude of yield that can be relied upon over a long period of time (similar to *sustained yield*)
saturated zone	zone in which all voids are filled with water (the water table is the upper limit)

slug-test — an aquifer test made by either pouring a small instantaneous charge of water into a well or by withdrawing a slug of water from the well (when a slug of water is removed from the well, it is also called a bail-down test)

specific capacity — the rate of discharge from a well divided by the drawdown in it. The rate varies slowly with the duration of pumping, which should be stated when known.

specific yield — ratio of volume of water released under gravity to total volume of saturated rock

steady-state — the condition when the rate of flow is steady and water levels have ceased to decline. It exists in the final stage of withdrawals when neither the water level nor the shape of the cone is changing.

storage — in groundwater hydrology, refers to 1) water naturally detained in a groundwater reservoir, 2) artificial impoundment of water in groundwater reservoirs, and 3) the water so impounded

storage coefficient "S" — volume of water taken into or released from aquifer storage per unit surface area per unit change in head (dimensionless) (for confined, S = 0.0001 to 0.001; for unconfined, S = 0.2 to 0.3)

storativity — the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (also called coefficient of storage)

sustained yield — continuous long-term groundwater production without progressive storage depletion (see also *safe yield*)

transmissivity — the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient

vadose zone — the zone containing water under pressure less than that of the atmosphere, including soil water, intermediate vadose water, and capillary water. Some references include the capillary water in the saturated zone. This zone is limited above by the land surface and below by the surface of the zone of saturation (i.e., the water table). Also called the unsaturated zone or zone of aeration. According to Freeze and Cherry (1979):

1. It occurs above the water table and above the capillary fringe.
2. The soil pores are only partially filled with water; the moisture content θ is less than the porosity n.
3. The fluid pressure p is less than atmospheric; the pressure head ψ is less than zero.
4. The hydraulic head h must be measured with a tensiometer.

5. The hydraulic conductivity K and the moisture content θ are both functions of the pressure head ψ.

water table surface of saturated zone area at atmospheric pressure; that surface in an unconfined water body at which the pressure is atmospheric. Defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water.

Section 1

GEOLOGY

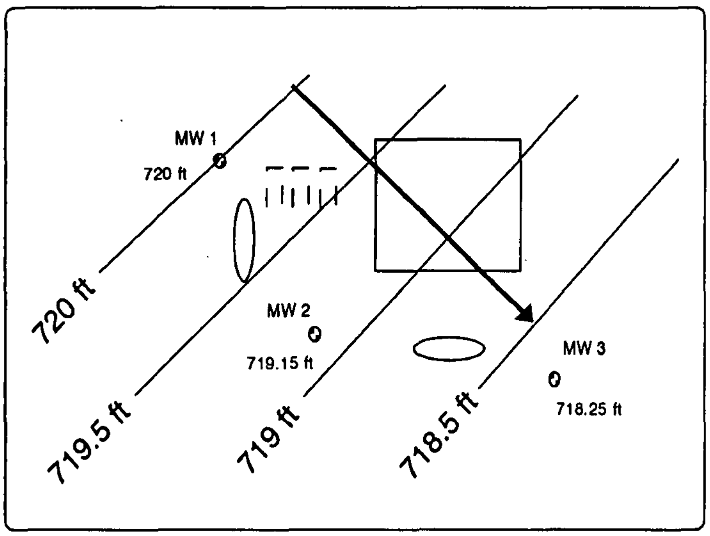
PERFORMANCE OBJECTIVES

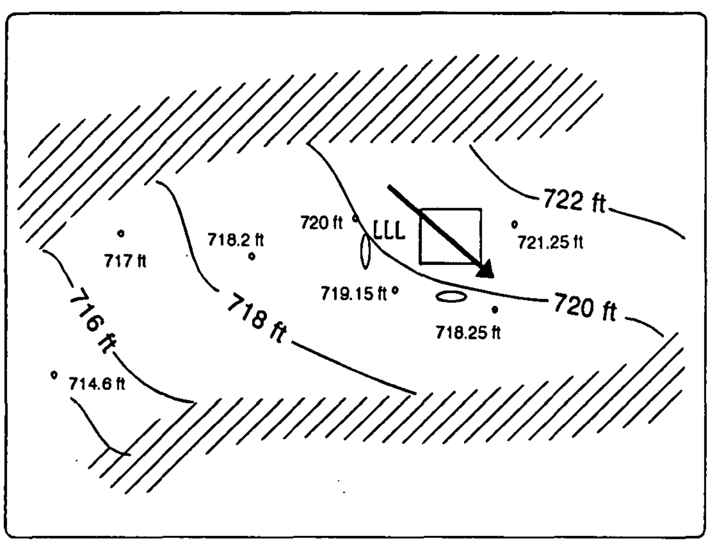
At the end of this lesson, participants will be able to:

- Define the Doctrine of Uniformitarianism
- Describe the three basic rock types and evaluate each as aquifers
- Describe the rock forming processes found on the Rock Cycle diagram
- Identify the medium responsible for the erosion and transport of sediments
- Describe the following depositional environments:
    - Alluvial fans
    - Braided streams
    - Meandering streams
    - Coastal (deltaic, interdeltaic, barrier island complexes)
    - Wind-blown deposits
    - Carbonates.

NOTES

GEOLOGY





NOTES

Doctrine

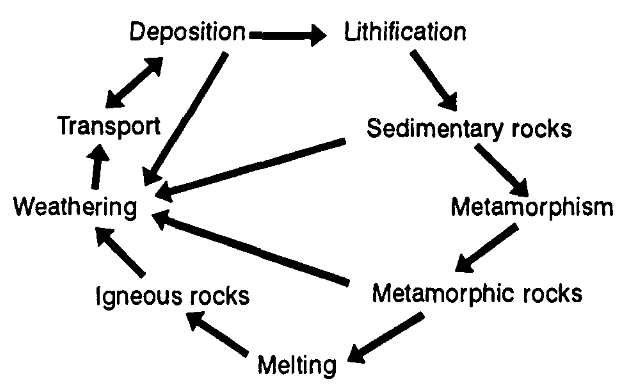
of

Uniformitarianism

"The Present is the Key to the Past"

James Hutton, 1785

THE ROCK CYCLE



NOTES

SEDIMENTATION

- Erosion processes (weathering)
- Transport agents
- Deposition
- Lithification

EROSION PROCESSES

- Wind
- Ice
- Water
- Biology
- Gravity

TRANSPORT AGENTS

- Wind
- Ice
- Water
- Biology
- Gravity

NOTES

DEPOSITION

- Wind
- Ice
- Water
- Gravity

LITHIFICATION

- Cementation
- Diagenesis

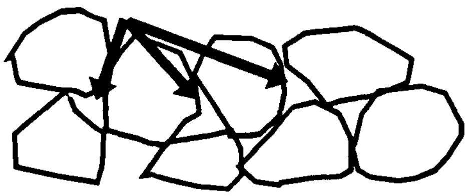
TYPES OF CEMENT

- Silica
- Iron oxides
- Kaolinite
- Montmorillonite
- Illite
- Calcite (aragonite)

NOTES

SEDIMENTARY ROCKS

- Composed of particles of any rock type
  - "Pores" form during deposition



- Most aquifers are sedimentary rocks

SEDIMENTARY ROCKS

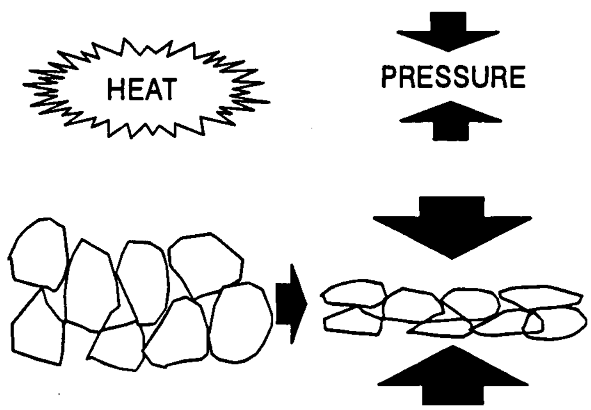
Limestone	Dolomite
Shale	Siltstone
Sandstone	Conglomerate
Coal	Evaporite

METAMORPHISM

- Recrystallization
- "Earth's sweat"

NOTES

METAMORPHIC ROCKS



METAMORPHIC ROCKS

Marble	Slate
Quartzite	Phyllite
Gneiss	Schist

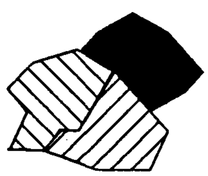
" EARTH"S SWEAT "

NOTES

MELTING/MAGMA

IGNEOUS ROCKS

- Intrusive
  e.g., granite



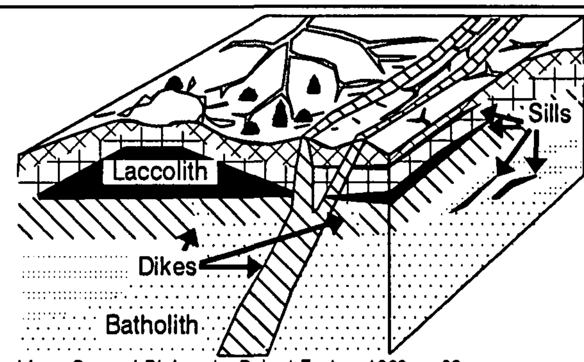
- Extrusive
  e.g., basalt

IGNEOUS ROCKS

Gabbro	Basalt
Granite	Rhyolite

NOTES

INTRUSIVE IGNEOUS ROCK BODIES



Adapted from *General Biology* by Robert Foster. 1969. p 63.

SEDIMENTARY ROCKS

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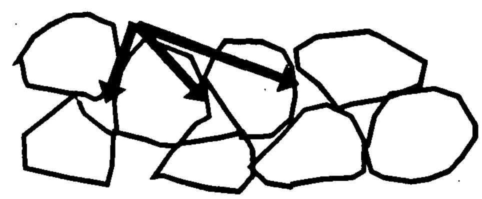
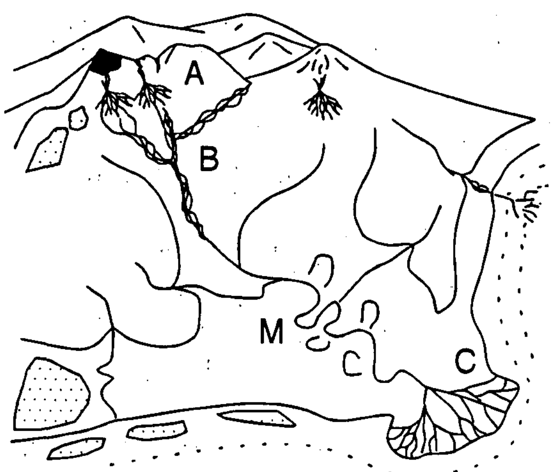


- Most aquifers are sedimentary rocks

ROCK TYPE	ENVIRONMENT
Conglomerate	Landslide, alluvial fan
Sandstone	Rivers, streams, beaches, deltas, dunes, sand bars
Clay/shale	Lagoon, lake, flood plain, deeper ocean
Limestone	Coral reef, atoll, deeper ocean

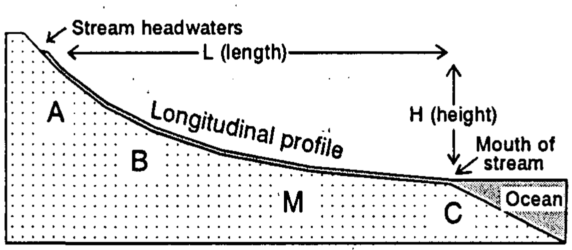
NOTES

CRITERIA TO DEFINE DEPOSITIONAL ENVIRONMENTS



LONGITUDINAL PROFILE

A Alluvial and landslide
B Braided stream
M Meandering stream
C Coastal



NOTES

CRITERIA

- Longitudinal channel profile
- Median channel-grain size
- Sphericity/sorting

CRITERIA

- Penetration of stream
- Width-to-depth ratio
- Degree of sinuosity

LONGITUDINAL CHANNEL PROFILE

NOTES

LONGITUDINAL PROFILE

A Alluvial and landslide
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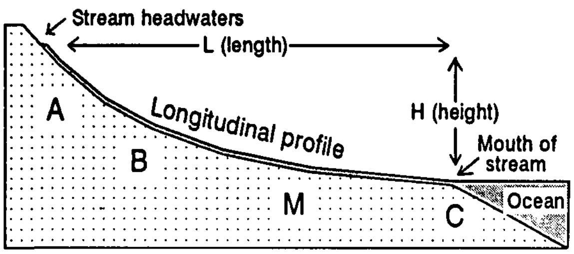
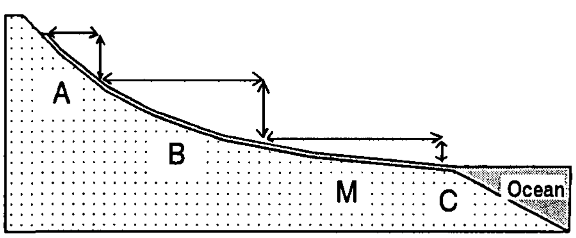


STREAM GRADIENTS

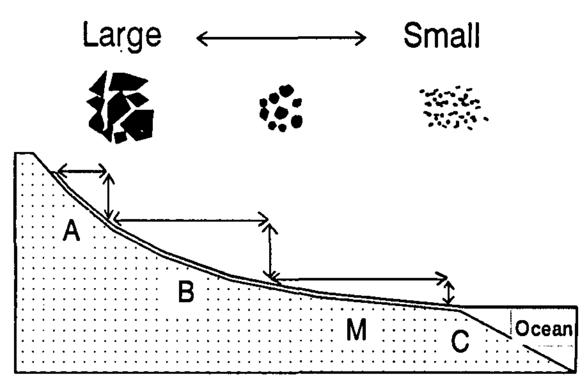
High ⟵⟶ Low



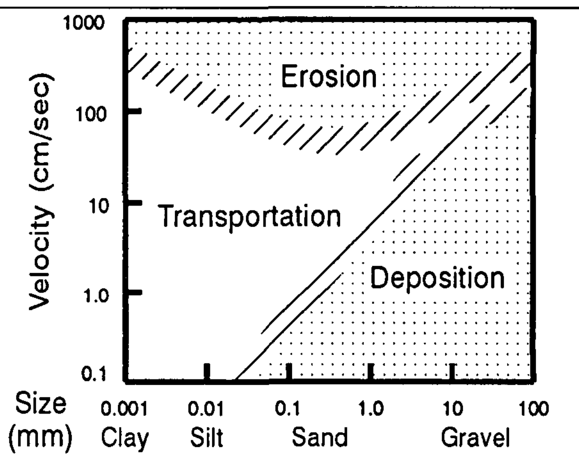
MEDIAN CHANNEL-GRAIN SIZE

NOTES

MEDIAN CHANNEL-GRAIN SIZE



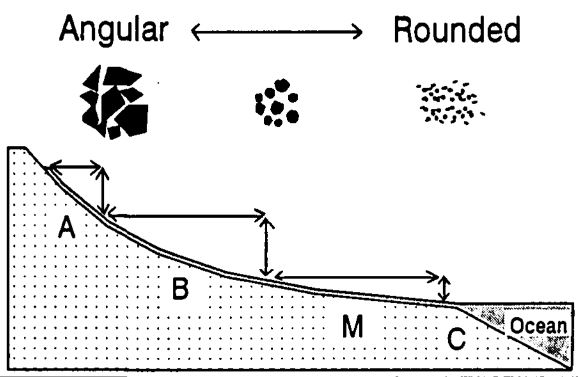
RELATIONSHIP OF STREAM VELOCITY



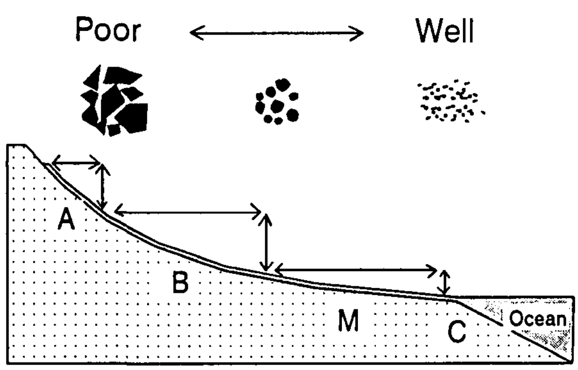
SPHERICITY/SORTING

NOTES

SPHERICITY



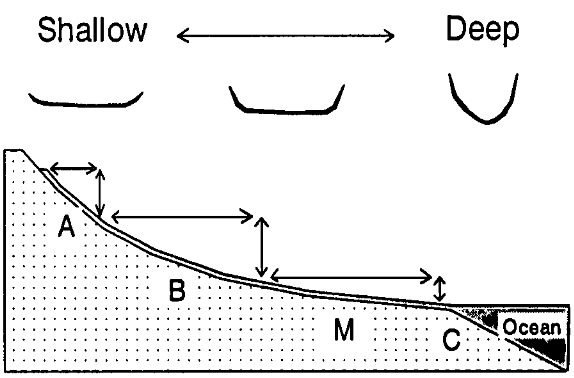
SORTING



PENETRATION OF STREAM

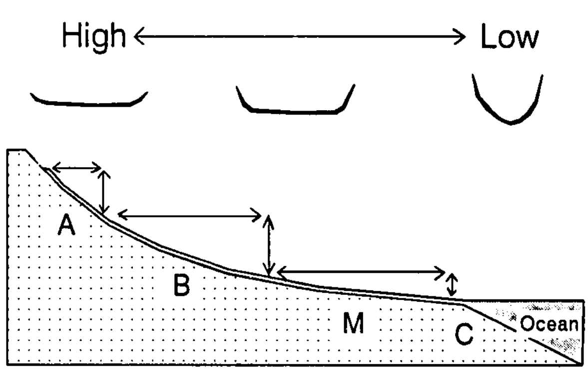
NOTES

STREAM CHANNEL
Penetration



WIDTH-TO-DEPTH RATIO

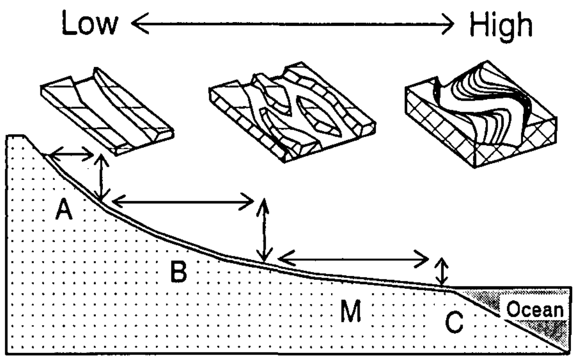
STREAM CHANNEL
Width-to-Depth Ratio



NOTES

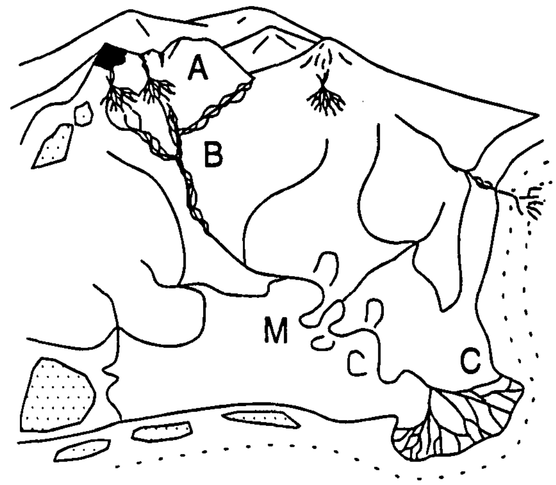
DEGREE OF SINUOSITY

STREAM CHANNEL
Sinuosity



DEPOSITIONAL ENVIRONMENTS

NOTES

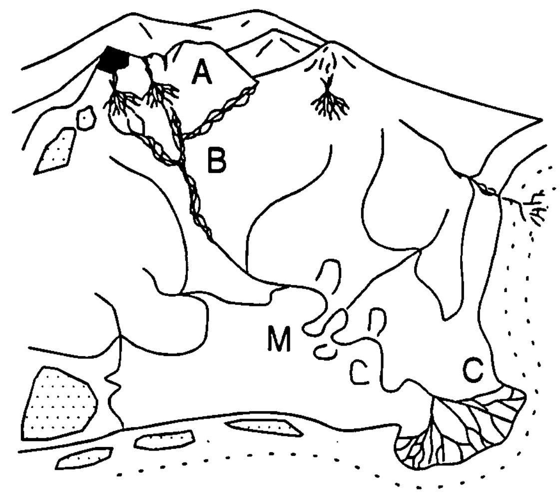


DEPOSITIONAL ENVIRONMENTS

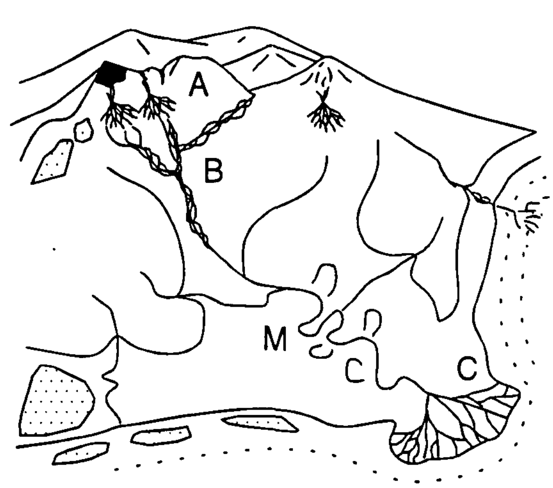
- Alluvial fan
- Braided stream
- Meandering stream
- Coastal deposits
- Wind-blown deposits

ALLUVIAL FAN

NOTES

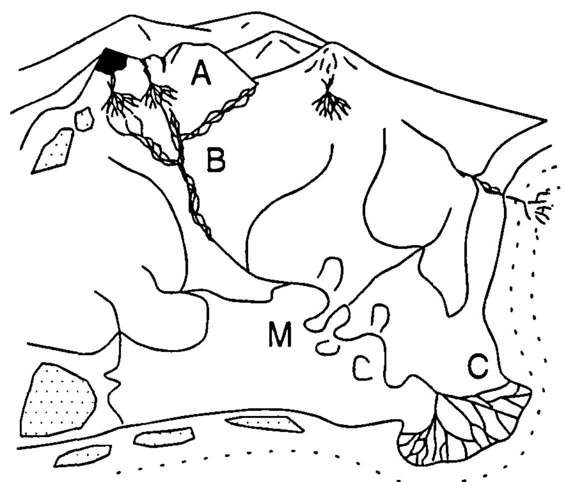


BRAIDED STREAM



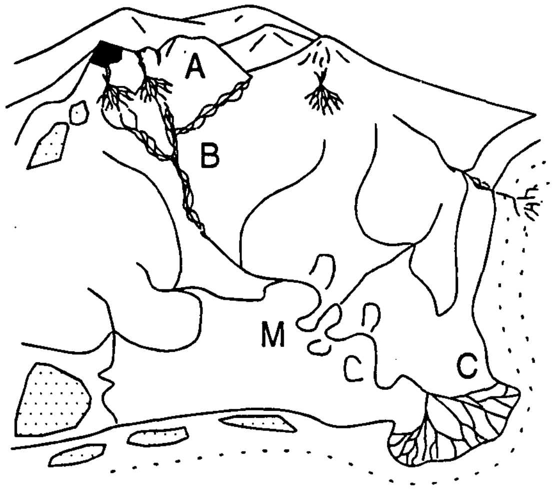
NOTES

MEANDERING STREAM

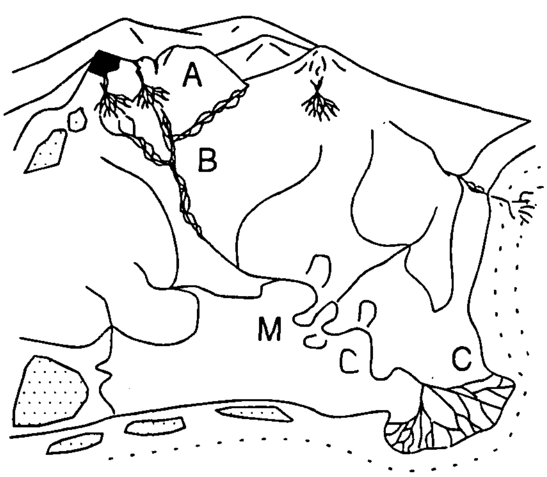


COASTAL DEPOSITS

NOTES



WIND-BLOWN DEPOSITS



NOTES

CARBONATES

- Limestones
- Dolomites

EVAPORITES

- Carbonates
- Sulfates
- Chlorides

GLACIATION

NOTES

GLACIERS/FREEZE-THAW

- Weathering and transport
- Large scale changes
- Poor to excellent sorting
  (e.g., glacial till and outwash)

PROCESSES OF GLACIATION

- Erosion
- Transportation
- Deposition

Geometry of Sandstone Reservoir Bodies[1]

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Abstract Natural underground reservoirs capable of containing water, petroleum, and gases include sandstones, limestones, dolomites, and fractured rocks of various types. Comprehensive research and exploration efforts by the petroleum industry have revealed much about the character and distribution of carbonate rocks (limestones and dolomites) and sandstones. Porosity and permeability of the deposits are criteria for determining their efficiency as reservoirs for fluids. Trends of certain sandstones are predictable. Furthermore, sandstone reservoirs have been less affected than carbonate reservoirs by postdepositional cementation and compaction. Fracture porosity has received less concentrated study; hence, we know less about this type of reservoir. The discussions in this paper are confined to sandstone reservoirs.

The principal sandstone-generating environments are (1) fluvial environments such as alluvial fans, braided streams, and meandering streams; (2) distributary-channel and delta-front environments of various types of deltas; (3) coastal barrier islands, tidal channels, and chenier plains; (4) desert and coastal eolian plains; and (5) deeper marine environments, where the sands are distributed by both normal and density currents.

The alluvial-fan environment is characterized by flash floods and mudflows or debris flows which deposit the coarsest and most irregular sand bodies. Braided streams have numerous shallow channels separated by broad sandbars; lateral channel migration results in the deposition of thin, lenticular sand bodies. Meandering streams migrate within belts 20 times the channel width and deposit two very common types of sand bodies. The processes of bank-caving and point-bar accretion result in lateral channel migration and the formation of sand bodies (point bars) within each meander loop. Natural cut-offs and channel diversions result in the abandonment of individual meanders and long channel segments, respectively. Rapidly abandoned channels are filled with some sand but predominantly with fine-grained sediments (clay plugs), whereas gradually abandoned channels are filled mainly with sands and silts.

The most common sandstone reservoirs are of deltaic origin. They are laterally equivalent to fluvial sands and prodelta and marine clays, and they consist of two types: delta-front or fringe sands and abandoned distributary-channel sands. Fringe sands are sheetlike, and their landward margins are abrupt (against organic clays of the deltaic plain). Seaward, these sands grade into the finer prodelta and marine sediments. Distributary-channel sandstone bodies are narrow, they have abrupt basal contacts, and they decrease in grain size upward. They cut into, or completely through, the fringe sands, and also connect with the upstream fluvial sands or braided or meandering streams.

Some of the more porous and permeable sandstone reservoirs are deposited in the coastal interdeltaic realm of sedimentation. They consist of well-sorted beach and shoreface sands associated with barrier islands and tidal channels which occur between barriers. Barrier sand bodies are long and narrow, are aligned parallel with the coastline, and are characterized by an upward increase in grain size. They are flanked on the landward side by lagoonal clays and on the opposite side by marine clays. Tidal-channel sand bodies have abrupt basal contacts and range in grain size from coarse at the base to fine at the top. Laterally, they merge with barrier sands and grade into the finer sediments of tidal deltas and mud flats.

The most porous and permeable sandstone reservoirs are products of wind activity in coastal and desert regions. Wind-laid (eolian) sands are typically very well sorted and highly crossbedded, and they occur as extensive sheets.

Marine sandstones are those associated with normal-marine processes of the continental shelf, slope, and deep and those due to density-current origin (turbidites). An important type of normal-marine sand is formed during marine transgressions. Although these sands are extremely thin, they are very distinctive and widespread, have sharp updip limits, and grade seaward into marine shales. Delta-fringe and barrier-shoreface sands are two other types of shallow-marine sands.

Turbidites have been interpreted to be associated with submarine canyons. These sands are transported from nearshore environments seaward through canyons and are deposited on submarine fans in deep marine basins. Other turbidites form as a result of slumping of deltaic facies at shelf edges. Turbidite sands are usually associated with thick marine shales.

[1] Manuscript received, March 17, 1972.

[2] Shell Oil Company. This paper is based on the writer's 30 years of experience in studies of modern and ancient clastic sediments—from 1941 to 1948, with the Mississippi River Commission, under the guidance of H. N. Fisk, and, since August 1948, with Shell Development Company and Shell Oil Company.

The writer is grateful to Shell Oil Company for permission to publish this paper, and he is deeply indebted to Alan Thomson for his critical review of the manuscript; he is also grateful to Nick W. Kusakis, John Bush, Dave C. Fogt, Gil C. Flanagan, and George F. Korenek for assistance in the preparation of illustrations and reference material; to Aphrodite Mamoulides and Bernice Melde for their library assistance; to Darleen Vanderford for typing the manuscript, and to Judy Breeding for her editorial assistance.

Numerous stimulating discussions of models of clastic sedimentation and the relationship of sedimentary sequences to depositional processes were held with Hugh A. Bernard and Robert H. Nanz, Jr., during the late 1940s and 1950s, when we were closely associated with Shell's early exploration research effort. The writer is particularly indebted to these two men for their numerous contributions, many of which are included in this paper.

The writer also wishes to thank W. B. Bull, University of Arizona, for his valuable suggestions concerning the alluvial-fan model of clastic sedimentation.

Introduction

Important natural resources such as water, oil, gas, and brines are found in underground reservoirs which are composed principally of the following types of rocks: (1) porous sands, sandstones, and gravels; (2) porous limestones and dolomites; and (3) fractured rocks of various types. According to the 1971 American Petroleum Institute report on reserves of crude oil and natural gas, sandstones are the reservoirs for about 75 percent of the recoverable oil and 65 percent of the recoverable gas in the United States. It is also estimated that approximately 90 percent of our underground water supply comes from sand and gravel (Walton, 1970).

Sandstone and carbonate (limestone and dolomite) reservoirs have been intensively studied during the past 2 decades; consequently, the general characteristics and subsurface distribution of these two important types of reservoirs are relatively well known in numerous sedimentary basins. The factors which control the origin and occurrence of fracture porosity have received less attention; thus, our knowledge and understanding of this type of reservoir are more limited.

The detection of subsurface porosity trends within sedimentary basins was recognized by the petroleum industry as one of its most significant problems, and for the past 2 decades it has addressed itself to a solution through extensive research. Largely as a result of this research, which is summarized below, our ability to determine trends of porous sedimentary rocks has progressed noticeably, especially during the past 10 years.

The amount of porosity and permeability present within sedimentary rocks and the geometry of porous rock bodies are controlled mainly by two important factors: (1) the environmental conditions under which the sediments were deposited and (2) the postdepositional changes within the rocks as a result of burial, compaction, and cementation. Postdepositional diagenetic processes have less effect on the porosity and permeability of sands and sandstones than they have on carbonate sediments; consequently, porosity trends are significantly more predictable for sandstones than for limestones and dolomites.

Organization of paper—The following two parts of this paper give a brief historical summary of the early research on clastic sediments and present a classification of environments of deposition and models of clastic sedimentation. A résumé of significant studies of modern clastic sediments—mainly by the petroleum industry, government agencies, and universities—follows. The main part of the paper concerns the sedimentary processes, sequences, and geometry of sand bodies which characterize each of the following models of clastic sedimentation: alluvial fan, braided stream, meandering stream, deltaic (birdfoot-lobate and cuspate-arcuate), coastal interdeltaic (barrier island and chenier plain), and marine (transgressive, submarine canyon, and fan).

Historical Summary of Early Research on Modern Clastic Sediments

Geologists are now capable of interpreting the depositional environments of ancient sedimentary facies and of predicting clastic porosity trends with a reasonable degree of accuracy (Peterson and Osmond, 1961; Potter, 1967; Rigby and Hamblin, 1972; Shelton, 1972). This capability stems from the extensive research conducted on Holocene sediments by several groups of geologists during the past 3 decades. Conditions which led to this research, and the most significant studies of clastic sedimentation which provided the models, criteria, and concepts necessary to make environmental interpretations, are summarized below.

During the late 1930s and early 1940s, petroleum geologists became aware that improved methods of stratigraphic interpretations were badly needed, and that knowledge and geologic tools necessary to explore for stratigraphic traps were inadequate. A detailed study made by the Research Committee of The American Association of Petroleum Geologists on the research needs of the industry ultimately led to the establishment of geologic research departments by major oil companies. By 1948, exploration research by the oil industry was in its early stages, and expansion proceeded rapidly thereafter.

Meanwhile, some very significant developments were occurring at Louisiana State University. H. V. Howe and R. J. Russell, together with their graduate students, had already published several Louisiana Geological Survey bulletins summarizing their pioneer work on the late Quaternary geology of southern Louisiana (Howe and Moresi, 1931, 1933; Howe *et al.*, 1935; Russell, 1936). Their early work on the Mississippi deltaic plain and the chenier plain of southwestern Louisiana is considered to be the beginning of the modern environmental approach to stratigraphy. Fisk became fascinated with the Howe and Russell approach, and he applied results of their research to his study of Tertiary sediments. The work of Fisk (1940) in central Louisiana, which included a study of the lower Red River Valley and part of the Mississippi Valley, attracted the attention of General Max Tyler, president of the Mississippi River Commission in Vicksburg. General Tyler engaged Fisk as a consultant and provided him with a staff of geologists to conduct a geologic investigation of the lower Mississippi River alluvial valley.

The Fisk (1944) report on the Mississippi Valley, which now has become a classic geologic document, established the relations between alluvial environments, processes, and character of sediments. The AAPG, recognizing the significance of this contribution, retained Fisk as Distinguished Lecturer, and the results and significance of his work became widely known. One of his most significant contributions came when, as the petroleum industry was getting geologic research under way, he was selected by a major oil company to direct its geologic research effort in Houston.

By 1950, a few major oil companies were deeply involved in studies of recent sediments. However, the small companies did not have staff and facilities to conduct this type of research, and American Petroleum Institute Project 51 was established for the purpose of conducting research on recent sediments of the Gulf Coast. Scripps Institution of Oceanography was in charge of the project, which continued for 8 years. Results of this research were available to all companies (Shepard *et al.*, 1960).

While the petroleum industry was conducting "in-house" research and supporting the API project, some significant research was being done by the U.S. Waterways Experiment Station in Vicksburg, Mississippi, and by the new Coastal Studies Institute at Louisiana State University under the direction of R. J. Russell. These two groups conducted detailed studies of recent sediments for many years, and results were made available to the petroleum industry.

By 1955, a fairly good understanding of processes of sedimentation and character of related sediments in several depositional environments had been acquired. Although the application of this wealth of knowledge to operational problems was very difficult, some useful applications nevertheless had been made by the middle 1950s, and it was generally agreed that the initial research effort was successful.

Since 1955, geologists all over the world have become involved in studying recent sediments and applying the results to research on older rocks. Geologists with the U.S. Geological Survey and several universities have conducted studies of alluvial fans, braided streams, and eolian deposits; and the oceanographic institutions, such as Scripps, Woods Hole, and Lamont, have investigated deep-marine sediments on a worldwide basis. Publication of papers on clastic sedimentation has been increasing rapidly. The first textbook on the geology of recent sediments cites more than 700 references, 75 percent of which have appeared since 1955 (Kukal, 1971). Many of these contributions, considered to be most significant to the current understanding of clastic sediments, are cited in this paper.

Models and Environments of Clastic Sedimentation

The realm of clastic sedimentation can be divided into several conceptual models, each of which is characterized by certain depositional environments, sedimentary processes, sequences, and patterns. What are considered to be some of the most common and basic models and environments[3] of clastic sedimentation, arranged in order from the periphery to the center of a depositional basin, are listed below and are shown on Figures 1–4.

- Continental
  - Alluvial (fluvial) models
    - Alluvial fan
    - Braided stream
    - Meandering stream (includes flood basins between meander belts)
  - Eolian (can occur at various positions within continental and transitional models)
- Transitional
  - Deltaic models
    - Birdfoot-lobate (fluvial dominated)
    - Cuspate-arcuate (wave and current dominated)
    - Estuarine (with strong tidal influence)
  - Coastal-interdeltaic models
    - Barrier-island model (includes barrier islands, lagoons behind barriers, tidal channels, and tidal deltas)
    - Chenier-plain model (includes mud flats and cheniers)
- Marine
  - (Note: Sediments deposited in shallow-marine environments, such as deltas and barrier islands, are

[3] The classification of depositional environments presented herein was initially developed by the writer and his colleague, Hugh A. Bernard, during the early 1950s (LeBlanc and Bernard, 1954) and was recently modified (Bernard and LeBlanc, 1965). For other classifications, refer to Laporte (1968), Selley (1970), Crosby (1972), and Kukal (1971).

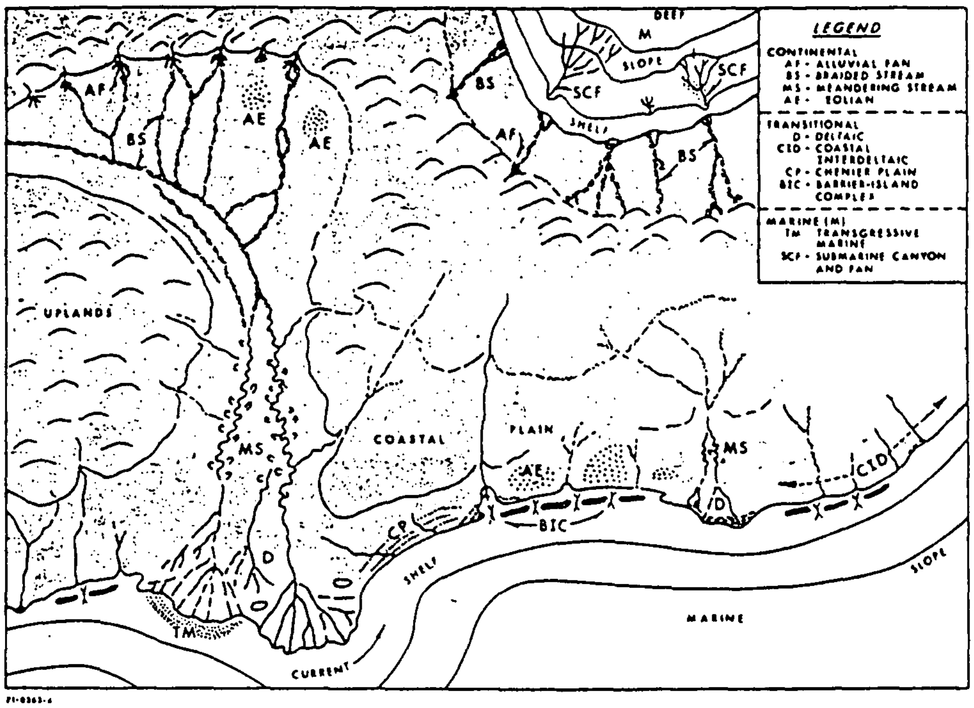

FIG. 1—Some common models of clastic sedimentation. See Figures 2–4 for details.

included under the transitional group of environments.)
Transgressive-marine model
Submarine-canyon and submarine-fan model

Résumé of Significant Studies of Modern Clastic Sedimentation

Alluvial Fans

Although much work has been done on alluvial fans, only a few papers discuss the relation of sedimentary sequences to depositional processes. Some of the more important contributions are by Rickmers (1913), Pack (1923), Blackwelder (1928), Eckis (1928), Blissenbach (1954), McKee (1957), Beaty (1963), Bull (1962, 1963, 1964, 1968, 1969, 1971), Hoppe and Ekman (1964), Winder (1965), Anstey (1965), Denny (1965, 1967), Legget *et al.* (1966), and Hooke (1967).

Braided Streams

Early papers on braided streams concerned channel patterns, origin of braiding, and physical characteristics of braided streams. Significant studies of this type were conducted by Lane (1957), Leopold and Wolman (1957), Chein (1961), Krigstrom (1962), Fahnestock (1963), and Brice (1964).

The relatively few papers on the relation of braided-stream deposits to depositional processes did not appear until the 1960s. Doeglas (1962) discussed braided-stream sequences of the Rhône River of France, and Ore (1963, 1965) presented some criteria for recognition of braided-stream deposits, based on the study of several braided streams in Wyoming, Colorado, and Nebraska. Fahnestock (1963) described braided streams associated with a glacial outwash plain in Washington. More recently, Williams and Rust (1969) discussed the sedimentology of a degrading braided river in the Yukon Territory, Canada. Coleman (1969) presented results of a study of the processes and sedimentary characteristics of one of the largest braided rivers, the Brahmaputra of Bangla Desh (formerly East Pakistan). N. Smith (1970) studied the Platte River from Denver, Colorado, to Omaha, Nebraska, and used the Platte model to interpret Silurian braided-stream deposits of the Appalachian region. Waechter (1970) has recently studied the braided Red River in the Texas Panhandle, and Kessler (1970, 1971) has investigated the Canadian River in Texas. Boothroyd (1970) studied braided streams associated with glacial outwash plains in Alaska.

ENVIRONMENTS				
CONTINENTAL	ALLUVIAL (FLUVIAL)	ALLUVIAL FANS (APEX, MIDDLE & BASE OF FAN)	STREAM FLOWS	CHANNELS
				SHEETFLOODS
				"SIEVE DEPOSITS"
			VISCOUS FLOWS	DEBRIS FLOWS
				MUDFLOWS
		BRAIDED STREAMS		CHANNELS (VARYING SIZES)
				BARS: LONGITUDINAL
				BARS: TRANSVERSE
		MEANDERING STREAMS (ALLUVIAL VALLEY)	MEANDER BELTS	CHANNELS
				NATURAL LEVEES
				POINT BARS
			FLOODBASINS	STREAMS, LAKES & SWAMPS
	EOLIAN	DUNES	COASTAL DUNES	TYPES: TRANSVERSE SEIF (LONGITUDINAL) BARCHAN PARABOLIC DOME-SHAPED
			DESERT DUNES	
			OTHER DUNES	

DEPOSITIONAL MODELS

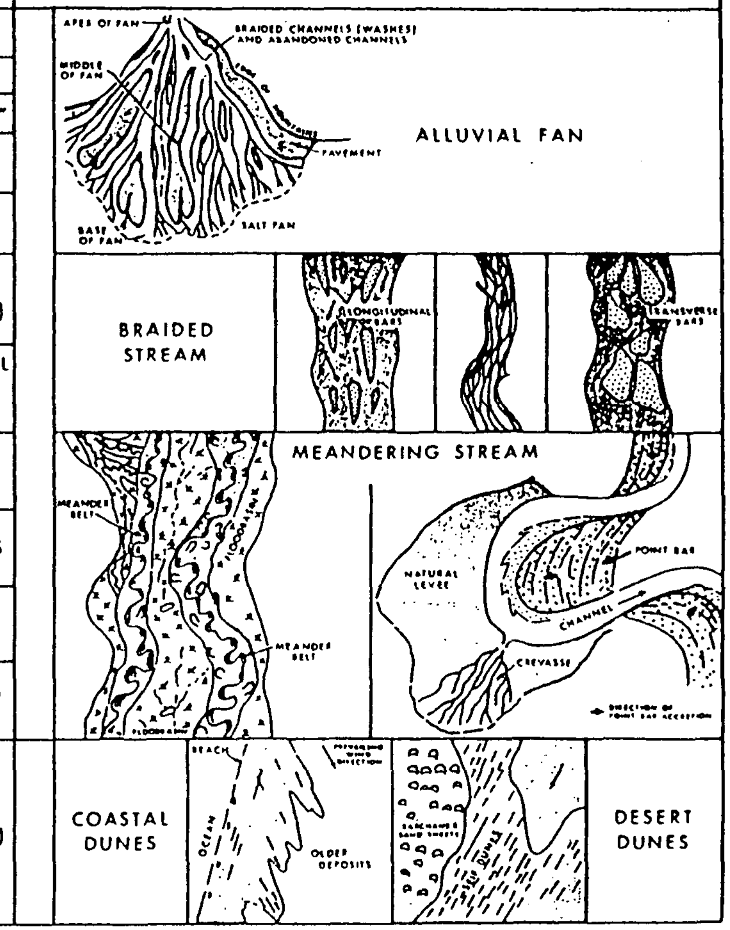

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FIG. 2—Alluvial (fluvial) and eolian environments and models of clastic sedimentation.

ENVIRONMENTS				
TRANSITIONAL	DELTAIC	UPPER DELTAIC PLAIN	MEANDER BELTS	CHANNELS
				NATURAL LEVEES
				POINT BARS
			FLOODBASINS	STREAMS, LAKES & SWAMPS
		LOWER DELTAIC PLAIN	DISTRIBUTARY CHANNELS	CHANNELS
				NATURAL LEVEES
			INTER-DISTRIBUTARY AREAS	MARSH, LAKES, TIDAL CHANNELS & TIDAL FLATS
		FRINGE	DELTA FRONT — INNER	RIVER-MOUTH BARS BEACHES & BEACH RIDGES TIDAL FLATS
			DELTA FRONT — OUTER	
		DISTAL		

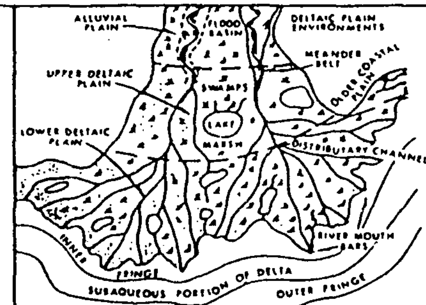
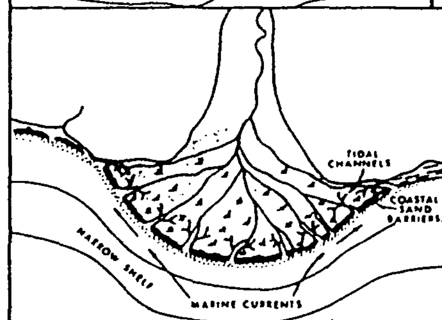
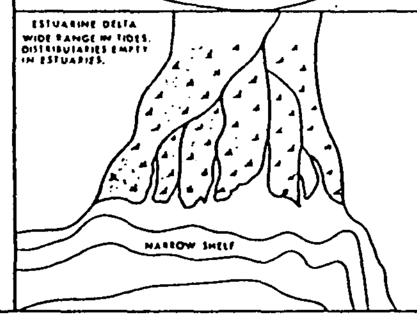
DEPOSITIONAL MODELS		
TYPES OF DELTAS		BIRDFOOT-LOBATE DELTA
		CUSPATE-ARCUATE DELTA
		ESTUARINE DELTA

Fig. 3—Deltaic environments and models of clastic sedimentation.

Meandering Streams

H. N. Fisk's studies of the Mississippi alluvial valley, conducted for the Mississippi River Commission during the period 1941–48, represent the first significant contribution on meandering stream environments and deposits. This pioneer effort provided geologists with knowledge of the fundamental processes of alluvial-valley sedimentation. Another study of a meandering stream, the Connecticut River, and its valley was made by Jahns (1947). Important work on alluvial sediments deposited by meandering streams was also done by Sundborg (1956) in Sweden, and by Frazier and Osanik (1961), Bernard and Major (1963), and Harms *et al.* (1963) on the Mississippi, Brazos, and Red River point bars, respectively. Thus, by 1963 the general characteristics of point-bar sequences, and the closely related abandoned-channel and flood-basin sequences, were sufficiently well established to permit geologists to recognize this type of sedimentary deposit in outcrops and in the subsurface.

Other important contributions were made by Allen (1965a) on the origin and characteristics of alluvial sediments, by Simons *et al.* (1965) on the flow regime in alluvial channels, by Bernard *et al.* (1970) on the relation of sedimentary structures to bed form in the Brazos valley deposits, and by McGowen and Garner (1970) on coarse-grained point-bar deposits.

Deltas

The early work by W. Johnson (1921, 1922) on the Fraser delta, Russell (1936) on the Mississippi delta, Sykes (1937) on the Colorado delta, and Fisk (1944) on the Mississippi delta provided a firm basis for subsequent studies of more than 25 modern deltas during the late 1950s and the 1960s.

Fisk continued his studies of the Mississippi delta for more than 20 years. His greatest contributions were concerned with the delta framework, the origin and character of delta-front sheet sands, and the development of bar-finger sands by seaward-migrating rivermouth bars.

Scruton's (1960) paper on delta building and the deltaic sequence represents results of API Project 51 on the Mississippi delta. Additional research on Mississippi delta sedimentation, sedimentary structures, and mudlumps was reported by Welder (1959), Morgan (1961), Morgan *et al.* (1968), Coleman *et al.* (1964), Coleman (1966b), Coleman and Gagliano (1964, 1965), and also by Kolb and Van Lopik (1966). Coleman and Gagliano (1964) also discussed and illustrated processes of cyclic sedimentation. The most recent papers on the Mississippi delta are by Frazier (1967), Frazier and Osanik (1969), and Gould (1970).

Studies of three small birdfoot deltas of Texas—the Trinity, Colorado, and Guadalupe—were made by McEwen (1969), Kanes (1970), and Donaldson (1966), respectively. In addition, Donaldson *et al.* (1970) presented a summary paper on the Guadalupe delta. These four contributions are valuable because each one presents photographs and logs of cores of complete deltaic sequences.

European geologists associated with the petroleum industry and universities also have made valuable contributions to our understanding of deltas. Kruit (1955) and Lagaaij and Kopstein (1964) discussed their research on the Rhône delta of southern France, Allen (1965c, 1970) summarized the geology of the Niger delta of western Africa, and van Andel (1967) presented a résumé of the work done on the Orinoco delta of eastern Venezuela. More recently, the Po delta of Italy was studied by B. Nelson (1970) and the Rhône delta of southern France by Oomkens (1970).

Other recent contributions on modern deltas are by Coleman *et al.* (1970) on a Malaysian delta, by R. Thompson (1968) on the Colorado delta in Mexico, and by Bernard *et al.* (1970) on the Brazos delta of Texas.

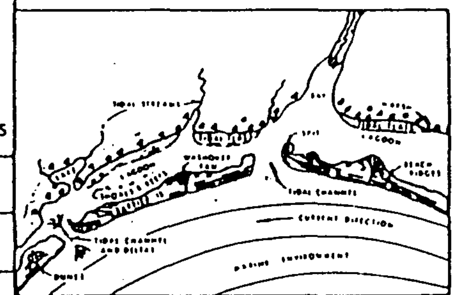
The deltaic model is probably the most complex of the clastic models. Although additional research is needed on this aspect of sedimentation, the studies listed have provided some valuable concepts and criteria for recognition of ancient deltaic facies.

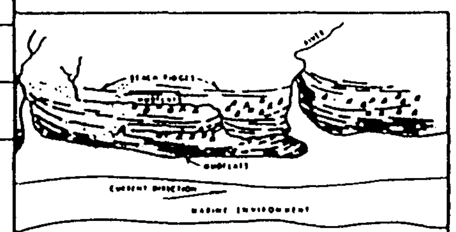
Coastal-Interdeltaic Sediments

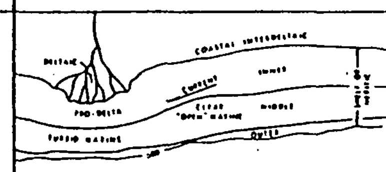
Valuable contributions to our knowledge of this important type of sedimentation have been made by several groups of geologists. In the Gulf Coast region, the extensive Padre Island–Laguna Madre complex was studied by Fisk (1959), and the chenier plain of southwestern Louisiana was studied by Gould and McFarlan (1959) and Byrne *et al.* (1959). The Galveston barrier-island complex of the upper Texas coast was investigated mainly by LeBlanc and Hodgson (1959), Bernard *et al.* (1959, 1962), and Bernard and LeBlanc (1965).

Among the impressive studies made by Europeans during the past 15 years are those by van Straaten (1954), who presented results of very

ENVIRONMENTS					DEPOSITIONAL MODELS
TRANSITIONAL	COASTAL INTER-DELTAIC	COASTAL PLAIN (SUBAERIAL)	BARRIER ISLANDS	BACK BAR, BARRIER, BEACH, BARRIER FACE, SPITS & FLATS, WASHOVER FANS	BARRIER IS. COMPLEX
			CHENIER PLAINS	BEACH & RIDGES	CHENIER PLAIN
				TIDAL FLATS	
			TIDAL	TIDAL FLATS	
				TIDAL DELTAS	
		SUBAQUEOUS	LAGOONS	SHOALS & REEFS	
			TIDAL CHANNELS		
			SMALL ESTUARIES		
MARINE	SHALLOW MARINE	SHELF (NERITIC)	INNER	SHOALS & BANKS	SHALLOW MARINE
			MIDDLE		
			OUTER		
	DEEP MARINE	CANYONS			DEEP MARINE
		FANS (DELTAS)			
		SLOPE & ABYSSAL			
		TRENCHES & TROUGHS			







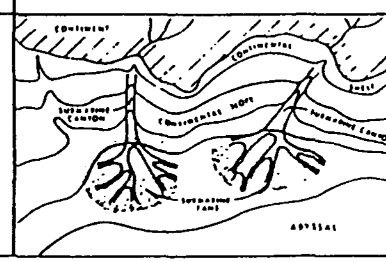


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FIG. 4—Coastal-interdeltaic and marine environments and models of clastic sedimentation.

significant work on tidal flats, tidal channels, and tidal deltas of the northern Dutch coast, and by Horn (1965) and H. E. Reineck (1967), who reported on the barrier islands and tidal flats of northern Germany.

During the past several years, a group of geologists has conducted interesting research on the coastal-interdeltaic complexes which characterize much of the U.S. Atlantic Coast region. Hoyt and Henry (1965, 1967) published several papers on barriers and related features of Georgia. More recently, results of studies at the University of Massachusetts on recent coastal environments of New England were reported by Daboll (1969) and by the Coastal Research Group (1969).

In addition, Curray *et al.* (1969) described sediments associated with a strand-plain barrier in Mexico, and Potter (1967) summarized the characteristics of barrier-island sand bodies.

Eolian Sand Dunes

Prior to the middle 1950s, eolian depositional environments were studied principally by European geologists (Cooper, 1958). Since that time, the coastal sand dunes of the Pacific, Atlantic, and Gulf coasts of the United States, as well as the desert dunes of the United States and other countries, have been investigated by university professors and by geologists with the U.S. Geological Survey. Some of the most significant contributions, especially those concerned with dune stratification, are discussed in the section on the eolian model of clastic sedimentation.

Marine Sediments

Early work on modern marine sands, exclusive of those deposited adjacent to and related to interdeltaic and deltaic depositional environments, was conducted largely by scientists associated with Scripps, Woods Hole, and Lamont oceanographic departments. Several aspects of marine sediments were discussed by Trask *et al.* (1955), and the recent sands of the Pacific Ocean off California were studied by Revelle and Shepard (1939), Emery *et al.* (1952), and Emery (1960a). Stetson (1953) described the northwestern Gulf of Mexico sediments, and Ericson *et al.* (1952, 1955) and Heezen *et al.* (1959) investigated the Atlantic Ocean sediments. Later, Curray (1960), van Andel (1960), and van Andel and Curray (1960) reported results of the API project on the Gulf of Mexico. A few years later, results of the API project studies on the Gulf of California were reported by van Andel (1964) and van Andel and Shor (1964). Menard (1964) discussed sediments of the Pacific Ocean. For a more complete list of references to studies of recent marine sands, the reader is referred to Kuenen (1950), Guilcher (1958), Shepard *et al.* (1963), and Kukal (1971).

Much of the early research on modern marine environments was devoted to submarine canyons, fans, and basins considered by the investigators to be characterized mainly by turbidity-current sedimentation. Several scientists affiliated with Scripps and the University of Southern California published numerous papers on turbidites which occur in deep marine basins.

It is extremely difficult to observe the processes of turbidity-current sedimentation under natural conditions; consequently, the relations between sedimentary sequences and processes are still relatively poorly understood. Much of the research dealing with turbidity currents has been concerned with theory, laboratory models, and cores of deep-water sediments deposited by processes which have not been observed.

Alluvial-Fan Model of Clastic Sedimentation

Occurrence and General Characteristics

Alluvial fans occur throughout the world, adjacent to mountain ranges or high hills. Although they form under practically all types of climatic conditions, they are more common and best developed along mountains of bold relief in arid and semi-arid regions (Figs. 5, 6).

The alluvial-fan model has the following characteristics: (1) sediment transport occurs under some of the highest energy conditions within the entire realm of clastic sedimentation, (2) deposition of clastic sediment occurs directly adjacent to the areas of erosion which provide the sediments, and (3) deposits are of maximum possible range in size of clastic particles (from the largest boulders to clays) and are commonly very poorly sorted compared with other types of alluvial sediments (Fig. 5).

The size of individual alluvial fans is controlled by drainage-basin area, slope, climate, and character of rocks within the mountain range. Individual fans range in radius from several hundred feet to several tens of miles. Coalescing fans can occur in linear belts that are hundreds of miles long. Fan deposits usually attain their maximum thicknesses and grain size near the mountain base (apex of fan) and

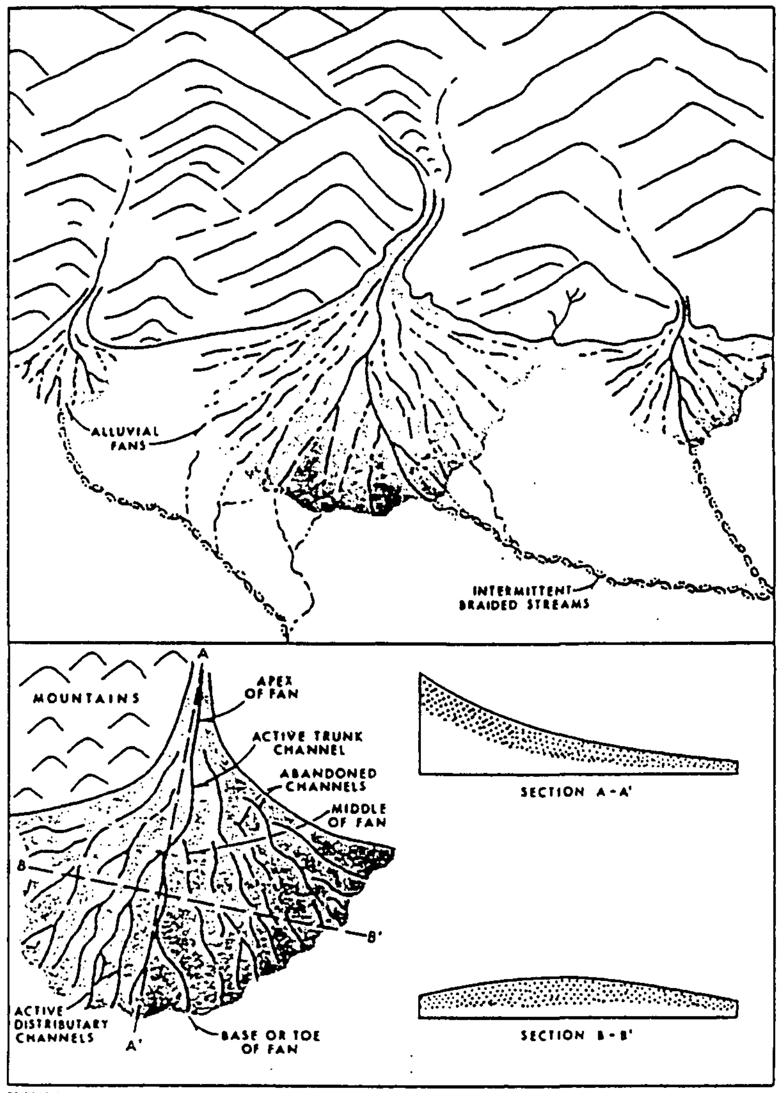

FIG. 5—Alluvial-fan model of clastic sedimentation.

gradually decrease in thickness away from the apex.

The alluvial-fan environments commonly grade downstream into braided-stream or playa-lake environments. In some areas, where mountains are adjacent to oceans or large inland lakes, alluvial fans are formed under both subaerial and submerged conditions. Such fans are now referred to as "Gilbert-type" deltas.

Alluvial-fan deposits form important reservoirs for groundwater in many areas, and adjacent groundwater basins are recharged through the fan deposits which fringe these basins.

Source, Transportation, and Deposition of Sediments

Tectonic activity and climate have a profound influence on the source, transportation, and deposition of alluvial-fan deposits. Uplift of mountain ranges results in very intensive erosion of rocks and development of a very high-gradient drainage system. The rate of weathering and production of clastic material is controlled mainly by rock characteristics and climate (temperature and rainfall).

Clastic materials are transported from source areas in mountains or high hills to alluvial fans by several types of flows: stream flows and sheetfloods and debris flows or mudflows. Sediment transport by streams is usually characteristic of large fans in regions of high to moderate rainfall. Mudflows or debris flows are more common on small fans in regions of low rainfall characterized by sudden and brief periods of heavy downpours.

Stream deposits—Streams which drain relatively small segments of steep mountain ranges have steep gradients; they may erode deep canyons and transport very large quantities of coarse debris. The typical overall stream gradient is concave upward, and the lowest gradient occurs at the toe of the fan (Fig. 5).

Hooke (1967) described a special type of stream-flow deposit, which he called "sieve deposits," on fans which are deficient in fine sediments. These gravel deposits are formed when water infiltrates completely into the fan. Bull (1969) described three types of water-laid sediments on alluvial fans: channel, sheetflood, and sieve deposits. Stream channels radiate outward from the fan apex and commonly are braided. The processes of channel migration, diversion, abandonment and filling, and development of new main channels and smaller distributary channels on the lower part of the fan surface are characteristic features. Most fan surfaces are characterized by one or a few active channels and numerous abandoned channels. Deposits on abandoned portions of gravelly and weathered fan surfaces are referred to as "pavement."

Alluvial-fan channel deposits have abrupt basal contacts and channel geometry; they are generally coarse. Bull (1972) described channel deposits as imbricated and massive or thick-bedded.

Heavy rainfall in mountainous source areas can result in floods on alluvial fans. The relatively shallow and wide fan channels are not capable of carrying the sudden influx of large volumes of water; consequently, the streams overtop their banks and flood part of the fan surface. The result is the deposition of thin layers of clastic material between channels. Bull (1969) reported sheetflood deposits to be finer grained than channel deposits, cross-bedded, and massive or thinly bedded.

Debris-flow deposits—Some workers refer to both fine-grained and coarse-grained types of plastic flowage in stream channels as mudflows, but others consider mudflows to be fine-grained debris flows. Examples of transportation and deposition of clastic sediments by mudflows were first described by Rickmers (1913) and Blackwelder (1928). The following conditions favor the development of mudflows: presence of unconsolidated material with enough clay to make it slippery when wet, steep gradients, short periods of abundant water, and sparse vegetation.

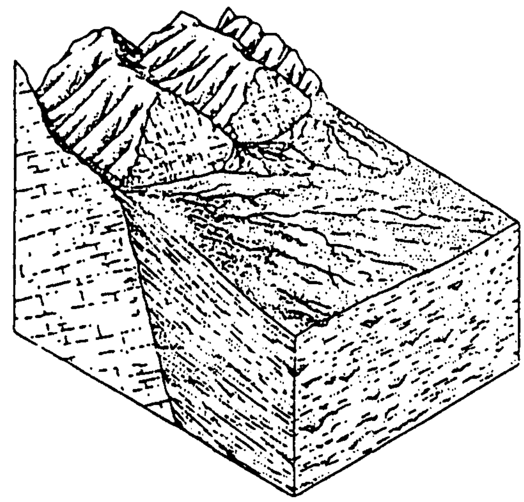

FIG. 6—Stratigraphic geometry of an alluvial fan. After Bull (1972).

Pack (1923) discussed debris-flow deposition on alluvial-fan surfaces. Debris flows occur as a result of very sudden, severe flooding of short duration. Beaty (1963) described eyewitness accounts of debris flows on the west flank of the White Mountains of California and Nevada. Debris flows follow channels, overtop the channel banks, and form lobate tongues of debris along channels. Debris-flow deposits are very poorly sorted, fine- to coarse-grained, and unstratified; they have abrupt margins. This type of deposit is probably most common on the upper parts of the fans between the apex and midfan areas.

Summary: Character and Geometry of Alluvial-Fan Deposits

Most of the alluvial-fan studies conducted thus far have been concerned primarily with the origin and general characteristics of fans and the distribution of sediments on the surfaces of fans. An exception is Bull's excellent summary paper (Bull, 1972), which contains significant data on the geometry of channel, sheetflood, debris-flow, mudflow, and sieve deposits. The abstract of Bull's paper is quoted below:

Alluvial fans commonly are thick, oxidized, orogenic deposits whose geometry is influenced by the rate and duration of uplift of the adjacent mountains and by climatic factors.

Fans consist of water-laid sediments, debris-flow deposits, or both. Water-laid sediments occur as channel, sheetflood, or sieve deposits. Entrenched stream channels commonly are backfilled with gravel that may be imbricated, massive, or thick bedded. Braided sheets of finer-grained sediments deposited downslope from the channel may be cross-bedded, massive, laminated, or thick bedded. Sieve deposits are overlapping lobes of permeable gravel.

Debris-flow deposits generally consist of cobbles and boulders in a poorly sorted matrix. Mudflows are fine-grained debris flows. Fluid debris flows have graded bedding and horizontal orientation of tabular particles. Viscous flows have uniform particle distribution and vertical preferred orientation that may be normal to the flow direction.

Logarithmic plots of the coarsest one percentile versus median particle size may make patterns distinctive of depositional environments. Sinuous patterns indicate shallow ephemeral stream environments. Rectilinear patterns indicate debris flow environments.

Fans consist of lenticular sheets of debris (length/width ratio generally 5 to 20) and abundant channel fills near the apex. Adjacent beds commonly vary greatly in particle size, sorting, and thickness. Beds extend for long distances along radial sections and channel deposits are rare. Cross-fan sections reveal beds of limited extent that are interrupted by cut-and-fill structures.

Three longitudinal shapes are common in cross section. A fan may be lenticular, or a wedge that is either thickest, or thinnest, near the mountains.

Ancient Alluvial-Fan Deposits

Some examples of ancient alluvial-fan deposits which have been reported from the United States, Canada, Norway, and the British Isles are summarized in Table 1, together with other types of alluvial deposits.

Braided-Stream Model of Clastic Sedimentation

Occurrence and General Characteristics

Braided streams occur throughout the world under a very wide range of physiographic and climatic conditions. They are common features on extensive alluvial plains which occupy a position in the clastic realm of sedimentation between the high-gradient alluvial-fan environment at the base of mountain ranges and the low-gradient meandering-stream model of sedimentation (downstream). In physiographic provinces characterized by mountainous areas adjacent to the sea, the braided-stream environment can extend directly to the coastline and thus constitute the predominant environment of alluvial deposition. In this type of situation, meandering streams do not exist (Fig. 7). The braided stream is also a common feature of glacial outwash plains associated with the fluvioglacial environment.

The braided-stream model is characterized by extremely variable rates of sedimentation in multiple-channel streams (Fig. 8), the patterns of which vary widely compared with meandering channels. Braided channels are usually wide and shallow; they contain numerous bars, are slightly sinuous or straight, and migrate at rapid rates. Stream gradients are high, are quite variable, and are less than those of alluvial fans but generally greater than those of meandering streams. Large fluctuations in discharge occurring over short periods of time are also common. The combination of steep gradients and high discharge rates results in the transporta-

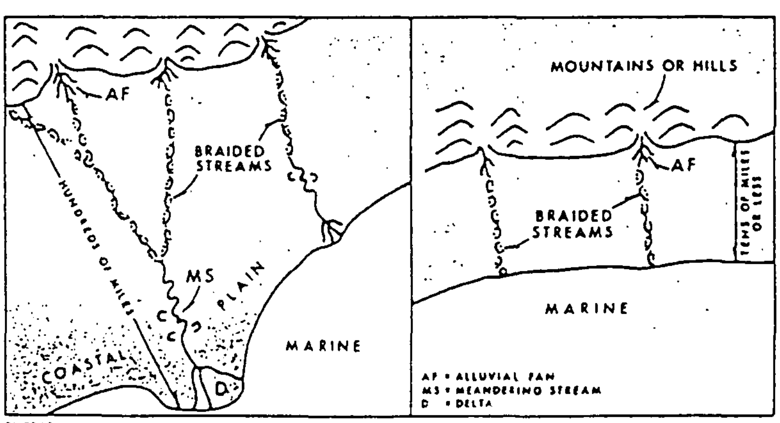

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Fig. 7—Braided-stream model of clastic sedimentation.

tion and deposition of large amounts of coarse material, ranging from boulders to sand. Braided-stream deposits overall are finer than those of alluvial fans, coarser than those of meandering streams, and quite varied in stratification.

Source, Transportation, and Deposition of Sediments

Aggrading braided streams transport very large quantities of clastic material derived from a variety of sources, such as outwash plains, alluvial fans, mountainous areas, and broad plains. Unlike that of meandering streams, the bulk of the sedimentary load of most braided streams is transported as bed load. Rates of sediment transport and deposition are extremely variable, the maximum rate occurring during severe floods of short duration. High-gradient upstream segments of braided streams close to source areas are characterized by deposition of poorly sorted clastic sediments which

Table 1. Examples of Ancient Alluvial-Fan, Braided-Stream, and Meandering-Stream Deposits

Alluvial Fan	*Braided Stream*	*Meandering Stream*	*Composite*	*Author*
Arizona			Arizona	Melton, 1965
California				Crowell, 1954
California			California	Flemal, 1967
			California	Galehouse, 1967
Colorado				Boggs, 1966
			Colorado	Bolyard, 1959
		Colorado		Brady, 1969
			Colo. Plateau	Finch, 1959
			Colo. Plateau	Stokes, 1961
Colorado				Howard, 1966
Colorado				Hubert, 1960
Connecticut Valley				Klein, 1968
		Illinois		Hewitt *et al.*, 1965
		Illinois		Shelton, 1972
			Kansas	Lins, 1950
		Kansas		Shelton, 1971
	Llano Estacado			Bretz & Horberg, 1949
	Maryland	Maryland		Hansen, 1969
Massachusetts				Wessel, 1969
Massachusetts				Stanley, 1968
			Massachusetts	Mutch, 1968
		Michigan		Shideler, 1969
		Montana		Gwinn, 1964
	Mississippi	Mississippi		Berg & Cook, 1968
Montana	Montana			Gwinn & Mutch, 1965
			Montana	Shelton, 1967
Montana				Wilson, 1967, 1970
Montana				Beaty, 1961
			Nebraska	Exum & Harms, 1968
			Nebraska	Harms, 1966
	New York	New York		Buttner, 1968
	New Jersey, New York			Smith, 1970; Shelton, 1972
			North Dakota	Royse, 1970
			Oklahoma	Visher, 1965b
		Pennsylvania		Beutner *et al.*, 1967
	Pennsylvania			Smith, 1970
		Pennsylvania		Ryan, 1965
			Rhode Island	Mutch, 1968
S.W. USA				Bull, 1972
			Texas	Fisher & McGowen, 1969
Texas				McGowen & Groat, 1971
		Texas		McGowen & Garner, 1965; Shelton, 1971
		West Virginia		Beerbower, 1964, 1969
		Wyoming		Berg, 1965
Wyoming	Wyoming			Spearing, 1969
			Alberta	Byers, 1966
			Quebec	Dineley & Williams, 1968
Northeastern Canada				Klein, 1962
		Nova Scotia		Way, 1968
Northwest Territories	Northwest Territories	Northwest Territories		Miall, 1970
		England		Allen, 1964; Laming, 1966
Wales and Scotland				Bluck, 1965, 1967
		South Wales		Kelling, 1968
Norway				Nilsen, 1969
	Scotland			Williams, 1966, 1969
	Spain			Nagtegaal, 1966
	Spitsbergen	Spitsbergen		Moody-Stuart, 1966
		New South Wales		Conolly, 1965

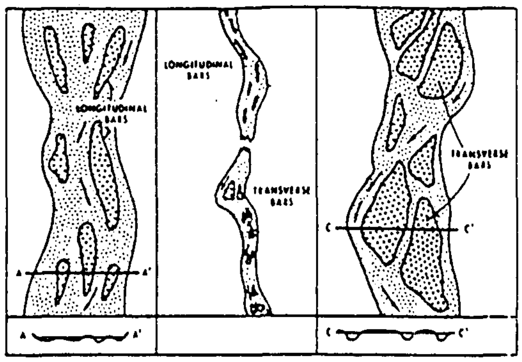

FIG. 8—Types of braided-stream channels and bars.

range in size from boulder to sand. Farther downstream, there is a gradual decrease in grain size and an increase in sorting.

The bed-load materials are transported under varying bed-form conditions, depending upon river stage. Coleman (1969) reported ripple and dune migration in the Brahmaputra River of Bangla Desh ranging from 100 ft to 2,000 ft (30–610 m) per day. Chein (1961) reported downstream movement of sandbars in the Yellow River of China to be as great as 180–360 ft (55–110 m) per day. (For comparison, the rate of bed-load movement in the meandering Mississippi is about 40 ft [12 m] per day.)

Process of channel division (braiding) by development of bars—The exact causes of channel division which results in the development of the braided pattern are not very well understood. Two methods in which channel division takes place have been described by Ore (1963) as follows:

> Leopold and Wolman (1957, p. 43–44), using results of both stream-table studies and observations of natural braided streams, discuss in some detail how channel division may take place. At any time, the stream is carrying coarser fractions along the channel center than at the margins, and due to some local hydraulic condition, part of the coarsest fraction is deposited. Finer material is, in part, trapped by coarser particles, initiating a central ridge in the channel. Progressive additions to the top and downstream end of the incipient bar build the surface toward water level. As progressively more water is forced into lateral channels beside the growing bar, the channels become unstable and widen. The bar may then emerge as an island due to downcutting in lateral channels, and eventually may become stabilized by vegetation. New bars may then form by the same process in lateral channels. These authors stress that braiding is not developed by the stream's inability to move the total quantity of sediment provided to it; as incapacity leads merely to aggradation without braiding. The condition requisite to braiding is that the stream cannot move certain sizes provided; that is, the stream is incompetent to transport the coarsest fraction furnished to a given reach. Observations for the present study substantiate the braiding process of Leopold and Wolman.
>
> Many features of streams, bars, and braided reaches result from changes in regimen (e.g., discharge, load, gradient), to a large extent representing seasonal fluctuations. Other features of bars result from normal evolution, and represent no change in regimen.
>
> The incipient longitudinal bar formed in a channel commonly has an asymmetric, downstream-pointing, crescentic shape. This coarse part is the "nucleus" of the bar, is coarser than successive additions to the downstream end, and largely retains its position and configuration as long as any part of the bar remains. During longitudinal bar evolution downstream of this incipient bar the water and its sediment load commonly sweep from one lateral channel diagonally across the downstream end of the bar, forming a wedge of sediment with an advancing front at its downstream edge. This wedge of sediment is higher at its downstream edge, both on the longitudinal bars described here, and where found as transverse bars to be considered later. The latter build up the channel floor, independent of longitudinal bar development, simply by moving downstream.
>
> After a certain evolutionary stage, bar height stops increasing because insufficient water for sediment transport is flowing over its surface, and deepening and widening of lateral channels slowly lower water level. From then on, the bar may be either stabilized by vegetation or dissected.
>
> Widening of a reach after bar deposition is in some cases associated with lateral dissection of the newly formed bar. Most erosion, however, apparently occurs on the outer channel margins. If water level remains essentially constant for long periods of time, lateral dissection may establish terraces along bar margins. A compound terrace effect may be established during falling water stages. The constant tendency of the stream to establish a cross-sectional profile of equilibrium is the basic cause of lateral cutting by the stream.
>
> Longitudinal bars which become awash during high-water stages may be dissected by small streams flowing transversely over their surfaces. In stream-table experiments, sediment added to a system eroding transverse channels on bar surfaces is first transported along lateral channels beside the bars. Eventually, these channels fill to an extent that sediment starts moving transversely over bar surfaces, and fills bar-top, transverse channels. The addition of sufficient sediment to fill lateral and bar-top channels often culminates in a transverse bar covering the whole bar surface evenly.
>
> Another process of braiding, in addition to that described by Leopold and Wolman, takes place in well sorted sediments, and involves dissection of transverse bars. This is in opposition to construction of longitudinal bars in poorly sorted sediment, the type of braiding discussed above. Both types may occur together geographically and temporally. During extended periods of high discharge, aggradation is by large tabular bodies of sediment with laterally sinuous fronts at the angle of repose migrating downstream. Stabilization of discharge or decrease in load after establishment of these transverse bars results in their dissection by anastomosing channels; bars in this case form as residual elements of the aggradational pattern.
>
> The transient nature of braided stream depositional surfaces is characteristic of the environment. The streams and depositional areas within the stream exhibit profound lateral-migration tendencies, especially during

periods of high discharge. Channel migration takes place on several scales. Individual channels erode laterally, removing previously deposited bars. They divide and coalesce, and several are usually flowing adjacent to one another concurrently within the main channel system. The whole channel system, composed of several flowing channels with bars between, also exhibits migrating tendencies.

Braided-stream deposits—Our knowledge of modern braided-stream deposits has increased substantially during the past several years as a result of studies of several rivers in Wyoming, Colorado, and Nebraska by Ore (1963, 1965); the Brahmaputra River of Bangla Desh (formerly East Pakistan) by Coleman (1969); the Platte River of Colorado and Nebraska by N. Smith (1970); the Red River of the Texas panhandle by Waechter (1970); the Canadian River of northwest Texas by Kessler (1970, 1971); and the Copper River of Alaska by Boothroyd (1970). These studies revealed that braided-stream deposits are laid down principally in channels as longitudinal bars and transverse bars. Abandoned-channel deposits (channel fills) have been reported by Doeglas (1962) and Williams and Rust (1969).

According to Ore (1963, 1965), longitudinal-bar deposits occur mainly in upstream channel segments and transverse bars are more common in downstream segments; however, in some places these two types of bars occur together (Fig. 8). Longitudinal-bar deposits are lens-shaped and elongated in the downstream direction. Grain size decreases downstream from coarse to fine in an individual bar; deposits are poorly sorted and mainly horizontally stratified but laterally discontinuous. Transverse-bar deposits occur as long thin wedges and are highly dissected by channels. The downstream edges of transverse bars migrate to produce planar cross-stratification and some festoon crossbedding. Sediments of transverse bars are generally finer and better sorted than those of longitudinal bars.

N. Smith (1970) described some very significant relations between types of bars, stratification, and grain size in the Platte River. In the upstream segment in Colorado, the deposits consist mainly of longitudinal bars characterized by low-relief stratification, generally horizontally bedded but including some festoon crossbedding. The downstream channel segment in Nebraska is characterized by transverse-bar deposits consisting of better sorted, fine-grained sand with abundant tabular cross-stratification and some festoon crossbedding.

The Red River braided-stream sediments of West Texas consist of longitudinal-bar deposits with low-angle or horizontal stratification; they are deposited during waning flood stages (Waechter, 1970). Low-river-stage deposits consist mainly of migrating transverse-bar deposits (in channels) with tabular cross-stratification and some festoon crossbedding. The migration of very shallow channels results in stratification sets that are horizontal, tabular or lenticular, and laterally discontinuous.

Kessler (1970) reported longitudinal-bar deposits consisting mainly of fine sand in upstream reaches of the Canadian River in West Texas. Transverse-bar deposits are predominant in the downstream part of the area studied. Kessler (1971) also discussed individual flood sequences of deposits which contain parallel bedding and tabular and small-ripple cross-laminations. These sequences are covered by clay drapes and are laterally discontinuous.

Coleman (1969) presented the results of a significant study of one of the largest braided rivers of the world, the Brahmaputra in Bangla Desh. This river is 2–6 mi (3–9.5 km) wide and migrates laterally as much as 2,600 ft (790 m) per year; deposition of sediments in its channels during a single flood occurs in a definite sequence of change, ranging from ripples up to 5 ft (1.5 m) high that migrate downstream 400 ft (120 m) per day to sand waves 50 ft (15 m) high that migrate up to 2,000 ft (610 m) per day.

Williams and Rust (1969) presented results of a very detailed study of a 4-mi (6.5 km) segment of a degrading braided stream, the Donjek River of the Yukon Territory, Canada. They divided the bar and channel deposits, which range from coarse gravels to clays, into seven facies. Ninety-five percent of the bar deposits are of the longitudinal type and consist of gravel, sand, and some finer sediments. Abandoned-channel deposits consist of gradational sequences of gravels, sand, and clays that become finer upward.

Summary: Braided-Stream Deposits

Most of the sediments of modern braided streams studied during the past decade have been referred to by authors as transverse- or longitudinal-bar deposits. These sediments were deposited within braided channels during varying discharge conditions ranging from low water to flood stage. Thus, all longitudinal and transverse bars should be considered as a special type of bed form occurring within active braided channels.

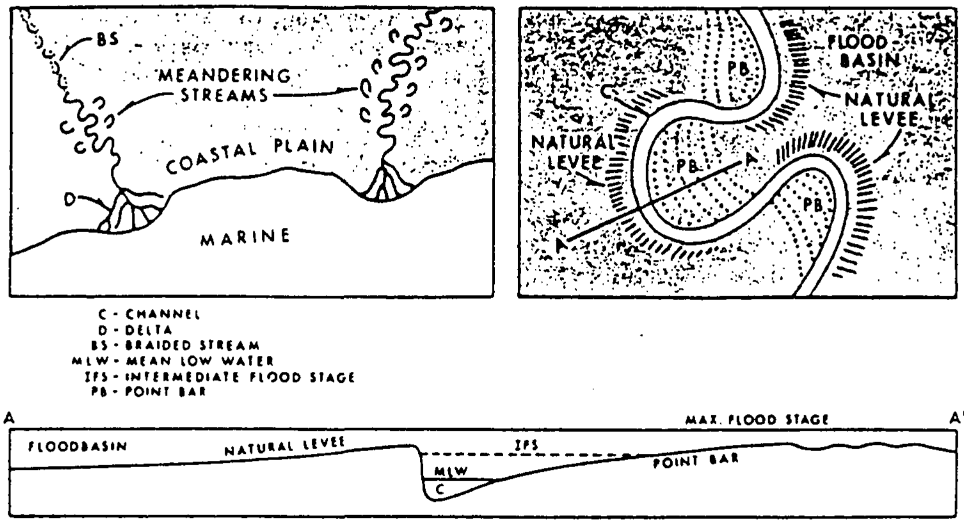

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FIG. 9—Setting and general characteristics of meandering-stream model of clastic sedimentation.

Studies by Doeglas (1962) and Williams and Rust (1969) are significant because they describe abandoned-channel deposits. Doeglas discussed the methods of channel abandonment and described the channel-fill deposits as coarse grained, with channel or festoon laminations, in the upstream portions of abandoned channels, and as fine grained, silty, and rippled in the downstream portions of abandoned channels.

Ancient Braided-Stream Deposits

Some examples of ancient braided-stream deposits which have been reported from the United States, Spitsbergen, and Spain are summarized in Table 1.

Meandering-Stream Model of Clastic Sedimentation

Occurrence and General Characteristics

Meandering streams generally occur in coastal-plain areas updip from deltas and downdip from the braided streams. The axis of sedimentation is usually perpendicular to the shoreline (Fig. 9).

This model is characterized by a single-channel stream which is deeper than the multichannel braided stream. Meandering streams usually have a wide range in discharge (cu ft/sec) which varies from extended periods of low-water flow to flood stages of shorter duration. Flooding can occur one or more times per year and major flooding once every several years. The meandering channel is flanked by natural levees and point bars, and it migrates within a zone (meander belt) about 15 to 20 times the channel width. Channel segments are abandoned and filled with fines as new channels develop.

Source, Transportation, and Deposition of Sediments

Sediments are derived from whatever type of deposit occurs in the drainage area. Clays and fine silts are transported in suspension (suspended load), and coarser sediments such as sand, gravel, and pebbles are transported as bed load. Sediment transport and deposition during extended low-water stages are confined to the channel and can be nil or very slow. Maximum sediment transport occurs during rising flood stage when the bed of the channel is scoured.

The maximum rate of sediment deposition occurs during falling flood stages. Grain size depends on the type of sediment available to the channel; the coarsest sediments are deposited in the deepest part of the channel, and the finest sediments accumulate in floodbasins and in some parts of the abandoned channels.

Channel migration and deposition of point-bar sediments—The most important processes of sedimentation in the meandering-stream model are related to channel migration which occurs as a result of bank caving and point-bar accretion (Fig. 10). The process of bank caving occurs most rapidly during falling flood

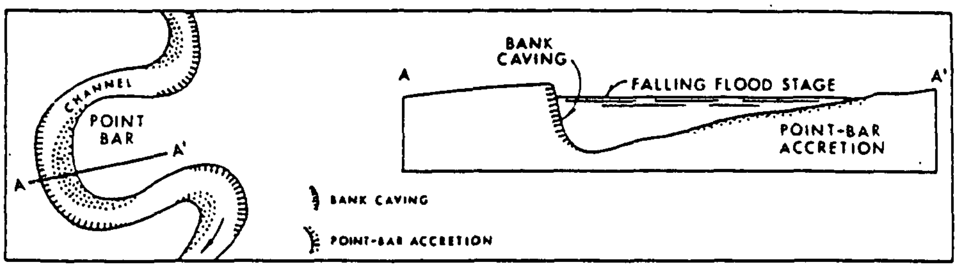

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FIG. 10—Areas of bank caving and point-bar accretion along a meandering channel.

stage, when currents of maximum velocities are directed against the concave bank. Bank caving occurs at maximum rates in bends where the bed and bank materials are very sandy. Rates are much slower in areas where banks are characterized by clayey sediments (Fisk, 1947).

Deposition occurs on the convex bar (point bar) simultaneously with bank caving on the concave bank.

Bank caving and point-bar accretion result in channel migration and the development of the point-bar sequence of sediments (Fig. 11). The point bar is probably the most common and significant environment of sand deposition. The thickness of this sequence is governed by channel depths. Point-bar sequences along the Mississippi River attain thicknesses in excess of 150 ft (45 m). Medium-size rivers like the Brazos of Texas produce point-bar sequences that are 50 ft (15 m) thick (Bernard *et al.*, 1970).

Channel diversions and filling of abandoned channels—The process of channel diversion and channel abandonment is another characteristic feature of meandering streams. There are two basic types of diversion and abandonment: (1) the neck or chute cutoff of a single meander loop and (2) the abandonment of a long channel segment as a result of a major stream diversion (Fisk, 1947).

Meander loops which are abandoned as a result of neck or chute cutoffs become filled with sediment (Fig. 12A). The character of the channel fill depends on the orientation of the abandoned loop with respect to the direction of flow in the new channel. Meanders oriented with their cutoff ends pointing downstream (Fig. 12B) are filled predominantly with clays (clay plugs); those oriented with the cutoff ends pointing upstream are filled principally with sands and silts.

A major channel diversion is one which results in the abandonment of a long channel segment or meander belt, as shown in Figure 13. Channeling of flood water in a topographically low place along the bank of the active channel can rapidly erode unconsolidated sediments and create a new channel. This process can happen during a single flood or as a result of several floods. The newly established channel has a gradient advantage across the topographically lower floodbasin. A diversion can occur at any point along the channel.

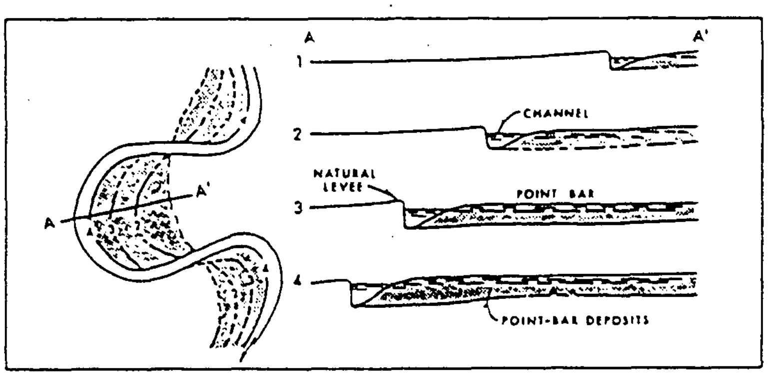

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FIG. 11—Development of point-bar sequence of sediments.

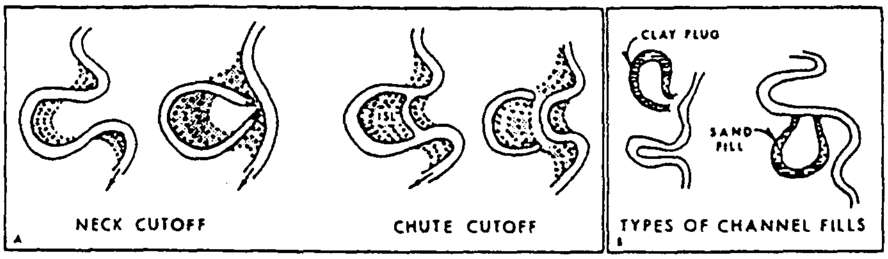

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FIG. 12—Channel diversion, abandonment, and filling as a result of neck and chute cutoffs.

The character of the sediments which fill long channel segments is governed by the manner of channel diversion. Abrupt abandonment (during a single flood or a few floods) results in the very rapid filling of only the upstream end of the old channel, thus creating a long sinuous lake. These long, abandoned channels (lakes) fill very slowly with clays and silts transported by flood waters (Fig. 14, left).

Gradual channel abandonment (over a long period) results in very gradual channel deterioration. Diminishing flow transports and deposits progressively smaller amounts of finer sands and silts (Fig. 14, right).

Summary: Characteristics of Meander-Belt and Floodbasin Deposits

The meandering-stream model of sedimentation is characterized by four types of sediments: the point bar, abandoned channel, natural levee, and floodbasin. The nature of each of these four types of sediments and their interrelations are summarized in Figure 15.

Only two main types of sand bodies are associated with a meandering stream: the point-bar sands and the abandoned-channel fills. The former, which are much more abundant than the latter, occur in the lower portion of the point-bar sequence and constitute at least 75 percent of the sand deposited by a meandering stream. Coalescing point-bar sands can actually form a "blanketlike" sand body of very large regional extent. The continuity of sand is interrupted only by the "clay plugs" which occur in abandoned meander loops or in the last channel position of meander belts which have been abandoned abruptly.

Examples of ancient alluvial deposits of meandering-stream origin which have been reported in the literature are summarized in Table 1.

Deltaic Models of Clastic Sedimentation

Occurrence and General Characteristics

Deltaic sedimentation occurs in the transitional zone between continental and marine (or inland seas and lakes) realms of deposition. Deltas are formed under subaerial and subaqueous conditions by a combination of fluvial and marine processes which prevail in an area where a fluvial system introduces land-derived sediments into a standing body of water.

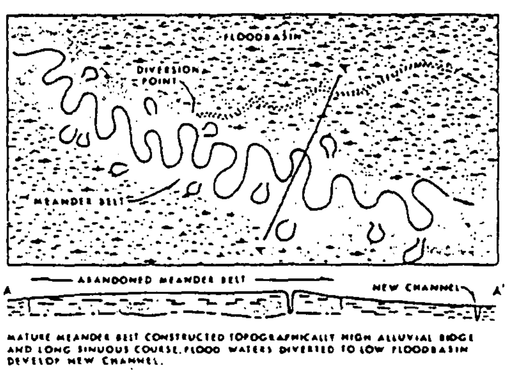

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FIG. 13—Major channel diversion and abandonment of a meander belt.

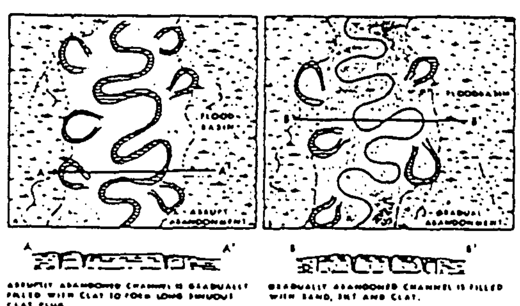

FIG. 14—Variations in character of abandoned channel fill typical of meander belts.

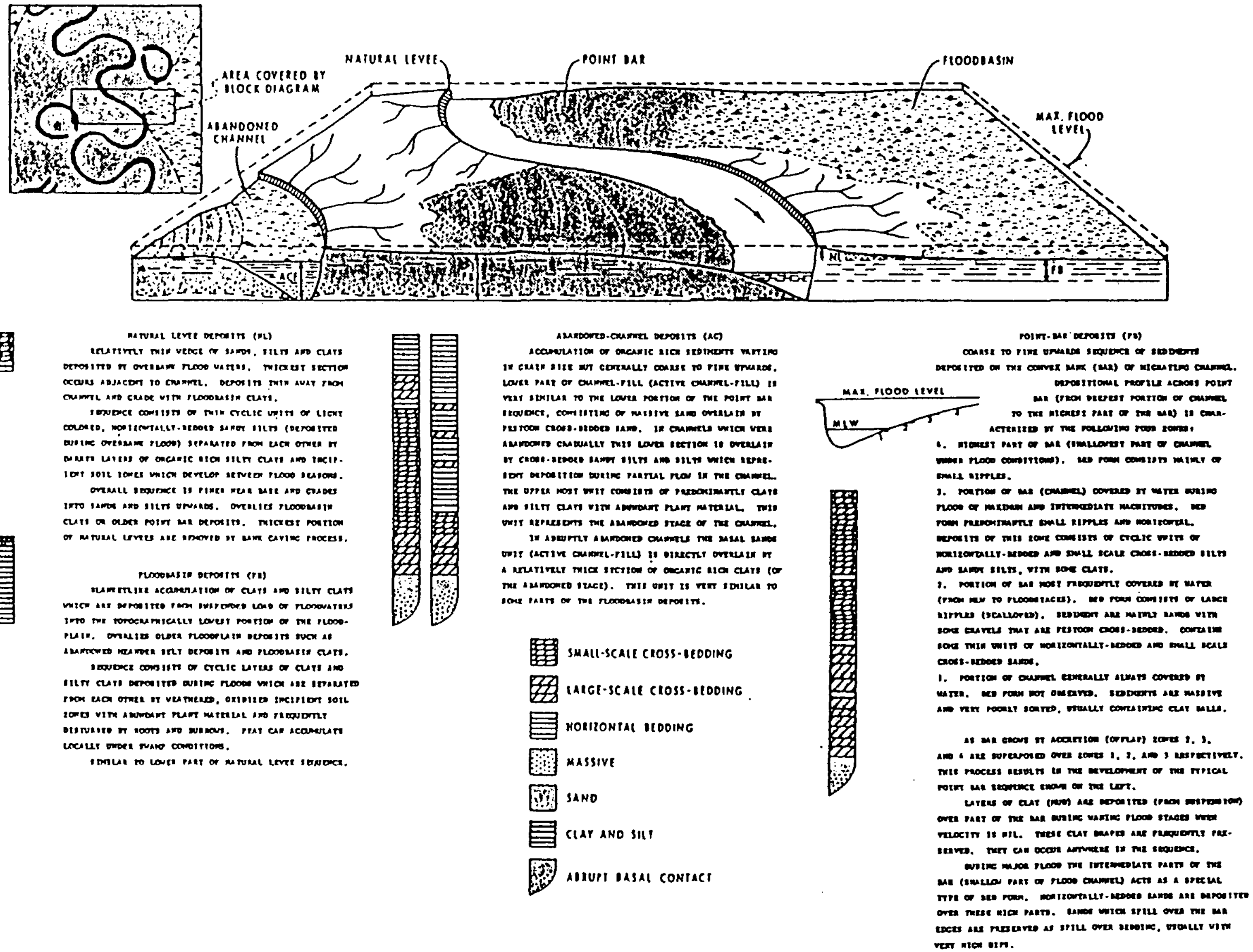

FIG. 15—Characteristics of meander-belt and floodplain deposits.

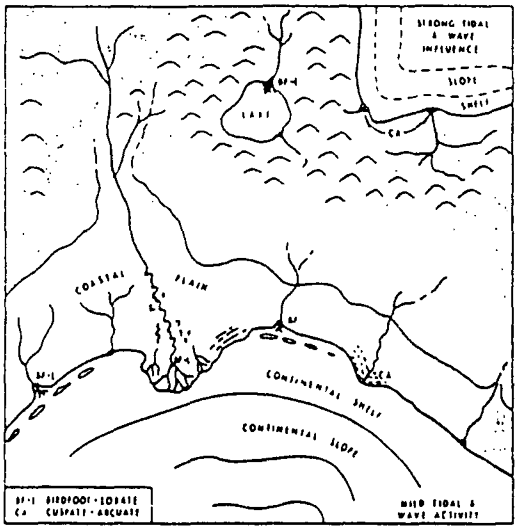

FIG. 16—Occurrence of deltaic models of clastic sedimentation.

Large deltas usually are associated with extensive coastal plains; however, all coastal plains do not include large deltas. The deltaic environment occurs downstream from the meandering-stream environment and is directly adjacent to, and updip (landward) from, the marine environment; it is flanked by the coastal-interdeltaic environment. Most large deltas occur on the margins of marine basins, but smaller deltas also form in inland lakes, seas, and coastal lagoons and estuaries (Fig. 16).

That portion of a delta which is constructed under subaerial conditions is called the "deltaic plain"; that portion which forms under water is called the "delta front," "delta platform," and "prodelta." The bulk of the deltaic mass is deposited under water.

Deltas are considered to be extremely important because they are the sites of deposition of sand much father downdip than the interdeltaic environment, as well as being the sites where clastic deposition occurred at maximum rates.

Source and Transportation of Sediments

Sediments deposited in large deltas are derived from extensive continental regions which are usually composed of rock types of varied compositions and geologic ages. Thus, the composition of deltaic sediments can be quite varied.

The sediment load of rivers consists of two parts: (1) the clays and fine silts transported in suspension and (2) the coarser silts and sands, and in some cases gravels, transported as bed load. The ratio of suspended load to bed load varies considerably, depending upon the rock types and climatic conditions of the sediment-source areas. The suspended load is generally much greater than the bed load.

The transportation of sediment to a delta is an intermittent process. Most rivers transport the bulk of their sediments during flood stages. During extended periods of low discharge, rivers contribute very little sediment to their deltas.

The extent to which deltaic sediments are dispersed into the marine environment is dependent upon the magnitude of the marine processes during the period that a river is in flood stage. Maximum sediment dispersal occurs when a river with a large suspended load reaches flood stage at the time the marine environment is most active (season of maximum currents and wave action). Minimum dispersal occurs when a river with a small suspended load (high bed load) reaches flood stage at a time when the marine environment is relatively calm.

Size of deltas—There is an extremely wide range in the size of deltas;[4] modern deltas range in area from less than 1 sq mi (2.6 sq km) to several hundreds of square miles. Some large deltaic-plain complexes are several thousand square miles in area. Delta size is dependent upon several factors, but the three most important are the sediment load of the river; the intensity of marine currents, waves, and tides; and the rate of subsidence. For a given rate of subsidence, the ideal condition for the construction of a large delta is the sudden large influx of sediments in a calm body of water with a small tidal range. An equally large sediment influx into a highly disturbed body of water with a high tidal range results in the formation of a smaller delta, because a large amount of sediment is dispersed beyond the limits of what can reasonably be recognized as a delta. Rapid subsidence enhances the possibility for a large fluvial system to construct a large delta.

Types of deltas—A study of modern deltas of the world reveals numerous types. Bernard

[4] Published figures on areal extent of deltas are based on size of the deltaic plain and do not include submerged portions of the delta, which in many cases are as large as or larger than the deltaic plains.

(1965) summarized some of the factors which control delta types as follows:

> Deltas and deltaic sediments are produced by the rapid deposition of stream-borne materials in relatively still-standing bodies of water. Notwithstanding the effects of subsidence and water level movements, most deltaic sediments are deposited off the delta shoreline in the proximity of the river's mouth. As these materials build upward to the level of the still-standing body of water, the remainder of deltaic sediments are deposited onshore, within the delta's flood plains, lakes, bays, and channels.
>
> Nearly 2,500 years ago, Herodotus, using the Nile as an example, stated that the land area reclaimed from the sea by deposition of river sediments is generally deltoid in shape. The buildup and progradation of deltaic sediments produces a distinct change in stream gradient from the fluvial or alluvial plain to the deltaic plain. Near the point of gradient change the major courses of rivers generally begin to transport much finer materials, to bifurcate into major distributaries, and to form subaerial deltaic plains. The boundaries of the subaerial plain of an individual delta are the lateral-most distributaries, including their related sediments, and the coast line. Successively smaller distributaries form sub-deltas of progressively smaller magnitudes.
>
> Deltas may be classified on the basis of the nature of their associated water bodies, such as lake, bay, inland sea, and marine deltas. Other classifications may be based on the depth of the water bodies into which they prograde, or on basin structure.
>
> Many delta types have been described previously. Most of these have been related to the vicissitudes of sedimentary processes by which they form. Names were derived largely from the shapes of the delta shorelines. The configuration of the delta shores and many other depositional forms expressed by different sedimentary facies appear to be directly proportional to the relative relationship of the amount or rate of river sediment influx with the nature and energy of the coastal processes. The more common and better understood types, listed in order of decreasing sediment influx and increasing energy of coastal processes (waves, currents, and tides), are: birdfoot, lobate, cuspate, arcuate, and estuarine. The subdeltas of the Colorado River in Texas illustrate this relationship. During the first part of this century, the river, transporting approximately the same yearly load, built a birdfoot-lobate type delta in Matagorda Bay, a low-energy water body, and began to form a cuspate delta in the Gulf of Mexico, a comparatively high-energy water body. Many deltas are compounded; their subdeltas may be representative of two or more types of deltas, such as birdfoot, lobate, and arcuate. Less-known deltas, such as the Irrawaddy, Ganges, and Mekong, are probably mature estuarine types. Others, located very near major scarps, are referred to the "Gilbert type," which is similar to an alluvial fan.

Additional studies of modern deltas are required before a more suitable classification of delta types can be established. J. M. Coleman (personal commun.) and his associates, together with the Coastal Studies Institute at Louisiana State University, are presently conducting a comprehensive investigation of more than 40 modern deltas. Results of their studies undoubtedly will be a significant contribution toward the solution to this problem.

Only three types of deltas will be considered in this report: the birdfoot-lobate, the cuspate-arcuate, and the estuarine.

Sedimentary Processes and Deposits of the Birdfoot-Type Delta

The processes of sedimentation within a delta are much more complex and variable than those which occur in the meandering-stream and coastal-interdeltaic environment of sedimentation. It is impossible to discuss these deltaic processes in detail in a short summary paper such as this; therefore, only a brief summary of the following significant processes is presented.

1. Dispersal of sediment in the submerged parts of the delta (from river mouths seaward);
2. Formation of rivermouth bars, processes of channel bifurcation, and development of distributary channels;
3. Seaward progradation of delta, deposition of the deltaic sequence of sediments, and abandonment and filling of distributary channels; and
4. Major river diversions, abandonment of deltas, and development of new deltas.

Dispersal and deposition of sediments—Riverborne sediments which are introduced in a standing body of water (a marine body or inland lakes and seas) are transported in suspension (clays and fine silts) and as bed load (coarse silts, sands, and coarser sediments). Most of the sands and coarse silts are deposited in the immediate delta-front environment as rivermouth bars and slightly beyond the bar-front zone. The degree of sand dispersal is, of course, controlled by the level of marine energy; however, in most birdfoot deltas, sands are not transported beyond 50-ft (15 m) water depths. Fisk (1955) referred to the sands deposited around the margins of the subaerial deltaic plain as "delta-front sands," and they are called "delta-fringe sands" herein.

The finer sediments (clays and fine silts), which are transported in suspension, are dispersed over a much broader area than the fringe sands and silts. The degree of dispersal is governed by current intensity and behavior. Accumulations of clays seaward of the delta-fringe sands are referred to as "prodelta" or "distal clays" (Fig. 17).

Channel bifurcation and development of distributary channels—Some of the most significant deltaic processes are those which result in the origin and development of distributary

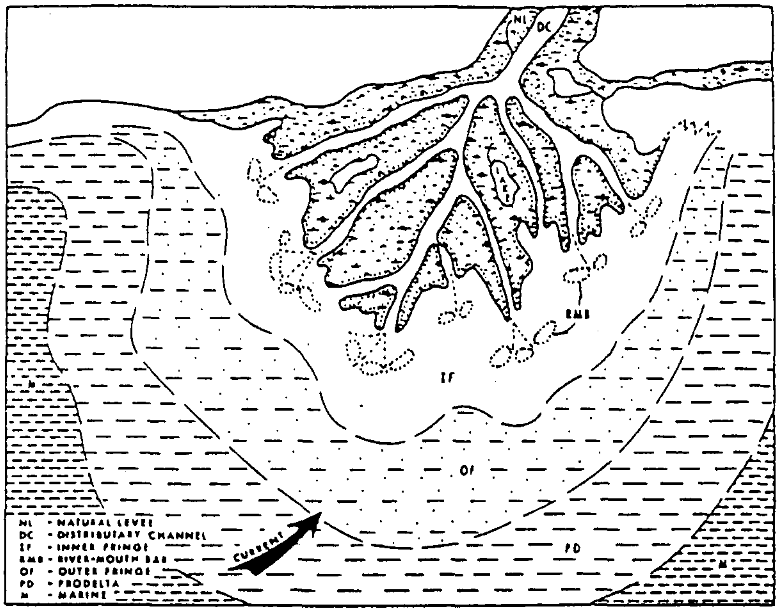

FIG. 17—Distribution of distributary-channel and fringe sands in a birdfoot-lobate delta.

channels. Welder (1959) conducted a detailed study of these processes in a part of the Mississippi delta, and Russell (1967a) summarized the origin of branching channels, as follows:

The creation of branching channels is determined by the fact that threads of maximum turbulence and turbulent interchange (Austausch; 1.2.3; 3.5) lie deep and well toward the sides of channels, particularly if they have flat beds (typical of clay and fine sediments in many delta regions). These threads are associated with maximum scour and from them, sediment is expelled toward areas of less turbulence and Austausch. Significant load is propelled toward mid-channel, where shoals are most likely to form.

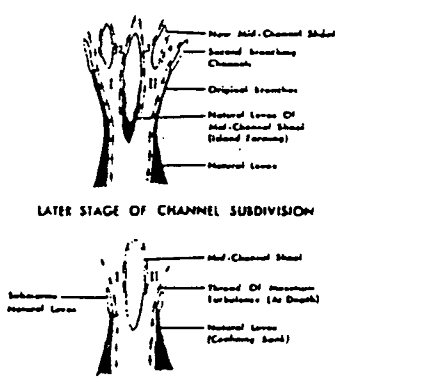

FIG. 18—Stages in development of channel bifurcation. After Russell (1967).

At its mouth, the current of a delta channel continues forward (as a result of momentum) and creates *jet flow* into the lake or sea it enters. After leaving the confinement imposed by fixed banks, however, the current flares marginally to some extent (widening the jet, reducing its velocity, and eventually dissipating its flow energy). Near the termination of confining banks the jet flow is concentrated and moves ahead into relatively quiet water. With flaring of jet flow comes an increase in spacing between threads of most intense turbulence and exchange. There is a tendency toward scour below each thread, but the exchange process sends most of the entrained material toward marginal quiet water on both sides (Fig. 8 [Fig. 18 of this paper]). Deposition creates a submarine natural levee on the outer side of each thread. Sediment is also attracted toward and deposited in the widening area of mid-channel water, where it builds a shoal. The channel divides around the shoal, creating two distributaries, each of which develops its own marginal threads of maximum turbulence, perpetuating conditions for other divisions below each new channel mouth. If not opposed by wave erosion and longshore currents, the subdivision continues in geometric progression (2, 4, 8, 16, etc.) as the delta deposit grows forward.

The marginal natural levees are submarine features at first and fish may swim across their crests. Later they grow upward, and for awhile become areas where logs and other flotsam accumulate and where birds walk with talons hardly submerged. Salt- or fresh-water-tolerant grasses invade the shallow water and newly created land, first along levee crests, later to widen as the levees grow larger. Salicornia and other plants become established pioneer trees such as willows, and eventually in the plant succession comes the whole complex characteristic of natural levees upstream. In tropical areas mangroves are likely to become the dominant trees.

A similar conversion exists in mid-channel, where the original shoal becomes land and either develops into a lenticular or irregular island or becomes the point of land at the head of two branching distributaries.

Progradation of delta and deposition of deltaic sequence—Fisk's discussion of the process of distributary-channel lengthening (progradation of delta seaward) is probably one of the most significant of his many contributions on deltaic sedimentation (Fisk, 1958). His description of this important aspect of delta development is presented below. (Stages in the development of a birdfoot-type delta are shown in Figure 19.)

Each of the pre-modern Mississippi River courses was initiated by an upstream diversion, similar to the one presently affecting the Mississippi as the Atchafalaya River enlarges (Fisk, 1952). Stream capture was a gradual process involving increasing flow through a diversional arm which offered a gradient advantage to the gulf. After capture was effected, each new course lengthened seaward by building a shallow-water delta and extending it gulfward. Successive stages in course lengthening are shown diagrammatically on Figure 2 [Fig. 19, this paper]. The onshore portion of the delta surface . . . is composed of distributaries which are flanked by low natural levees, and interdistributary troughs holding near-sea-level marshes and shallow water bodies. Channels of the principal distributaries extend for some distance across the gently sloping offshore surface of the delta to the inner margin of the steeper delta front where the distributary-mouth bars are situated. The offshore channels are bordered by submarine levees which rise slightly above the offshore extensions of the interdistributary troughs.

In the process of course lengthening, the river occupies a succession of distributaries, each of which is favorably aligned to receive increasing flow from upstream. . . . The favored distributary gradually widens and deepens to become the main stream . . . ; its natural levees increase in height and width and adjacent interdistributary troughs fill, permitting marshland development. Levees along the main channel are built largely during floodstage; along the distal ends of distributaries, however, levee construction is facilitated by crevasses . . . which breach the low levees and permit water and sediment to be discharged into adjacent troughs during intermediate river stages as well as during floodstage. Abnormally wide sections of the levee and of adjacent mudflats and marshes are created in this manner, and some of the crevasses continue to remain open and serve as minor distributaries while the levees increase in height. Crevasses also occur along the main stream during floodstages . . . and permit tongues of sediment to extend into the swamps and marshes for considerable distances beyond the normal toe position of the levee.

Distributaries with less favorable alignment are abandoned during the course-lengthening process, and their channels are filled with sandy sediment. Abandoned distributaries associated with the development of the present course below New Orleans vein the marshlands. . . . Above the birdfoot delta, the pattern is similar to that of the older courses . . . ; numerous long, branching distributaries diverge at a low angle.

Stream diversions, abandonment of deltas, and development of new deltas—Deltas prograde seaward but they do not migrate laterally, as a point bar does, for example. A delta *shifts position* laterally if a major stream diversion occurs upstream in the alluvial environment or in the upper deltaic-plain region (Fig. 20). Channel diversions were discussed in the section on the meandering-stream model.

Deltas, like meander belts, can be abandoned abruptly or gradually, depending upon the time required for channel diversion to occur. Once a delta is completely abandoned, all processes of deltaic sedimentation cease to exist in that particular delta. With a standing sea level, the sediments of the abandoned delta compact, and subsidence probably continues. The net result is the encroachment of the marine environment over the abandoned delta. This process has erroneously been referred to by some authors as "the destructive phase of deltaic sedimentation." The author maintains that the proper terminology for this process is "transgressive marine sedimentation." The two processes and their related sediments are significantly different, as the discussion of the transgressive marine model of sedimentation demonstrates (see the succeeding section on this model).

As the marine environment advances landward over an abandoned subaqueous delta front and the margins of the deltaic plain, the upper portion of the deltaic sequence of sediment is removed by wave action. The amount of sediment removed depends on the inland extent of the transgression and on the rate of subsidence. The front of the transgression is usually characterized by deposition of thin marine sand units. Seaward, sediments become finer and grade into clays. Thus, local marine transgressions which occur because of delta shifts result in the deposition of a very distinctive marine sedimentary sequence which is easily distinguished from the underlying deltaic sequence.

Concurrent with marine transgression over an abandoned delta, a new delta will develop on the flanks of the abandoned delta. Sedimentary processes in the new delta are similar to those described under the discussion of progradation of deltas.

Repeated occurrences of river diversions result in the deposition of several discrete deltaic masses which are separated by thin transgressive marine sequences (Fig. 20). Under ideal conditions, deltaic facies can attain thicknesses

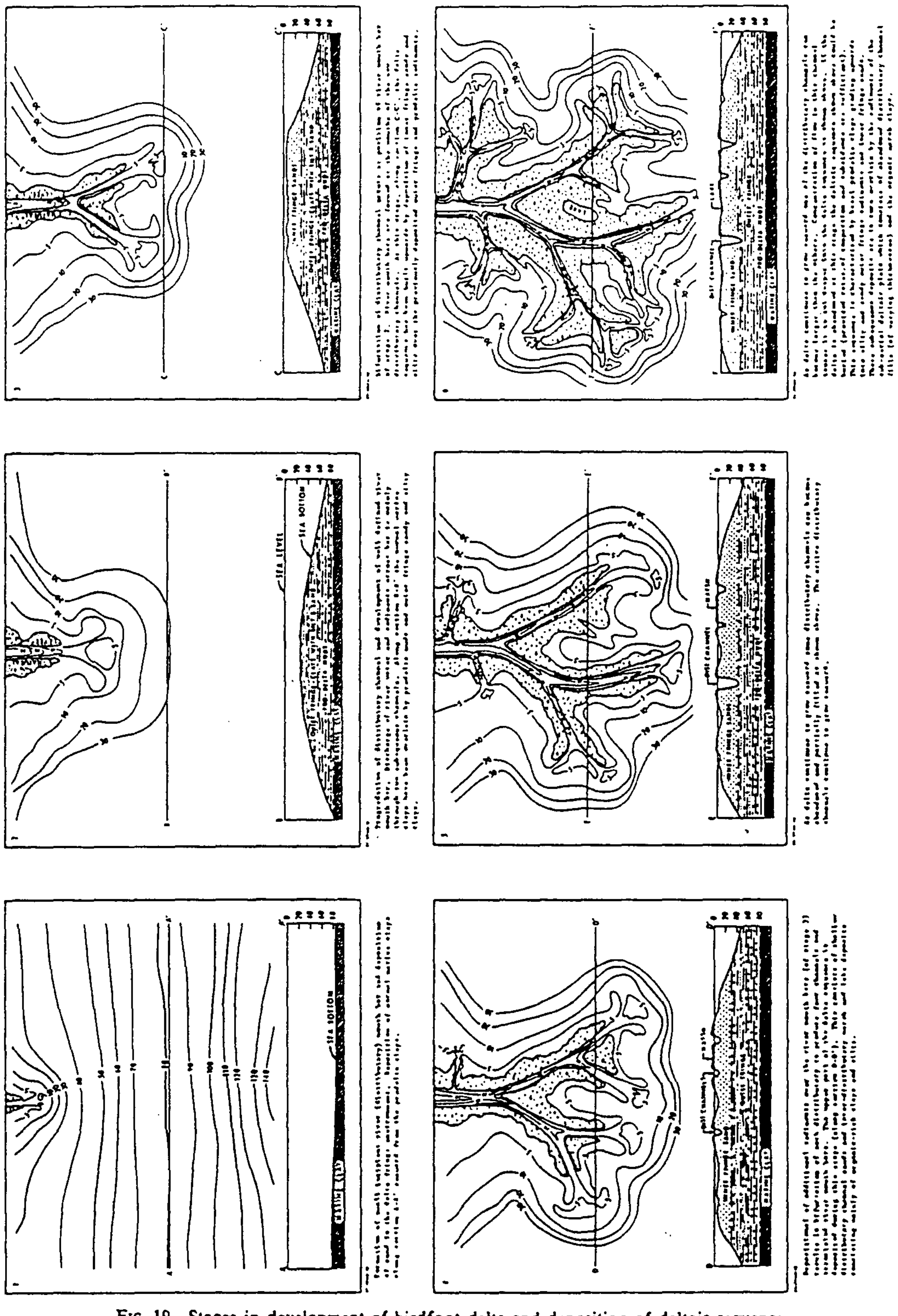

Fig. 19—Stages in development of birdfoot delta and deposition of deltaic sequence.

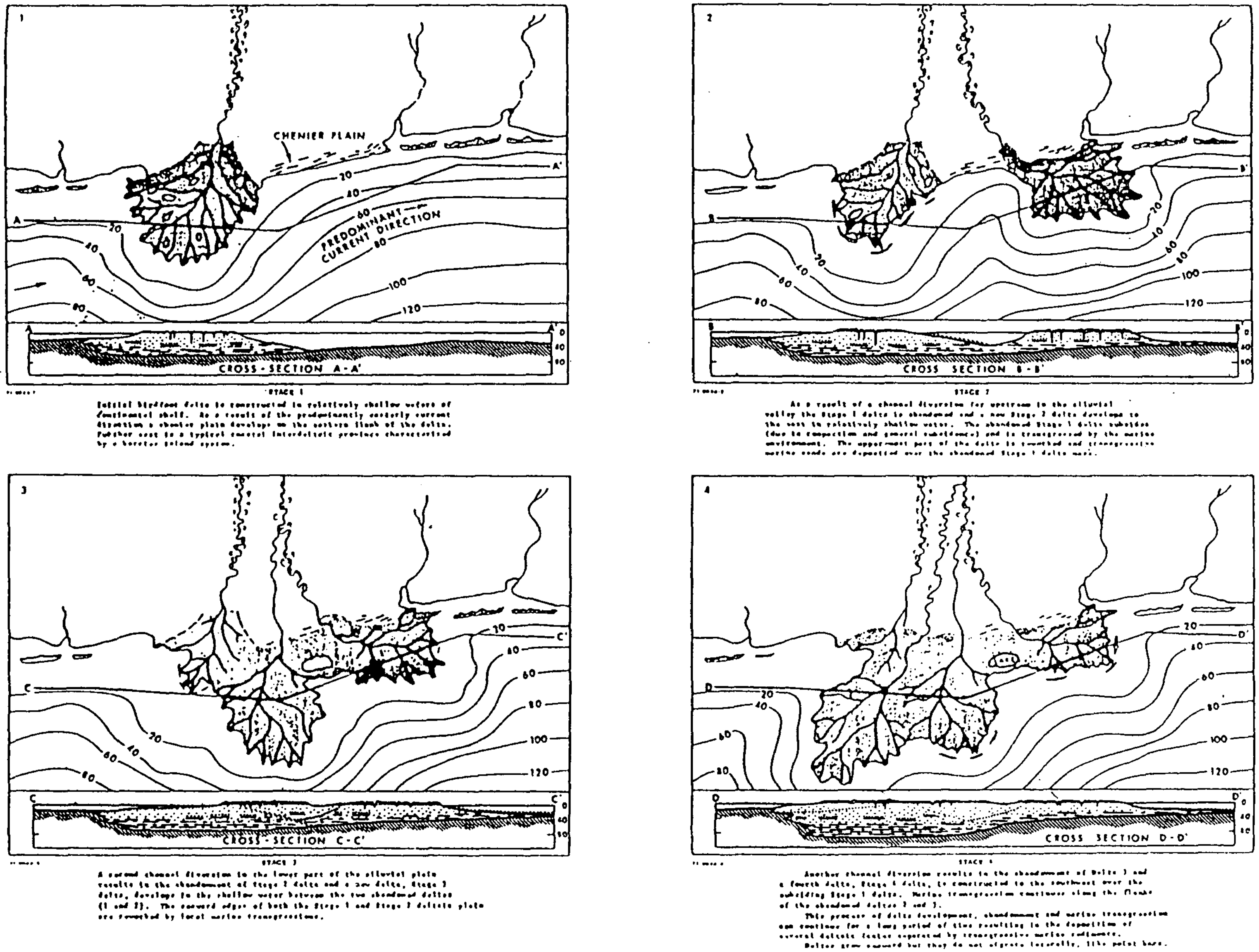

FIG. 20—Stages in development of a deltaic-plain complex and related deltaic facies.

of several hundreds of feet in a large sedimentary basin.

Sedimentary Processes and Deposits of the Cuspate-Arcuate Type of Delta

The shape of a delta is controlled by the influence of marine processes which are active against the delta front (Table 2). Russell (1967a) presented the following excellent summary of the modification of deltas by marine processes.

> The depositional processes characteristic of river mouths are opposed by marine processes that work toward removal of deposits. In a quiet sea or lake the geometric increase in number of distributaries is most closely approached. Below the most inland and earliest forking of the river, the delta builds out as a fan-shaped accumulation, with distributaries creating ribs with natural levees separating basins that widen and open toward the sea. The point deserving greatest emphasis is that the entire delta system originates underwater and only later becomes features visible as land.
>
> The ideal delta front is *arcuate* or has a *bird-foot* shape as viewed from the air or indicated on a chart. The latter pattern indicates a condition in which the deposition of load is dominant over the efforts of marine processes. It results from the forward growth of natural levees and the inability of longshore currents to carry away sediment about as rapidly as it is brought to the river mouth. The delta of the Mississippi is the largest and most typically cited example. Some talons of the foot extend out more than 20 miles and the basins between natural levees flank V-shaped marshes and bays up to about 1.5 fathoms deep. Many smaller bird-foot deltas occur in lakes and estuaries, where there is relatively little distance for fetch to generate high waves and where there are only feeble longshore currents.
>
> The arcuate-front deltas, such as those of the Nile and Niger, indicate sufficient wave action and removal of sediment by longshore currents to maintain relatively stable, smooth fronts. In some cases the momentum of jet flow is apparently sufficient to prevent much flaring, and a single pair of natural levees advances seaward to form a *cuspate* delta front, localized along a single channel. The Tiber, Italy, is the commonly cited example. The Sakayra River, on the Black Sea coast of Turkey has such a delta, but the reason is dominance of wave action. Ahead of it is a large area of shoal water with an extremely irregular system of channels and natural levees (changing so rapidly that a pilot keeps daily watch over them in order to guide boats back to the river mouth). Levees are prevented from growing up to sea level because wave erosion keeps them planed off to a depth of a few feet and because longshore currents entrain and transport sediment away effectively enough to prevent seaward growth of land area. This leaves but one channel mouth in a central position as a gently protruding single cusp.

The modern Brazos River delta of Texas (constructed since 1929) is a good example of a small modern arcuate delta which has been strongly influenced by marine processes. Bernard *et al.* (1970) discussed this small delta and its vertical sequence of sediments. Stages in the development of this type of delta are shown in Figure 21.

The modern Niger delta of western Africa is a classic example of a large arcuate-type delta that is highly influenced by marine processes and tidal currents. Allen (1965c, 1970) described the environments, processes, and sedimentary sequences of this interesting delta. On the basis of data presented by Allen, it is obvious that, although there are many similarities between the Niger delta and the birdfoot-type Mississippi delta, there are certainly some significant differences. For example, from the standpoint of sand bodies, the characteristics and geometry of the delta-fringe sands of the Niger are considerably different from those of the Mississippi. As indicated on Figure 22, a very large quantity of the sand that is contributed to rivermouth bars by the Niger is transported landward and deposited on the front of the deltaic plain as prominent beach ridges (this is a special form of delta-fringe sand according to the writer's deltaic classification). This process results in the development of a thick body of clean sands along the entire front of the deltaic plain.

Another important difference between the Niger and the Mississippi is the occurrence of a very extensive tidal-marsh and swamp environment on the Niger deltaic plain behind (landward of) the prominent beach ridges. This environment is characterized by a network of numerous small channels which connect with the main distributary channels. These channels, which are influenced by a wide tidal range, migrate rather freely and become abandoned to produce extensive point-bar deposits and many abandoned channel fills. In contrast, the Mississippi River distributary channels migrate very little and, hence, point-bar sands constitute only a small percentage of the deltaic deposits.

In summary, the Niger arcuate delta is characterized by prominent delta-fringe sands (which include the beach-ridge sands) occurring as a narrow belt along the entire front of the deltaic plain. Point-bar sand bodies are very common directly adjacent to and landward of the delta-fringe sands. The combination of high-level marine energy and strong tidal currents results in development of a relatively large quantity of distributary and point-bar (migrating channels) sands.

Table 2. Factors Which Influence Characteristics of Deltaic Deposits

Characteristics of Deltaic Deposits		Factors Which Influence Deltaic Sedimentation						
		Magnitude of Fluvial Processes (Sediment Influx)	Magnitude of Marine Processes (Wave Energy, Range in Tide & Currents)	Depth of Water	Subsidence Rate	Sea Level	Salinity of Water	Climate and Vegetation
Thickness of Deltaic Sequence		Large sediment influx required to produce thick sequence.	High wave and current energy tends to disperse sediments and reduce rate of sedimentation.	Water depths in basin controls max. thickness possible. Subsidence permits development of sequence thicker than depth.	Rapid subsidence produces thick sequence. Thin sequences occur in stable areas.	Rising sea level results in thicker sequences.		Abundant vegetation promotes development of thick organic rich layer in upper part of sequence.
Sand Content	Distributary Channel Fills	Percent of sand in channels depends on rapid or gradual diversion. Gradual abandonment produces more sand in fills.	Large tidal range can transport sand upstream near river mouths and increase sand content in fills.					
	Fringe	Amount of sand in fringe depends on sand load of river. Small for muddy rivers; large for rivers with high sand load.	Strong currents may transport sand along coast away from delta thus reducing sand content of fringe.					
Porosity and Permeability	Distributary Channel Fills		Large tidal range results in deposition of clays and silts in lower reaches of channels thus lowering porosity and permeability.					
	Fringe	High sand content. Rivers generally have best developed fringe sands.	Strong wave and current winnows fines and deposition of clean sand occurs. Dirty sands are deposited in areas of low marine energy.					
Geometry of Deltaic Mass			Strong marine currents can disperse sediment over extensive area in form broad subaqueous fringe and pro-delta mass.	Relatively thin blanket-like deltaic masses form in shallow water. Geometry influenced by bottom topography.	Thin blanket-like delta masses occur in stable areas. Local downwarps result in ladle-shape delta masses.	Rising sea level will produce on-lap fringe over marsh facies. Falling sea level causes strong off-lap of marsh over fringe.	Fine sediments in suspension flow over denser sea water and may be dispersed over broad areas by currents.	
Influence of Organisms on Sediments		Rapid influx of sediment and high turbidity greatly reduces organism population and degree of bioturbation.	Organisms have little influence on sediments in near shore zone with large wave energy.					
Number of Distributary Channel Fills			Strong wave and current action prevents normal development of river mouth bars necessary for bifurcation of channel.	Deltas constructed in shoal water have largest number of distributary channels.				
Thickness (Depth) of Dist. Channel Fills					Rapidly subsiding deltaic plain may result in thicker dist. channel fills.	Falling sea level may cause deepening of channels. Rising sea level causes shoaling.		
Rate of Sedimentation		Rates of sedimentation generally greatest in deltas of rivers with large sediment.	Strong currents can disperse sediments and reduce deposition rates.					Rapid growth of vegetation traps sediments and increases rate of deposition.
Thickness of Organic Rich Clays and Peats (Conc) in Upper Part of Sequence					Thick section of peat and organic clays can accumulate in a near sea level environment (with subsidence).	A rising sea level will result in thick section of organic material in upper portion of sequence.		Warm, wet deltas with dense vegetation are characterized by thick peats and organic rich clays.

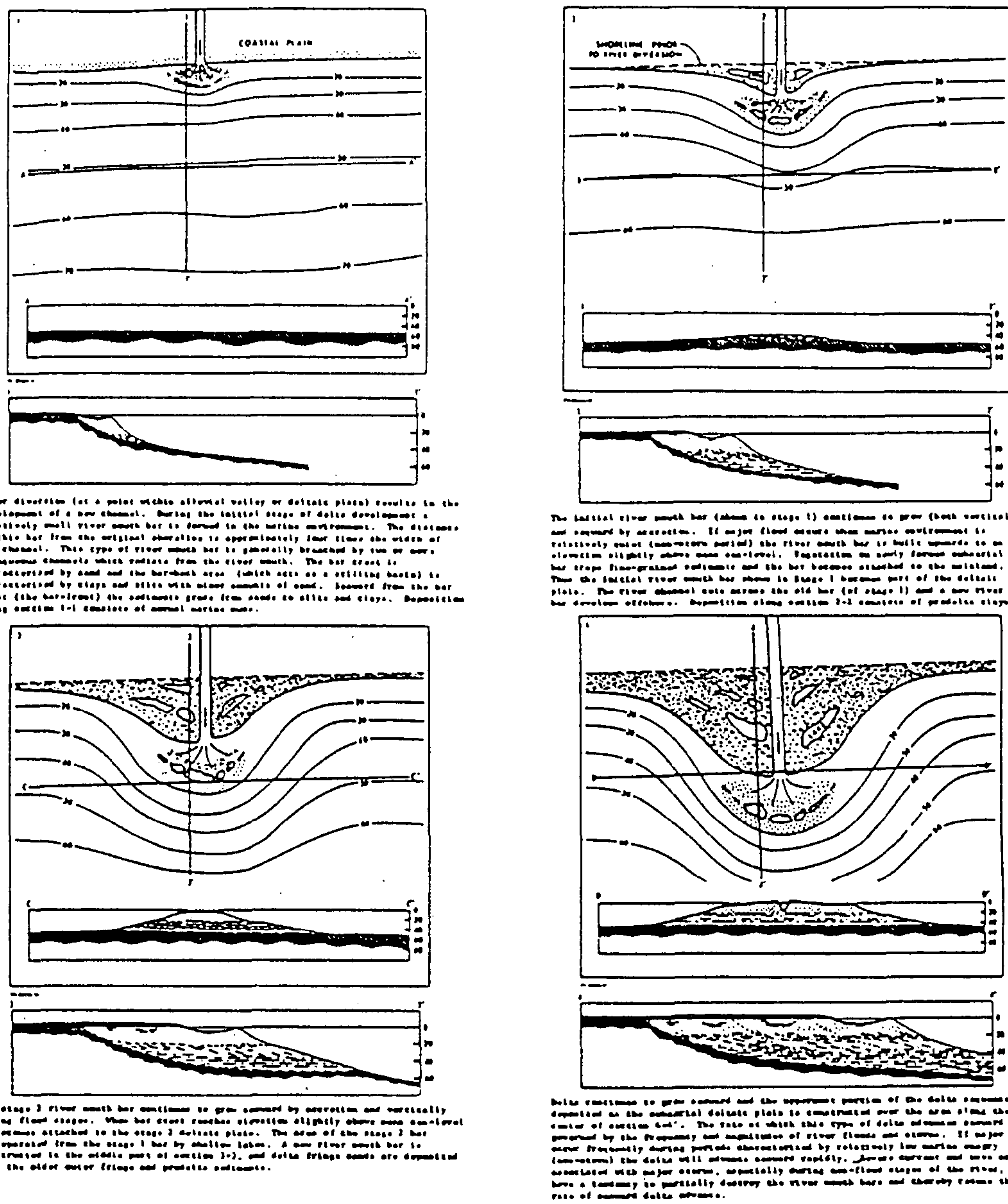

FIG. 21—Stages in development of a cuspate delta.

Sedimentary Processes and Deposits of Estuarine-Type Delta

Large deltas such as the Ganges, Amazon, and Colorado (in Gulf of California) are considered to be examples of estuarine-type deltas. Although our knowledge of these deltas is extremely limited, it is now reasonably well established that they are associated with extreme tidal conditions (up to 25 ft [8 m] at the mouth of the Colorado River). It is apparent that very strong tidal currents have a profound influence on the distribution of sediments. Sands are known to be transported for great distances in front of these deltas; however, the geometry of these sand bodies is unknown. Additional studies of this type delta are badly needed.

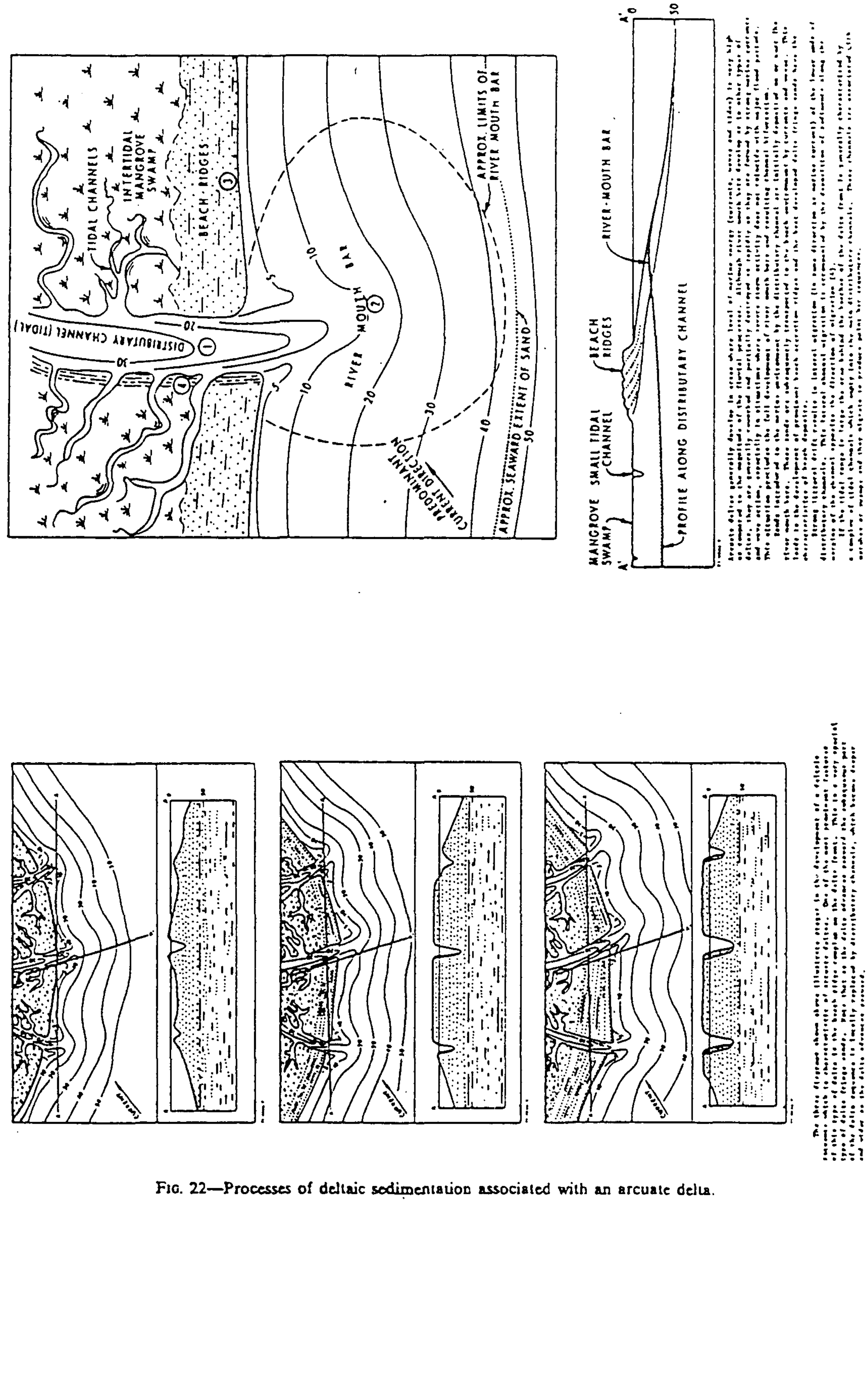

FIG. 22—Processes of deltaic sedimentation associated with an arcuate delta.

Table 3. Examples of Ancient Deltaic Deposits

Geographic Occurrence	*Author*
California	Todd and Monroe, 1968
Illinois	Lineback, 1968
	Swann *et al.*, 1965
Indiana	Hrabar and Potter, 1969
	Wier and Girdley, 1963
Iowa & Illinois	Laury, 1968
Kansas	Brown, 1967
	Hattin, 1965
Louisiana	Clark and Rouse, 1971
	Curtis, 1970
Michigan	Asseez, 1969
Miss., La. & Ala.	Galloway, 1968
Montana	Sims, 1967
Nebraska	Shelton, 1972
New Mexico	Schlee and Moench, 1961
New York	Friedman and Johnson, 1966
	Lumsden and Pelletier, 1969
New York & Ontario	Martini, 1971
New York	Wolff, 1967
North Dakota	Shelton, 1972
Ohio	Knight, 1969
	Lené and Owen, 1969
Oklahoma	Busch, 1953, 1971
	Shelton, 1972
	Visher *et al.*, 1971
Oregon	Dott, 1964, 1966
	Snavely *et al.*, 1964
Pa., W. Va., Ohio	Beerbower, 1961
	Ferm and Cavaroc, 1969
South Dakota	Pettyjohn, 1967
Texas	Brown, 1969
	Fisher and McGowen, 1969
	Gregory, 1966
	LeBlanc, 1971
	Nanz, 1954
	Shannon and Dahl, 1971
	Wermund and Jenkins, 1970
	Shelton, 1972
W. Va., Pa., Ohio	Donaldson, 1969
Wyoming	Barlow and Haun, 1966
	Dondanville, 1963
	Hale, 1961
	Paull, 1962
	Weimer, 1961b
Wyoming & Colorado	Weimer, 1965
Several states, U.S.A.	Fisher *et al.*, 1969
N. Appalachians	Ferm, 1970
Central Appalachians	Horowitz, 1966
Central Appalachians	Dennison, 1971
Upper Miss. embayment & Illinois basin	Pryor, 1960, 1961
Upper Miss. Valley	Swann, 1964
Okla., Iowa, Mo., Kans., Ill., Ind., Ky.	Manos, 1967
Okla. to Penn.	Wanless *et al.*, 1970
Central Gulf Coast	Mann and Thomas, 1968
Alberta, Canada	Carrigy, 1971
	Shawa, 1969
	Shepheard and Hills, 1970
	Thachuk, 1968
England	Allen, 1962
	Taylor, 1963
Ireland	Hubbard, 1967
Scotland	Greensmith, 1966

Summary: Deltaic Sand Bodies

There are three basic types of deltaic sand bodies: delta-fringe, abandoned distributary-channel, and point-bar sands. The relative abundance and general characteristics of these sand bodies in the three types of deltas considered herein are summarized below.

Birdfoot-type delta—The most common sands are those of the delta-fringe environment. These sands occur as relatively thin, widespread sheets, and they contain a substantial amount of clays and silts.

Abandoned distributary channels contain varied amounts of sand, probably composing less than 20 percent of the total delta sand content. These sand bodies are long and narrow, are only slightly sinuous, and are encased in the delta-fringe sands or prodelta clays, depending upon channel depths and the distance that the delta has prograded seaward.

Cuspate-arcuate type of delta—Delta-fringe sand complexes are wide (width of delta), though individual sand bodies are relatively narrow, and are generally much cleaner than delta-fringe sands of the birdfoot-type delta.

Distributary-channel sands and point-bar sands are much more common than in birdfoot-type deltas and can constitute up to 50 percent of the total sand content of the delta. These two types of sands are encased in delta-fringe and prodelta sediments.

Estuarine-type delta—Delta-fringe sands appear to be much more common than distributary and point-bar sands. They probably extend for great distances within the marine environment in front of the delta; however, their geometry remains unknown.

Ancient Deltaic Deposits

Deposits of deltaic origin have been reported from more than 40 states and from several foreign countries. Some examples are summarized in Table 3.

Coastal-Interdeltaic Model of Sedimentation

Setting and General Characteristics

This type of sedimentation occurs in long, narrow belts parallel with the coast where shoreline and nearshore processes of sedimentation predominate. The ideal interdeltaic deposit, as the name implies, occurs along the coast between deltas and comprises mud flats and cheniers (abandoned beach ridges) of the chenier-plain complex and the barrier-island–lagoon–tidal-channel complex (Fig. 23). It can also occur along the seaward edge of a coastal plain which is drained by numerous small streams and rivers but is devoid of any sizable deltas at the marine shoreline.

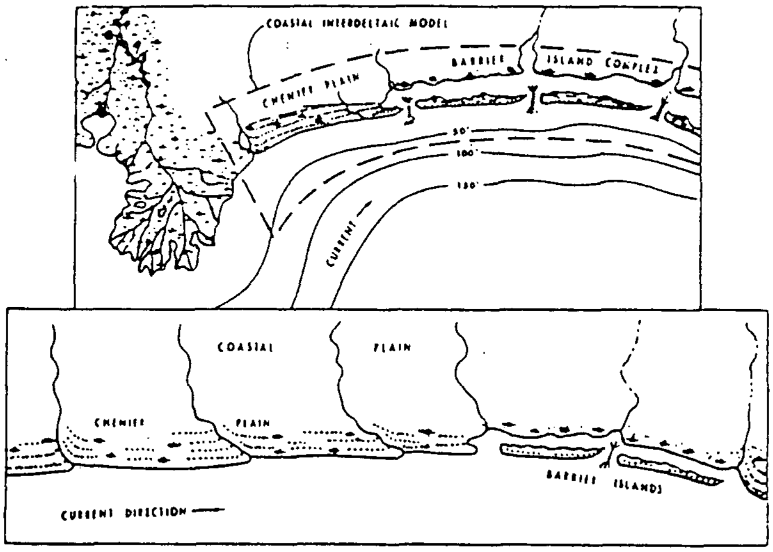

FIG. 23—General setting and characteristics of coastal-interdeltaic model of clastic sedimentation.

Source and Transportation of Sediments

Most of the sediments deposited are derived from land, but minor amounts come from the marine environment. A portion of the sediment transported to the marine shoreline by rivers and smaller streams is dispersed laterally by marine currents for great distances along the coast. Clays and fine silts are carried in suspension, and sand is transported mainly as bed load or by wave action in the beach and nearshore zone. The suspended silt and clay load is dispersed at a rapid rate and is most significant in the development of the mud flats of the chenier plain. Lateral movement of the sand bed load occurs at a relatively slow rate and is most significant in the development of the cheniers and the barrier-island complex.

A minor amount of sediment can also be derived from adjacent continental-shelf areas if erosion occurs in the marine environment.

Sedimentary processes and deposits of chenier plain—Major floods result in the sudden large influx of sediments at river mouths. Much of the suspended load introduced to the coastal-marine environment is rapidly dispersed laterally along the coast by the predominant longshore drift. A considerable portion of this suspended load is deposited along the shoreline (on the delta flank) as extensive mud flats. This period of regressive sedimentation (progradation or offlap) occurs in a relatively short period when rivers are at flood stages (Fig. 24).

During long periods when rivers are not flooding, the supply of sediment to the coast is reduced considerably or is nil. Coastal-marine currents and wave action rework the seaward edge of the newly formed mud flat, and a transgressive situation develops. A slight increase in

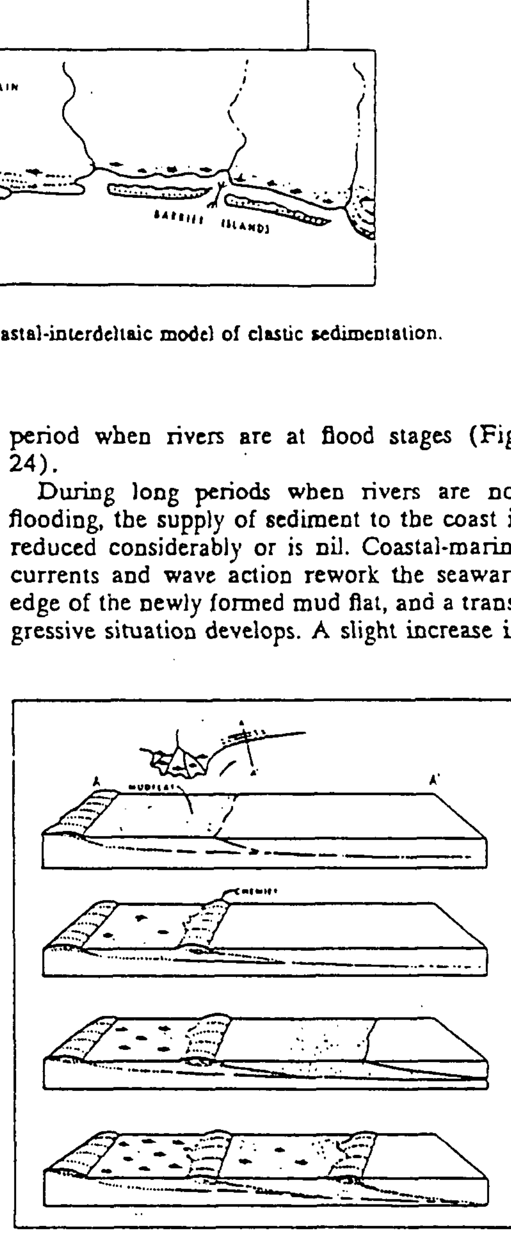

FIG. 24—Stages in development of a chenier plain.

sand supply can result in a regressive situation, and the initial transgressive beach accumulation will grow seaward by regressive beach accretion to form a long, narrow, well-defined chenier on the seaward edge of the extensive mud flat.

Another period of river flooding develops another mud flat on the seaward edge of the chenier. During the subsequent nonflood season, the coastal-transgressive processes produce another beach ridge. Thus, over a long period, a chenier plain consisting of mud flat and beach ridges is constructed.

The width of a mud flat is varied and is dependent on the magnitude and duration of a river flood. The size of the chenier (height and width) is determined by two factors: duration of the nonflood season (absence of muds) and magnitude of coastal-marine processes, including storm tides and waves.

Small streams which drain to the coastline across a chenier plain contribute little sediment to the chenier-plain environment. The mouths of these streams are generally deflected in the direction of the littoral drift.

Sedimentary processes and deposits of barrier-island complex—The typical barrier-island complex comprises three different but related depositional environments: the barrier island, the lagoon behind the barrier, and the tidal channel–tidal deltas between the barriers.

The seaward face of a barrier island is primarily an environment of sand deposition. Coastal-marine energy (currents and wave action) is usually much greater than in the chenier–mud-flat regions. Sediments are transported along the coast in the direction of the predominant littoral drift. Coarser sands are deposited mainly on the beach and upper shoreface, and finer sands are deposited in the lower shoreface areas. Silts and clays are deposited in the lower shoreface zones on the adjacent shelf bottom—at depths greater than 40–50 ft (12–15 m). Storm tides and waves usually construct beach ridges several feet above sea level, depending on the intensity of storms, and also transport sandy sediments across the barrier from the beach zone to the lagoon.

Under ideal conditions, a barrier grows seaward by a beach-shoreface accretion process to produce a typical barrier-island sequence of sediments which grades upward from fine to coarse (Figs. 25, 27). The various organisms which live in the beach, shoreface, and adjacent offshore areas usually have a significant influence on the character of sedimentary structures.

Dry beach sand can be transported inland by the wind and redeposited as dune sand on the barrier, in the lagoon, or on the mainland across the lagoon.

Tidal channel–tidal delta—Tidal action moves a large quantity of water in and out of lagoons and estuaries through the tidal channels which exist between barrier islands. These channels are relatively short and narrow and vary considerably in depth. Maximum channel depths occur where the tidal flow is confined between the ends of barriers. The channel cross section is asymmetric: one side of the channel merges with the tidal flats and spit; the opposite side of the channel has abrupt margins against the barrier (Fig. 26).

As marine waters enter the lagoon or estuary system during rising tides, the inflow attains its maximum velocity in the deepest part of the confined channel. The tidal flow is dispersed as it enters the lagoon, and current velocities are greatly reduced. The result is the deposition of sediment in the form of a tidal delta which consists of a shallow distributary channel separated by sand or silt shoals. Similar tidal deltas are also formed on the marine side of the system by similar processes associated with the falling or outgoing tide.

The depth of tidal channels and the extent of tidal deltas are dependent on the magnitude of the tidal currents. The deepest channels and the largest deltas are associated with large lagoons and estuaries affected by extreme tidal ranges.

Tidal channels migrate laterally in the direction of littoral drift by eroding the barrier head adjacent to the deep side of the channel and by spit and tidal-flat accretion on the opposite side.

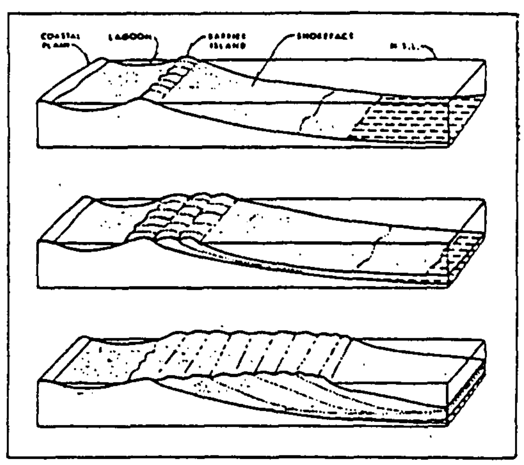

FIG. 25—Stages in development of a barrier island.

Lateral migration of the tidal system results in the deposition of the tidal-channel and tidal-delta sequences of sediments.

Summary: Characteristics of Coastal-Interdeltaic Deposits

The coastal-interdeltaic model of sedimentation is characterized by six distinct but related types of deposits: mud flat, chenier, barrier island, lagoon, tidal channel, and tidal delta. Characteristics of these deposits are summarized in Figure 27.

Three main types of sand bodies are associated with this model: barrier island, chenier, and tidal channel–tidal delta. The barrier-island sand body, which is the largest and most significant of the three, is long (usually tens of miles) and narrow (2–6 mi or 3–10 km), is oriented parallel with the coastline, and attains maximum thicknesses of 50–60 ft (15–18 m). The chenier sand bodies are very similar to those of the barriers; however, they are generally only about a third as thick. Tidal-channel sand bodies are oriented perpendicular to the barrier sands, and their thickness can vary considerably (less than, equal to, or greater than that of the barrier sands), depending on the depth of tidal channels.

Ancient Coastal-Interdeltaic Deposits

Examples of ancient coastal-interdeltaic deposits reported from 13 states are summarized in Table 4.

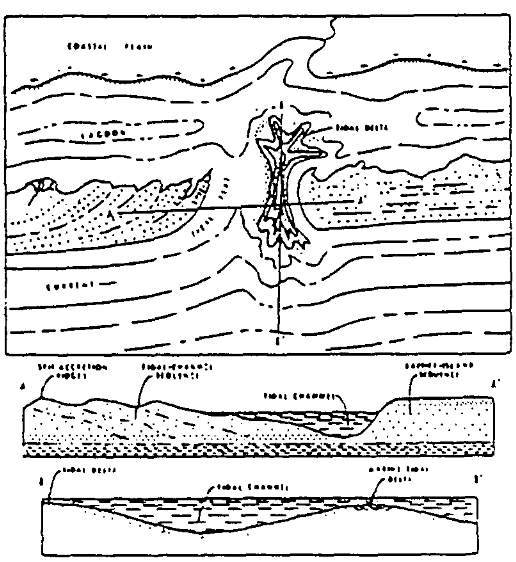

Fig. 26—Relation of tidal channels and tidal deltas to barrier islands.

Table 4. Examples of Ancient Coastal-Interdeltaic Deposits

Geographic Occurrence	*Author*
Colorado	Griffith, 1966
Florida	Gremillion *et al.*, 1964
Georgia	Hails and Hoyt, 1969
	MacNeil, 1950
Illinois	Rusnak, 1957
Louisiana	Sloane, 1958
Louisiana & Arkansas	Thomas and Mann, 1966
	Berg and Davies, 1968
Montana	Cannon, 1966
	Davies *et al.*, 1971
	Shelton, 1965
New Mexico	Sabins, 1963
New York	McCave, 1969
Oklahoma & Kansas	Bass *et al.*, 1937
	Boyd and Dyer, 1966
	Dodge, 1965
Texas	Fisher and McGowen, 1969
	Fisher *et al.*, 1970
	Shelton, 1972
	Harms *et al.*, 1965
	Jacka, 1965
Wyoming	Miller, 1962
	Paull, 1962
	Scruton, 1961
	Weimer, 1961a

Eolian Model of Sand Deposition

Occurrence and General Characteristics

A very common process of sedimentation is transportation and deposition of sand by the wind. Two basic conditions are necessary for the formation of windblown sand deposits: a large supply of dry sand and a sufficient wind velocity. These conditions are commonly present along coastlines characterized by sandy beaches and also in semiarid regions and deserts, where weathering and fluvial sedimentation produce a large quantitiy of sand (Fig. 28).

Under certain conditions, sands on the downstream parts of alluvial fans and along braided streams are transported and redeposited by the wind (Glennie, 1970). Sands originally deposited on point bars of meandering streams and along distributary channels of some deltas are also picked up by the wind and redeposited locally as dune sand. Similarly, sands deposited along beaches of the coastal-interdeltaic environments are redeposited by onshore winds as sand dunes on barrier islands or on the mainland. Thus, the eolian process of sand deposition is likely to occur within all models of clastic sedimentation discussed in the preceding sections.

Eolian Transport and Sedimentation

The complex processes of sand transport and deposition by the wind were studied and de-

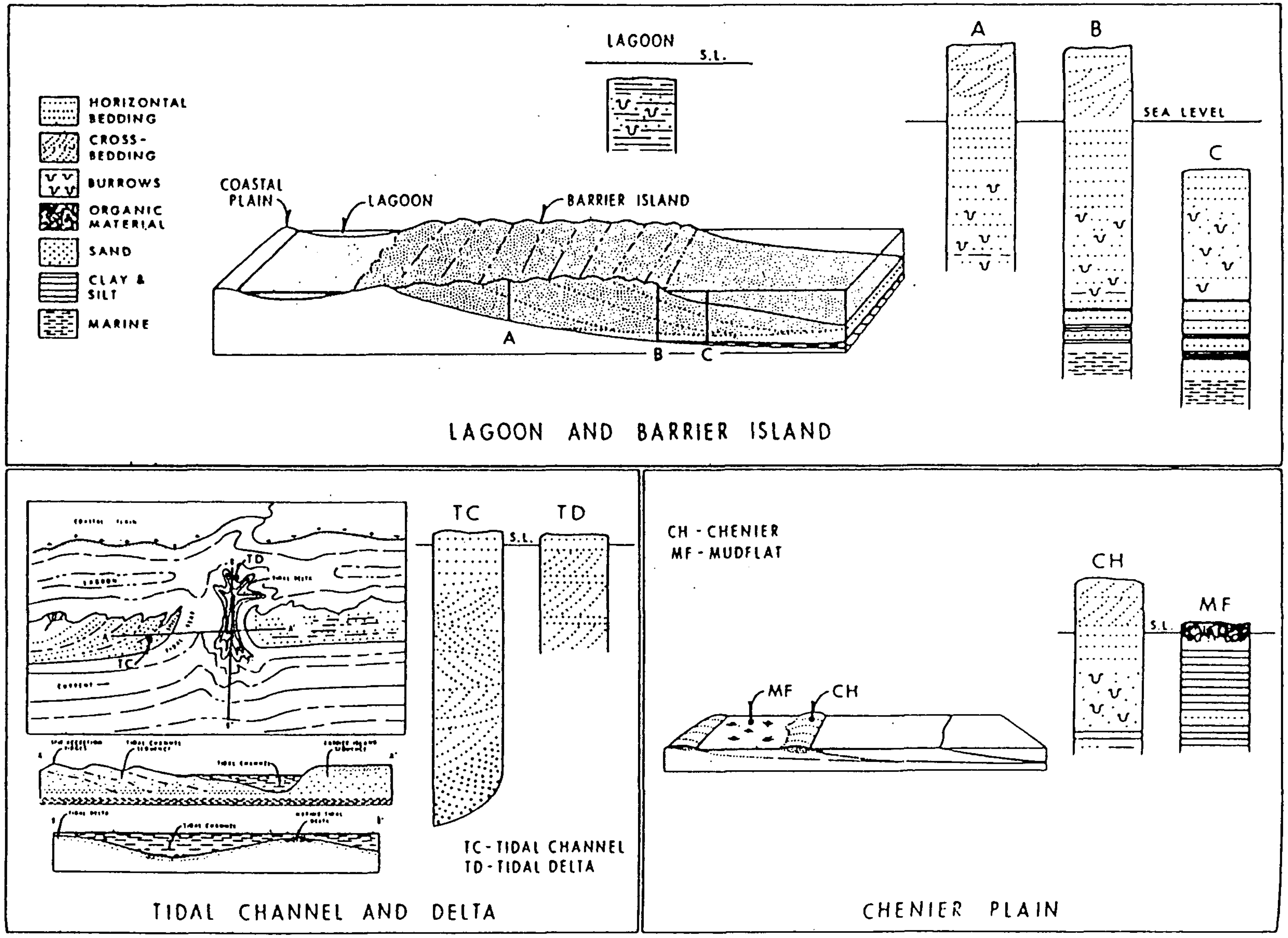

FIG. 27—Sedimentary sequences typical of chenier-plain and barrier-island complexes of coastal-interdeltaic model of clastic sedimentation.

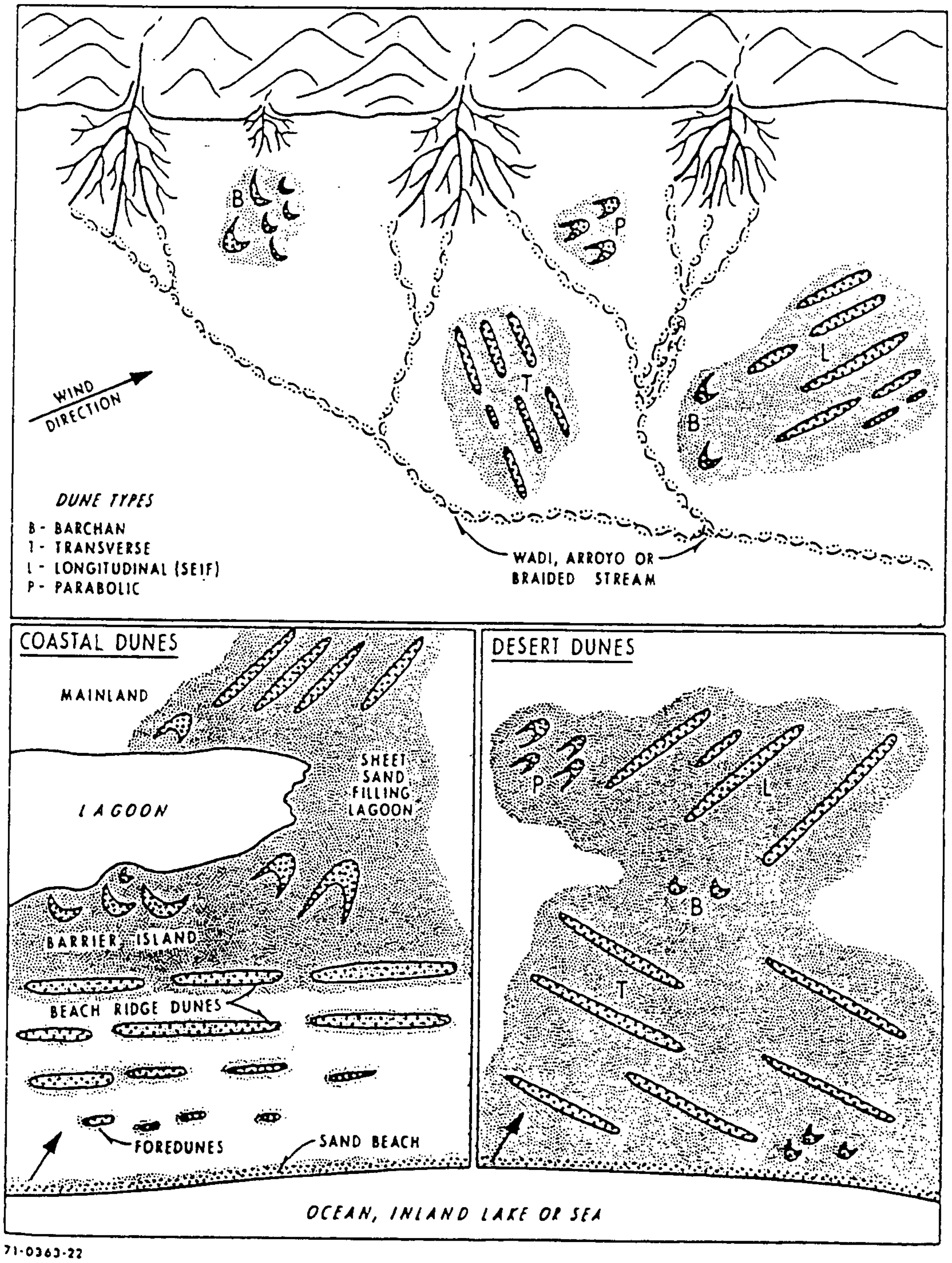

FIG. 28—Occurrences of eolian sands in coastal and desert regions.

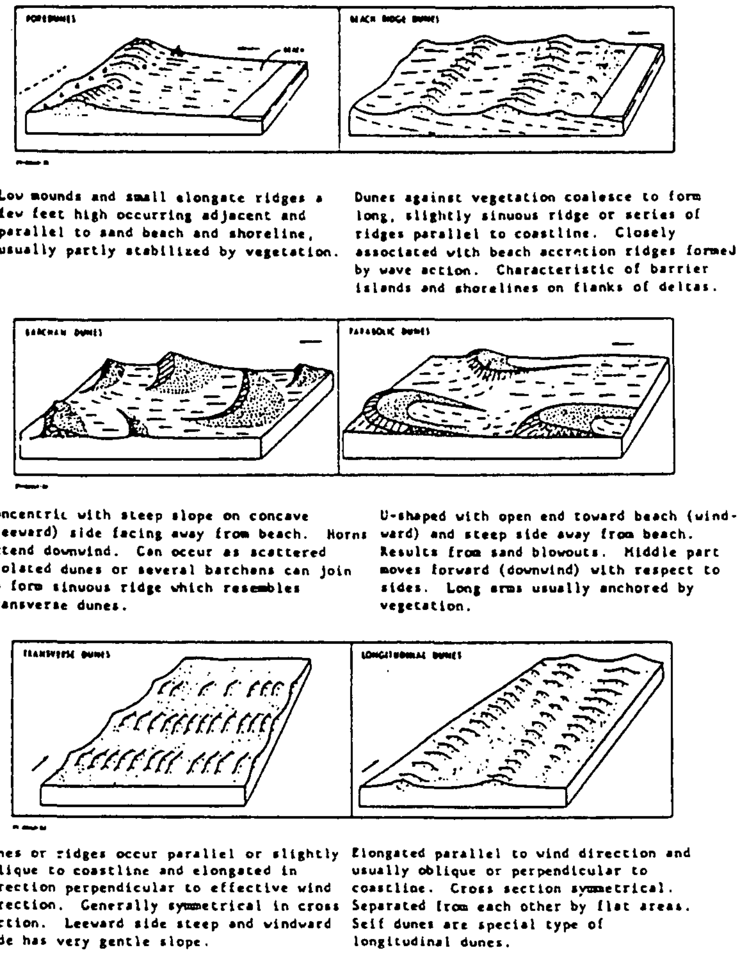

FIG. 29—Some common types of coastal dunes which also occur in deserts.

scribed by Bagnold (1941). Recently, Glennie (1970) summarized this type of sedimentation as observed under desert conditions.

The most common method of sand deposition is in the form of sand dunes. Many types of dunes have been recognized and described by numerous authors (Fig. 29). H. Smith (1954) presented the following classification and description of coastal dunes which can occur either under active or stabilized conditions.

1. Foredune ridges, or elongate mounds of sand up to a few tens of feet in height, adjacent and parallel with beaches.
2. U-shaped dunes, arcuate to hairpin-shaped sand ridges with the open end toward the beach.
3. Barchans, or crescentic dunes, with a steep lee slope on the concave side, which faces away from the beach.
4. Transverse dune ridges, trending parallel with or oblique to the shore, and elongated in a direction essentially perpendicular to the dominant winds. These dunes are asymmetric in cross profile, having a gentle slope on the windward side and a steep slope on the leeward side.
5. Longitudinal dunes, elongated parallel with wind direction and extending perpendicular or oblique to the shoreline; cross profile is typically symmetric.
6. Blowouts, comprising a wide variety of pits, troughs, channels, and chute-shaped forms cutting into or across other types of dunes or sand hills. The larger ones are marked by conspicuous heaps of sand on the landward side, assuming the form of a fan, mound, or ridge, commonly with a slope as steep as 32° facing away from the shore.
7. Attached dunes, comprising accumulations of sand trapped by various types of topographic obstacles.

McKee (1966) described an additional type, the dome-shaped dune, from White Sands National Monument, and Glennie (1970) described the seif dune of Oman, which is a special type of longitudinal dune. Many other dune types have been described; however, the above types appear to be the most common.

Studies of modern eolian sand bodies—Cooper (1958) reviewed the early studies of sand dunes, mainly by Europeans, and summarized the status of dune reseach in North America. Additional sand-dune studies in the United States since 1959 were made in Alaska by Black (1961), on the Texas coast by McBride and Hayes (1962), on the Georgia coast by Land (1964), in the Imperial Valley of California by Norris (1966), in coastal California by Cooper (1967), and in the San Luis Valley of Colorado by R. Johnson (1967). Additional studies outside the United States were made in southern Peru by Finkel (1959), in Baja California by Inman *et al.* (1966), in Libya by McKee and Tibbitts (1964), in Russia by Zenkovich (1967), and in Australia by Folk (1971).

During the past several years, some very important studies on eolian sands, which included detailed observations of internal dune structure and stratification in deep trenches cut through dunes, were made along the Texas coast by McBride and Hayes (1962), in White Sands National Monument by McKee (1966), along the Dutch coast by Jelgersma *et al.* (1970), and in the deserts of the Middle East by Glennie (1970). These authors presented photographs and sketches of various types of sedimentary structures exposed in trench walls and described their relations to dune types, wind regime, and grain-size distribution. These studies have provided some badly needed criteria for recognition of ancient eolian sands. The following summary of the geometry and general characteristics of modern eolian sand bodies was prepared largely from the references cited above.

Summary: Coastal Eolian Sand Bodies

Coastal eolian sand bodies, consisting of several types of dunes, are very long and quite narrow; they range in thickness from a few feet to a few hundreds of feet, and are aligned parallel with or oblique to the coastline. Because these sands are derived from beach deposits and form in vegetated areas, they commonly contain fragments of both shells and plants. They are characterized by high-angle crossbedding and are usually well sorted. The adjacent and laterally equivalent beach deposits are generally horizontally bedded and have some low-angle crossbedding.

Summary: Eolian Sand Bodies of Desert Regions

Desert eolian sand bodies differ from coastal eolian sands mainly in their distribution. The internal sedimentary structures and their relations to dune types are similar (Bigarella *et al.*, 1969). Seif dunes are products of two wind directions and appear to occur more commonly in desert areas. These dunes are characterized by high-angle crossbedding in two directions.

Ancient Eolian Deposits

Ancient eolian deposits have been reported from the Colorado Plateau by Baars (1961) and Stokes (1961, 1964, 1968), from the southwestern United States by McKee (1934), from England by Laming (1966), and from Brazil and Uruguay by Bigarella and Salamuni (1961). Criteria for recognition of eolian deposits have been summarized by Bigarella (1972).

Marine Clastic Sedimentation

Transportation and deposition of sand in the marine environment occur under a wide range of geologic and hydrologic conditions, ranging from those of the coastal shallow-marine environments to the deeper water environments of the outer continental shelves, the slopes, and the abyssal plains (Fig. 30).

As indicated in the Introduction, sands deposited under regressive (progradational) conditions within the coastal shallow-marine environments are considered herein as products of either the coastal-interdeltaic or the deltaic model of sedimentation. Other important shallow-marine sand bodies are produced as a result of marine transgressions.

During the past several years, studies made principally by the major oceanographic institutions on the modern deep-marine environments and research by petroleum geologists, university professors, and graduate students on ancient clastic sediments of various geologic ages have revealed that sand bodies of deep-marine origin are rather common throughout the world. Although most geologists now accept the fact that some sands are of deep-marine origin, our understanding of the various geologic processes which produce these sand bodies is relatively poor. The writer's personal experience with this type of clastic sedimentation is limited; however, on the basis of familiarity with the literature on marine sediments, it appears that most deep-marine sands are depos-

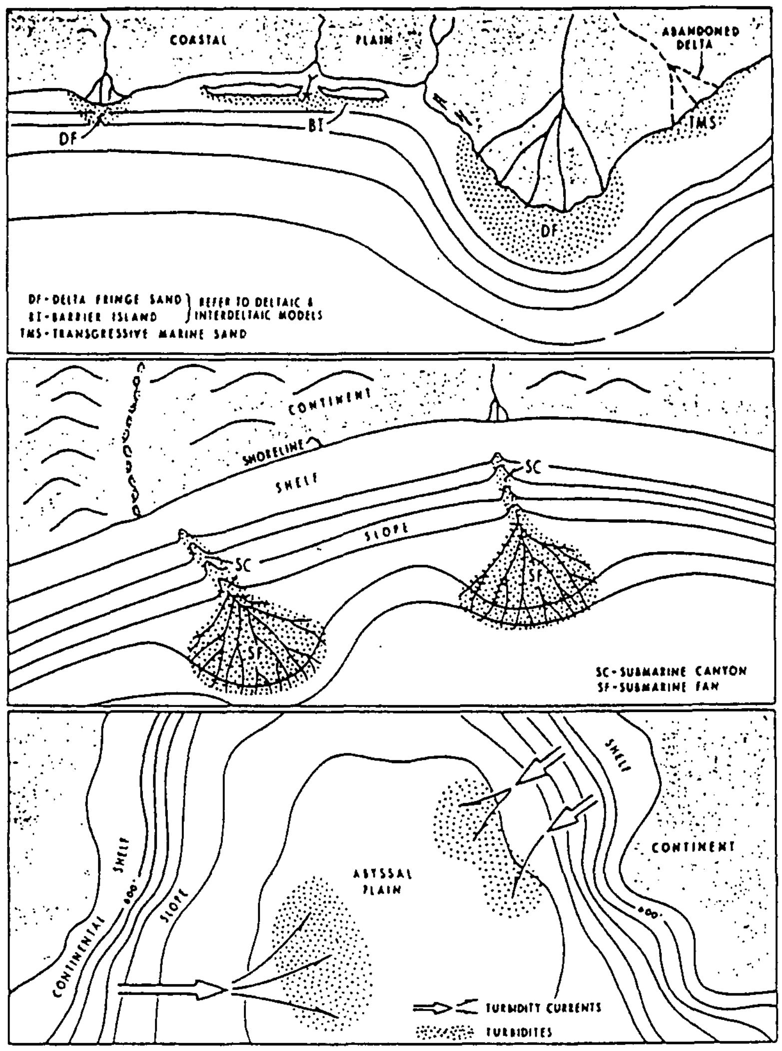

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FIG. 30—Deposition of sand in marine environments.

ited under three principal types of environmental conditions: (1) on the outer shelf, the slope, and the continental rise, as a result of slumping, sliding, and tectonic activity such as earthquakes; (2) in abyssal plains, by density (turbidity) and bottom currents; and (3) in submarine canyons, fan valleys, and fans, by both bottom and density currents.

Only two of these several types of marine sands are discussed in this paper: (1) the shallow-marine sands deposited as a result of transgressive-marine sedimentation associated with the shifting of deltas and (2) the deep-marine sands deposited in submarine canyons, fan valleys, and fans.

Transgressive-Marine Model of Clastic Sedimentation

Setting and general characteristics—Deposition of clastic sediments during periods of marine transgressions (onlap) is a common process of sedimentation in most basins. There are two basic types of marine transgression: that which is associated with the shifting of deltas as a result of major river diversions during a period of standing sea level, and that which occurs as a result of a relative rise in sea level (due to subsidence of a coastal plain or eustatic rise in sea level). The inland and lateral extents of marine transgressions resulting from delta shifts are limited in size, depending on the dimensions of the abandoned deltaic plains. Marine transgressions resulting from relative changes in sea level extend over much broader regions and are commonly referred to as regional transgressions. Their dimensions are governed mainly by the topography of the coastal plain being transgressed and by the amount of relative rise in sea level. Thus, transgressive-marine deposition can occur locally over abandoned deltas or regionally over eolian, alluvial, interdeltaic, and deltaic deposits of a large part of a coastal plain.

Modern marine transgressions resulting from major changes in drainage and delta shifts have been described by several authors: Russell, 1936; Russell and Russell, 1939; Kruit, 1955; van Straaten, 1959; Scruton, 1960; Curray, 1964; Coleman and Gagliano, 1964; Rainwater, 1964; Coleman, 1966b; Scott and Fisher, 1969; L. Brown, 1969; and Oomkens, 1970.

Sources, transportation, and deposition of sediments—After a delta is abandoned because of upstream channel diversion, a very significant change occurs in conditions of sedimentation. The abandoned deltaic plain and subaqueous delta front no longer receive sediment and gradually subside owing to the compaction of the deltaic deposits. The seaward edge of the abandoned delta is attacked by marine wave and current action and recedes landward at relatively slow rates. As marine processes erode the upper part of the deltaic sequence, the sandy sediments within the sequence are winnowed and deposited along the advancing shoreline as barrier islands, beaches, and shallow-marine sands; finer sediments are deposited farther offshore. Thus, the transgressive-marine depositional profile is characterized by sands and shell material nearshore and by progressively finer sediments offshore. Over a period of time, as the transgression proceeds inland, the thin veneer of shallow-marine sands which are deposited over the underlying delta sediments is in turn overlain by marine silts and clays. Stages in the development of such a trangressive-marine sand body are illustrated in Figure 31.

Character of sediments—This type of sedimentation, although largely restricted in extent to abandoned deltas and adjacent and laterally

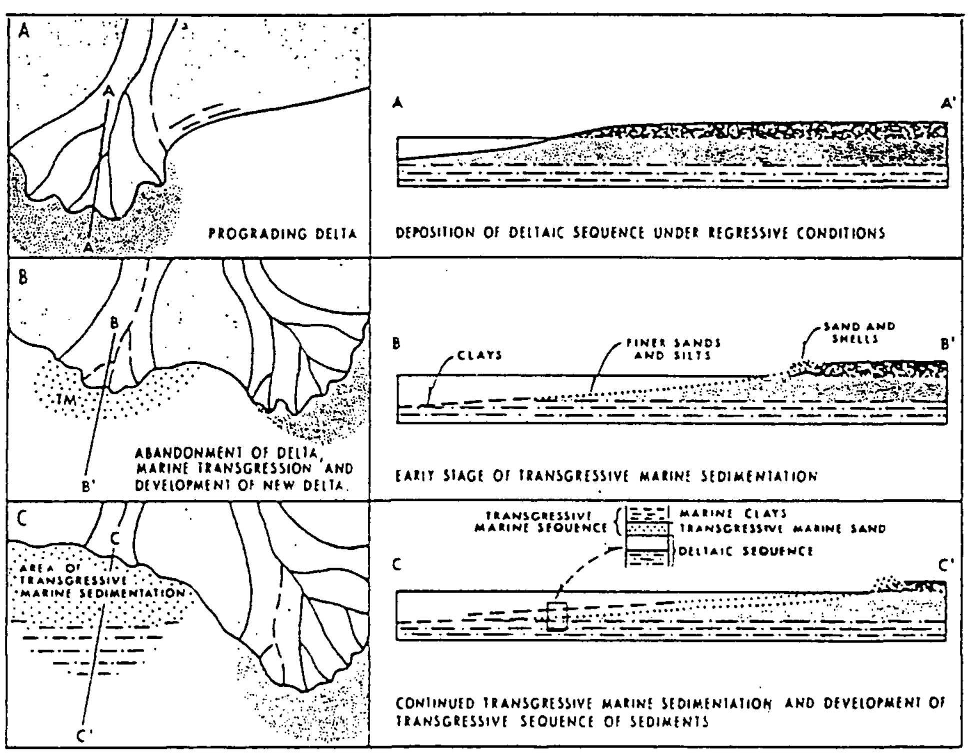

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FIG. 31—Transgressive-marine sedimentation resulting from delta shifts.

equivalent interdeltaic and offshore-marine environments, is significant because it produces very diagnostic blanketlike layers of marine sediments (thin shallow-marine sand overlain by clays) which separate the individual deltaic units (Fig. 31). These layers usually provide the only good correlations within thick deltaic facies, and the marine shales act as impervious seals between deltaic sand bodies. The transgressive-marine sands containing calcareous shell material usually become cemented and thus do not form very efficient reservoirs.

Submarine Canyon-Fan Model of Clastic Sedimentation

Occurrence and general characteristics—The occurrence of modern and Pleistocene sands in deep-marine environments of the world is well documented as a result of numerous deep-sea investigations by oceanographic institutions during the past 20 years. Although there is much controversy regarding the origin of these sands, it is certain that such sands do exist. An analysis of the literature reveals that some of the most common deep-sea sands are those associated with submarine canyons and fans. (For a discussion of types of submarine canyons, troughs, and valleys, the reader is referred to Shepard and Dill, 1966.)

Submarine canyons and fans are common features associated with continental shelves, slopes, and rises. The canyons and fans off the Pacific Coast of the United States and Canada have received the most attention. Significant papers on these features off the coasts of Washington, Oregon, California, and Baja California, and off the Gulf and Atlantic coasts, are listed in the selected references. Also included are references to papers on canyons and fans in the Mediterranean, the Atlantic Ocean off Africa, and the Indian Ocean off Pakistan.

Characteristics and origin of submarine canyons have been discussed by numerous authors (for summary, see Shepard and Dill, 1966). Although it is still uncertain how some deep-sea canyons and valleys originated, it is now reasonably well established that a large number of canyons and fans are related to rivers, and that they were formed during stages of low sea level of the Quaternary Period (Figs. 32, 33). For

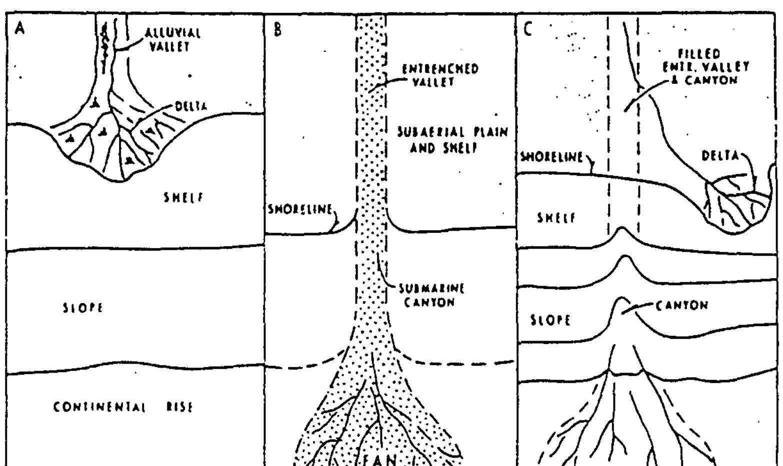

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FIG. 32—Stages in development of submarine canyon and fan.

Stage A: Standing sea-level situation. Development of alluvial valley and delta and deposition of marine clays on shelf and slope. Base of aggrading river is well below sea level.

Stage B: Falling and low-sea-level situation. Development of entrenched-valley system on coastal plain and of submarine canyon offshore. Bases of entrenched valley (near coast) and of canyon are well below sea level. Rates of sedimentation are very high. Material removed by canyon-cutting and sediments flowing through canyon while it formed are deposited as extensive submarine fan.

Stage C: Rising and standing sea-level situation. Alluviation of entrenched-valley system and partial filling of canyon. Rates of sedimentation are greatly reduced after sea level reaches a stand. Slight modification of fan by normal-marine processes occurs.

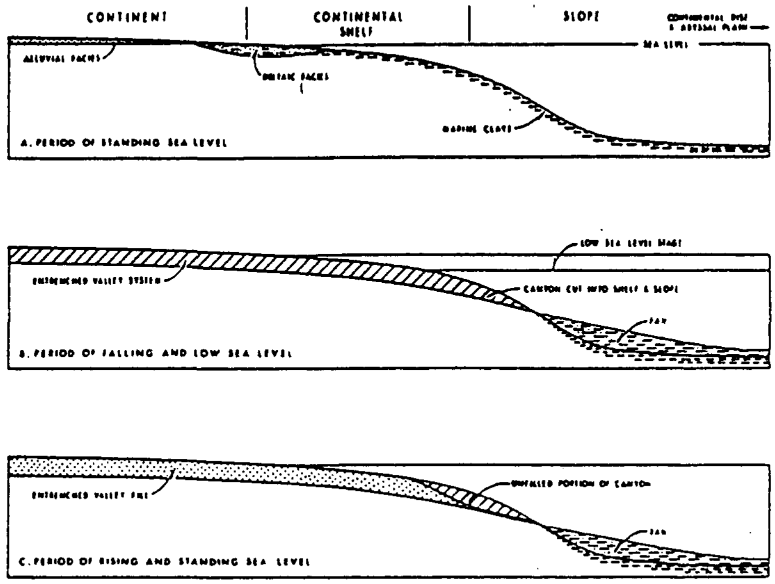

FIG. 33—Relation of submarine-fan deposits to submarine-canyon and entrenched-valley system.

example, the Mississippi Canyon off southern Louisiana is a continuation of the late Pleistocene Mississippi entrenched valley system (Fisk, 1944; Osterhoudt, 1946; Fish and McFarlan, 1955; and Bergantino, 1971). Also, the Astoria canyon and fan off Oregon are related to the Columbia River (Duncan and Kulm, 1970); the Newport Canyon is related to the Santa Ana River of California (Felix and Gorsline, 1971); the Congo Canyon connects with the Congo River (Heezen *et al.*, 1964); the Monterey and Soquel canyons and fans occur off the Great Valley of California (Martin and Emery, 1967); the Bengal deep-sea fan and the "Swatch-of-No-Ground" canyon occur off the Ganges River delta (Curray and Moore, 1971); and the Inguri canyon is related to a river flowing in the Caspian Sea (Trimonis and Shimkus, 1970). The *National Geographic* magazine maps of the Indian and Atlantic Ocean floors (Heezen and Tharp, 1967, 1969) show large fans off the Indus and Amazon Rivers and also off the Laurentian Trough, and the Hudson Canyon is associated with the Hudson River. Seismic reflection surveys between canyon heads (on shelves) and the coastline most probably will reveal more examples of canyons related to entrenched river valleys on land.

There is an extremely wide variation in the size of submarine canyon-fan systems. Some of the small ones off California studied by Gorsline and Emery (1959) include short canyons 5–10 mi (8–16 km) long and fan areas of about 50 sq mi (130 sq km). The largest canyon-fan systems studied thus far are those of the Congo, Ganges, and Rhône Rivers. The Bengal fan is 2,600 km long and 1,100 km wide; the Congo fan is more than 520 km long and 185 km wide; and one of the largest fans off the Pacific coast of the United States, the Delgade fan, is 300 km long and 330 km wide (Normark, 1970). Menard (1960) discussed the dimensions of several other fans.

Some very significant studies of deep-sea sands associated with canyons and fans—based on core, seismic reflection, and bathymetric data, and bottom observations and photography by divers—have been made during the past 3 years (Winterer *et al.*, 1968; Carlson and Nelson, 1969; Shepard *et al.*, 1969; Curray and Moore, 1971; Normark, 1970; Nelson *et al.*, 1970; Piper, 1970; Duncan and Kulm, 1970; and Felix and Gorsline, 1971).

Physiographic features.—Detailed bathymetric surveys over several canyons and fans of various sizes have revealed that these submarine features are characterized by physiographic features very similar to those of subaerial alluvial fans. The canyons are V-shaped and have steep walls and gradients. The surfaces of the fans are characterized by lower gradient distributary channels with natural levees and by topographically low interchannel areas. Some fans are crossed by relatively large fan valleys

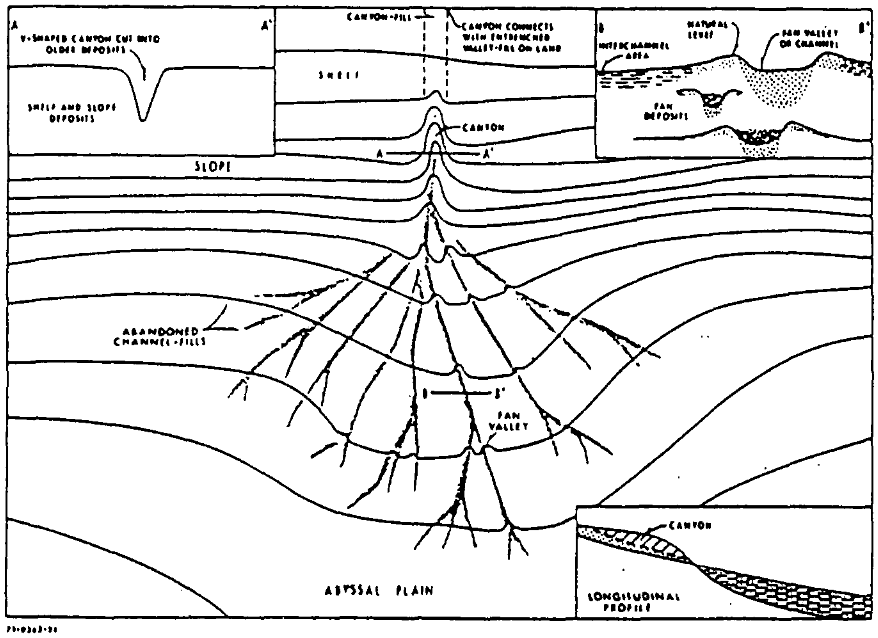

FIG. 34—Submarine-canyon and fan model of clastic sedimentation.

which also have natural levees. The principal physiographic features of a typical canyon and fan are illustrated in a generalized fashion in Figure 34.

The overall shape of a submarine fan can either be symmetrical or asymmetrical, depending on strong current directions and on the presence of high topographic features on the abyssal plains. Sizes of the distributary channels and natural levees are widely varied; the larger channels usually have the highest and broadest natural levees. The lower parts of fans merge with the abyssal plains. Channels on fan surfaces were probably formed by depositional processes. Erosional channels that have been reported probably represent an entrenchment stage, as is the case with subaerial alluvial fans.

Many canyons were cut across continental shelves and slopes, and the fans were constructed at the base of the slopes or on the continental rises. Some canyons presently do not extend landward across the continental shelves (*e.g.*, the Mississippi Canyon) because they have been filled with sediments. Seismic surveys reveal that this type of canyon was once connected with inland entrenched valley systems.

Longitudinal profiles of canyons and fans are concave upward. The steepest gradients occur in the upper (landward) portions of canyons, and the lowest gradients occur on the outer or lower portions of fans.

Depositional processes and character of sediments—It is absolutely certain that large quantities of sediment, including a significant amount of sand, have been transported through submarine canyons and deposited as submarine fans in deep-sea environments. The manner in which these sediments were transported, especially the sands, is much less certain. Nearly 2 decades ago, some very strong statements were made by oceanographers regarding the turbidity-current origin of both the canyons and the fan deposits. Although no one had actually seen or measured a turbidity current in a canyon or over a submarine fan, the turbidity-current concept was very popular with most oceanographers during the early 1950s. During the past 20 years, numerous additional observations have been made, but no one has yet seen a live turbidity current in a natural marine environment. On the basis of direct observations of the ocean bottom and sedimentary structures in cores, many oceanographers now believe that some submarine-fan sand deposits were transported mainly by normal bottom currents, especially during low stages of sea level of the Pleistocene. A typical example is the origin of the sand associated with the Mississippi cone in

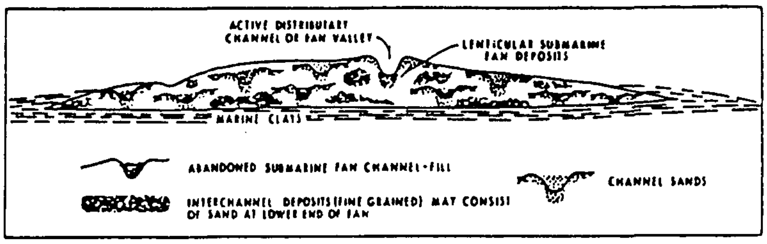

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FIG. 35—Generalized distribution of submarine-fan deposits.

the Gulf of Mexico off southern Louisiana. Greenman and LeBlanc (1956) did not consider these sands to be of turbidity-current origin, but Ewing *et al.* (1958) were certain that the sands were transported and deposited by turbidity currents. Twelve years later, Huang and Goodell (1970) concluded, on the basis of detailed studies of sedimentary structures observed in numerous cores, that the sands are not of turbidity-current origin, but that the mechanisms of transport are bottom currents, differential pelagic settling, and mass movement by sliding and slumping. Walker and Massingill (1970) reported that part of the Mississippi cone sediments were recently involved in large-scale slumps. They presented evidence that one slump moved from near the mouth of the Mississippi Canyon southeastward for at least 160 n. mi. Thus, the origin of these deep-sea sands and many others remains a problem.

Regardless of the mechanisms of sediment transport through submarine canyons and of deposition of fans, the general nature and distribution of fan deposits have been determined for several fans. The coarsest and most poorly sorted sediments occur in canyons. Sands are common in distributary channels and fan valleys and on the lower parts of the open fan. Sandy sediments also occur on natural levees, but the interchannel areas are characterized by fine-grained sediments (Fig. 35). Core data from several fans indicate that sand bodies are usually thin and very lenticular, and are interbedded with fine-grained sediments.

For details concerning the sedimentary structures which characterize submarine-canyon and fan deposits, the reader is referred to Carlson and Nelson (1969); Shepard *et al.* (1969); Stanley (1969); Huang and Goodell (1970); and Haner (1971).

Horn *et al.* (1971) described the characteristics of sediments related to submarine canyons, fans, and adjacent abyssal plains of the northeast Pacific Ocean off Alaska, Canada, Washington, Oregon, and northern California. They interpreted sediments with a wide range in layer thickness, with graded and nongraded layers, and with sand in the basal parts of graded units to be proximal turbidites related to main routes followed by turbidity currents (probably channels). The finer grained sediments, mainly graded silts and clays, were interpreted as distal turbidites deposited beyond the main avenues of turbidite flows.

It is the opinion of the writer that many of the submarine canyons and related fans which now are found off rivers are the products of entrenchment (canyons) and deposition (fans) during stages of low sea level of the Pleistocene. Oceanographers who have studied several of these fan deposits have concluded that they are of Miocene to Pleistocene age. The geologic-age determinations were made on the basis of present sediment load of the related rivers and known thickness of fan deposits. This writer suggests that rates of sedimentation were probably several times greater during Pleistocene low-sea-level stages than at the present time (period of higher and standing sea level) and, consequently, that the fan deposits are probably chiefly of Pleistocene age.

Ancient examples of submarine canyon and fan deposits—Some examples of ancient deposits of submarine canyon and fan origin have been described from the Gulf coast by Osterhoudt (1946), Bornhauser (1948, 1960), Hoyt (1959), Paine (1966), and Sabate (1968); from California by Sullwold (1960), Martin (1963), Bartow (1966), Dickas and Payne (1967), Normark and Piper (1969), Piper and Normark (1971), Davis (1971), Fischer (1971), and Shelton (1972); from Canada by Hubert *et al.* (1970); from Europe by Walker (1966), Stanley (1967, 1969), and Kelling and Woollands (1969); and from Australia by Conolly (1968).

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Discussion

EDWARD N. WILSON, Kentucky Geological Survey, Lexington, Kentucky

You remarked that some of the deltaic bodies were rather thin and not very extensive. In the central United States, the Pennsylvania System contains several of these deltaic sequences and some of them are fairly thick. I should like to ask if there is anything inherently disadvantageous to these sandstone bodies for emplacement of limited volumes of waste?

R. J. LEBLANC

I do not think so, for the following reasons. Deltas of various sizes can prograde seaward into a basin over long periods of time. Thus, they can produce relatively thick deltaic sand bodies over extensive areas which consist of several individual genetic units stacked over each other. It is true that some of the Pennsylvanian sandstones are thick and occur over extensive areas. There is nothing wrong with these sandstones from the standpoint of the emplacement of limited amounts of waste into them. It is important to mention that deltaic sands grade seaward into prodelta silts and clays.

PAUL WITHERSPOON, University of California, Berkeley, California

First, I want to compliment you on a very excellent review of depositional conditions. I wanted to ask if you have looked at conditions such as the Mount Simon Sandstone of central United States; 1,000–2,000 ft thick, it can be traced all the way across Indiana, Illinois, Ohio, and up to New York, where it is called the "Potsdam," and to Minnesota and southern Illinois. Would the mechanisms you have described relate to accumulation of that thick sand body over those hundreds of miles?

R. J. LEBLANC

I cannot answer that specific question because I am not familiar with the Mount Simon Sandstone. However, I can comment on other sandstones which occur over very extensive areas. For example, the Castlegate Sandstone of northwestern Utah extends for many miles from west to east; but the Castlegate is not a uniform sandstone deposited in one environment. Actually, it consists of alluvial-fan, braided-stream, and deltaic sandstones. I believe that many other sandstones are similar to the Castlegate in that they are extensive but of multiple origin; therefore, the models I described can explain their origin.

JIM HALLORAN, Montana Water Resources Board, Helena, Montana

Can you give us some idea what this barrier-island model will look like after marine transgression or regression?

R. J. LEBLANC

One of the largest oil fields discovered in the United States during the past several years is the Bell Creek field of Montana. Two professors from Texas A&M University correctly interpreted this reservoir as a barrier-island sandstone body. I refer you to Dr. R. R. Berg's[1] excellent paper on this barrier-bar sandstone, because time does not permit a detailed answer to your question.

[1] Berg, R. R., and D. K. Davies, 1968, Origin of Lower Cretaceous Muddy Sandstone at Bell Creek field, Montana: Am. Assoc. Petroleum Geologists Bull., v. 52, no. 10, p. 1888–1898.

Section 2

HYDROGEOLOGY

PERFORMANCE OBJECTIVES

At the end of this lesson, participants will be able to:

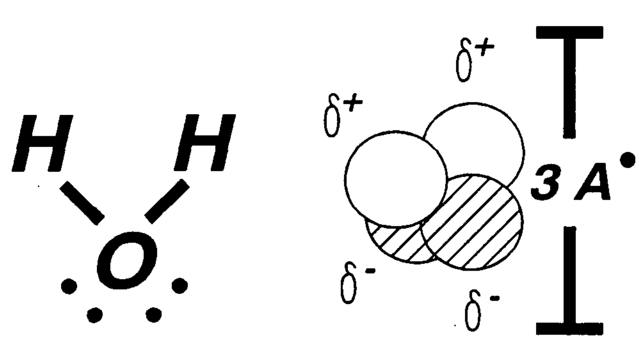
- Explain the hydrologic cycle and its relationship to rocks and groundwater
- Differentiate between recharge and discharge areas
- Describe the relationship between porosity and permeability
- Describe the effect of porosity and permeability on groundwater flow
- Define aquifer, aquitard, and aquiclude
- Compare confined aquifers and unconfined aquifers.

NOTES

HYDROGEOLOGY

HYDROGEOLOGY

The study of the interrelationships of geologic materials and processes with water, especially groundwater



NOTES

EARTH'S WATER RESOURCES

- 80% oceans
- 19% groundwater
- 1% ice
- 0.002% streams and lakes
- 0.0008% atmosphere

EARTH'S WATER USES

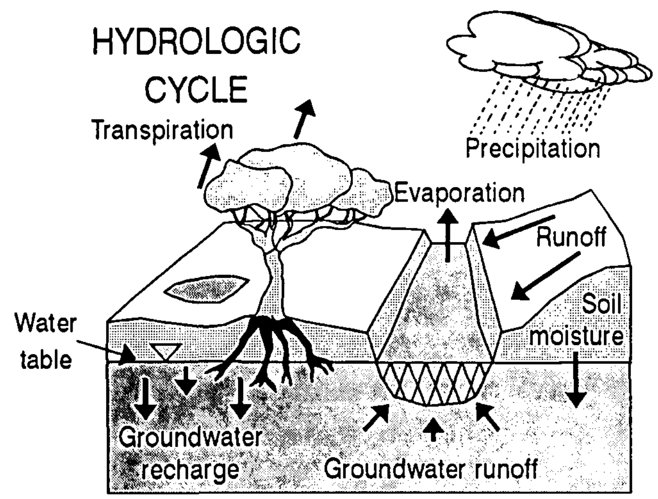
- Drinking
- Irrigation
- Fisheries
- Individual processes
- Transportation
- Waste disposal

HUMAN WATER CONTENT

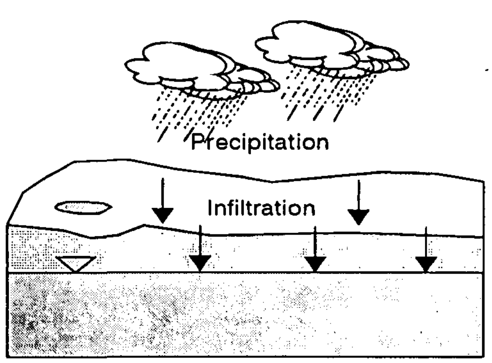
- 45 - 75% by weight
- 65% average male
- 55% average female

NOTES

Precipitation is a beginning point for the hydrologic cycle



DIRECT INFILTRATION

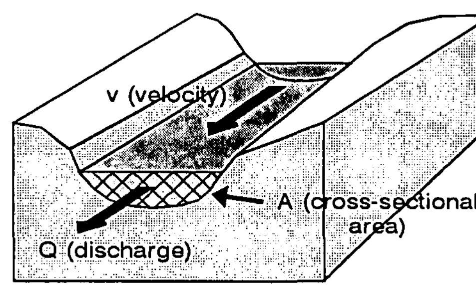


NOTES

CONTROLS ON INFILTRATION

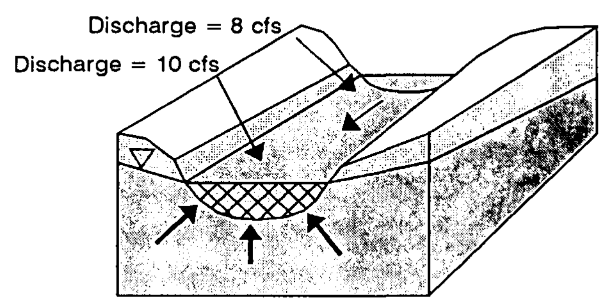
- Soil moisture
- Compaction of soil
- Microstructures in the soil
- Vegetative cover
- Temperature
- Surface gradient

STREAM FLOW



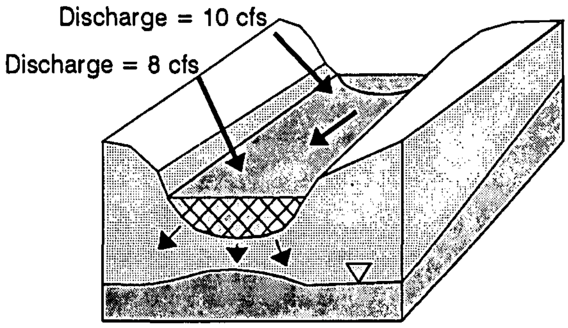
$Q = Av$

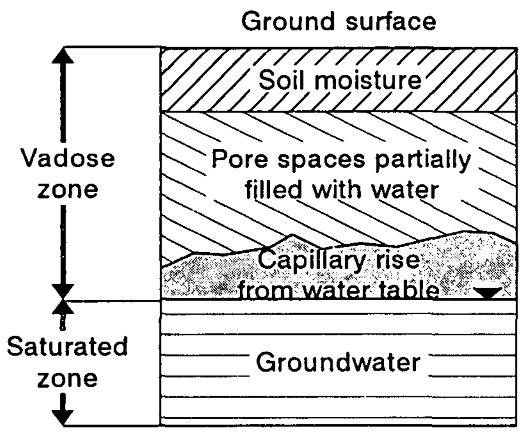
GAINING STREAM



NOTES

LOSING STREAM





POROSITY
(n)

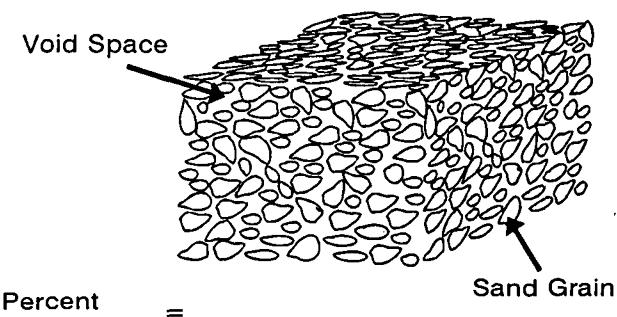
The volumetric ratio between the void spaces (V_v) and total rock (V_t):

$$n = \frac{V_v}{V_t} \quad ; \quad n = S_y + S_R$$

NOTES

PRIMARY POROSITY

Refers to voids that were formed at the same time the rock was formed



Percent Porosity =

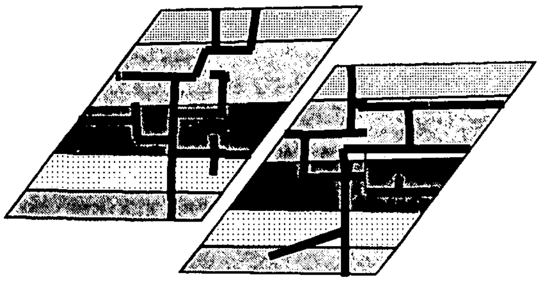
$$\frac{\text{Total Volume - Volume Soil Particles}}{\text{Total Volume}} \times 100$$

SECONDARY POROSITY

Refers to voids that were formed after the rock was formed

NOTES

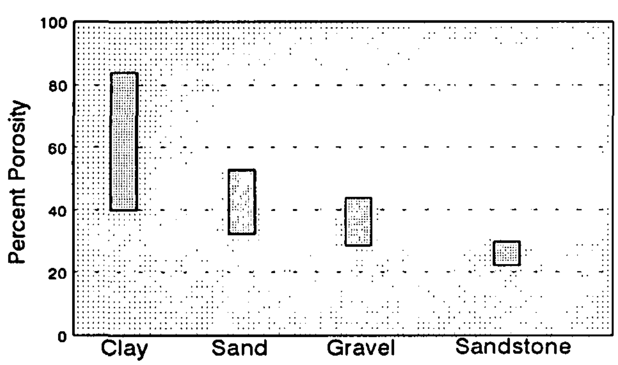
SECONDARY POROSITY



PERMEABILITY

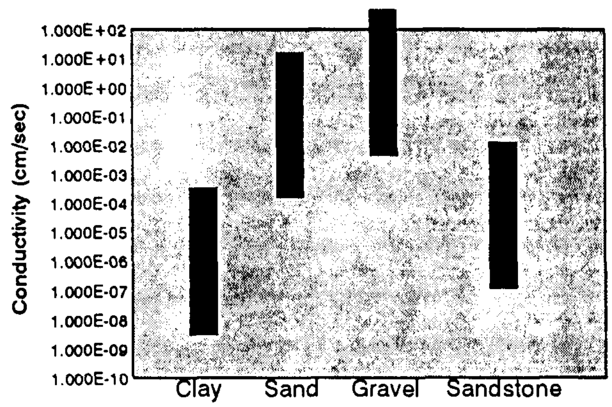
The ease with which water will move through a porous medium

POROSITY



NOTES

CONDUCTIVITY



AQUIFER

A permeable geologic unit with the ability to store, transmit, and yield water in usable quantities

AQUITARD

A layer of low permeability that can store and transmit groundwater from one aquifer to another

NOTES

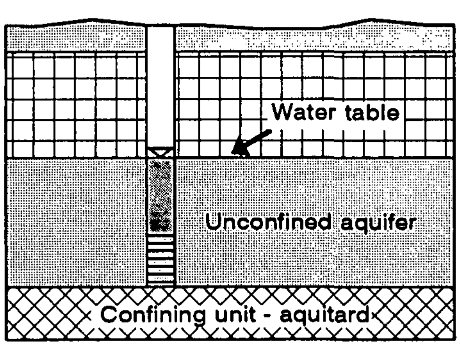
AQUICLUDE

A confining layer with low permeability that is essentially impermeable

UNCONFINED AQUIFER
(Water Table)

A permeable geologic unit having the ability to store, transmit, and yield water in usable quantities

UNCONFINED AQUIFER

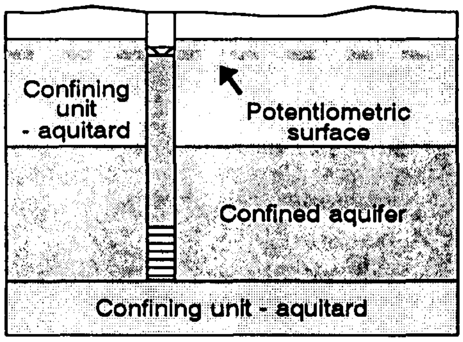


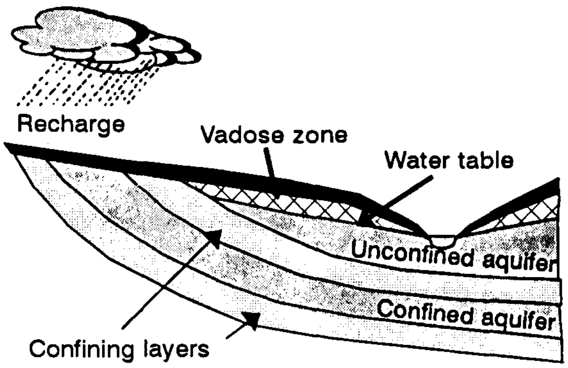
NOTES

CONFINED AQUIFER
(Artesian)

An aquifer overlain by a confining layer whose water is under sufficient pressure to rise above the base of the confining layer if it is perforated

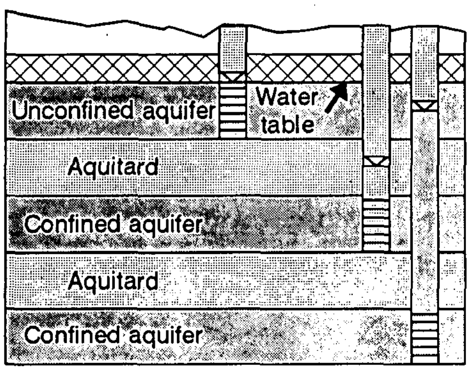
CONFINED AQUIFER



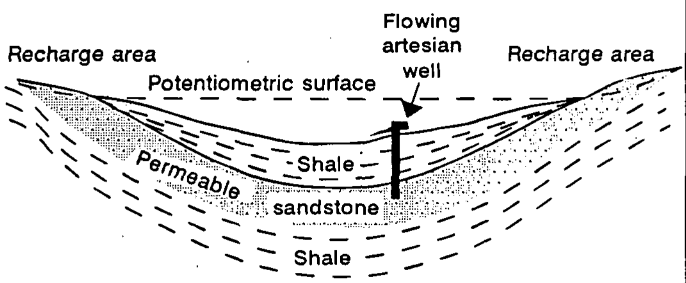


NOTES

AQUIFERS AND AQUITARDS



ARTESIAN GROUNDWATER SYSTEM



POTENTIOMETRIC SURFACE

The elevation that water will rise to in an opening (well) if the upper confining layer of a confined aquifer is perforated

NOTES

TOTAL HEAD
(h_t)

- Combination of elevation (z) and pressure head (h_p)

$$h_t = z + h_p$$

- Total head is the energy imparted to a column of water

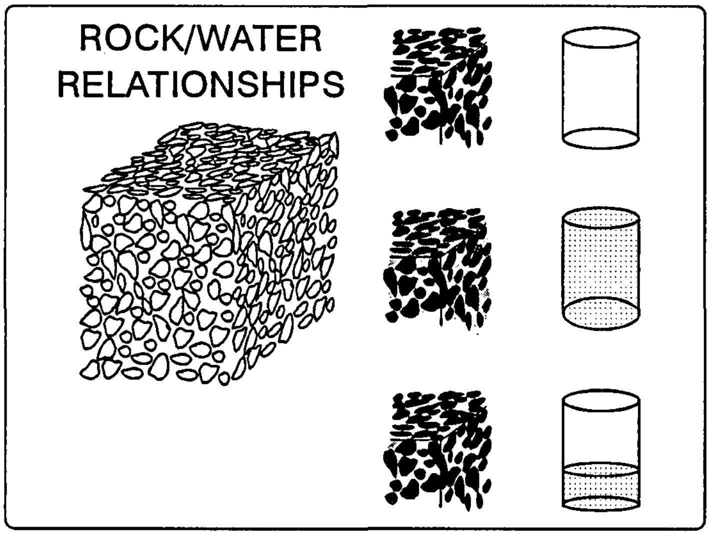
SPECIFIC RETENTION
(S_R)

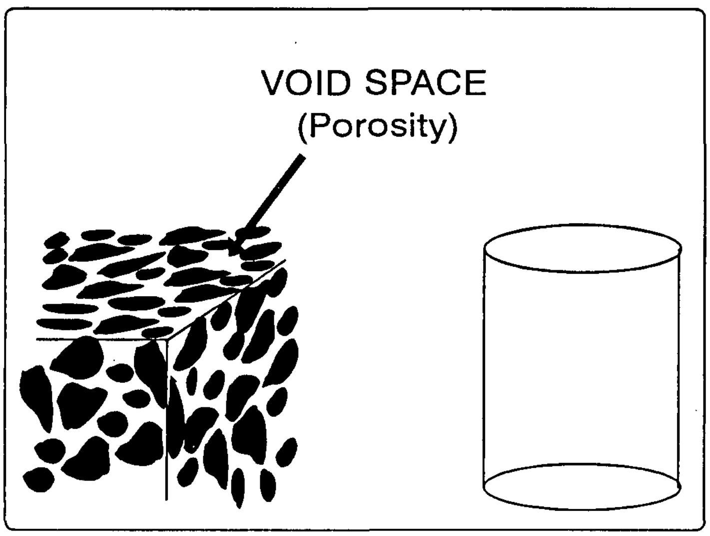
The water in an aquifer that will not drain by gravity and remains attached to the aquifer media

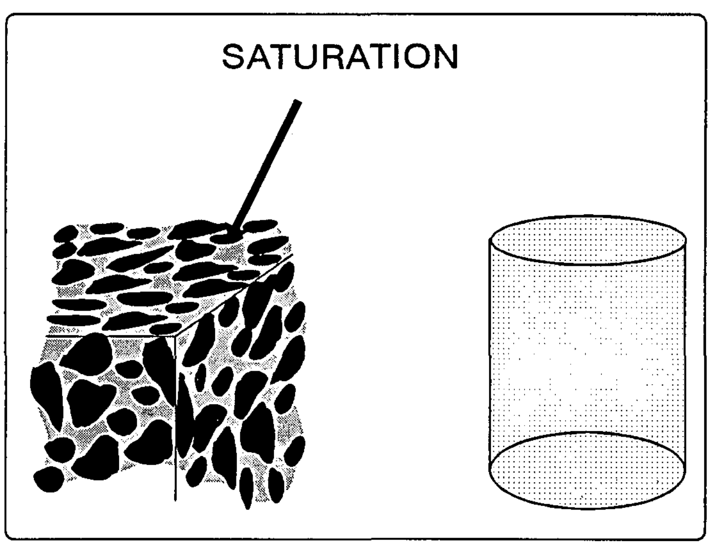
SPECIFIC YIELD
(S_Y)

The water in an aquifer that will drain by gravity

NOTES



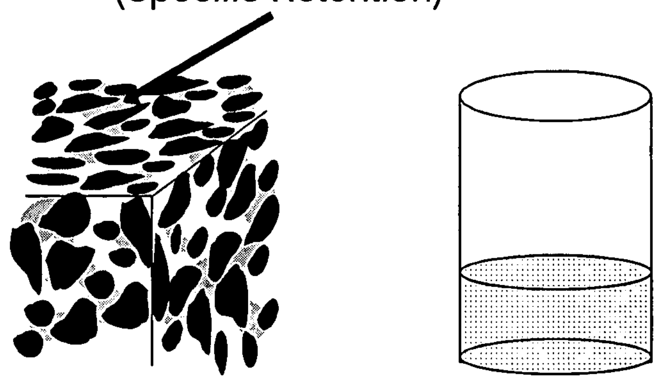




NOTES

WATER RETAINED AFTER GRAVITY DRAINAGE

(Specific Retention)



HYDRAULIC CONDUCTIVITY (K)

The volume of flow through a unit cross section of an aquifer per unit decline of head

HOMOGENEOUS

Hydraulic conductivity is not dependent on position within a geologic formation

NOTES

HETEROGENEOUS

Hydraulic conductivity is dependent on position within a geologic formation

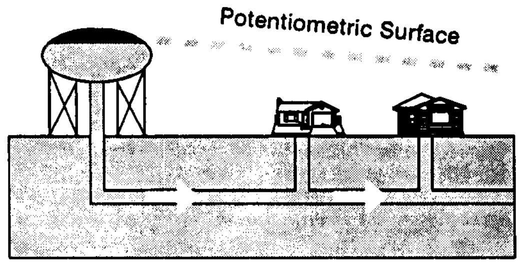
ISOTROPIC

Hydraulic conductivity is independent of the direction of measurement at a point in a geologic formation

ANISOTROPIC

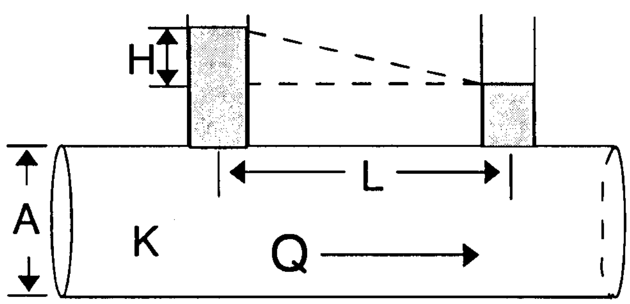
Hydraulic conductivity varies with the direction of measurement at a point in a geologic formation

NOTES



DARCY'S LAW

- The flow rate through a porous material is proproportional to the head loss and inversely proportional to the length of the flow path
- Valid for laminar flow
- Assume homogeneous and isotropic conditions



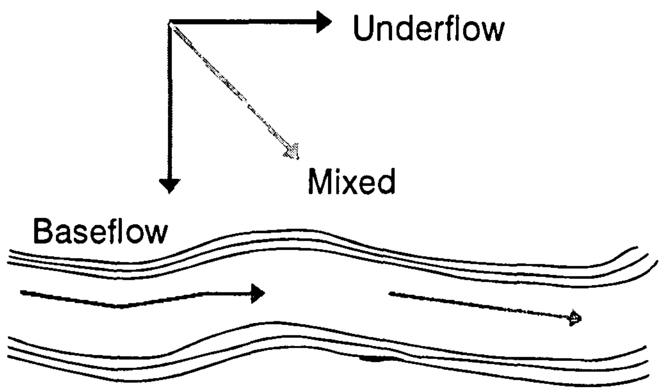
Gradient = H/L = I, the energy required to move water the distance L
Q = quantity of flow(gpd)
A = cross-sectional area of flow(ft^3)
K = hydraulic conductivity = gpd/ft^3

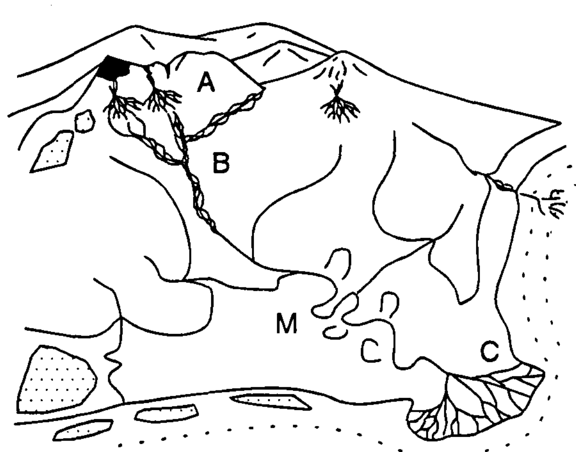
NOTES

DARCY'S LAW
Q = KIA

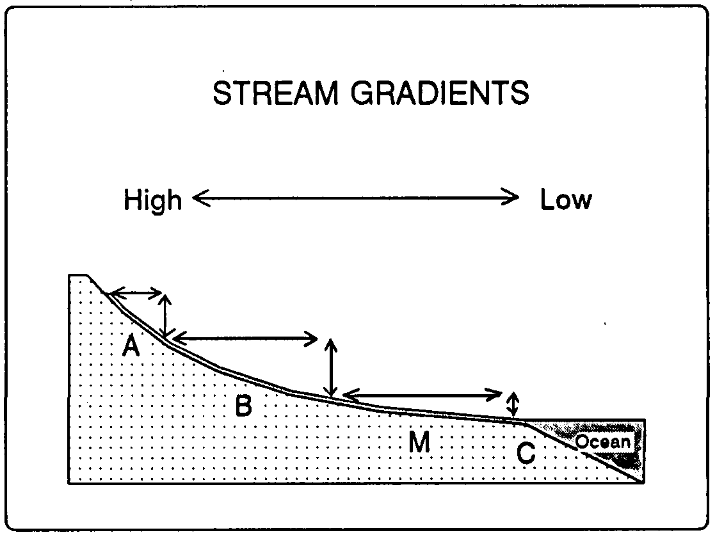
- Q = discharge
- K = hydraulic conductivity
- I = hydraulic gradient
- A = area

GROUNDWATER FLOW DIRECTION

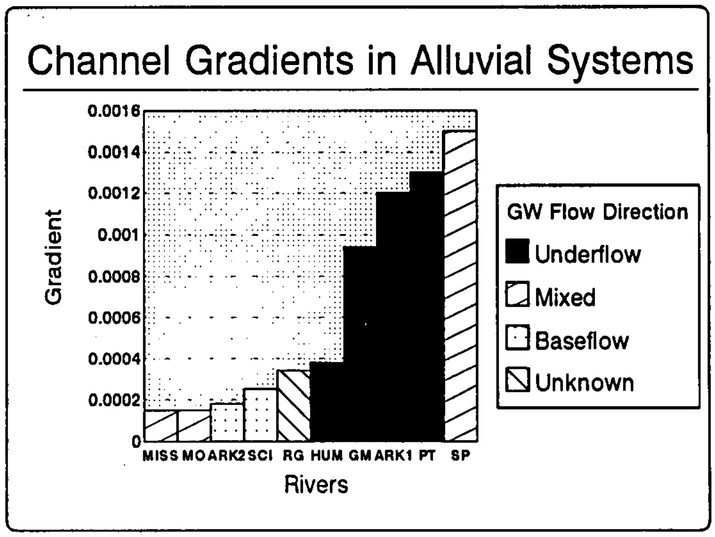




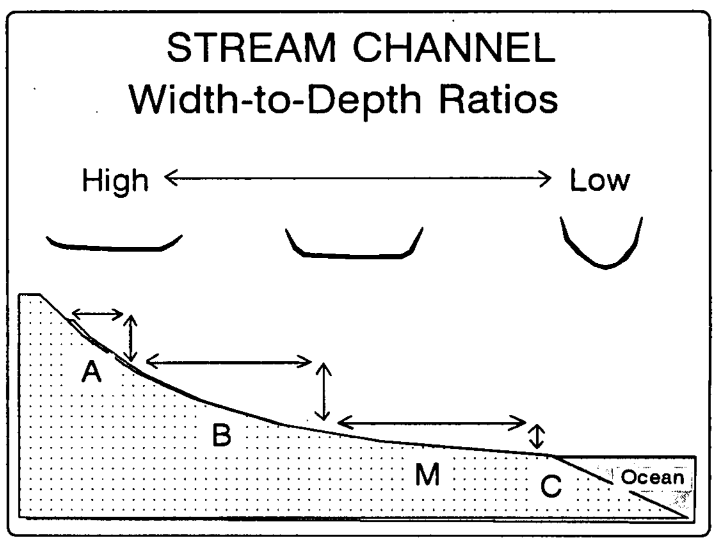
NOTES



STREAM GRADIENTS
High
Low
A
B
M
C
Ocean

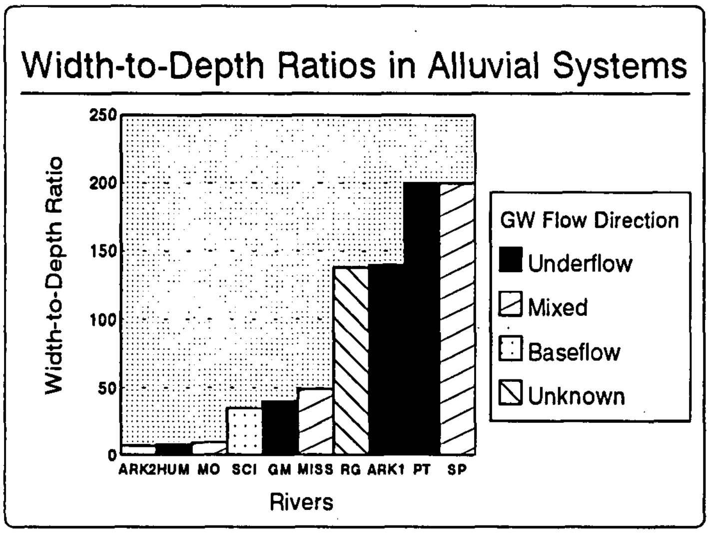


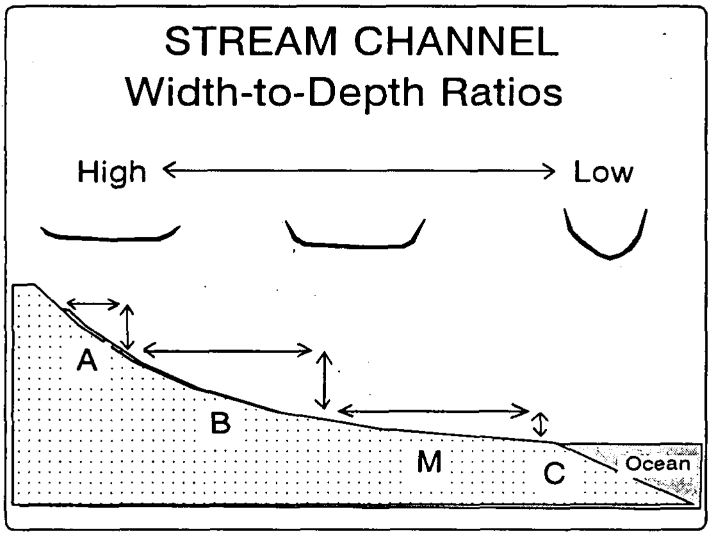
Channel Gradients in Alluvial Systems
Gradient
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
MISS MO ARK2 SCI RG HUM GM ARK1 PT SP
Rivers
GW Flow Direction
Underflow
Mixed
Baseflow
Unknown

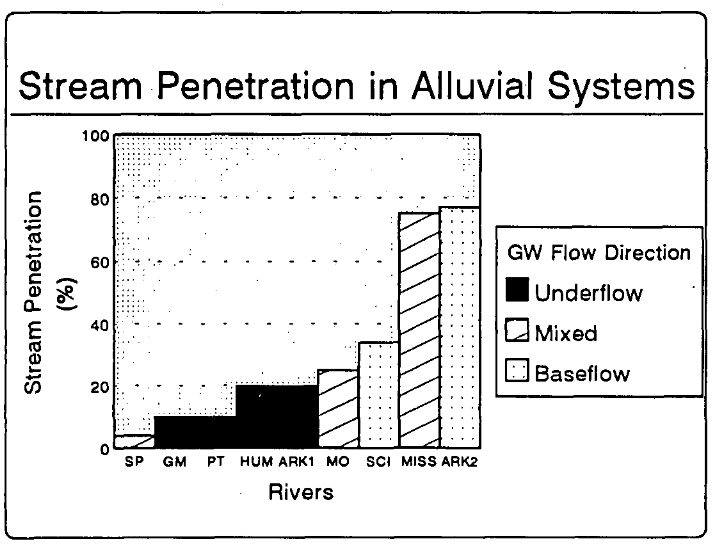


STREAM CHANNEL
Width-to-Depth Ratios
High
Low
A
B
M
C
Ocean

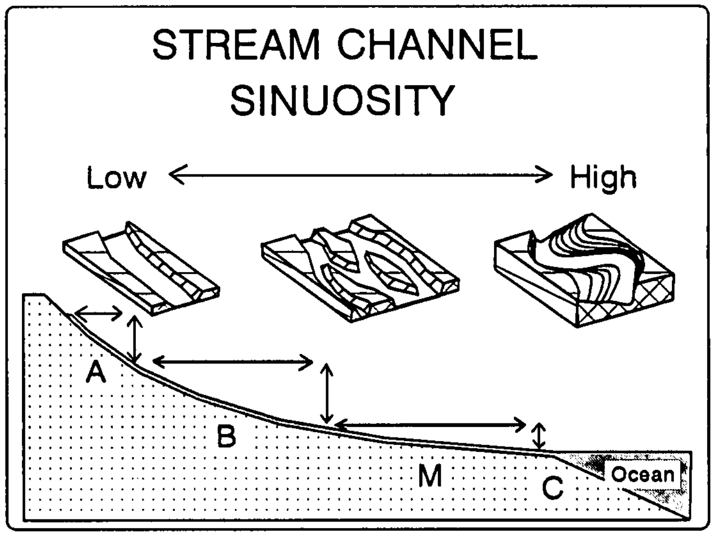
NOTES

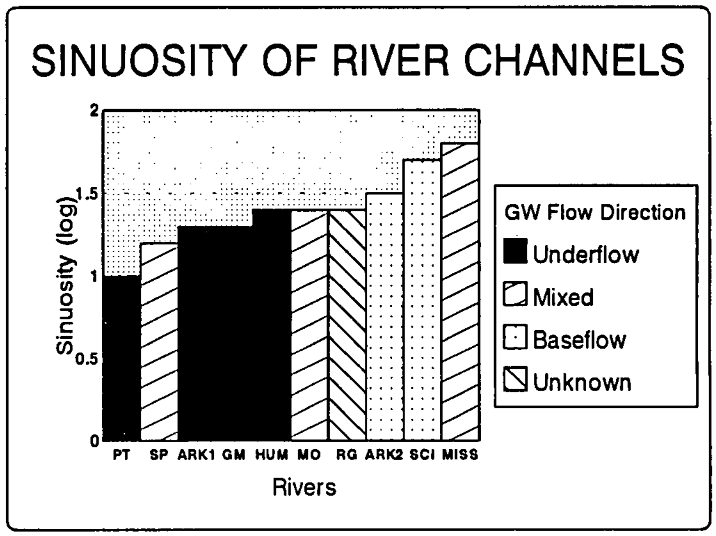

Width-to-Depth Ratios in Alluvial Systems
Width-to-Depth Ratio
250
200
150
100
50
0
ARK2 HUM MO SCI GM MISS RG ARK1 PT SP
Rivers
GW Flow Direction
Underflow
Mixed
Baseflow
Unknown

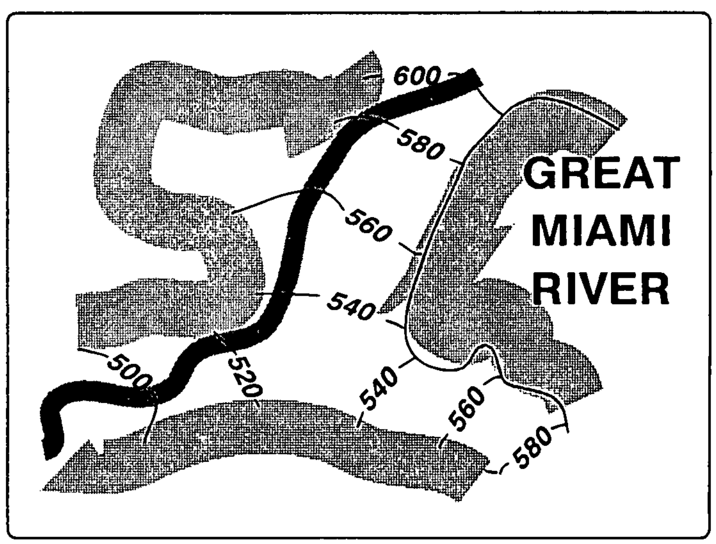

STREAM CHANNEL
Width-to-Depth Ratios
High
Low
A
B
M
C
Ocean


Stream Penetration in Alluvial Systems
Stream Penetration (%)
100
80
60
40
20
0
SP GM PT HUM ARK1 MO SCI MISS ARK2
Rivers
GW Flow Direction
Underflow
Mixed
Baseflow

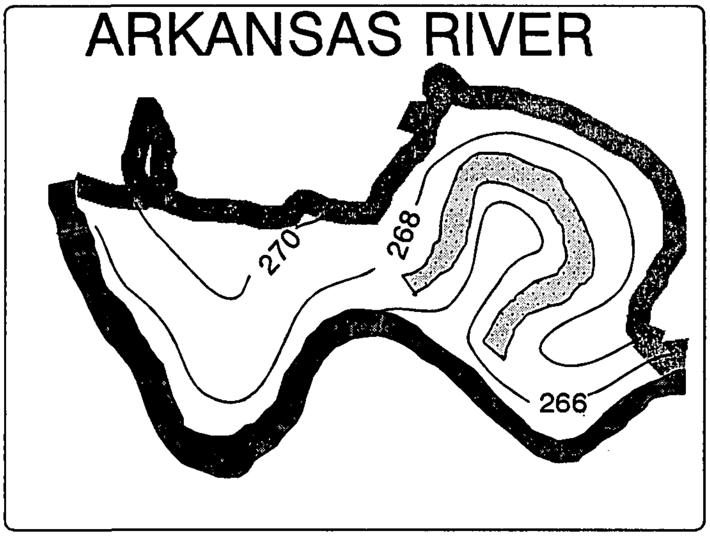
NOTES

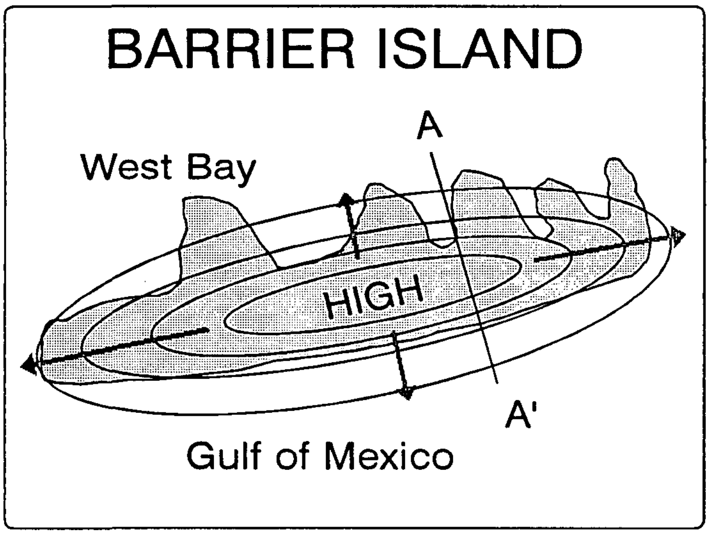

STREAM CHANNEL
SINUOSITY
Low
High
A
B
M
C
Ocean

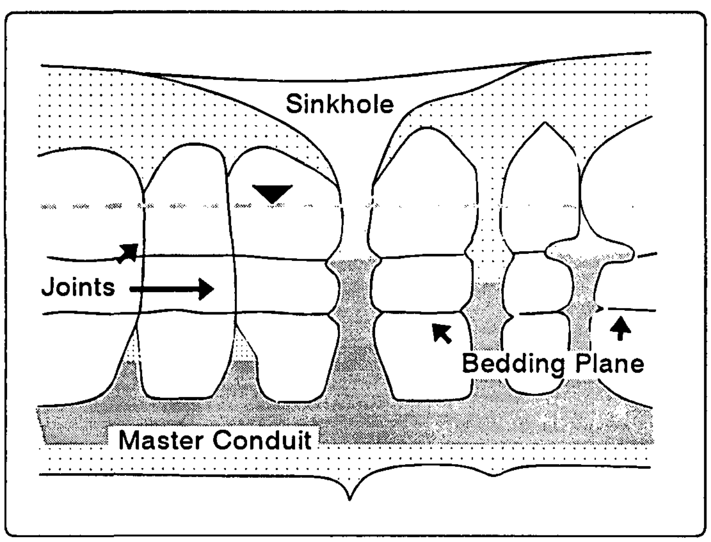

SINUOSITY OF RIVER CHANNELS
Sinuosity (log)
2
1.5
1
0.5
0
PT SP ARK1 GM HUM MO RG ARK2 SCI MISS
Rivers
GW Flow Direction
Underflow
Mixed
Baseflow
Unknown


GREAT
MIAMI
RIVER
600
580
560
540
520
500
540
560
580

NOTES


ARKANSAS RIVER
270
268
266


BARRIER ISLAND
A
West Bay
HIGH
A'
Gulf of Mexico


Sinkhole
Joints
Bedding Plane
Master Conduit

Section 3

THE HYDROGEOLOGICAL INVESTIGATION

PERFORMANCE OBJECTIVES

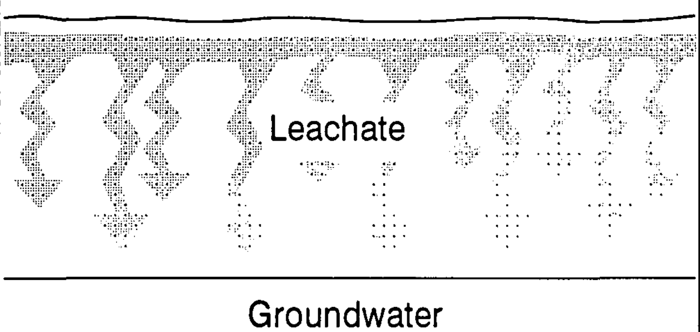
At the end of this lesson, participants will be able to:

- Describe three types of hydrogeological investigations
- Given a list of seven elements involved in conducting a hydrogeological investigation, describe the processes involved in accomplishing each element
- List three pertinent questions that must be addressed when investigating groundwater contamination.

NOTES

THE HYDROGEOLOGICAL INVESTIGATION

CONTAMINATION



REGIONAL INVESTIGATIONS

- Cover large areas (10-100 square miles)
- Are used to
  - Locate potential sources
  - Determine regional geology
  - Determine regional hydrology

NOTES

REGIONAL INVESTIGATIONS

- Include evaluation of
  - General geology
  - General hydrology
  - Regional water quality
- Are not detailed studies

REGIONAL INVESTIGATION OF COLBERT LANDFILL, SPOKANE, WA

Geology and hydrology

"...hydrogeologic conditions...

...dominated by...

...most recent glacial period..."

REGIONAL INVESTIGATION OF COLBERT LANDFILL, SPOKANE, WA

Climate

"...values at site...are similar...

...to airport...

...because elevations are...

...similar."

NOTES

LOCAL INVESTIGATIONS

- Cover few square miles
- Are used to
  - Define geology, hydrology, geochemistry, and water quality
  - Locate sources

LOCAL INVESTIGATIONS

- Include
  - Topographic maps, geologic maps, soils maps, well location maps, and source locations
- Are more detailed studies

LOCAL INVESTIGATION OF COLBERT LANDFILL, SPOKANE, WA

Hydrogeology

"...system...defined as containing three aquifers and three aquitards."

NOTES

SITE INVESTIGATIONS

- Cover immediate area of site
- Are used to determine
  - Site geology
  - Site hydrology
  - Contaminant migration controls

SITE INVESTIGATIONS

- Include
  - Water level maps, geophysical surveys, soil samples, water samples, tank location maps, tank inventories, and monitoring wells
- Are most detailed (expensive) studies

CONDUCTING THE INVESTIGATION

1. Establish objectives
2. Collect data
3. Conduct field investigation
4. Compile data
5. Interpret data
6. Develop conclusions
7. Present results

NOTES

ESTABLISH OBJECTIVES

- Detection
- Monitoring
- Site evaluation
- Selection of control methods
- Selection of treatment/remedial methods

ESTABLISH THE OBJECTIVES COLBERT LANDFILL, SPOKANE, WA

Focus

- Do affected residents have supplied water?
- Is the landfill a continuing source?
- What are extent and processes for offsite movement?

COLLECT DATA Research Records

- Maps (soil, geologic, topographic, county, and state)
- Aerial photographs
- Location of pumping centers (wells) and discharge rates
- Stream discharge

NOTES

AERIAL PHOTOGRAPHY

- Historical photography (1920 - present)
- Contract photography (current site)

EPIC

Environmental Photographic Interpretation Center

Western Region - EMSL/Las Vegas, Nevada
Eastern Region - EPA-EPIC/Warrenton, Virginia

USDA ASCS

(Agricultural Stabilization & Conservation Service)

Aerial Photography Field Office
Salt Lake City, Utah
(801) 525-5856

1945 - present
black & white
color infrared

NOTES

SANBORN FIRE INSURANCE MAPS

- 1869 to 1950s
- Communities over 2000 population
- Updated periodically
- Locations of industries, pipelines, storage vats, old dumps, and wetlands

COLLECT DATA Research Records

- Well logs
- Climatological data
- Chemical data
- Source or potential source location

COLLECT BACKGROUND DATA COLBERT LANDFILL, SPOKANE, WA

Previous site use

"...electronics manufacturing...

...spent organic solvents...

...poured...down sides...

...hundred gallons a month."

NOTES

INFORMATION SOURCES

- U.S. Geological Survey
- State water commission
- State geological survey
- Departments of agriculture

INFORMATION SOURCES

- Soil Conservation Service
- Weather service
- Site records
- University research (theses, papers, etc.)

CONDUCT FIELD INVESTIGATION (After Record Search)

- Note topography
- Locate outcrops
- Note joint patterns
- Measure stream flow
- Measure stream temperature
- Note stream patterns

NOTES

CONDUCT FIELD INVESTIGATION COLBERT LANDFILL, SPOKANE, WA

Monitoring wells

"...intended to compliment...

...wells installed during...

...previous investigations..."

CONDUCT FIELD INVESTIGATION (After Record Search)

- Note flora
- Locate springs and seeps
- Conduct geophysical survey
- Note soil characteristics
- Note rock type
- Install monitoring wells

CONDUCT FIELD INVESTIGATION (After Record Search)

- Measure water levels
- Conduct aquifer tests
- Note aquifer thickness
- Note confining layers
- Determine hydrogeologic characteristics
- Determine limits (hydrologic, geologic, and climatic)

NOTES

CONDUCT FIELD INVESTIGATION COLBERT LANDFILL, SPOKANE, WA

Soil characteristics

"...percolation tests indicate..

...surface runoff...

...occurs very infrequently..."

CONDUCT FIELD INVESTIGATION (After Record Search)

- Conduct tracer studies
- Note hydraulic connections
- Collect samples
- Determine background water quality
- Identify types of contaminants
- Locate potential sources
- Determine types of aquifers involved

COMPILE DATA

- Prepare water level maps
- Prepare cross sections
- Plot potentiometric surface
- Determine contaminant mobility characteristics

NOTES

COMPILE DATA
COLBERT LANDFILL, SPOKANE, WA

Contaminant mobility

- Moving with gravity - DNAPLs
- Solubilized in groundwater flow
- Volatilized in vadose - molecular diffusion

INTERPRET DATA

- Locate recharge areas
- Locate discharge areas
- Identify sources (responsible parties)
- Predict contaminant impact and fate

INTERPRET DATA
COLBERT LANDFILL, SPOKANE, WA

Identify responsible parties

"...'secondary' sources...

...may be major source...

...continued contamination..."

NOTES

DEVELOP CONCLUSIONS

- Is there a problem?
- How bad is it?
- Who is responsible?
- Can it be remediated?
- How?

PRESENT RESULTS

- Review of reports by others (responsible parties, consultants, etc.)
- Formal report of investigation
- Hearings
- Public meetings

CHECKLIST FOR A HYDROGEOLOGICAL INVESTIGATION

HAZARDOUS WASTE SITES INFORMATION LIST

When evaluating activities at sites where hazardous wastes may be causing or contributing to groundwater contamination, it is important to gather as much information as possible. The development of as much site information as possible can often provide valuable insight about site history, waste disposal practices, regional and local geology and the potential for impacts to the environment in the site vicinity.

In order to make your information gathering efforts easier, what follows is a list of the types of questions which may be helpful to a site investigation. While these questions are oriented more towards field activities, the questions also may prove to be helpful to those people responsible for evaluating the adequacy of other site assessment documents.

Sources

National Water Well Association. 1991. Groundwater and Unsaturated Zone Monitoring and Sampling. 45 pp. *In:* Practical Handbook of Groundwater Monitoring.

U.S. EPA. 1986. RCRA Ground Water Monitoring Technical Enforcement Guidance Document. 208 pp.

Stropes, D.F. 1987. Unpublished Research: Technical Review of Hazardous Wastes Disposal Sites. 25 pp.

I. SITE/FACILITY HISTORY

A. Waste disposal history of the site.

1. Is this a material spill or other emergency response activity not at a Toxic Substances Storage and Disposal Facility (TSSDF) ?

2. What hazardous wastes are being manufactured, stored, treated or disposed of at the site?

3. For active manufacturing operations, what industrial processes are being used and what raw materials are used in the industrial processes?

4. Are the raw materials altered or transformed in any way during industrial processes to result in waste materials which are different from the raw materials?

5. How long has the facility been in operation?

6. Have the types of hazardous wastes manufactured, stored, treated or disposed of at the site changed during the history of the site?

7. Have the industrial processes used at the site changed over the history of the site?

8. If the industrial processes are different, what previous industrial processes were used in the past, how long, and what types of wastes were end products of the processes.

9. What environmental media (air, land, water) have been or are being affected by the facility/site activities?

10. What is the form of the site wastes (sludge, slurry, liquid, powder, containerized, bulk storage)?

11. How much waste is generated or disposed of at the location daily?

12. What is the history of above and underground storage tank use at the site?

13. What types of regulated manufacturing or pollution control units exist at the facility?

14. What governmental agencies are responsible for the regulated units?

15. Do any historical records about the site exist? If so, where are these records?

16. Has a check of any existing historical maps or aerial photos been done to provide further insight as to past site activities?

17. Is there any history of groundwater contamination as a result of the site activities?

B. Details of the site disposal activities.

1. Are the site disposal units currently in compliance with all applicable rules, regulations and standards?

2. Are disposal areas isolated from the subsurface by the use of liners, impermeable material, etc.?

3. What type of isolating material is in use?

4. Are multiple isolation systems in use?

5. Is a leachate/contaminant collection system in use?

6. Are any monitoring wells installed adjacent to the disposal/collection system units?

7. Is there a surface water run-off control system?

8. Are any parts of the site/facility capped with an impermeable cover material?

9. What is the condition of the cap?

10. Are areas of previous wastes disposal well defined?

C. What is the nature of groundwater usage from aquifers beneath the site or in adjacent areas?

1. Do any water supply wells exist in the aquifers beneath the site and adjacent areas?

2. Are water supply wells used for potable water supplies or for industrial process water?

3. Is the groundwater treated prior to use?

4. What are the water supply wells' pumpage rates? Daily? Monthly? Annually?

5. What are the depths of the wells' screened intervals?

6. What other well drilling, well construction or well completion information is available?

7. Do subsurface geologic well logs exist for the wells?

8. Are the wells up gradient, at, or down gradient of the site/facility?

9. Does pumping from these wells modify the regional groundwater table or potentiometric surface?

II. HYDROGEOLOGIC CHARACTERIZATION

A. Has the purpose of the hydrogeologic investigation been clearly and adequately defined?

1. Characterize the hydrogeologic system at the site.

2. Determine whether there has been downgradient degradation of water quality from a potential source of contamination.

3. Determine the upgradient source of contamination at a known downgradient contamination receptor (well, spring, or surface water body).

B. Has the site location and all major site features been shown on a map?

1. Has the site been located on a state map?

2. Has the site been located on a USGS 7-1/2 minute topographic quadrangle map published at a scale of 1:25,000?

3. Have coordinates for further site identification (latitude, longitude, degrees, minutes, seconds, or a site specific grid system) been provided?

C. Has a base map of the site been prepared?

1. What is the map source?

2. Are air photos available?

3. Are all components of a map (north arrow, scale, map legend) shown and defined on the base map?

4. Does the map show elevations and contours?

5. Is the scale of the map adequate to delineate on-site features' dimensions adequately?

6. Does the map show features adjacent to the site which may be pertinent to the hydrogeologic investigation?

7. Are all natural physical features (topography, surface waters, surface water flow divides, etc.) shown on the map?

D. Has the subsurface geology been identified?

1. Is the geologic interpretation based on soil borings and well drilling logs?

2. Have any other reference materials been used?

3. Are aquifers present beneath the site?

4. Is the first aquifer encountered confined or unconfined?

5. Are all aquifers and confining units continuous across the site?

6. Have all geologic strata been described (thickness, rock type, unconsolidated/consolidated materials, depth, etc.)?

7. Do multiple aquifers exist at the site?

8. Have any porous versus fractured flow media been described?

E. Do the driller's logs of the deepest borings at each well cluster show that soil material samples were collected at five foot intervals? If not at what intervals were samples taken?

1. Is there a stratigraphic log of the deepest boreholes?

2. Were the borings extended to a depth below any confining beds beneath the shallowest aquifer?

3. Have enough borings of the area been done to adequately define the continuity and thickness of any confining beds?

4. Have all logs been prepared by a qualified geologist, soil scientist or engineer using a standardized classification system?

5. Were any laboratory tests conducted on the soil and soil material samples? What types of tests were performed?

6. Were grain size distributions used to determine the size of the gravel pack or sand filter placed in the annular space opposite the well screen?

F. Have field and/or laboratory permeability tests been performed to identify variations in aquifer and confining bed properties?

1. What type(s) of tests were performed?

2. What was the range of hydraulic conductivity values found in the aquifer? What was the arithmetic mean value?

3. What was the range of hydraulic conductivity values found in the confining bed? What was the arithmetic mean value?

4. Where are the most permeable subsurface zones located relative to the waste disposal facility?

5. Have geologic cross-sections been constructed?

G. Have field and/or laboratory tests been performed to determine the specific yield, storativity or effective porosity of the aquifer?

1. What type(s) of tests were performed?

2. What is the range of specific yield, storativity or effective porosity values?

3. What are the average values?

H. Has the horizontal groundwater flow direction been determined?

1. Have a minimum of three piezometers been installed to determine the direction of flow in the aquifer?

2. Do any water-level readings show local variations of the water table caused by mounds or sinks?

3. Do any identified mounds or sinks result in alterations of the regional or local horizontal groundwater direction of flow?

4. Do any surface features which may have an effect on the horizontal flow exist?

5. Have all piezometer installations in the uppermost aquifer been screened at approximately the same depth below the water table?

6. Do any discernible seasonal variations in water levels exist?

7. Do any short term variations in water levels exist? If so what possible causes may explain these variations?

I. Has the magnitude of the horizontal hydraulic gradient been determined at various locations across the site?

1. What is the average horizontal hydraulic gradient at the site?

2. Where is the horizontal hydraulic gradient the steepest?

3. Does this location correlate to a known area of lower hydraulic conductivity in the aquifer?

4. Does this location correlate to a known area of lower aquifer thickness?

5. Where is the horizontal hydraulic gradient the lowest (flat)?

6. Does this location correlate to a known area of greater hydraulic conductivity in the aquifer?

7. Does this location correlate to a known area of greater aquifer thickness?

J. If multiple aquifers exist, have wells been installed in each aquifer to determine the vertical component of groundwater flow?

1. Have the wells in each aquifer been installed in a single borehole or in separate boreholes?

2. If a single borehole was used, what tests were conducted to assure that no leakage between the upper and lower aquifers exist?

3. If a single borehole was used, what well installation, construction and development techniques were used to assure that no leakage between the upper and lower aquifers exist?

4. Based on the difference in hydraulic head between upper and lower aquifers can the site be described as:

   a. predominantly a recharge area?

   b. predominantly a discharge area?

   c. predominantly an area of horizontal flow?

5. If recharge, discharge or horizontal flow areas exist, have these locations been shown on a hydrogeologic map (including supporting cross-sections) of the site?

K. Has the magnitude of the vertical hydraulic gradients been determined at various locations across the site?

1. What is the average vertical hydraulic gradient at the site?

2. Where is the vertical hydraulic gradient the steepest?

3. Can this location be correlated to any known areas of lower hydraulic conductivity?

4. Where is the vertical hydraulic gradient the flattest?

5. Based upon the vertical hydraulic gradient, what relationship exists between the shallow and deeper aquifers?

6. Is there any regional or off-site vertical hydraulic gradient information which may support or conflict with the site's vertical hydraulic gradient data?

L. Determination of seepage velocities and travel times.

1. What is the average seepage velocity of water moving from the waste facility to the downgradient site boundary?

2. What is the average travel time of water to move from the waste facility to the nearest downgradient monitoring wells?

3. What is the basis for the seepage velocity and travel time determinations?

M. Have potentiometric maps, flow nets, geologic maps and cross-sections been prepared for the purpose of showing the direction of groundwater flow at the site?

Horizontal Flow Components (plan view)

1. Do the contours and contour intervals between the equipotential lines adequately describe the flow regime?

   Suggested Contour Intervals:

   a. 0.1 to 0.5 feet if the horizontal flow component is relatively flat.

   b. 0.5 to 1.0 feet if the horizontal flow component is moderately steep.

   c. 1.0 to 5.0 feet if the horizontal flow component is extremely steep.

2. Have the equipotential lines been accurately drawn?

   a. With respect to the elevations of water levels in the wells or piezometers?

   b. With respect to nearby or on-site rivers, lakes, wells or other boundary conditions?

   c. With respect to other naturally occurring or manmade physical features that might cause groundwater mounds or sinks in the area?

   d. Do variations in the spacing of equipotential lines correspond to known areas with relative transmissivity variations?

3. Do the constructed groundwater-flow lines cross equipotential lines at right angles?

4. Can conclusions about the aquifer(s) relative homogeneity and isotropy be made based on variations in the flow lines?

Vertical Flow Components (cross-sections)

1. Is the transect for the vertical flow component cross-section(s) laid out along the line of a groundwater flow path as seen in the plan view?

2. Is the variation in land-surface topography accurately represented on the cross-section(s)?

3. Have both vertical and horizontal scales been provided?

4. What differences exist between the vertical and horizontal scales?

5. Are all monitoring wells, piezometers, and screened intervals accurately shown?

N. What is the site water quality and geochemistry?

1. What are the upgradient-groundwater quality conditions?

2. What are the downgradient-groundwater quality conditions?

3. What water-quality parameters have been determined downhole?

4. What water-quality parameters have been determined at the well head?

5. Have all appropriate field water-quality determinations, equipment used and procedures been followed?

6. Does an adequate QA/QC procedure exist?

7. What if any, relationship exists between the site water-quality conditions and the past and/or present activities at the site?

III. DETECTION MONITORING SYSTEM

A. Are the facility upgradient and downgradient monitoring wells properly located to detect any water-quality degradation from the waste source(s)?

<u>Horizontal Flow</u>

1. Will groundwater from the upgradient well locations flow through or under the waste source in an unconfined aquifer?

2. Will groundwater from the upgradient well locations flow beneath the waste source and under an overlying confining bed in a confined aquifer?

3. Will groundwater from the upgradient well locations flow beneath the waste source in an unconfined aquifer separated from the waste source by an impervious liner?

4. Will groundwater from the waste-source area flow toward downgradient wells?

Vertical Flow

1. Are the monitoring wells correctly screened to intercept a possible contaminant plume from the waste source based on an accurate interpretation of the vertical flow regime (recharge area, discharge area, or area of horizontal flow)?

B. Are the monitoring wells located adequately to provide sufficient groundwater- flow information?

1. Are regional water levels unaffected by local groundwater mounds or sinks?

2. Are additional monitoring wells located to provide water-level information from local groundwater mounds or sinks?

3. Do upgradient and downgradient monitoring wells provide representative samples?

C. Monitoring Well Construction

1. Were precautions taken during the drilling of the borehole and installation of the well to prevent introduction of contaminants into the well?

2. Is the well casing and screen material inert to the probable major contaminants of interest?

3. What type of well casing and screen material was used?

4. Does the casing and screen material manufacturer have any available information about possible leaching of contaminants from the casing and screen material?

5. How are the well casing and screen segments connected?

6. If cement or glue has been used what is the potential for contaminants to leach into the groundwater?

7. Were all downhole well components steam cleaned prior to installation?

8. If another cleaning technique was used, what materials were used?

D. Are there as built drawings or details of each monitoring well nest or cluster showing depth of well, screen intervals, type and size of screen, length of screen and riser, filter packs, seals, protective casings, etc.?

1. Do the figures show design details of as built wells as opposed to details of proposed wells?

2. Are the well depth(s) and diameter(s) shown?

3. Are the screened intervals and type and size of screen openings shown?

4. Is the length of the screen shown?

5. Is the length of the riser pipe and stick-up above the land surface shown?

6. Is the filter pack around the screened interval shown?

7. Does the filter pack extend at least one foot above and below the screened intervals?

8. What type of sealant was placed in the annulus above the filter pack?

9. What is the thickness of the seal?

10. How was the seal put in place?

11. Will a protective casing or reinforced posts be necessary to protect the monitoring well from damage?

12. Is any manufacturer's information available to verify that all materials used in the well construction do not represent potential sources of water contamination?

13. Have samples of well construction materials used been kept for future analysis to verify that the materials do not represent sources of water contamination?

E. Are the screened intervals appropriate to the geologic setting and the sampling of a potential problem?

1. Is the screen set opposite a stratigraphic layer with relatively high hydraulic conductivity?

2. Is the screened interval set sufficiently below the water table so that water-level measurements can be taken and water samples can be collected during periods of low water level?

3. Is the screened interval placed in the aquifer(s) of concern?

4. If a single long screen was installed over the entire saturated thickness of the aquifer, what effect will this have on analytical data from this monitoring well?

5. Has the entire aquifer thickness been penetrated and screened?

6. Have piezometers been installed to determine vertical and horizontal flow directions?

7. Is the base of the waste disposal unit above the seasonal high water table?

8. What is the thickness of the unsaturated zone between the base of the waste disposal unit and the seasonal high water table?

F. Has a professional survey been conducted to determine the elevation and location of the measuring point at each well with reference to a common datum?

1. Is the survey at each monitoring well accurate to $\pm$0.01 feet?

2. Is each surveyed measuring point located at the top of the well casing?

3. What benchmark was used as a starting point for the survey?

4. Are the elevations of the measuring point at each well referenced to mean sea level and not some local datum?

G. Has an adequate sampling and analysis program been written for the site?

1. Are the major contaminants inorganic compounds?

2. Will field filtering and preservation be done in the field?

3. Are the major contaminants organic coumpounds?

4. Where would you expect to find the contaminants in the aquifer?

   a. Floating at the top of the aquifer (LNAPLs)?

   b. Dissolved in the groundwater and flowing with it?

   c. Concentrated at the bottom of the aquifer (DNAPLs)?

5. What are the possible degradation end products of the original organic contaminants?

6. Is the sampling method adequate to prevent any loss of volatile constituents?

7. Are field measurements such as pH, Eh, specific conductance, dissolved oxygen and temperature taken in the field?

8. Does a generic sampling and analysis protocol exist?

9. Does the sampling and analysis protocol address sample preservation, storage, transport, container identification and chain of custody procedures?

10. Is the analysis laboratory certified by EPA for the analyses to be performed?

11. Did the laboratory provide input to the sampling and analysis program?

12. Is the sampling and analysis program written, clear, concise, understandable and site specific?

H. Has a QA/QC plan been written for the groundwater monitoring program?

Water-Level Measurements

1. Have worksheets containing relevant fixed data, some of which are indicated below, been prepared for use by the person taking water-level readings?

    a. Well identification number?

    b. Location of measuring point of each well?

    c. Elevation of measuring point at each well relative to mean sea level?

    d. Elevations of screened interval at each well?

    e. Type of measuring instrument to be used?

2. Do the worksheets for use by the person taking water-level readings have columns for computation of:

    a. Depth to the water table?

    b. Measuring point data to be added to or subtracted from readings of measuring instrument?

    c. Adjusted depth to water surface?

    d. Conversion of depth to water surface?

3. Do the worksheets have a space for pertinent comments?

Sample Collection

1. Are well purging procedures prior to sampling described as written procedures?

2. Is the method of purging specified?

3. Is the sample collection technique specified?

4. Is the sample storage vessel described?

5. Is the sample volume specified?

6. Is the sample identification system described?

7. Are there provisions for:

   a. Trip blanks?
   b. Spiked samples?
   c. Duplicate, replicate or blind samples?

8. Is the sampling frequency specified?

<u>Sample Analysis</u>

1. Does the laboratory have a QA/QC program for all samples?

2. Is the QA/QC program written?

3. Does the laboratory provide information on the accuracy and precision of the analytical results?

4. Did the laboratory participate in the development of the sampling and analysis plan for the groundwater monitoring program and the QA/QC plan for the non-laboratory portion of the sampling program?

I. Is the QA/QC plan being followed during implementation of the sampling and analysis program?

   1. Is the same consultant who prepared the QA/QC plan responsible for its implementation?

   2. How many copies are there of the QA/QC plan?

   3. Who has copies and where are they located?

   4. Does the field person taking water-level measurements and collecting samples have a copy?

   5. Does the field person understand the importance of following the QA/QC plan explicitly each time?

   6. What safeguards and checks are there to assure there will be no deviation from the QA/QC plan in the field and the laboratory?

J. If any more field work or data will be necessary to meet the objectives of the hydrogeologic investigation, what types of additional field installations and data will be needed?

Section 4

GEOPHYSICAL METHODS

PERFORMANCE OBJECTIVES

At the end of this lesson, participants will be able to:

- Describe the five geophysical techniques listed below:

    1. Magnetics
    2. Electromagnetics (EM)
    3. Electrical resistivity
    4. Seismic refraction
    5. Ground-penetrating radar

- List the physical properties measured by the five geophysical techniques

- Identify interferences for each the geophysical technique

- Explain the need for geological control when making geophysical interpretations.

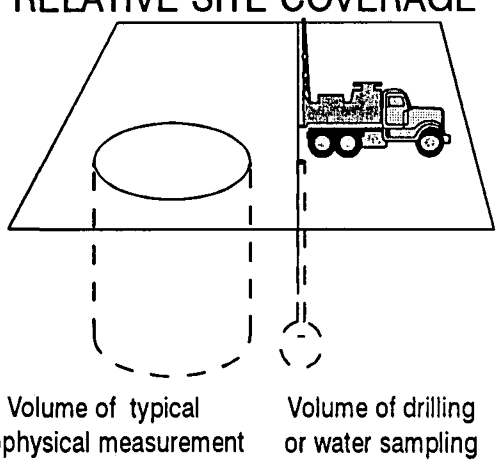
NOTES

GEOPHYSICAL METHODS

GEOPHYSICS

- Nonintrusive, investigative tool
- Methods are site specific
- Data must be "ground truthed"
- Professional interpretation necessary

RELATIVE SITE COVERAGE



NOTES

"GROUND TRUTHING"

Correlation of physical evidence (i.e., rock cores) to geophysical data

ANOMALY

Significant variation from background

GEOPHYSICAL TECHNIQUES

- Magnetics
- Electromagnetics (EM)
- Electrical resistivity
- Seismic refraction
- Ground-penetrating radar
- Borehole geophysics

NOTES

MAGNETICS

- Measurement of magnetic field strength in units of gammas
- Anomalies in magnetic field strength are primarily caused by variations in concentrations of ferromagnetic materials in the vicinity of the sensor

MAGNETICS Advantages

- Relatively low cost (cost-effective)
- Short time frame required
- Little, if any, site preparation needed
- Simple survey sufficient (Brunton)

MAGNETICS Disadvantages

- Cultural noise limitations
- Difficulty in differentiating between steel objects

NOTES

ELECTROMAGNETICS

- Based on physical principles of inducing and detecting electrical flow within geologic strata
- Measures bulk conductivity (the inverse of resistivity) of geologic materials beneath the transmitter and receiver coils
- Currents are induced by application of time-varying magnetic fields

ELECTROMAGNETICS
Advantages

- Rapid data collection with minimum personnel
- Lightweight, portable equipment
- Commonly used in groundwater pollution investigations

ELECTROMAGNETICS
Disadvantages

- Cultural noise limitations
- Limitations in areas where geology varies laterally (anomalies can be misinterpreted as plumes)

NOTES

ELECTRICAL RESISTIVITY

- Measures the bulk resistivity of the subsurface in ohm-meters
- Current is injected into the ground through surface electrodes

ELECTRICAL RESISTIVITIES OF GEOLOGIC MATERIALS

Function of:

- Porosity
- Permeability
- Water saturation
- Concentration of dissolved solids in pore fluids

ELECTRICAL RESISTIVITY Advantages

- Qualitative modeling is possible
- Models can be used to estimate depths, thicknesses, and resistivities of subsurface layers
- Layer resistivities can be used to estimate resistivity of saturating fluid

NOTES

ELECTRICAL RESISTIVITY
Disadvantages

- Cultural noise limitations
- Large area free from grounded metallic structures required
- Labor intensive (2-3 person crew)

SEISMIC TECHNIQUES

- Seismic refraction
- Seismic reflection

SEISMIC REFRACTION

- Measures travel time of acoustic wave refracted along an interface
- Most commonly used at sites where bedrock is less than 500 feet below ground surface

NOTES

SEISMIC REFRACTION
Advantages

- Can determine layer velocities
- Can calculate estimates of depths to different interfaces
- Can obtain subsurface information between boreholes
- Can determine depth to water table

SEISMIC REFRACTION
Assumptions

- Velocities of layers increase with depth
- Velocity contrast between layers is sufficient to resolve interface
- Geometry of geophones in relation to refracting layers will permit detection of thin layers

SEISMIC REFRACTION
Disadvantages

- Assumptions must be made
- Assumptions must be valid

NOTES

SEISMIC REFLECTION

- Measures travel time of acoustic wave reflected along an interface
- Precise depth determination cannot be made without other methods
- Magnitude of energy required is limiting factor

GROUND-PENETRATING RADAR

A transmitter emits pulses of high-frequency electromagnetic waves into the subsurface which are scattered back to the receiving antenna on the surface and recorded as a function of time

GROUND-PENETRATING RADAR

- Depth penetration is severely limited by attenuation of electromagnetic waves into the ground
- Attenuating factors
  - Shallow water table
  - Increase in clay content in the subsurface
  - Electrical resistivity less than 30 ohm-meters

NOTES

GROUND-PENETRATING RADAR
Advantages

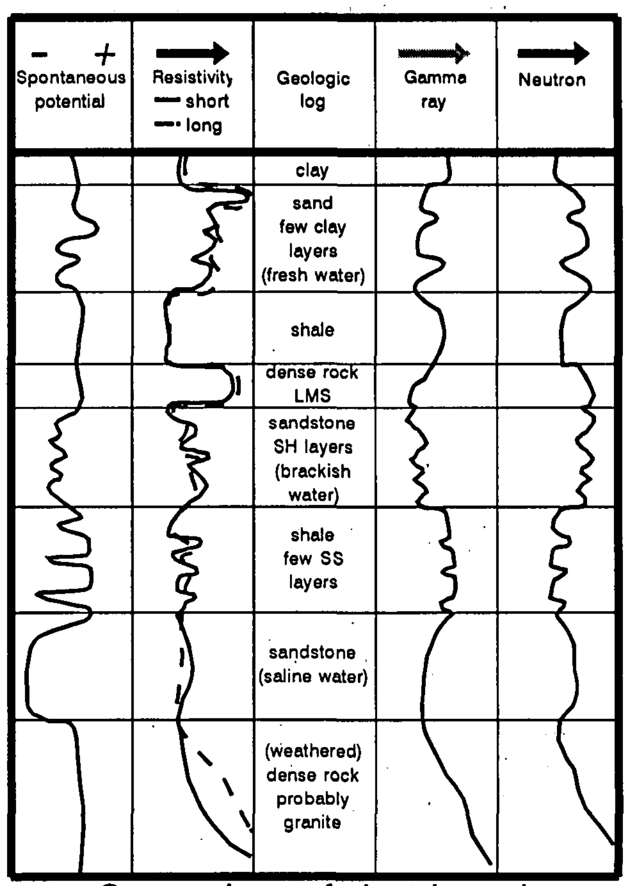
- Continuous display of data
- High resolution data under favorable site conditions
- Real-time site evaluation possible

GROUND-PENETRATING RADAR
Disadvantages

- Limitations of site-specific nature of technique
- Site preparation necessary for survey

BOREHOLE GEOPHYSICS

NOTES



Comparison of electric and radioactive borehole logs

BOREHOLE GEOPHYSICS

- Spontaneous potential
- Normal resistivity
- Natural-gamma
- Gamma-gamma

NOTES

BOREHOLE GEOPHYSICS

- Neutron
- Caliper
- Acoustic
- Temperature

SPONTANEOUS POTENTIAL

- Records natural potential between borehole fluid and surrounding materials
- Mainly used for geologic correlation, determining bed thickness, and separating nonporous from porous rocks (i.e., shale-sandstone, shale-carbonate)
- Can only be run in open, fluid-filled boreholes

RESISTIVITY

- Measures apparent resistivity of a volume of rock/soil surrounding the borehole
- Radius of investigation is generally equal to the distance between the borehole current and measuring electrodes
- Can only be run in open, fluid-filled boreholes

NOTES

GAMMA

- Measures the amount of natural-gamma radiation emitted by rocks/soils
- Main use is for identification of lithology and stratigraphic correlation
- Can be run in open or cased and fluid- or air-filled boreholes

GAMMA-GAMMA

- Measures the intensity of gamma radiation from a source in the probe after it is backscattered and attenuated in the rock/soils surrounding the borehole
- Main use is for identification of lithology and measurement of bulk density and porosity of rocks/soils
- Can be run in open or cased and fluid- or air-filled boreholes

NEUTRON

- Measures moisture content in the vadose zone and total porosity in sediments and rocks
- Neutron sources and detector are arranged in logging device so that output is mainly a function of water within the borehole walls
- Can be run in open or cased and fluid- or air-filled boreholes

NOTES

CALIPER

- Records borehole diameter and provides information on fracturing, bedding plane partings, or openings that may affect fluid transport
- Can be run in open or cased and fluid- or air-filled boreholes

ACOUSTIC

- A record of the transit time of an acoustic pulse emitted and received by the logging tool
- Response is indicative of porosity and fracturing in sediments or rocks
- Can be run in open or cased, fluid-filled boreholes

TEMPERATURE

- A continuous record of the temperature of the environment immediately surrounding the borehole
- Information can be obtained on the source and movement of water and the thermal conductivity of rocks
- Can be run in open or cased, fluid-filled boreholes

MONITORING THE VADOSE ZONE

PERFORMANCE OBJECTIVES

At the end of this lesson, participants will be able to:

- Describe the vadose zone
- List three reasons why the vadose zone is important in groundwater investigations
- Describe the principles of soil gas wells
- Describe the operation of pressure vacuum lysimeters
- Characterize the limitations of soil gas wells
- Characterize the limitations of vacuum lysimeters.

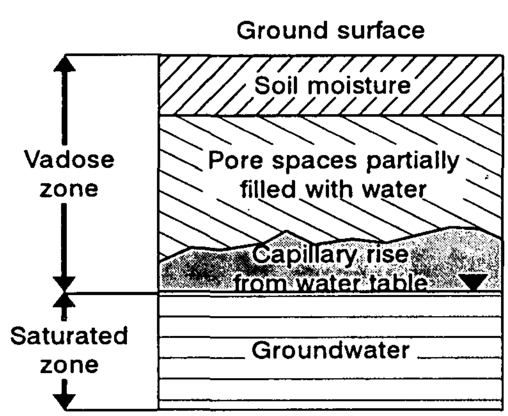
NOTES

MONITORING THE VADOSE ZONE

THE VADOSE ZONE

Consists of:

- Soils and particulate material
- Vapors in pore spaces
- Liquids on grain surfaces



NOTES

PHYSICAL PROPERTIES
Vadose Zone

- Organic matter
- Lithology/stratigraphy
- Thickness
- Grain size distribution

PHYSICAL PROPERTIES
Vadose Zone

- Water content
- Soil density
- Specific yield
- Specific retention

CHEMICAL CHARACTERISTICS
Vadose Zone

- Soil vapors/gases
- Pore water

NOTES

WATER QUALITY
Common Parameters

- Temperature
- pH
- Conductivity
- Chemical analysis

THE VADOSE ZONE

Consists of:

- Soils and particulate material
- Vapors in pore spaces
- Liquids on grain surfaces

TENSIOMETER

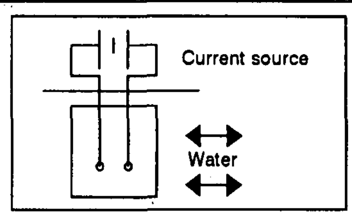
- Measures the capillary pressure in soil
- Advantages
  - Inexpensive
  - Durable
  - Easy to operate

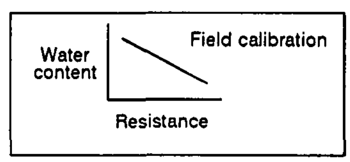
NOTES

TENSIOMETER

- Disadvantages
  - Ineffective under very dry conditions because of air entry
  - Sensitive to temperature changes
  - Sensitive to atmospheric pressure changes
  - Sensitive to air bubbles in lines
  - Requires a long time to achieve equilibrium

ELECTRICAL RESISTANCE BLOCKS





ELECTRICAL RESISTANCE BLOCK

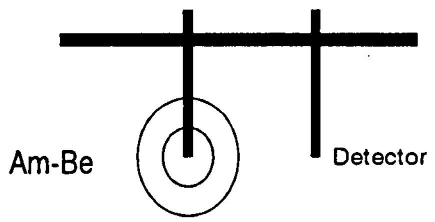
- Measures moisture content in soil
- Advantages
  - Suited for general use
  - Inexpensive
  - Can determine suction or moisture content
  - Requires little maintenance

NOTES

ELECTRICAL RESISTANCE BLOCK

- Disadvantages
  - Ineffective under very dry conditions
  - Sensitive to temperature
  - Calibration is time-consuming
  - Affected by salinity

NEUTRON MOISTURE LOGGING



- Neutrons from source are slowed down by hydrogen cloud
- Hydrogen sources are water and contaminants

NEUTRON MOISTURE LOGGING

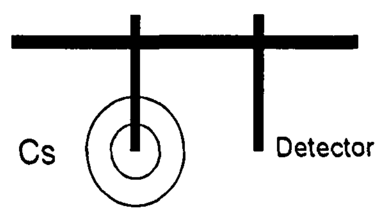
- Interacts with hydrogen in water
- Advantages
  - Readings directly related to soil moisture
  - Moisture content can be measured regardless of physical state

NOTES

NEUTRON MOISTURE LOGGING

- Disadvantages
  - Expensive
  - No information on soil-water pressure
  - No information on changes in density
  - Not accurate for small changes
  - Requires care in handling source
  - Requires license to use instrument

GAMMA-RAY ATTENUATION



- Changes in attenuation indicate differences in moisture content

GAMMA-RAY ATTENUATION

- Determines soil density
- Advantages
  - Can measure wetting front within 2 cm

NOTES

GAMMA-RAY ATTENUATION

- Disadvantages
  - Expensive
  - Radioactive source requires special care
  - Changes in bulk density affect calibration (e.g., swelling and frost heave)

PSYCHROMETER

- Measures relative humidity of soil water
- Advantages
  - Measures capillary pressure under very dry conditions

PSYCHROMETER

- Disadvantages
  - Very sensitive to temperature fluctuations
  - Expensive
  - Complex
  - Performs poorly in wet media

NOTES

FLOW RATES

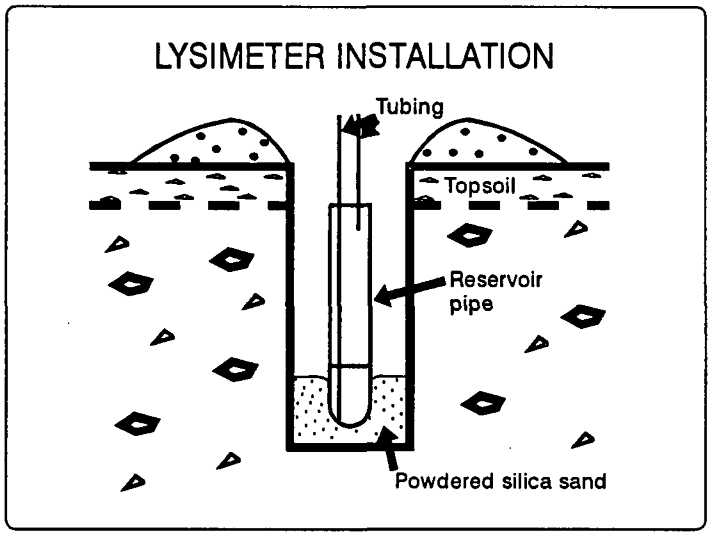
- Infiltrometers (constant head)
- Test basins (falling head)
- Water budgets (hydrologic cycle)
- Tracer studies
  - Dyes
  - Radioactive isotopes
  - Selected ions

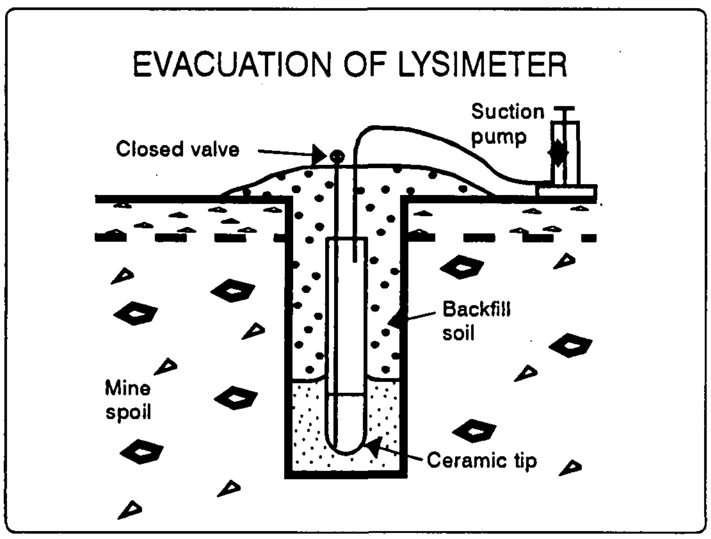
- Problem:
  Water is held under tension in the vadose zone and will not flow into wells
- Solution:
  Create an area of lower potential to induce flow into a sampling device

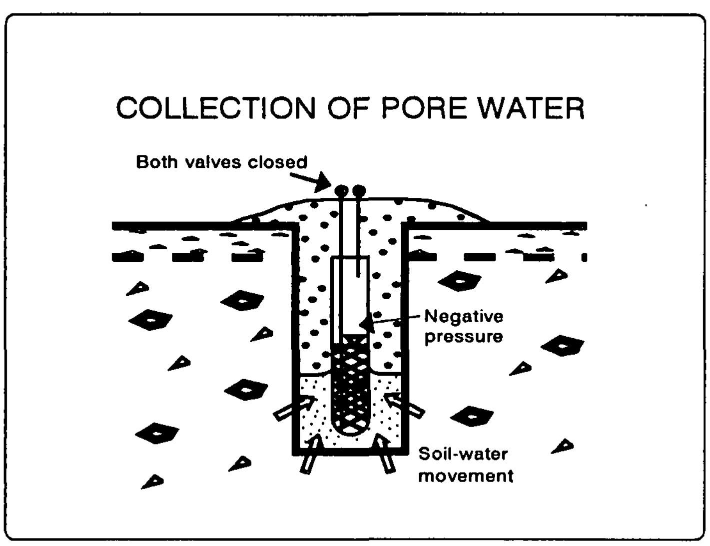
LYSIMETER

A device for sampling interstitial moisture in the unsaturated zone

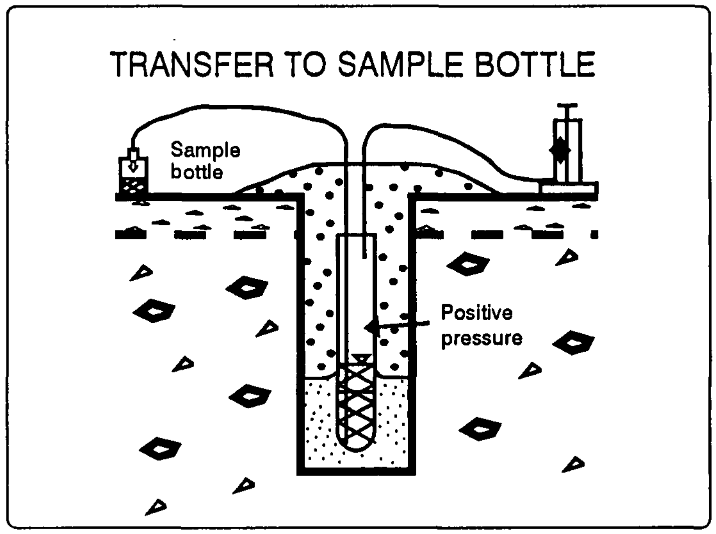
NOTES

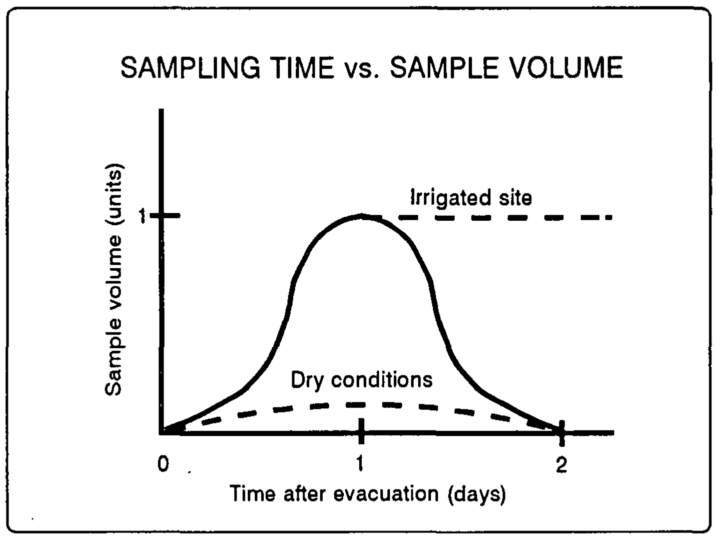

LYSIMETER INSTALLATION
Tubing
Topsoil
Reservoir pipe
Powdered silica sand

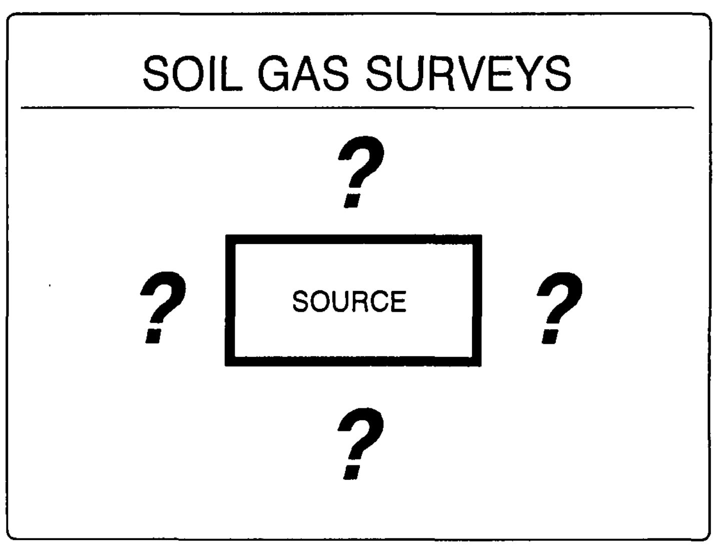

EVACUATION OF LYSIMETER
Closed valve
Suction pump
Backfill soil
Mine spoil
Ceramic tip


COLLECTION OF PORE WATER
Both valves closed
Negative pressure
Soil-water movement

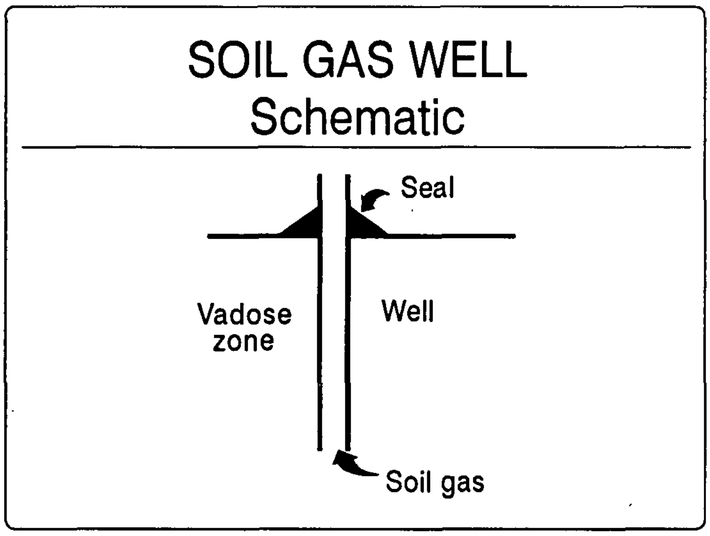
NOTES

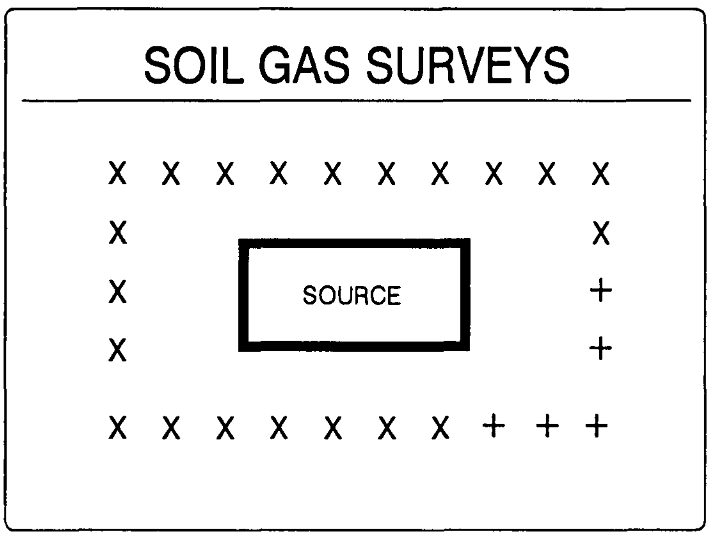

TRANSFER TO SAMPLE BOTTLE
Sample bottle
Positive pressure

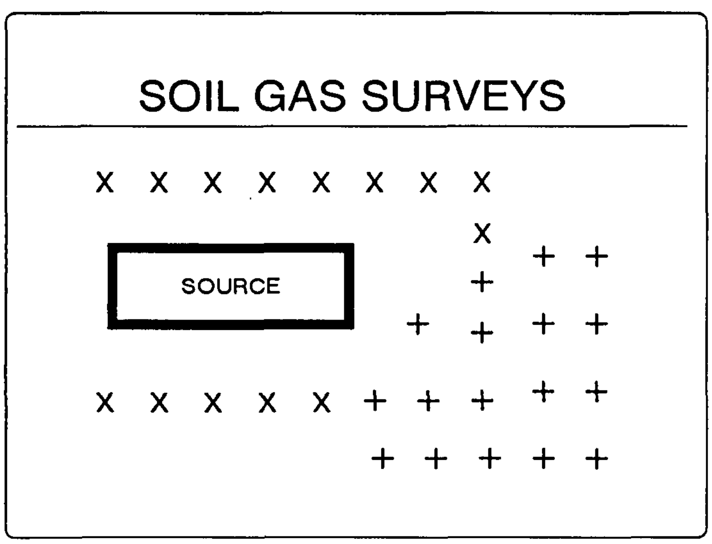

SAMPLING TIME vs. SAMPLE VOLUME
Sample volume (units)
1
Irrigated site
Dry conditions
0
1
2
Time after evacuation (days)


SOIL GAS SURVEYS
?
?
SOURCE
?
?

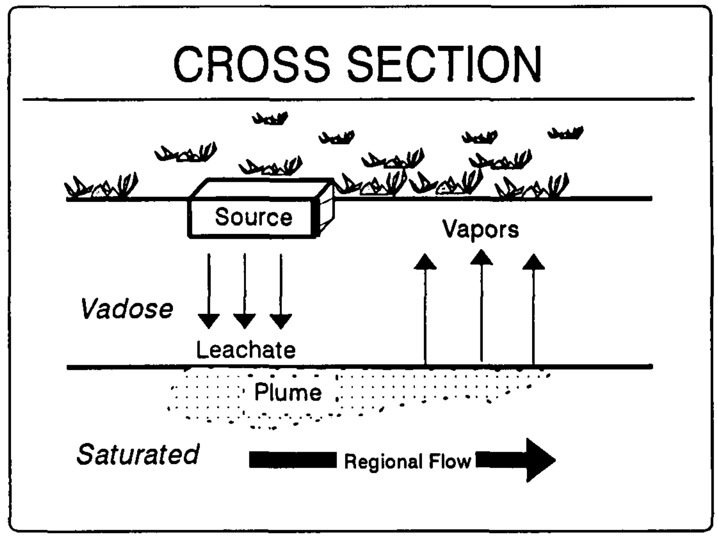
NOTES

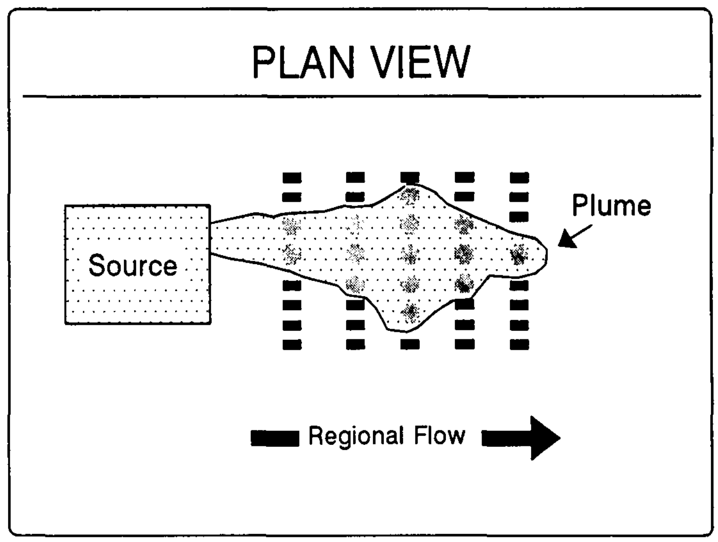

SOIL GAS WELL
Schematic
Seal
Vadose zone
Well
Soil gas


SOIL GAS SURVEYS
SOURCE


SOIL GAS SURVEYS
SOURCE

NOTES


CROSS SECTION
Source
Vapors
Vadose
Leachate
Plume
Saturated
Regional Flow


PLAN VIEW
Source
Plume
Regional Flow

Section 6

WELL CONSTRUCTION

PERFORMANCE OBJECTIVES

At the end of this lesson, participants will be able to:

- List six types of drilling methods
- Identify conditions under which the following types of drilling methods would be used:
    1. Air rotary
    2. Mud rotary
    3. Cable tool
    4. Hollow-stem auger
- Describe three methods of well development
- Define the major components of a monitoring well from a diagram
- List three uses for wells.

NOTES

WELL CONSTRUCTION

USES FOR WELLS

- Monitoring
- Remediation
- Lithology
- "Ground truthing"

TYPES OF DRILLING METHODS

- Mud rotary
- Air rotary
- Cable tool
- Reverse circulation
- Solid-stem auger
- Hollow-stem auger

NOTES

MUD ROTARY
Advantages

- Availability
- Satisfactory drilling in most formations
- Good depth capability
- Wide variety of formation logging
- Modest cost
- Good gravel pack and casing seal

MUD ROTARY
Disadvantages

- Requires drilling fluid
  - Difficult to remove
  - May affect sample integrity
- Circulates contaminants
- Mobility may be limited
- Poor rock or soil sample recovery

AIR ROTARY
Advantages

- No drilling fluid required
- Excellent drilling in hard rock
- Good depth capability
- Excellent delineation of water-bearing zones
- Potential to evaluate hydraulic properties of water-bearing zones

NOTES

AIR ROTARY
Disadvantages

- Casing may be required during drilling
- Cross contamination of different formations possible
- Limited equipment availability/mobility
- Difficult formation sampling
- High cost of drilling

CABLE TOOL
Advantages

- Good sample recovery
- Good delineation of water-bearing zones during drilling
- Highly mobile
- Good drilling in most formations
- Inexpensive

CABLE TOOL
Disadvantages

- Slow
- Requires driving casing in unconsolidated formations
- May be necessary to double case hole for good seal or gravel pack installation

NOTES

REVERSE CIRCULATION
Advantages

- Formation water is not contaminated by the drilling water
- Good sample recovery
- No caving in unconsolidated formations

REVERSE CIRCULATION
Disadvantages

- Not readily available
- Expensive
- Sealing of wells and placement of grout may be difficult

SOLID-STEM AUGER
Advantages

- Fast in shallow, unconsolidated formations
- Inexpensive to operate
- Highly mobile
- Requires no drilling fluid

NOTES

SOLID-STEM AUGER
Disadvantages

- Cannot be used in consolidated formations
- Limited depth capability (175-200 feet)
- Possible borehole collapse after auger is removed
- Difficult sampling

HOLLOW-STEM AUGER
Advantages

- Highly mobile
- No drilling fluid required
- Problems of hole caving minimized
- Soil sampling relatively easy

HOLLOW-STEM AUGER
Disadvantages

- Cannot be used in consolidated formations
- Limited depth capability (175-200 feet)
- Cross contamination of permeable zones is possible
- Limited casing diameter

NOTES

MONITORING WELL CONSTRUCTION

WELL CONSTRUCTION MATERIALS

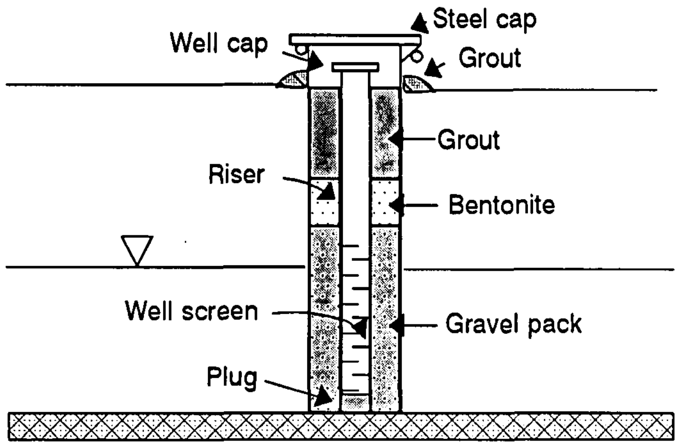
- Well screen/riser/well points
  - Teflon®
  - Stainless steel
  - PVC
- Sand/gravel/filter pack
- Bentonite/grout/cement

MONITORING WELL CONSTRUCTION

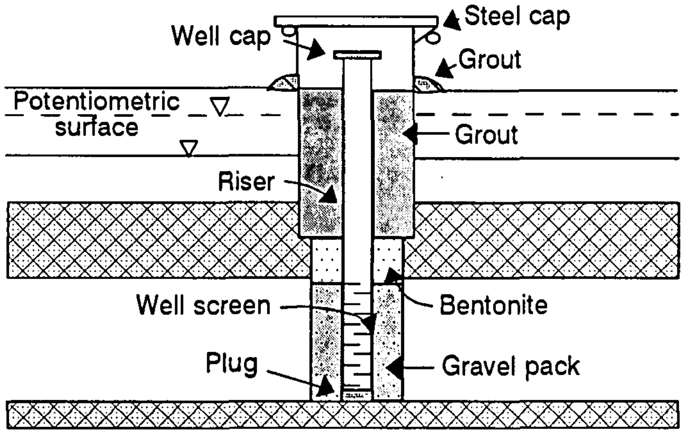
- Unconfined aquifer
- Confined aquifer

NOTES

MONITORING WELL - UNCONFINED AQUIFER



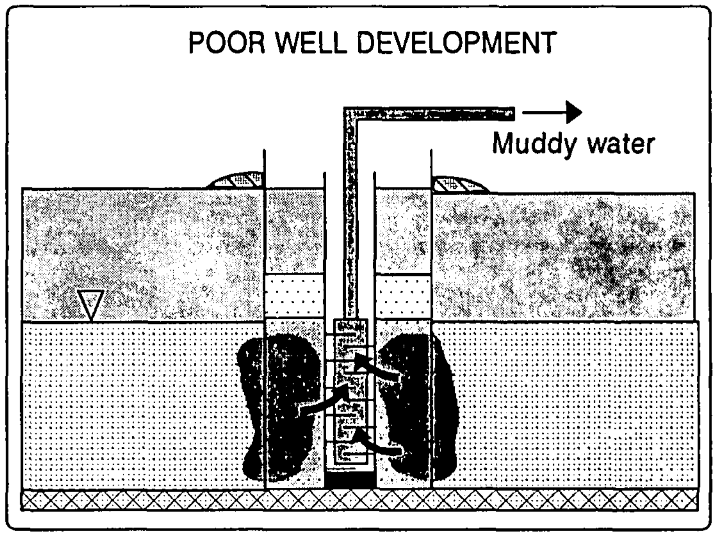
MONITORING WELL - CONFINED AQUIFER

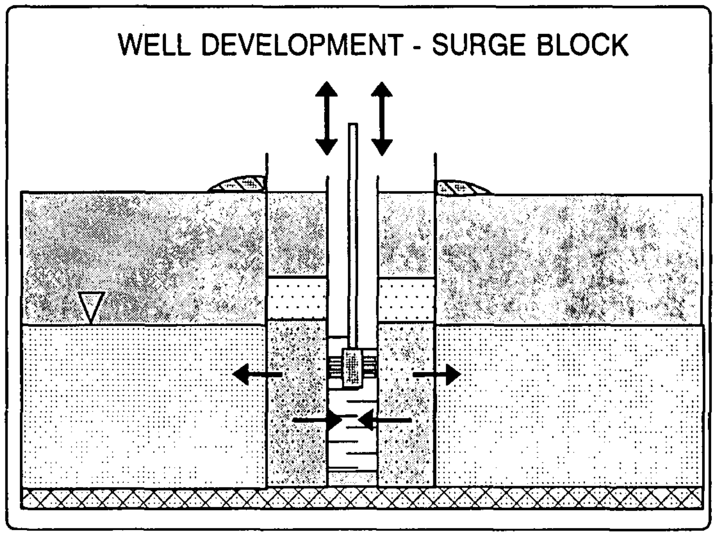


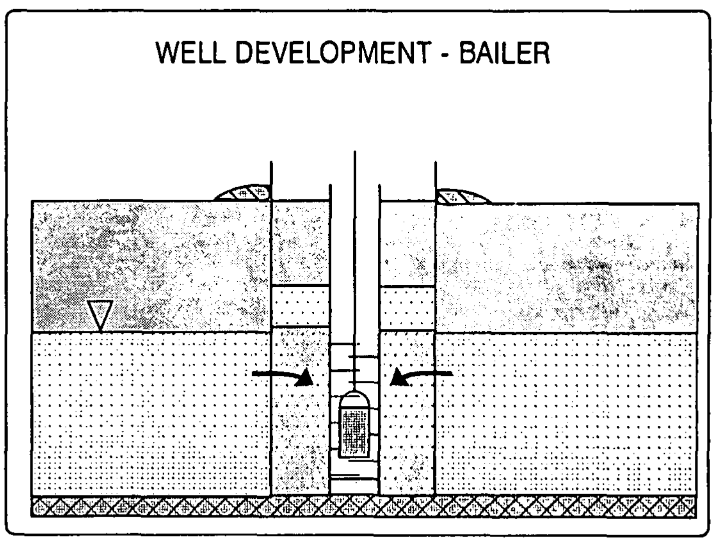
WELL AND AQUIFER DEVELOPMENT

- Surge block
- Bailer
- Pulse pumping
- Air surging

NOTES

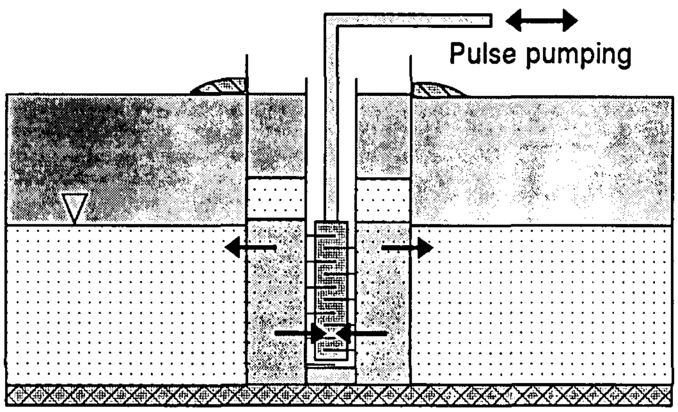

POOR WELL DEVELOPMENT
Muddy water


WELL DEVELOPMENT - SURGE BLOCK

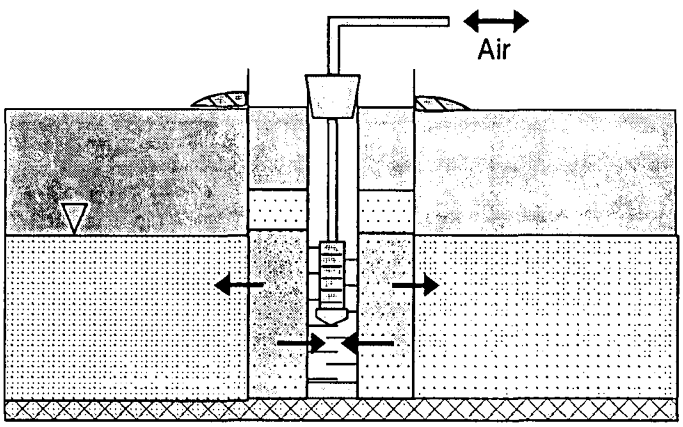

WELL DEVELOPMENT - BAILER

NOTES

WELL DEVELOPMENT - PULSE PUMPING



WELL DEVELOPMENT - AIR SURGING



SUMMARY OF DRILLING AND MONITORING WELL CONSTRUCTION

- Hydrogeologic environment
  - Type of formation
  - Depth of drilling
- Type of pollutant
- Drilling location
- Monitoring well design
- Drilling equipment availability
- Cost

Section 7

HYDROGEOCHEMISTRY

PERFORMANCE OBJECTIVES

At the end of this lesson, participants will be able to:

- Evaluate groundwater uses based on chemical parameters
- Identify the basic inorganic constituents in groundwater
- Identify the driving factors that control the concentration of inorganic constituents, including:
  - pH and Eh
  - Temperature
  - Total dissolved solids
  - Dissolved gases
- Identify how the driving factors that control the concentration of inorganic constituents influence:
  - Dissolution and precipitation
  - Redox potential (Eh)
  - Adsorption
  - Hydrolysis
  - Carbonate equilibrium
- List the chemical characteristics important to the concentration of organic constituents in groundwater

- Define the terms weight fraction of organic carbon in the soil (f_{oc}), organic-carbon partition coefficient (K_{oc}), distribution coefficient (K_D), retardation factor (R_D), and octanol-water partition coefficient (K_{ow})

- Define dense nonaqueous phase liquids (DNAPLs) and light nonaqueous phase liquids (LNAPLs).

NOTES

HYDROGEOCHEMISTRY

PRIMARY DRINKING WATER STANDARDS

- Inorganics
- Microbiological
- Pesticides/herbicides
- Volatile organic compounds
- Radioactivity

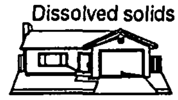
SECONDARY DRINKING WATER REGULATIONS

Chloride	Manganese
Color	Odor
Copper	pH
Corrosivity	Sulfate
Fluoride	Total dissolved solids
Foaming agents	Zinc
Iron	

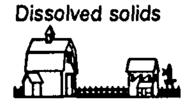
NOTES

QUALITY DETERMINES USABILITY

Taste		
Odor		
Poisons	pH	
Fluoride	Acidity	
Nitrate	Alkalinity	
Iron	Silica	Boron
Hardness	Hardness	Alkalinity
Sediment	Sediment	Sodium-calcium ratio
Dissolved solids	Dissolved solids	Dissolved solids


DOMESTIC


INDUSTRIAL


IRRIGATION

INORGANIC GEOCHEMISTRY

SURFACE WATER CHEMICAL COMPOSITION

- Rain water
- Seawater
- River water

NOTES

SURFACE WATER COMPOSITION

Chemical	Rain Water	River Water
Fe^{++}	0.015	0.020
Ca^{++}	0.075	38.000
Mg^{++}	0.027	10.000

All concentrations in mg/L

SURFACE WATER COMPOSITION

Chemical	Rain Water	River Water
Na^{+}	0.220	20.000
K^{+}	0.072	2.900
Cl^{-}	-----	24.000
F^{-}	-----	0.300

All concentrations in mg/L

SURFACE WATER COMPOSITION

Chemical	Rain Water	River Water
$SO_4^{=}$	1.100	51.000
HCO_3^{-}	----	113.000
NO_3^{-}	----	2.400

All concentrations in mg/L

NOTES

DOMESTIC WATER QUALITY
Example

Bolton Well Field

Great Miami River Aquifer

DOMESTIC WATER SUPPLY
Bolton Plant-Great Miami River

Chemical	Raw Water	Finished Water
Fe^{++}	0.136	0.034
Ca^{++}	90.000	31.000
Mg^{++}	21.000	20.000

All concentrations in mg/L

DOMESTIC WATER SUPPLY
Bolton Plant-Great Miami River

Chemical	Raw Water	Finished Water
Na^{+}	33.800	32.000
K^{+}	-----	-----
Cl^{-}	54.000	59.000
F^{-}	0.250	1.020

All concentrations in mg/L

NOTES

DOMESTIC WATER SUPPLY
Bolton Plant-Great Miami River

Chemical	Raw Water	Finished Water
$SO_4^{=}$	54.000	51.000
HCO_3^-	----	----
NO_3^-	2.200	2.310

All concentrations in mg/L

OTHER WATER QUALITY PARAMETERS

Chemical Parameter	Rain Water	River Water	Seawater	Great Miami River
				R. / F.
Hardness	----	138	6581.55 C.	318 / 164
TDS	1.609	232	34500	463 / 323
pH	4.9	7.4	8.0 - 8.4	7.4 / 9.3

All concentrations in mg/L
C. Calculated; R. Raw Water; F. Finished Water

GROUNDWATER QUALITY

- Chemicals/compounds present
- Chemical concentration
- Subsurface distribution

NOTES

NATURAL ORGANIC CONSTITUENTS

Constituent	mg/L
Bicarbonate (HCO_3)	150-200
Carbonate (CO_3)	150-200
Calcium (Ca)	25-30
Magnesium (Mg)	25-30
Chloride (Cl)	250
Fluoride (F)	0.7-1.2
Iron (Fe)	>0.3
Manganese (Mn)	>0.05
Sodium (Na)	20-170
Sulfate (SO_4)	300-1000

CHARACTERISTICS

- Hardness
- pH (or hydrogen ion activity)
- Specific electrical conductance
- Total dissolved solids (TDS)

HARDNESS

- Expressed as calcium carbonate in milligrams per liter or grains per gallon of water
- One grain is equivalent to 17 mg/L

NOTES

HARDNESS

Type	mg/L
Soft	0-60
Moderately hard	61-120
Hard	121-180
Very hard	>180

DRIVING FACTORS

DRIVING FACTORS

- pH and Eh
- Temperature
- Total dissolved solids
- Dissolved gases
- Aquifer and soil mineral composition

NOTES

Chemical Processes

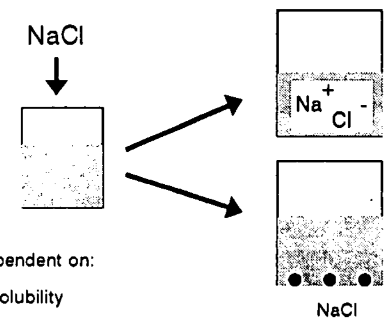
Affected by These

Driving Factors

CHEMICAL PROCESSES

- Dissolution and precipitation
- Carbonate equilibrium
- Hydrolysis
- Adsorption
- Redox potential

DISSOLUTION/PRECIPITATION



Dependent on:

Solubility

pH

Temperature

NOTES

DISSOLUTION ⇌ PRECIPITATION

$$Ca^{++} + CO_3^{=} \rightleftharpoons CaCO_3$$

$$Mg^{++} + CO_3^{=} \rightleftharpoons MgCO_3$$

$$Na^{+} + Cl^{-} \rightleftharpoons NaCl$$

$$Ca^{++} + SO_4^{=} \rightleftharpoons CaSO_4$$

CARBONATE EQUILIBRIA

$$H_2O + CO_2 \rightleftharpoons H_2CO_3$$

$$H_2CO_3 \rightleftharpoons H^{+} + HCO_3^{-}$$

$$HCO_3^{-} \rightleftharpoons H^{+} + CO_3^{=}$$

$$CaCO_3 \rightleftharpoons Ca^{++} + CO_3^{=}$$

HYDROLYSIS

$$R\text{-}X + H_2O \longrightarrow R\text{-}OH + H^{+} + X^{-}$$

$$R\text{-}X + OH^{-} \longrightarrow R\text{-}OH + X^{-}$$

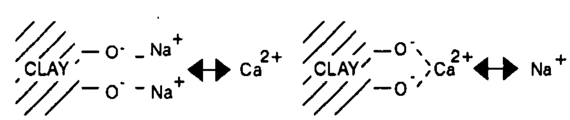
NOTES

ADSORPTION

- Partitioning of elements
- Cation exchange capacity

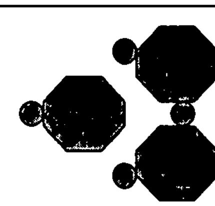
(CAT)ION EXCHANGE CAPACITY

- Retards movement of chemical constituents in groundwater
- Amount of exchangeable ions in milliequivalents per 100 grams soil at pH = 7

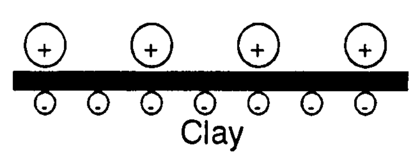


ADSORPTION/DESORPTION

Physical



Electrical



NOTES

OXIDATION/REDUCTION REACTIONS

Oxidation = reaction resulting in a loss of electrons

Reduction = reaction resulting in a gain of electrons

Eh = "redox" potential

Low or negative Eh = reduction
High or positive Eh = oxidation

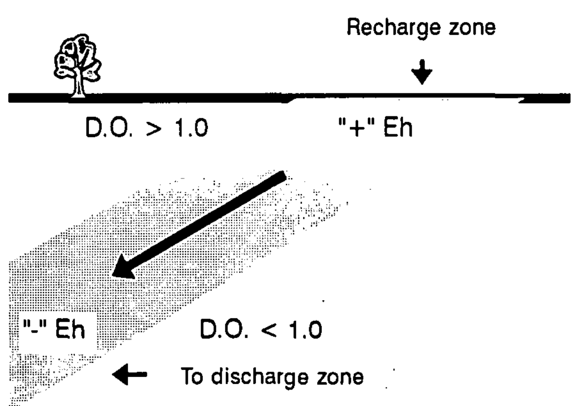
SOIL ZONE REACTIONS
(O_2 > 0.1 ppm)

sulfide oxidation $HS^- \rightarrow SO_4^{2-}$
iron oxidation $Fe^{2+} \rightarrow Fe^{3+}$
nitrification $NH_4^+ \rightarrow NO_3^-$
manganese oxidation $Mn^{2+} \rightarrow Mn^{4+}$
iron sulfide oxidation $Fe_2S \rightarrow Fe^{3+} + SO_4^-$
aerobic respiration $CH_2O + O_2 \rightarrow CO_2 + H_2O$

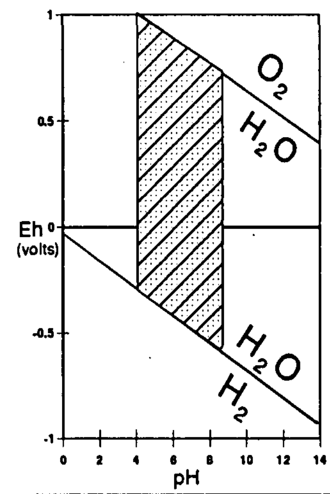
SATURATED ZONE REACTIONS

denitrification $NO_3^- \rightarrow N_{2(gas)}$
manganese reduction $Mn^{4+} \rightarrow Mn^{2+}$
iron III reduction $Fe^{3+} \rightarrow Fe^{2+}$
sulfate reduction $SO_4^{2-} \rightarrow HS^- + H_2S$
methane fermentation $CH_2O \rightarrow CH_{4(gas)}$

Eh: 780 mv — 0 — -200 mv



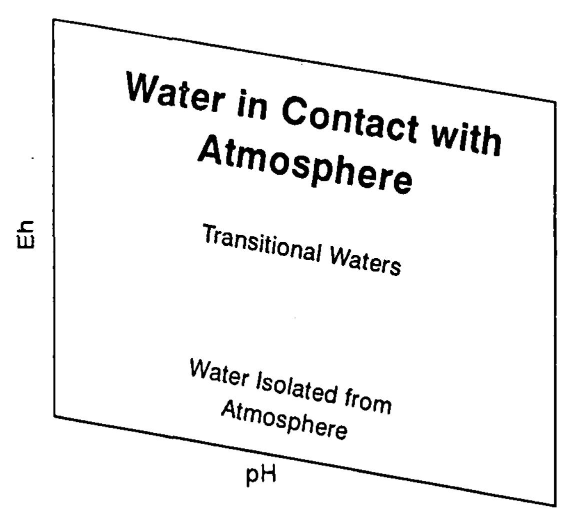
NOTES



THE LIMITS OF WATER STABILITY

$$O_2 + 2H^+ + 2e^- = 2H_2O$$

$$H_2 + O^= - 2e^- = H_2O$$



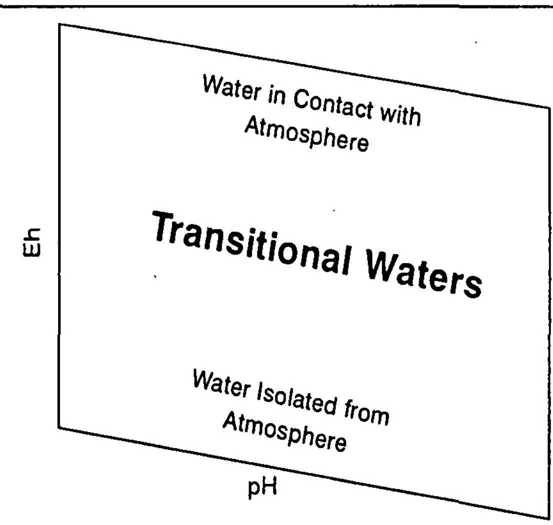
NOTES

WATER IN CONTACT WITH ATMOSPHERE

Mine waters	Rain	Streams	Normal ocean water	Aerated saline residues

4.0 ⟵ pH ⟶ 10.0

0.8 V ⟵ Eh ⟶ 0.3 V



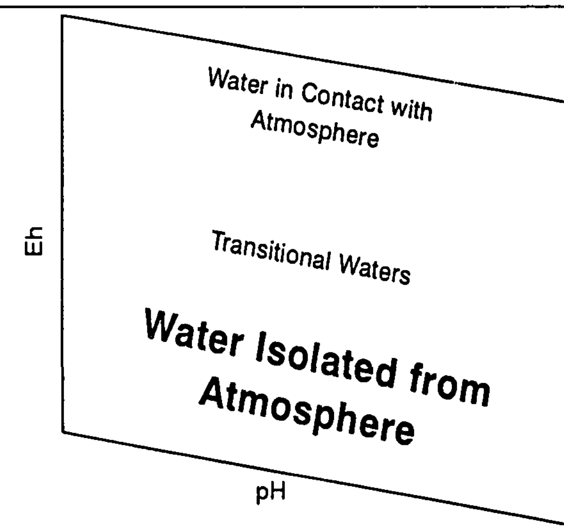
TRANSITIONAL WATERS

Bog waters	Groundwater

3.0 ⟵ pH ⟶ 9.0

0.1 V ⟵ Eh ⟶ - 0.2 V

NOTES



WATER ISOLATED FROM ATMOSPHERE

Saturated soils	Euxenic marine environment	Organic-rich saline waters

5.0 —— pH —— 11.0

- 0.1 V —— Eh —— - 0.5 V

ORGANIC CHEMISTRY

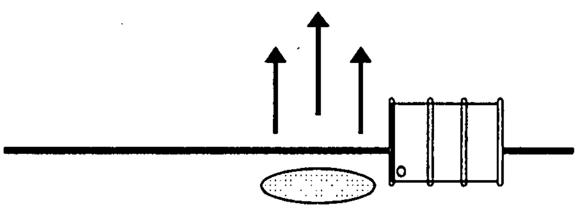
NOTES

CHEMICAL-SPECIFIC CHARACTERISTICS

Chemical phase (solid, liquid, gas)

- Solubility
- Vapor pressure
- Specific gravity
- K_{oc}
- K_{ow}

VOLATILIZATION



Dependent on: Vapor pressure
Henry's Law constant

CHEMICAL DEGRADATION

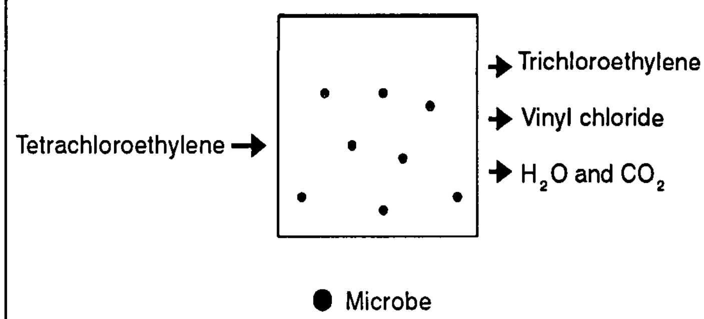
Hydrolysis

UV Photolysis

DDT ⟶ DDE

NOTES

BIODEGRADATION



Eh

Redox potential

SOIL ZONE REACTIONS

($O_2 > 0.1$ ppm)

780 mv

sulfide oxidation $HS^- \rightarrow SO_4^{2-}$

iron oxidation $Fe^{2+} \rightarrow Fe^{3+}$

nitrification $NH_4^+ \rightarrow NO_3^-$

manganese oxidation $Mn^{2+} \rightarrow Mn^{4+}$

iron sulfide oxidation $Fe_2S \rightarrow Fe^{3+} + SO_4^-$

aerobic respiration $CH_2O + O_2 \rightarrow CO_2 + H_2O$

Eh

SATURATED ZONE REACTIONS

0

denitrification $NO_3 \rightarrow N_{2(gas)}$

manganese reduction $Mn^{4+} \rightarrow Mn^{2+}$

iron III reduction $Fe^{3+} \rightarrow Fe^{2+}$

sulfate reduction $SO_4^{2-} \rightarrow HS^- + H_2S$

methane fermentation $CH_2O \rightarrow CH_{4(gas)}$

-200 mv

NOTES

REDUCTION OF MANGANESE (Mn) AND IRON (Fe)

$$3\ MnO_2 + 18\ H^+ + 6\ OH^- = 3\ Mn^{++} + 12\ H_2O$$

$$8\ H^+ + 2\ Fe_2O_3 = 4\ Fe^{++} + 4\ H_2O + O_2$$

REDUCTION OF SULFATE

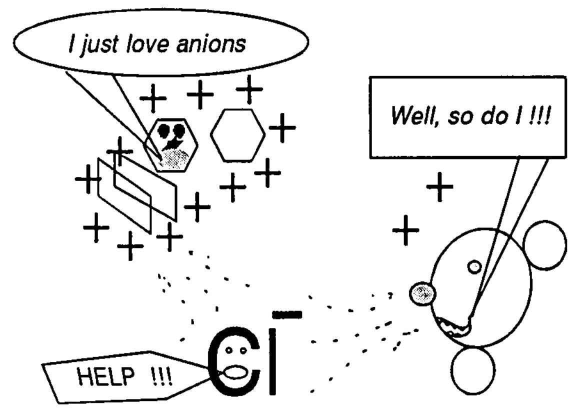
$$HS^- + 4\ H_2O = SO_4^= + 9\ H^+ + 8\ e^-$$

ADSORPTION

- Partitioning of elements
- Cation exchange capacity

NOTES

PARTITIONING OF ELEMENTS



ADSORPTION OR DISTRIBUTION COEFFICIENT

$$K_d$$

ORGANIC CARBON FRACTION (f_{oc})

The fraction of the aquifer solid material that is organic carbon

NOTES

ORGANIC CARBON PARTITION COEFFICIENT (K_{oc})

The distribution coefficient for the organic solute between water and natural solid organic matter

K_d

$$K_d = K_{oc} \times f_{oc}$$

$$\log K_d = \log K_{oc} + \log f_{oc}$$

K_d

$$K_d = K_{om} \times f_{om}$$

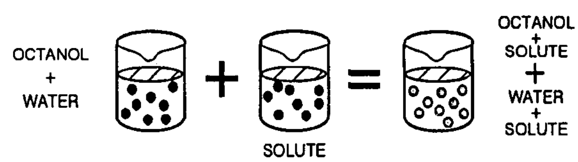
$$\log K_d = \log K_{om} + \log f_{om}$$

NOTES

$$K_{oc} = 1.72 \times K_{om}$$

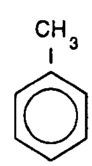
OCTANOL-WATER PARTITION COEFFICIENT (K_{ow})

The adsorption of the nonpolar organic molecules to the solid organic material in the formation



RATIO OF THE AMOUNT OF SOLUTE THAT PARTITIONS OUT OF THE AQUEOUS PHASE ONTO THE SOLID ORGANIC MATTER

K_{oc} for Toluene



$$\log K_{oc} = 0.72 \log K_{ow} + 0.49$$

NOTES

$$K_d = K_{oc} f_{oc}$$

$$\log K_d = 0.72 \log K_{ow} + \log f_{oc} + 0.49$$

K_d = distribution coefficient

K_{oc} = organic carbon partition coefficient

K_{ow} = octanol-water partition coefficient

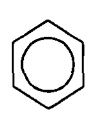
f_{oc} = organic carbon fraction

K_d for Toluene

$$\log K_d = \log K_{oc} + \log f_{oc}$$

$$\log K_d = 0.72 \log K_{ow} + \log f_{oc} + 0.49$$

K_{oc} for Benzene



$$\log K_{oc} = -0.54 \log S + 0.44$$

NOTES

K_d for Benzene

$$\log K_d = \log K_{oc} + \log f_{oc}$$

$$\log K_d = -0.54 \log S + \log f_{oc} + 0.44$$

RETARDATION FACTOR

$$R_d = 1 + \frac{(K_d)(pb)}{n}$$

R_d = Retardation factor (unitless)

K_d = Distribution coefficient (ml/g)

$K_d = K_{oc} f_{oc}$

pb = Bulk density (g/cc)

n = Porosity (decimal fraction)

RETARDATION

$$R = 1 + \frac{\rho_b}{n} \times K_d$$

R = Retardation factor
ρ_b = Bulk density
K_d = Distribution coefficient = $K_{oc} f_{oc}$
n = Porosity

Contaminant Velocity:

$$v_x = \frac{v}{R_x}$$

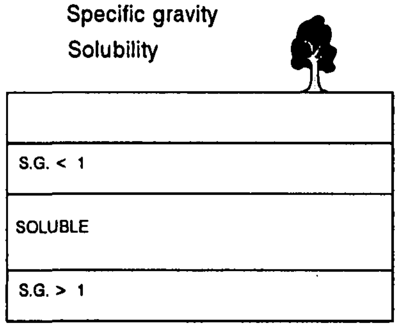
v_x = Contaminant velocity
v = Groundwater flow velocity
R_x = Retardation factor for contaminant x

NOTES

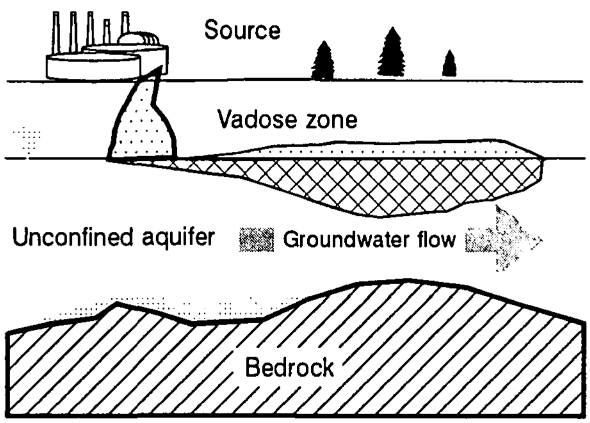
DENSITY STRATIFICATION

Dependent on:

- Specific gravity
- Solubility



PLUME STRATIFICATION



Migration of Chlorophenolic Compounds at the Chemical Waste Disposal Site at Alkali Lake, Oregon — 1. Site Description and Ground-Water Flow

by James F. Pankow[a], Richard L. Johnson[a], James E. Houck[b], Susan M. Brillante[a], and W. Jerry Bryan[b]

ABSTRACT

The hydrogeology of the chemical waste disposal site in the closed basin at Alkali Lake, Oregon has been examined. Interest in the site is due to the burial (November 1976) of 25,000 drums of herbicide manufacturing residues in unlined trenches on the playa of the basin. Included in the wastes were large amounts of chlorophenols and polymeric chlorophenoxyphenols. The flow of the alkaline (pH ≃ 10) ground water in the site area is driven by: (1) springs which create a mound east of the site; and (2) the sump effect of "West Alkali Lake," a topographic low to the west of the site. Porosity, bulk mass densities, and grain-size distributions were determined. At one piezometer, the depth to ground water ranged between 0.9 m and 2.2 m. With the bottoms of the trenches in which the chemicals were buried between 0.60 and 0.75 m below the level of the ground surface, the bottom portions of the trenches may, at least occasionally, be in direct contact with the ground water.

INTRODUCTION

The by-products of a wide variety of chemical processes are often disposed of together—nonuniformly, and noninstantaneously in one chemical disposal site. Such disposal usually results in complicated ground-water contaminant plumes which are difficult to model. The disposal of chemical waste in the Alkali Lake Basin (Lake County, Oregon, Figure 1) does not follow this typical model. Wastes there were received over a fairly narrow time frame. In addition, nearly all of the wastes were from one chemical manufacturing operation (the production of chlorophenoxy herbicides). As a result, most of the individual compounds making up the waste were chemically similar (chlorophenolic), differing primarily by molecular weight. Thus, while the value of the partitioning coefficient of the contaminants between the soil matrix and the ground water (K_d) may vary between the compounds, the physicochemical processes which control their values in the soil and ground-water media will be similar.

Early interest in the Alkali Lake area was oriented towards the mining of soda (Na_2CO_3). Claims were first filed by an Oregon firm in the late 1800s. These claims changed ownership several times. They were purchased by Chem Waste, Inc. (Portland, OR) in 1967 for the purpose of establishing a 4 ha waste chemical storage site. The location for the site was selected such that it was just inside the mining claim boundary. Areas further inside the playa would have been subject to greater amounts of playa water as well as greater hauling distances. The site was licensed by the Oregon Department of Agriculture (ODA) in 1968 for pesticide waste storage. Little or no prior study was carried out to determine the suitability of the site to receive chlorophenolic wastes. Storage of wastes at the site began in 1969. The feasibility of using shallow land application to degrade the wastes was investigated in 1970 on several plots of land near the site (Goulding, 1973). The largest of the plots was 4 ha in area (Figure 1). The possibility of using the waste material as a rangeland-improving herbicide was also investigated (Figure 1).

By late 1971, a total of twenty-five thousand 206 l (55 gallon) drums of manufacturing wastes from the production of 2,4-D (2,4-dichlorophenoxyacetic acid), and MCPA (4-methyl-2-chlorophenoxyacetic acid) had been stockpiled on pallets at the site. The wastes represented primarily the distillation residues ("still-bottoms") which resulted during the separation of desired chlorophenols from a phenol chlorination process mixture. Included in the still-bottoms were various chlorophenols and a large variety of polymeric

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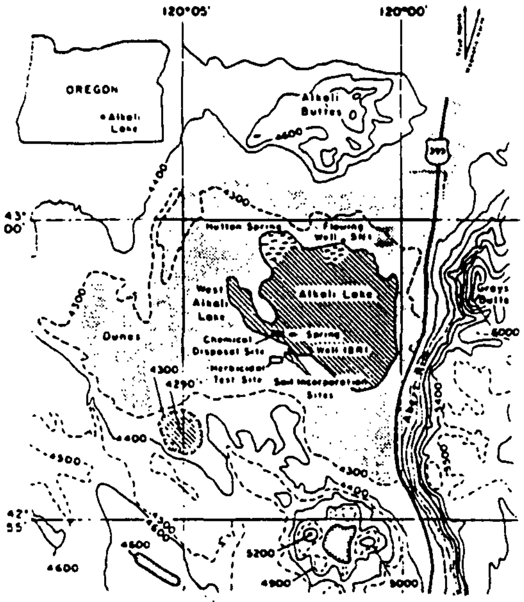

Fig. 1. Topographic map of Alkali Lake playa and surrounding area. Major contours are at 200 foot intervals with supplemental contours at 100 foot intervals. (Prepared on the basis of maps obtained from the Defense Mapping Agency Topographic Center, Washington, D.C.)

chlorophenoxyphenols (CPP) (Pankow *et al.*, 1981). In addition to the still-bottoms, the waste materials also included the herbicides 2,4-D, and MCPA. All available evidence indicates that no 2,4,5-T (2,4,5-trichlorophenoxyacetic acid) or 2,4,5-T wastes were present in the disposed materials. The structures of these various compounds are presented elsewhere (Johnson *et al.*, 1984a).

In 1971, the Oregon Department of Environmental Quality (ODEQ) and ODA stopped additional wastes from being hauled to the site. Between 1972 and 1974, ODEQ pursued cleanup of the site by its owners through State courts, but ultimately lost. The State of Oregon condemned the site and took possession in October 1976. In July 1976, remedial action funds were requested and subsequently received from the Oregon Legislature. Given the general corrosiveness of the waste (the chlorophenols, CPP, and phenoxy herbicides are all acids) (Johnson *et al.*, 1984a) by this point in time, many of the drums had begun to leak. In October 1976, the U.S. Environmental Protection Agency (EPA) Alkali Lake Task Force took samples from five different barrels and tested them for solubility and pH when mixed both with the local ground water and with deionized water. Their report, dated December 1976, indicates that on the average, 70% of the material in the drums was soluble in the highly alkaline (pH ≈ 10), local ground water (EPA, 1976). The waste/ground-water volume or mass ratio used in the solubility tests was not indicated. When 2 g of each of the five samples were mixed with 100 ml of deionized water, pH values of 4.5, 7.0, 5.0, 5.0, and 8.0 were obtained. The acidic pH values are in the range expected based on the pK_a [−log (acidity constant)] values for chlorophenols. The neutral to alkaline pH values were probably due to the presence in some of the barrels of basic residues from the alkaline coupling of 2,4-dichlorophenol with chloroacetic acid to give 2,4-D. A contract was let by ODEQ to crush and bury the drums in 12 shallow (0.60 to 0.75 m deep), unlined trenches 130 m long and 20 m apart (EPA, 1976; ODEQ, 1977a). This operation, carried out in November 1976, converted the storage site into a disposal site. The major portion of the wastes were therefore injected into the ground-water system in a narrow time period. Although the water table in the area of the site is very shallow (typically only 1 to 3 m deep), it was hoped that the location of the site inside of the closed Alkali Lake basin would limit the movement of the contaminants in the alkaline ground water.

HYDROLOGY, GEOCHEMISTRY, AND GEOLOGY

The site is located on the northwestern edge of the Basin and Range Physiographic Province (Fenneman, 1931). This area is characterized by a large graben occurring between two dramatic, north-south-trending fault scarps, Abert Rim on the east (840 m high) and Winter Ridge on the west (360 m high). As is typical for the Province as a whole, the graben contains a variety of closed basins. The Lake Abert and Summer Lake basins (2,200 and 1,000 km^2, respectively) have been the most studied (Donath, 1958; Phillips and Van Denburgh, 1971; Van Denburgh, 1975). In Pleistocene times, "Lake Chewaucan" occupied a large portion of the Lake Abert and Summer Lake basins. A second Pleistocene lake once occupied the Alkali Lake basin. In terms of that former lake, the Alkali Lake basin has a drainage area of 750 km^2 (Mundorff, 1947). Abert Rim bounds the Alkali Lake basin on the east. The land to the west slopes gently upward (400 m gain over 10 km), and possesses numerous small eolian deflation areas (diameters up to 2 km).

The site is located on the southwest edge of

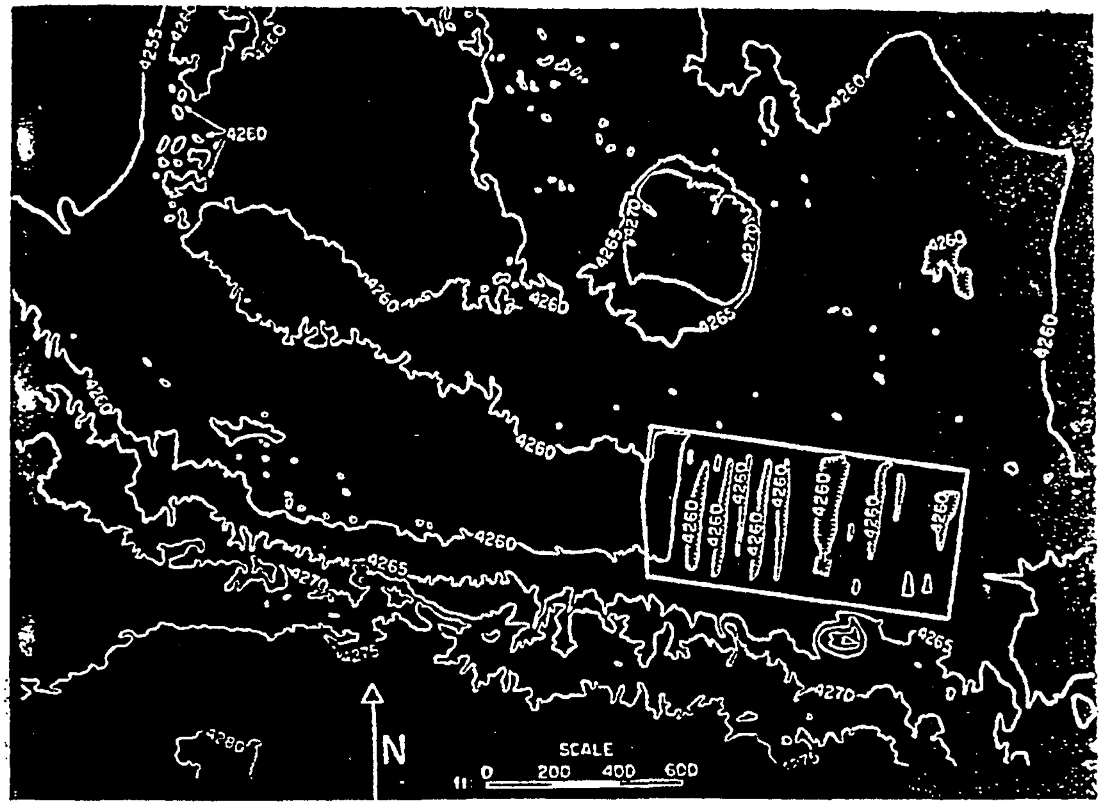

Fig. 2. Photograph and superimposed topographic map of the site vicinity. Contours are shown at 5 foot intervals. All unlabeled contours north of the site are 4265 foot contours. Unlabeled contours east of the site are 4260 contours. [Prepared with the assistance of U.S. EPA (1983) data.]

the 5 km diameter playa in the Alkali Lake basin (Figures 1 and 2). The playa serves as a sump for both surface- and ground-water discharge. Two flowing wells were drilled in the playa area by Stott (1952), well 5N1 (45 m deep), and well 18R1 (90 m deep) (Newton and Baggs, 1971). The regular flow of the former well has created a small marshy environment. The natural surface- and ground-water discharges lead to the formation of a shallow ephemeral lake. Standing water is occasionally within 100 m of the site. As mentioned above, the water table at the site is usually 1 to 3 m below the ground surface. As is typical for closed basins, net evapotranspiration exceeds net precipitation in the playa area. Ground water flowing into the playa is fresh [total dissolved solids (TDS) = 200 to 500 mg/l; specific conductance = 100 to 250 μmhos/cm; and pH = 7.5 to 8.5], but ground water within 6 to 12 m of the playa surface is saline and strongly alkaline (up to 55,000 mg/l TDS; specific conductance ≃ 25,000 μmhos/cm; pH ≃ 10). The ground water passing beneath the site is typically characterized by: TDS ≃ 10,000 mg/l, specific conductance = 4,000 to 12,000 μmhos/cm, and pH ≃ 10.0. The high salinities and alkalinities are due to the accumulation of both properties over the history of the closed drainage basin.

Ground-water flow in the site area is driven by: (1) springs which create a mound east of the site; and (2) the sump effect of "West Alkali Lake," a topographic low on the playa where the presence of surface water and/or the close proximity of ground water to the surface causes large evapotranspiration (specific conductance ≃ 40,000 μmhos/cm), and correspondingly low water table levels. Slug tests in the vicinity of the site have given hydraulic conductivities in the range of 0.01-0.10 cm/s (Johnson and Pankow, 1984). Pumping tracer tests have indicated that the porosity available for flow is 1 to 5% (Johnson *et al.*, 1984b). A topographically-low finger, partially-filled with either eolian or lacustrine deposits, extends southeast from West Alkali Lake directly to the site (Figure 2). This geological feature appears to provide a conduit for groundwater flow between the springs and West Alkali Lake.

The geology of the Alkali Lake area is discussed by Mundorff (1947) and Newton and Baggs (1971). Pleistocene and Recent deposition include alluvium, lake sediments, eolian deposits, and capping flows of basalt (Newton and Baggs, 1971). The playa region is believed to be a deflation area (Mundorff, 1947). The important geologic units include Recent and Pleistocene eolian and lacustrine beds of gravel, sand, silt, and some clay-sized particles. [Grain-size determinations carried out in this study (see below) indicate predominantly silt-sized materials in the site area.] Near the site, the beds are believed to be in excess of 30 m thick (Newton and Baggs, 1971). Underlying these surface beds are 30 to 100 m of Pliocene-Pleistocene pyroclastics, basalt, andesite, and some interbedded lake sediments. These materials are in turn underlain by more than 100 m of Pliocene lavas and lacustrine beds, then more than 100 m of Miocene-Pliocene andesite and basalt flows.

Contemporary surficial influence is predominantly eolian with eolian deposits observable throughout the area. Many of the topographic highs suggest eolian control. Eolian deposits on the playa west of the site contain grain sizes from silt to medium-grained sand. The grains are subangular to well-rounded, and consist of quartz and volcanic fragments. The fragments include basalt, andesite, and well-indurated tuff. The area surrounding the playa is characterized by the presence of many vegetation-stabilized dunes.

PHYSIOGRAPHY AND CLIMATE

The topography in the direct vicinity of the site is indicated in Figure 2. The climate is typical of a high altitude western North American desert. Meteorological measurements have been made at a highway maintenance station 4.8 km from the site since 1961 (NOAA, 1984). During 1972 to 1981, the annual precipitation averaged 17.5 cm. Summer temperature highs reach 38°C and winter lows are often less than −23°C. The soil freezes to a depth of 7 to 15 cm. The average annual temperature is 8.5°C. Due to rapid radiant night-time heat loss in clear weather, diurnal temperature ranges can reach 28°C. Due to this variation, a 10 to 30% relative humidity at mid-day can reach 100% at night, and frost can occur in mid-summer. As mentioned above, evapotranspiration in the playa area substantially exceeds precipitation. As in other closed basins, the water deficit is made up

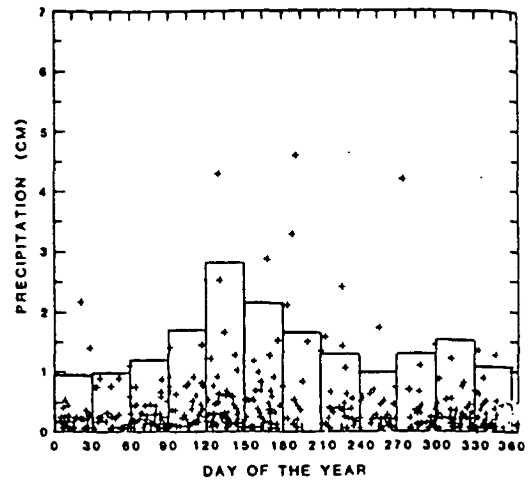

Fig. 3. Individual precipitation event values plotted vs. day of the year together with monthly averages. [Based on 1972 to 1981 data, NOAA (1984).]

by ground water flowing towards the playa.

The period of lowest precipitation occurs during November to February (Figure 3). This contrasts with the nearby Lake Abert area where the precipitation rate is relatively constant except for a dry period in July to September (Van Denburgh, 1975). The precipitation-weighted frequency plot (Figure 4) indicates that >80% of the precipitation falls in events of <1.5 cm. Nevertheless, significant runoff events occur due to episodes involving >1.5 cm of rain. In the contaminant plume area, the primary plant is greasewood

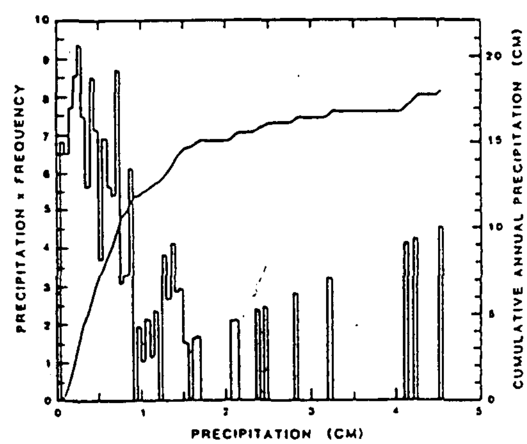

Fig. 4. (Precipitation x frequency) vs. precipitation (cm) histogram and average cumulative annual precipitation vs. precipitation (cm) curve. [Based on 1972 to 1981 data, NOAA (1984).]

(*Sarcobatus vermiculatus*), and it covers approximately ~12% of the playa surface. In the less alkaline upland areas surrounding the playa, it covers approximately 48% of the land surface.

PRIOR STUDIES AT THE SITE

In 1976, two 4 m long, 7.5 cm I.D. PVC piezometer/sample tubes were installed (by hand-augering) and sampled by ODEQ (1977a). The open-bottom tubes were randomly slotted below 1 m. They were designated "Wells 1 and 2" (Figure 5). In an effort to find and keep pace with the location of the leading edge of the shallow ground-water contaminant plume, Wells 3 to 21 (constructed and installed as above) were added to the sampling network by ODEQ between 1977 and 1981 (1977a, 1977b, 1978, 1979, 1981, 1982). Both total phenols and 2,4-D concentrations were determined. These data indicated that the plume was moving west-northwest and towards West Alkali Lake (ODEQ, 1979) as predicted by EPA (1976).

The site is of interest for further study since: (1) the contaminant plume is moving at a measureable rate; (2) similar chemicals with a range of molecular weights are present; (3) the modeling and the comparison of model results with the moving plume are possible for the range of similar compounds; (4) the zone of contamination is shallow and accessible by hand-augering; (5) access to the site and the surrounding lands is facilitated due to the low level of economic development in the area; and (6) the plume constituents are well above modern analytical detection limits.

AQUIFER CHARACTERIZATION AND GROUND-WATER FLOW

Aquifer Properties

Representative core samples of soil materials were taken downgradient (west) of the site in the saturated zone. The samples contained intact angular blocks which measured 1 to 2 cm across and which appeared relatively undisturbed by sampling. The blocks were weighed and their volumes determined by immersion in water. They were reweighed to verify that no water had been adsorbed, then dried to a constant weight at 50°C. The contribution to the dry weight from the dissolved solids was subtracted from the dry weight. The bulk mass density was calculated as the corrected-dry mass to volume ratio. The porosity was calculated as the weight loss to volume ratio. Additional samples for mineralogical examination and grain-size analyses were taken in

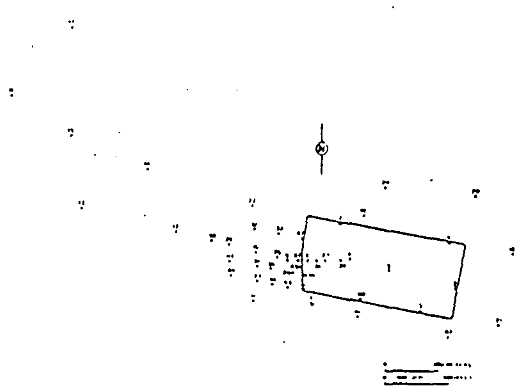

Fig. 5. Map showing the location of Wells 1 to 49 used for water sampling and water table measurements.

the area of Well 34 (Figure 5) at depths of 1.2 and 2.4 m. They were extracted with 4:1 methanol: water to remove contaminants. Mineral content was determined by X-ray analysis and by examination with a petrographic microscope. Grain-size analyses were carried out by sieving with number 40, 50, 100, and 200 standard U.S. screens. The sample fractions which passed through the 200 screen were further analyzed for size distribution using a hydrometer. The liquid limit, the plastic limit, and the plasticity index or "Atterburg Number" (liquid limit minus plastic limit) values were determined for the sample fractions which passed the number 40 screen.

Piezometer/Sample Wells

Between October 1981 and the present, 28 piezometer/sample wells were added by the authors to the sampling network of 21 such wells already installed at the site by ODEQ (1977 to 1982). The new devices were also 4 m long, 7.5 cm I.D., open-bottomed, and were constructed from the same type of PVC tubing used in the installation of the previous 21 wells. No contamination problems with PVC casings are expected at this site since PVC contains no chlorophenolic material. Each tube was slotted so as to be 9% open below the water table. They were designated "Wells 22 to 49," and were installed at the site by hand-augering a 9 cm diameter hole and dropping in the tube. No caving problems were experienced during augering. No backfilling of the augered hole was necessary. As with Wells 1 to 21, each PVC tube was fitted with a removable PVC cap. All of the sample wells were surveyed with respect to the top of the Well 2 casing which was assigned an arbitrary height of 1,000 cm. No sinking of the tubes into the ground after installation has been observed.

Specific Conductance Measurements

Specific conductance measurements were made using a Model 33 YSI (YSI, Inc., Yellow Springs, OH) portable conductivity meter. During field monitoring, the calibration and linearity of the meter were checked twice daily with standards ranging from 600 to 50,000 μmhos. Single-point calibration corrections were made several times daily. At the beginning of the field monitoring program, several standing columns of water were bailed from the PVC wells prior to sampling. However, this practice was discontinued later in the study since the high hydraulic conductivity in the area of the site causes a flushing of the water over the slotted interval. Measurements were made in the PVC wells by lowering the probe down to one meter below the water surface, and waiting one minute for the signal to stabilize. In order to obtain more spatial resolution than would be provided by the PVC wells, additional points were sampled using 1.8 to 2.5 m long, 0.64 cm O.D., 0.46 cm I.D. type 316 stainless steel (SS) tubes (unslotted, open-bottomed). After placing a 0.45 cm O.D. rod inside each of the tubes, they were pushed 1.5 to 2.3 m into the ground by hand. The inner rod was then retracted leaving a clear sampling tube. A hand vacuum/pressure pump (Nalge, Inc., Rochester, NY) was attached to the steel tube via FEP Teflon tubing, and 100 ml were withdrawn and placed in a 125 ml vial. The conductivity was measured after allowing the electrodes to equilibrate for one minute.

RESULTS

Bulk Mass Density, Porosity, Grain-Size, and Mineralogical Determinations

Bulk mass density and porosity values found for several samples obtained near Well 25 ranged between 0.85 to 0.95 and 0.60 to 0.70, respectively. The two soil samples subjected to grain-size distribution analysis were similar (Figure 6). In both cases, 90% of the material possessed diameters greater than 0.006 mm. Very little material was found in the operationally-defined "clay" size range. Examinations with a petrographic microscope revealed that both samples consisted largely of fine glass (volcanic ash) only partly devitrified, often entirely vitreous. The index of refraction of n = 1.51 indicated a silica content near 68% and a rhyolitic or rhyodacitic composition. An occasional fragment of pumice was observed. In addition, the samples contained fine particles of calcite and small amounts of plagioclase feldspar, quartz, basaltic glass, ortho and clinopyroxene, and diatom

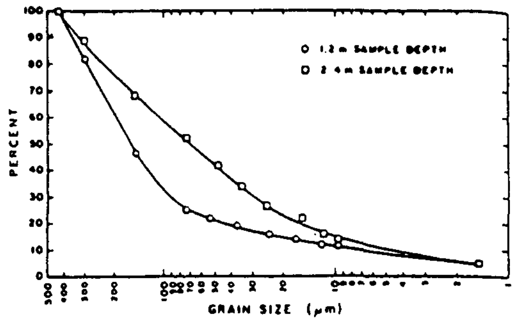

Fig. 6. Percent of soil material below a given grain size vs. grain size for two samples taken near Well 34.

tests. While the sample obtained at 2.4 m was found to contain a small quantity of clinoptilolite (a zeolite), almost no clay minerals were found. This observation is consistent with the nature of the size distributions. Atterburg tests applied to the material passing the number 40 screen gave liquid limits, plastic limits, and Atterburg Numbers of 70%, 48%, and 22 and 73%, 58%, and 15 for the samples obtained at 1.2 and 2.4 m, respectively. These results are also consistent with the detection of little clay mineral material, though: (1) visual inspection of materials obtained in the augering of some sample wells has suggested the presence of some clays in portions of the aquifer; and (2) Jones and Weir (1983) have found authigenic clay materials in nearby Lake Abert.

Ground-Water Flow System

The locations of the PVC wells are shown in Figure 5. The water table maps (Figure 7) were drawn using data from that well series. Since some of the wells were installed at separate times, each of the maps shows the location of the sampling points which provided the database for that map. Figure 8 presents water level data as a function of time. All data have been plotted relative to a datum level of 1,000 cm as the height of the casing on Well 2. The general direction of ground-water flow is westward. As mentioned earlier, this direction results from the relative locations of the springs, West Alkali Lake, and the ground-water conduit provided by the partially-filled topographic low.

For the annual cycles presented in Figures 7 and 8, the highest and lowest water table levels in the area of the site occur in March to April and in September to November, respectively. The large evapotranspiration losses which occur in the basin

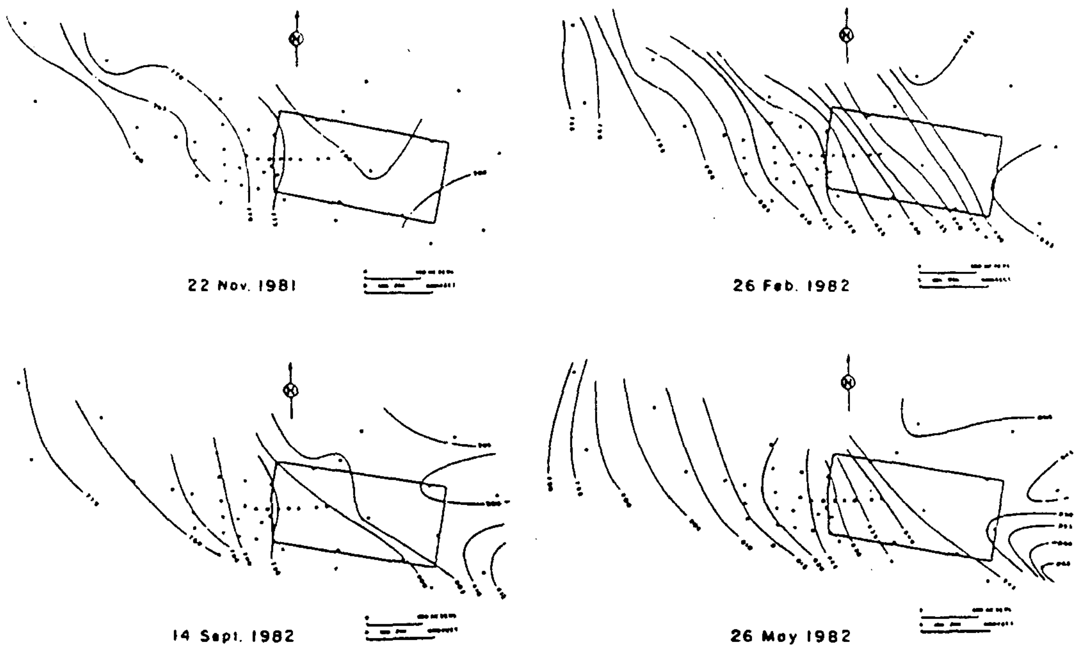

Fig. 7. Water table maps in centimeters obtained during November 1981, and February, May, and September 1982. The points at which data were taken for the preparation of the maps are shown in each of the figures. All data are relative to the datum: top of Well 2 casing = 1,000 cm.

in the summer months [maximal losses at nearby Lake Abert occur in July to August (Van Denburgh, 1975)] are no doubt largely responsible for this cycle. Since the average annual precipitation in the basin is only 17.5 cm, other than promoting evaporation, the decrease in precipitation during the summer months probably plays a minimal role. If summertime losses at West Alkali Lake were substantially greater than at other areas near the site, the hydraulic gradient across the site would be expected to maximize during the summer. This does not occur. Rather, as Figure 9 shows, it tends

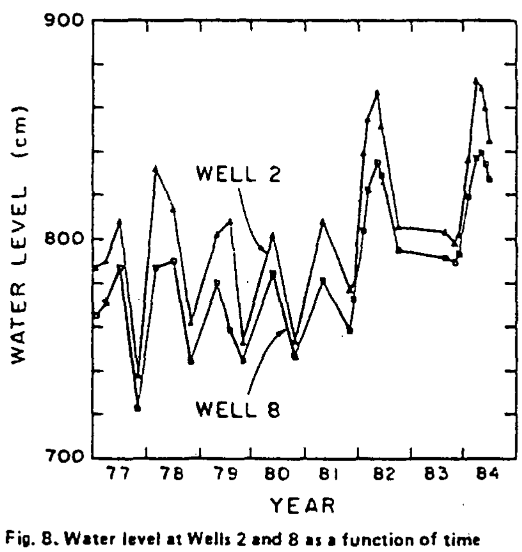

Fig. 8. Water level at Wells 2 and 8 as a function of time over the period 1977 to 1984.

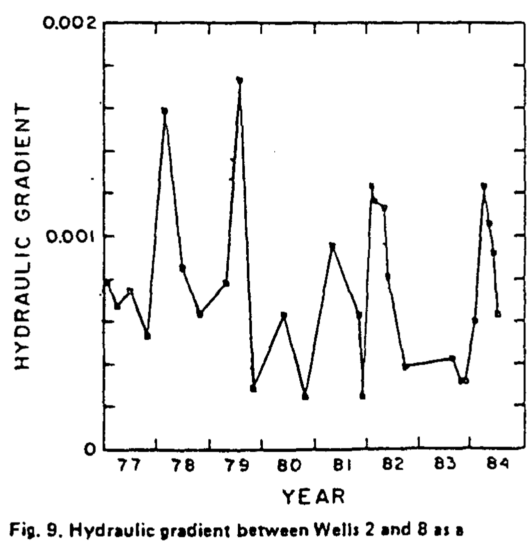

Fig. 9. Hydraulic gradient between Wells 2 and 8 as a function of time over the period 1977 to 1984.

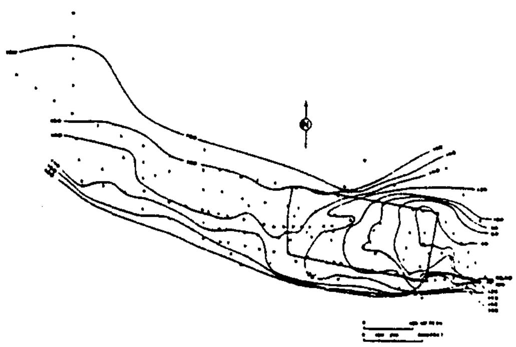

Fig. 10. Specific conductance isopleths (April 1983), μmhos/cm x 10^{-2}.

to maximize during February to June and has its lowest values during September to November. This may be because of large summertime evapotranspiration losses from the playa area east of the site. While the ground-water mound caused by the springs to the east of the site remains in place throughout the year, such losses could cause sufficient decay of the mound to allow a decrease in the east to west gradient. The seasonal variation in the water table would then be due to the interplay between the evapotranspiration losses in the various areas. Variable spring output could also explain the observed temporal behavior of the gradient and the water table, though such cycling is not common in springs discharging from volcanic rock aquifers (Todd, 1980). The causes of the seasonal variation in the hydraulic gradient continue to be investigated by the authors.

The average value of the annual fluctuation in the water table height at Well 2 was 0.6 m (Figure 8). The actual average fluctuation must be greater because discrete and not continuous data were obtained. This fluctuation, however, does not provide an estimate of the evapotranspiration losses from the playa area since a substantial amount of the fluctuation is no doubt due to the growth and subsidence of the ground-water mound near the site. The depth to ground water at Well 2 ranged between 0.9 m (April 1982) and 2.2 m (October 1977). With the bottoms of the trenches in which the chemicals were buried between 0.60 and 0.75 m below the level of the ground surface (ODEQ, 1977a), the bottom portions of the trenches may, at least occasionally, be in direct contact with the ground water. Since historical data for nearby Lake Abert indicate a water level fluctuation of more than 5 m in the period since the early 1930s (Phillips and Van Denburgh, 1971), there is a possibility that the wastes will be hydraulically lifted out of the trenches and onto the playa some time in the future. Given the freshness of the springs to the east of the site and the high salinity of the near-surface playa ground water, the specific conductance contours obtained near the site (Figure 10) confirm that the springs are important in determining the rate and direction of ground-water movement. Since the seasonal water table maps do not show major changes in the direction of ground-water flow, it is likely that the conductivity contours are similar throughout the year. The fact that the low conductivity water flows directly along the major axis of the site has proven convenient in plume modeling work to be described elsewhere.

SUMMARY AND CONCLUSIONS

The fact that the playa surface was initially selected for chemical storage was due to the purchasability of the mining patent whose boundaries closely followed the playa boundaries. The subsequent disposal of the waste in trenches at the same site is unfortunate because: (1) the water table is close to the ground surface; and (2) there is a strong local ground-water flow. The direction of ground-water movement is westward throughout the year. The conductivity contours confirm the directional nature of the flow as well as the importance of the springs east of the site as a source of a local ground-water mound. With hydraulic gradients across the site, hydraulic conductivities, and porosities of the order of 2.0×10^{-4} to 1.2×10^{-3}, 0.01 to 0.10 cm/s, and 0.65, respectively, local ground-water velocities of 0.3 to 16.0 cm/day would be inferred if the total porosity was available for flow. Since Johnson *et al.* (1984b) have shown that the porosity available for flow at this site is only 0.01 to 0.05, the actual ground-water velocities are much higher, i.e. in the range of 3.9 to 1,040. cm/day. The manner in which this ground-water flow has influenced the shape of the compound-dependent contaminant plume downgradient of the site is the subject of the second paper in this series (Johnson *et al.*, 1984a).

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Migration of Chlorophenolic Compounds at the Chemical Waste Disposal Site at Alkali Lake, Oregon — 2. Contaminant Distributions, Transport, and Retardation

by Richard L. Johnson[a], Susan M. Brillante[a], Lorne M. Isabelle[a], James E. Houck[b], and James F. Pankow[a]

ABSTRACT

The behaviors of five chlorophenols and three chlorophenoxyphenols (CPPs) have been investigated at the chemical waste disposal site at Alkali Lake, Oregon. All of the compounds demonstrated similar trends in areal distribution hydraulically downgradient from the site. The transport distances for the di- and trichlorophenols were influenced greatly by their ionization in the high pH (~10) ground water. In batch equilibrium experiments, these compounds were found to have K_p values of ~0.0 for the soil and ground water taken from the site. While also largely ionized at pH ≃ 10, a tetrachlorophenol, pentachlorophenol, and the CPPs demonstrated substantial sorption in the batch equilibrium experiments as well as retardation relative to the di- and trichlorophenols at the site. The retardations observed relative to 2,6-dichlorophenol were less than predicted based on the batch equilibrium results. Possible reasons include cosolvent effects due to the plume itself, nonuniform contaminant distributions at the time of the original burial, the fractures which are present in the aquifer, and a decreasing ground-water velocity with distance westward of the site. Evidence is presented to support the last reason. These results show, for the first time, well-behaved concentration contours embodying compound-dependent retardation in the transport of sorbing and nonsorbing organic compounds from an existing waste disposal site.

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INTRODUCTION

The widespread contamination of ground water by organic compounds requires that the processes which control their transport in ground-water systems be understood. Sorption has been recognized as playing a fundamental role in retarding the movement of organic compounds (Freeze and Cherry, 1979; Roberts *et al.*, 1982). When studying the retardation of compounds in contaminated ground-water systems, one must also consider the possibility of confounding effects due to: (1) the presence of large concentrations of contamination-related organic compounds which may lead to decreased retardation through cosolvation; (2) spatially nonuniform and compound-dependent contamination; (3) time-dependent source strength(s); (4) the presence of fractures in the geological medium comprising the zone of contamination; and/or (5) changes in the ground-water velocity or irregularities in the hydraulic conductivity (K_h) with distance downgradient of the source. All of these processes and conditions must be considered in the study of migration of contaminants at the Alkali Lake, Oregon chemical waste disposal site (Pankow *et al.*, 1984).

The equilibrium partition coefficient [K_p, g sorbed solute/g soil (dry-weight basis)] of a compound is commonly determined by means of batch equilibrium experiments. Both the role of concentration in sorption (O'Connor *et al.*, 1980; Karickhoff, 1981, 1983, 1984; Schwarzenbach and Westall, 1981; Chiou *et al.*, 1983) and the kinetics of the sorption process (Karickhoff, 1983) may be studied by this technique. The value of K_p depends upon the nature of the soil, the solute, and to a lesser extent the nature of the aqueous phase. The soil organic carbon (SOC) content of the soil is generally the most important factor influencing sorption. It is usually denoted f_{oc} where

$$f_{oc} = \text{g of SOC/g of soil} \quad (1)$$

When the SOC content is on the order of 0.1% or greater ($f_{oc} > 0.001$), it has been possible, especially for nonionizing compounds, to predict the degree of sorption of a given solute for a variety of soils based on the f_{oc} of the soils. Under such conditions, K_p may be estimated as

$$K_p = K_{oc} f_{oc} \quad (2)$$

where K_{oc} (g sorbed solute/g organic carbon) is the organic carbon distribution coefficient (Karickhoff, 1981). If a compound can ionize by protonation or deprotonation, the literature K_{oc} value for that compound is usually reported for the neutral form of the compound. For a compound that can become negatively charged (e.g., a phenol), the negative form will generally not sorb to the *neutral to negatively-charged* soil organic matter as well as will the neutral form. In such a case, pH-dependent ionization can lead to a much reduced K_p value.

In practice, most modeling of the transport of sorbing organics has employed the Freundlich isotherm $S = K_p C^n$ where S = (g sorbed solute)/(g soil); C = (g dissolved solute)/(cm³ pore water); and n is a constant usually less than 1.0. Linearity of the isotherm is often assumed (n = 1).

For flow through homogeneous porous media with linear sorption, the degree of retardation relative to the ground-water velocity is given by

$$R = 1 + (K_p \rho_b / \theta) \quad (3)$$

where R = retardation factor (dimensionless); ρ_b = soil bulk density (g/cm³); and θ is the soil porosity. For a nonsorbed compound, $K_p = 0$, and the migration velocity equals the actual physical ground-water velocity. For a sorbed compound, the migration velocity will be less (by a factor of R) than the physical ground-water velocity. R will be given correctly by equation (3) only when the assumptions of equilibrium and linear sorption are satisfied. When a relative retardation factor R_r is computed as the migration velocity of a sorbed compound relative to that for a nonsorbed compound, under these conditions, R_r will equal R as given by equation (3).

When fractures are present in the medium of interest, solutes will diffuse into zones of the aquifer matrix where the water is immobile and there is no advective flow. This process has been much discussed recently as a mechanism for retardation. These zones can be either porous media between fractures (Freeze and Cherry, 1979; Grisak and Pickens, 1980, 1981; Sudicky and Frind, 1982), or simply small volumes of aquifer of low hydraulic conductivity (van Genuchten, 1974). In such systems, even compounds with K_p values of 0 will move more slowly than the physical velocity of the ground water in the mobile regions since even nonsorbed compounds will diffuse into the immobile regions. A principal difference between the effect of "matrix" diffusion and that of sorption is that the former is less compound-specific. That is, while the matrix diffusion coefficients for different species in a given matrix material can vary over a single order of magnitude, K_p values can vary over many orders of magnitude.

The mechanism of retardation in a mobile/immobile system rests in the fact that all compounds spend a fraction of their time in the immobile zone. If the mobile water moves sufficiently slowly that sorption and physical partitioning equilibrium is reached rapidly between the mobile and immobile water, then the retardation *relative to the physical velocity of the mobile water* will be given by (Johnson, 1984)

$$R = (1 + K_p \rho_b / \theta)(1 + \theta_{im} B / \theta_{mf} b) \quad (4)$$

where θ is the overall porosity of the system, θ_{mf} is the porosity of the region in which the mobile water is flowing, θ_{im} is the porosity of the immobile region, B is the average immobile region halfwidth, and b is the average mobile region halfwidth. As noted above, even when K_p is zero, R is greater than 1.0. In fact, although K_p for water itself is 0.0, the velocity of *tagged* (e.g., tritiated) water relative to the mobile-water velocity also would be retarded relative to the physical velocity of the mobile water. This is the definition of retardation that is usually implicit in discussions of mobile/immobile-water systems (Feenstra *et al.*, 1984). Unlike the porous medium case then, in mobile/immobile systems, the actual time-averaged velocity of a specific water molecule is *less* than the physical velocity of water in the mobile regions.

Since the migration velocity of a nonsorbed compound in a mobile/immobile system is an obvious reference for considering the behavior of other compounds, it is often of interest to compute the retardation of a sorbed compound relative to that of a nonsorbed compound. When equilibrium is established quickly between the mobile and immobile water, that R_r value will be given by equation (3): the factor involving the specific mobile and immobile parameters in equation (4) cancels out. In this case, the system acts like one in which ground water is moving at the velocity it would have if all of the porosity was open and available for flow. *This is the equivalent porous medium (EPM) case.*

If mass transport limitations prevent the rapid establishment of an equilibrium partitioning (both physical and sorptive) between the mobile and the immobile regions, then: (1) the velocity of both nonsorbed and sorbed compounds will be closer to the velocity of the mobile water; and (2) since the velocity of a sorbed compound will be closer to that for a nonsorbed compound, the R_r as computed by the ratio of the former to the latter will be less than R as given by equation (3). (This *mass transport* kinetics effect is phenomenologically distinct from slow sorption/desorption *chemical* kinetics.)

The R_r concept is useful in the study of field data. When carrying out controlled laboratory tracer experiments in simulated soil media, well-defined physical boundaries and tracer source functions are employed, and retardation factors are conceptually well-defined. At a contaminated field site, however, such well-defined features are usually absent. As a result, it may well become necessary to measure: (1) the transport distances of the breakthrough fronts of various contaminants relative to some hopefully uniformly meaningful physical boundary; and (2) the retardation of various contaminants, relative to the front of one of the contaminants which hopefully may be assumed to be nonsorbing and conservative. The meaningfulness of an R_r factor produced by this mechanism will suffer from inaccuracies if: (1) the various contaminants of interest moved relative to one another before their arrival at the selected transport reference boundary; (2) the various contaminants were deposited in the source area at different times and/or in different, non-uniform distributions; (3) the subjective assignment of the location of the various breakthrough fronts cannot be done in a meaningful manner; (4) a spatial variability of the ground-water velocity is (has been) present; and/or (5) relatively large amounts of dissolved organic compounds which affect sorption are (have been) present in the ground water.

Depending upon their exact nature, the first four conditions could lead to either a decrease or increase in the R_r values. As an example of the fourth condition, if the ground-water velocity decreases away from the source, the relatively fast-moving nonsorbing compounds will experience the decreasing velocity first while the more retarded compounds will remain longer in the region of higher velocity: the R_r values will be reduced. The fifth condition will generally lead to a reduction in the measured R_r values due to either: (a) an increased water solubility of the sorbing compounds; and/or (b) an overloading of the sorbing SOC. For mobile/immobile-water systems which are complicated by any of the above five conditions, if R_r values less than those predicted by equation (3) are observed, it may be difficult to ascertain the extent to which disequilibrium between the two types of regions is responsible.

To date there have been very few field-scale studies of the transport and retardation of organic compounds in undisturbed ground-water systems. The water-table aquifer system at the chemical disposal site at Alkali Lake, Oregon (Pankow *et al.*, 1984) provides a good opportunity to study some of the factors controlling these phenomena. Chlorophenolic organic compounds with K_p values ranging from ~0.0 to greater than 50 are present in the waste materials. Some compounds have migrated over 600 m in 8 years. Field examination of the aquifer materials has indicated the presence of a large number of fractures (and/or bedding plane openings) spaced from mm to cm apart (Johnson, 1984). We believe that this system comprises a well-defined mobile/immobile-water system.

In this paper, the R_r values of the sorbing compounds calculated relative to a nonsorbing compound have been compared to R_r values calculated using equation (3) together with K_p results from batch equilibrium experiments. The differences between the retardation factors obtained by these two methods are discussed with regard to various physical and chemical processes. The role of ground-water movement through regions of higher mobility at this site is examined.

CHEMICAL WASTES AT ALKALI LAKE

During the period 1960 to 1970, considerable quantities of the herbicide 2,4-D (2,4-dichlorophenoxyacetic acid) were manufactured for use as a defoliant in Vietnam (Young *et al.*, 1978). Large amounts of 2,4-D by-product wastes were disposed of at Alkali Lake (Pankow *et al.*, 1984). The 2,4-D was produced by the etherification of 2,4-dichlorophenol (2,4-DCP) and chloroacetic acid. Much of the 2,4-DCP used in this process was manufactured

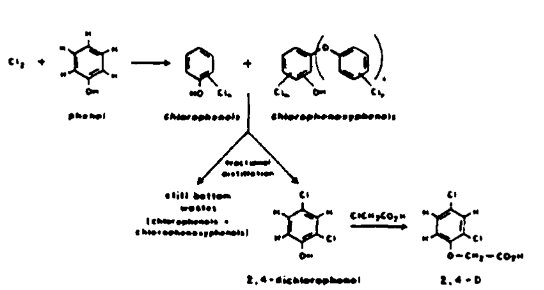

Fig. 1. Products and waste by-products in the synthesis of 2,4-D (where n and p = 1 to 5, m = 1 to 4, and x > 1).

by the direct Cl_2 chlorination of phenol (Figure 1). This step led to the production of a majority of the unwanted by-products. These included 2,6-dichlorophenol (2,6-DCP); 2,4,6-trichlorophenol (2,4,6-TCP); 2,3,4,6-tetrachlorophenol (TeCP); pentachlorophenol (PCP) (Figure 2); and a host of polymerization products known as the chlorophenoxyphenols (CPPs) (Figure 1). The CPPs were formed by the linear addition of chlorophenol units. This process led to CPP dimers, trimers, tetramers, pentamers, etc. Since the coupling process can occur at any one of the chlorine positions, and since a variety of different chlorophenols were present in the phenol chlorination process mixture, a wide variety of CPP compounds were formed.

After the Cl_2 chlorination step, the desired 2,4-dichlorophenol was separated from the by-products by distillation. The "still-bottom" mixture has been found to include oligomers with up to at least five rings, and a total of from two to seven chlorine atoms (Pankow *et al.*, 1981). A large number of structural isomers (compounds with the same overall formula, but different specific structures) will occur in the CPP compound class.

The various waste compounds display a wide range of water solubilities. Many of the chlorophenols are quite acidic, in part because of the presence of chlorine atoms on the phenol ring. The ground water flowing beneath the disposal site at Alkali Lake is very alkaline (pH ≃ 10). As a result, most of the chlorophenols exist primarily as anions and are therefore quite soluble. The CPPs, while also rather acidic, contain a hydrophobic phenoxy group substituent. They are therefore less soluble, and show greater sorption to the soil. This paper will consider the distributions of eight different chlorophenolics (five chlorophenols and three CPPs) at the Alkali Lake site.

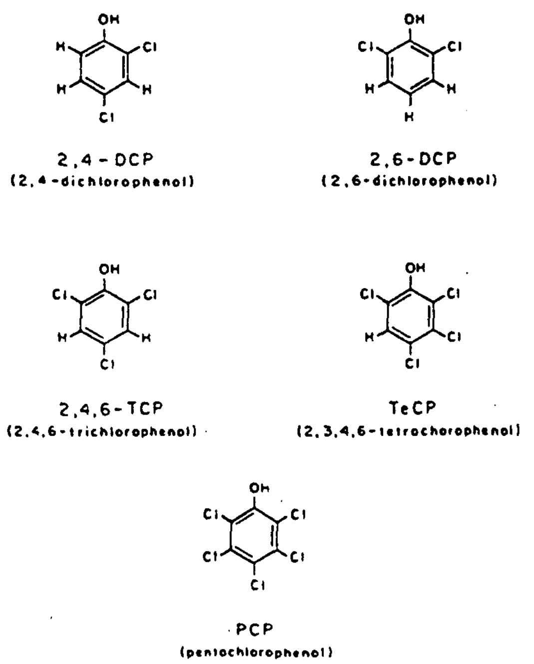

Fig. 2. Structures of chlorophenols.

EXPERIMENTAL

Sampling

Sample bottles (40 or 125 ml capacity) were washed with warm water and laboratory detergent, rinsed with deionized water, dried, and then rinsed with methylene chloride. Samples were collected on April 30 and May 1, 1984 from 1.6 cm O.D. (0.9 cm I.D.) PVC tubes. Since the PVC tubes were slotted to three m below the water table, samples obtained with them reflected an approximate concentration average over that interval. (Contamination is limited primarily to the top three m of the ground water.) Samples were collected using a hand-operated vacuum pump (Nalge, Inc., Rochester, NY). Because the chlorophenolics are primarily in an ionized state at pH 10, their vapor pressures were very low, and it is unlikely that any losses occurred during the reduced pressure sampling. Upon return to the laboratory and prior to analysis, the samples were stored at 4°C.

2,4-Dichlorophenol, 2,6-Dichlorophenol, and 2,4,6-Trichlorophenol Determinations

Sample work-up was carried out using a special apparatus (Figure 3) by means of the following steps: (1) 10 ml of sample placed in

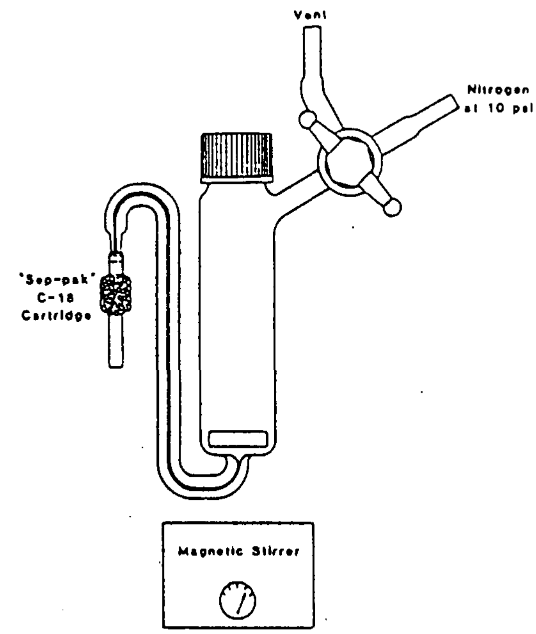

Fig. 3. Apparatus for sample work-up and passage through "Sep-pak" C-18 cartridge.

apparatus; (2) stirrer activated, pH electrode inserted, and sample acidified to pH 2-3 with 6 N HCl to protonate all organic acid analytes; (3) electrode rinsed with 2 ml of organic-free water; then removed; (4) vessel capped; (5) Waters Assoc. (Milford, MA) C-18 Sep-Pak cartridge placed on vessel, and vessel pressurized to 10 psi with nitrogen gas to obtain 5 ml/min flow rate until the sample was exhausted; (6) Sep-Pak removed, then aspirated for 30 s to remove residual water; (7) organic compounds eluted with 2 ml of methylene chloride, the first drop (residual water) discarded; (8) volume reduced to 1.0 ml using a micro Kuderna-Danish/Snyder column apparatus and a 95°C water bath; (9) 5 µl of an external standard (ES) solution in methylene chloride added containing 10 µg/µl of meta-chlorophenol, and 10 µl of an ES solution in methylene chloride containing 100 ng/µl each of chrysene and fluoranthene; (10) 50 mg of anhydrous sodium sulfate added for desiccation; (11) concentrated extract transferred to a precleaned 3.5 ml amber glass minivial (Pierce Chemical, Rockford, IL); (12) sample stored at 4°C; and (13) extract analyzed by gas chromatography (GC). Standard chemicals were obtained from Chem Service (West Chester, PA).

The use of the term "external standard" (ES) here is as described by others (Research Triangle Institute, 1983). An ES is a standard compound which is added to the sample extract just prior to the analytical determination step: it is "external" to the work-up. The ES allows compensations to be made for (1) changes in instrument response between calibrations, and (2) variations in volume of sample injected into the analytical instrument. An "internal standard" (IS) is added to the sample prior to the work-up to monitor the efficiency of the extraction process: it is "internal" to the work-up.

The analyses took place without derivitization using fused silica capillary gas chromatography (GC) with helium carrier gas on a Hewlett-Packard (Palo Alto, CA) 5880A capillary GC equipped with a flame ionization detector (FID). [Samples were also run on a Finnigan (Sunnyvale, CA) 4000 GC/mass spectrometer/data system (GC/MS/DS) to ensure that no misidentifications or coelution problems would go unnoticed.] The column used was a 30 m, 0.25 mm I.D., 0.25 µm film thickness DB-5 (SE-54) fused silica capillary column (J&W Scientific, Rancho Cordova, CA). The carrier gas linear velocity used was 20 cm/s (at 175°C). With the injector at 275°C and the FID at 310°C, 1.0 µl volumes were injected splitless at 45°C. The GC temperature program used was: hold at 45°C for two min; program to 175°C at 10°C/min; then hold at 175°C for 5 min.

A three-point quadratic calibration curve (based on peak areas) was developed for the GC/FID analyses for each compound using the HP 5880A system software. Samples were run following calibration. For quality assurance (QA), the calibration was randomly verified by running an intermediate concentration standard. If the response varied by more than ±10% from the known concentration, the calibration was repeated. In addition, for every set of ten samples, a duplicate, a spiked (recovery) sample, and a blank were also analyzed. The latter was prepared by processing 10 ml of deionized water through the concentration procedure.

2,3,4,6-Tetrachlorophenol (TeCP), Pentachlorophenol PCP), and Chlorophenoxyphenol (CPP) Determinations

The sample extracts described above for the di- and trichlorophenol determinations were also analyzed for TeCP, PCP, and for three CPPs denoted CL2D2, CL3D3, and CL4D2. These are all chlorophenoxyphenol dimers, with two, three, and four chlorines, respectively. Specific structures for these compounds could not be obtained because reference compounds are not currently available.

The compounds fluoranthene and chrysene, added during the sample work-up, served as the ES compounds. Analyses were carried out by injection of 1.0 μl of the extract using an on-column injector and the same type of column used in the chlorophenol analyses. The column was mounted in an HP5790 GC substituted for the Finnigan 9610 GC on the Finnigan GC/MS/DS (Pankow and Isabelle, 1984). The transfer line, source, and MS manifold temperatures were maintained at 225, 225, and 100°C, respectively. The helium carrier gas linear velocity used was 30 cm/s (at ambient temperature). The on-column injections were carried out with the oven at 80°C. The GC temperature program used was: immediate temperature program at 10°C/min to 320°C, then hold at 320°C for 4 min. The analytes were detected using multiple ion detection (MID, or "selected ion monitoring"). The ions monitored for each of the compounds were (in their order of GC elution): TeCP (131, 232, 234); PCP (200, 266, 268); CL2D2 (184, 252, 254); fluoranthene, ES compound (101, 202); CL3D3 (225, 254, 288, 290); CL4D2 (146, 322, 324); chrysene, ES compound (114, 228); and 5-chloro-2-(2,4-dichlorophenoxy)-phenol (Irgasan DP300) (146, 288, 290). For QA, every tenth sample was analyzed both in duplicate and spiked with a recovery standard. TeCP and Irgasan DP300 were used as recovery standards. The latter was obtained from Ciba-Geigy, Basil, Switzerland.

Bulk Mass Density and Porosity Determinations

Core samples of soil material taken downgradient from the site in the saturated zone contained intact angular blocks which appeared relatively undisturbed by sampling. Measuring 1-2 cm across, they were representative of the aquifer material. To determine density, the blocks were weighed and their volume determined by immersion in water. They were reweighed to verify that no appreciable amount of water had been absorbed, then dried at 50°C to a constant weight. The bulk mass density was calculated as the dry mass to volume ratio. The porosity was calculated as the weight loss to volume ratio.

Soil Organic Carbon (SOC) Determinations

The soil was obtained and composited from the depth range of 1-3 m from a location 10 m east of Well 2. The well locations are given by Pankow *et al.* (1984). Composite samples of 1.0 g were treated with 5 ml of a 5% stannous chloride, 3 N HCl solution, then heated for 4 hours at 50°C under vacuum to volatilize inorganic carbon (carbonate and bicarbonate) as CO_2. Small aliquots (10 mg) of the dried soil were weighed, then combusted in an apparatus developed by Johnson *et al.* (1985) based on previous work by Johnson (1981). The combustion was carried out at 600°C in a 10% O_2-90% He gas mixture. The CO_2 formed was catalytically converted to methane, then measured with an FID. Calibration of the FID response was carried out using injections of methane. The stannous chloride was used in the carbonate volatilization step to prevent premature oxidation of the SOC (Allison and Moodie, 1965).

Batch Equilibrium Experiments

Batch equilibrium experiments were carried out using contaminated water and uncontaminated soil from the site. The water used was collected at Well 38. The soil was the same composite for which the SOC values were obtained. Three sets of experiments were carried out, each in triplicate. In the first, 20 ml of Well 38 water (spiked with the control compound naphthalene at 12 mg/l) and 2 g of dry soil were mixed in a 35 ml glass vial. In the second experiment, 2 ml of Well 38 water was diluted with 18 ml of Well 2 water, spiked with naphthalene at 12 mg/l, and mixed with 2 g of soil in a 35 ml vial. The third experiment was identical to the second, except that each sample was spiked with an additional 500 mg/l of 2,4-DCP. The latter was done to investigate if the presence of high concentrations of the chlorophenol would decrease sorption of the other compounds. The samples were equilibrated by end-over-end rotation at 20 ± 3°C for 24 hours (30 inversions/min). Each sample was then centrifuged for 15 min. An amount of 12-15 ml of the supernatant was withdrawn into a 20 ml syringe, then forced through a glass fiber prefilter followed by a silver membrane filter (Selas Corp., Huntingdon Valley, PA). Ten ml was then processed as described above for chlorophenol determinations.

The ground water at the site ranges between 7-12°C. This is ~10°C lower than the temperature at which the sorption measurements were made. Because sorption generally increases with decreasing temperature (Karickhoff, 1984), it is expected that the sorption of the compounds at the site will be somewhat greater than predicted by the sorption measurements.

Fig. 4. Distribution of 2,4-dichlorophenol (2,4-DCP). Contours are given in units of mg/l.

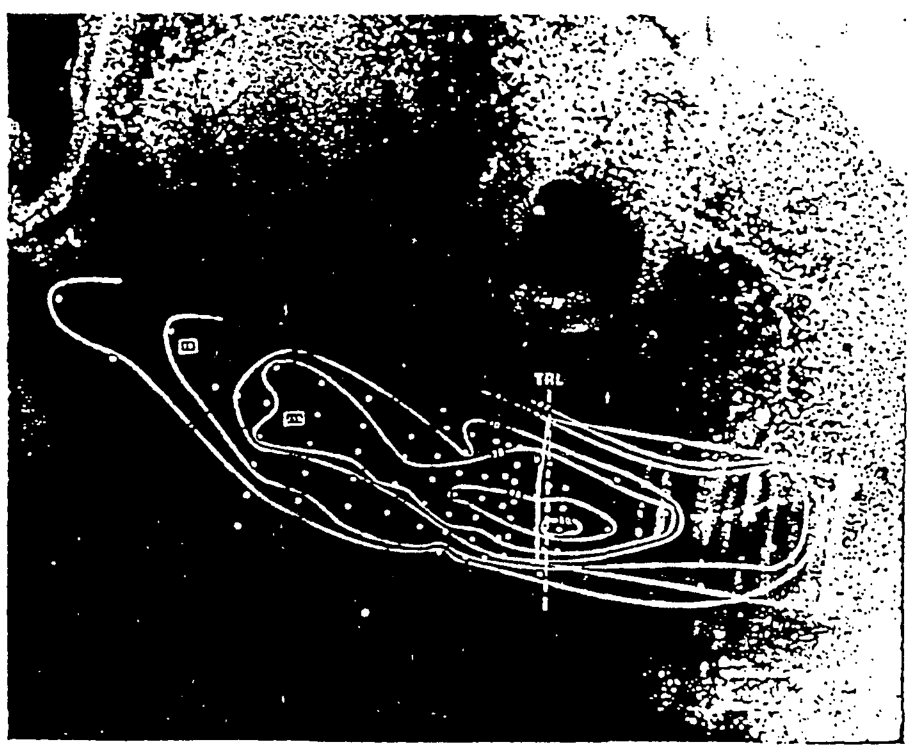

Fig. 5. Distribution of 2,6-dichlorophenol (2,6-DCP). Contours are given in units of mg/l.

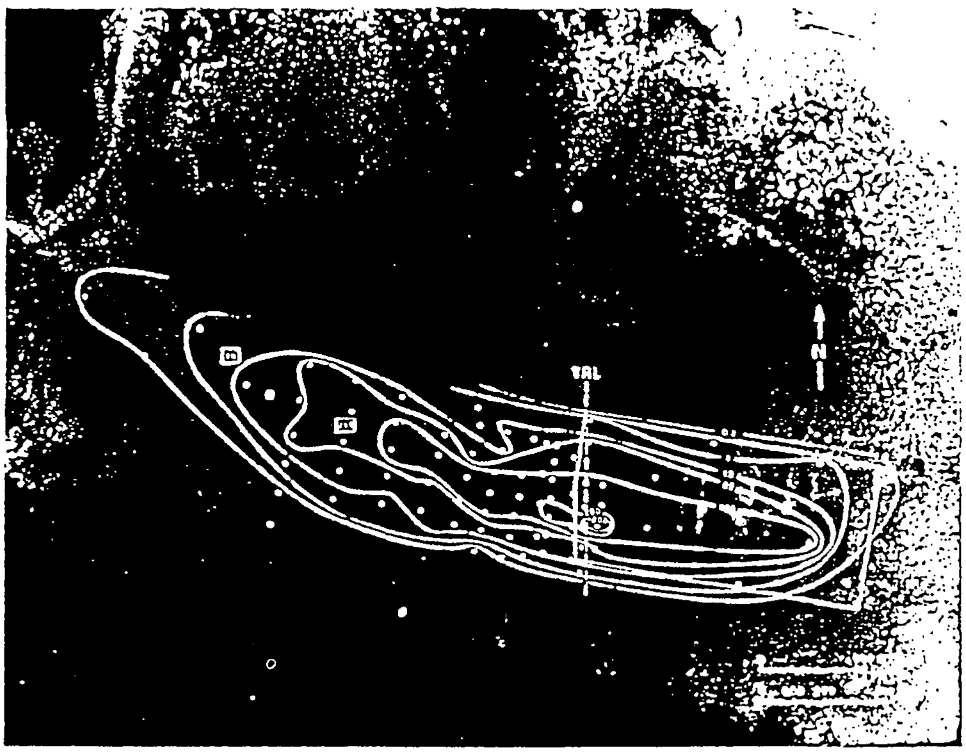

Fig. 6. Distribution of 2,4,6-trichlorophenol (2,4,6-TCP). Contours are given in units of mg/l.

RESULTS

2,4-DCP, 2,6-DCP, and 2,4,6-TCP Distributions

The distributions of 2,4-DCP, 2,6-DCP, and 2,4,6-TCP in the ground water at Alkali Lake are given in Figures 4-6. The sampling points for which data were obtained and used in the drawing of the contours are shown on the figures. These three chlorophenols display almost identical patterns. This implies that these chlorophenols (1) have similar source functions, (2) have been subject to the same hydrology, and (3) have experienced similar degrees of sorption or lack thereof. Based on the pH of the ground water (≈ 10), the acidity of these compounds, and their low molecular weights, one could predict that sorption would be similarly unimportant for all three. Because the sampling network used was fairly extensive and the analytical precision quite good (relative standard deviation 5%), it is possible to discern a narrowing of the contaminant plume ~150 m downgradient of the western edge of the site. This narrowing may be caused by irregularities in the K_h of the aquifer surrounding the zone of contamination. This will be discussed further below.

The true north-south line which passes through the northwest corner of the site was selected as the uniform transport reference line (TRL) from which to measure transport distances. This TRL, marked on the figures, was selected because: (1) the maximum concentrations of most of the chlorophenolics (even the retarded ones discussed below) are near this line; and (2) R_f values calculated using transport distances measured from this line will be upper bounds on R_f values relative to other, if any, more "meaningful" reference lines to the east (i.e., upgradient).

For each compound, the specific point selected from which to measure transport distances was the point on the TRL at which the concentration of the compound was at a maximum. In Figures 4-6, boxes are then used to mark the locations of the positions (as located on the line of shallowest rate of descent, i.e., approximate plume center line for each compound) at which the concentration drops to 2% and 25% of the reference point value. These are the endpoints of the 2% and 25% transport distances which are listed in Table 1. The concentrations of the three chlorophenols

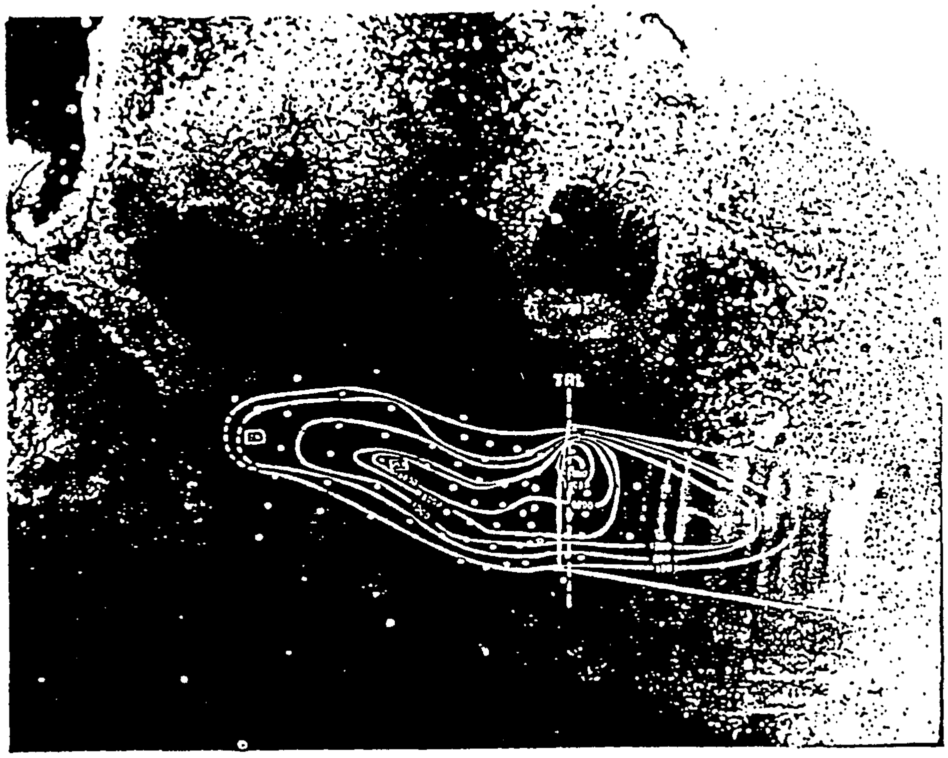

Fig. 7. Distribution of 2,3,4,6-tetrachlorophenol (TeCP). Contours are given in units of μg/l.

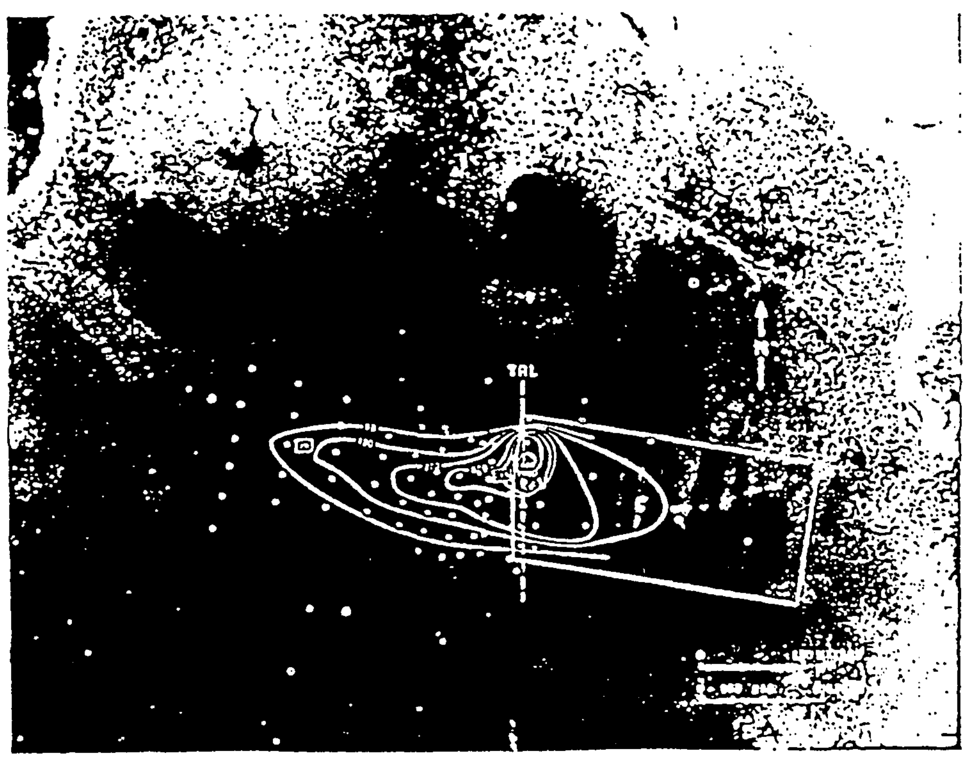

Fig. 8. Distribution of pentachlorophenol (PCP). Contours are given in units of μg/l.

Table 1. Distance Traveled (X) and Relative Retardation (R_r) Values

Compound	X(2%)	X(25%)	$R_r(2\%)^a$	$R_r(25\%)^b$	$R_r(pred)^c$
2,4-DCP	400.	250.	1.0	1.1	1.0
2,6-DCP	420.	270.	1.0	1.0	1.0
2,4,6-TCP	400.	270.	1.0	1.0	1.0
TeCP	330.	210.	1.2	1.3	3.5
PCP	260.	40.	1.6	6.8	13.5
CL2D2	230.	70.	1.8	3.9	34.
CL3D3	280.	150.	1.5	1.8	20.
CL4D2	210.	40.	2.0	6.8	40.

[a] $R_r(2\%)$ = retardation factor relative to 2,6-DCP = $X_{2,6\text{-}DCP}(2\%)/X(2\%)$.
[b] $R_r(25\%)$ = retardation factor relative to 2,6-DCP = $X_{2,6\text{-}DCP}(25\%)/X(25\%)$.
[c] $R_r(pred)$ = $R(pred)/R_{2,6\text{-}DCP}(pred)$.

drop to 2% of their reference values at distances of 400 to 420 m. The 50% transport distances are not given in Table 1 since their comparatively low values are subject to much error, particularly for the more retarded compounds to be discussed below.

TeCP and PCP Distributions

Due to the larger relative standard deviations for the low (μg/l) level determinations of TeCP and PCP (14% and 19%, respectively), it was not possible to draw the concentration contours of these two compounds (Figures 7 and 8) with the same degree of detail present in the 2,4-DCP, 2,6-DCP, and 2,4,6-TCP contours. The minimum detectable concentrations were nevertheless an order of magnitude below the lowest values reported. The general patterns of contamination were similar to those for the other three chlorophenols, though the concentrations of TeCP and PCP were ~100 times lower than those of the former. Using the same criteria described above, the concentrations of TeCP and PCP dropped to 2% of their reference values at distances of approximately 330 and 260 m, respectively (Table 1). These distances are shorter than those for the other three chlorophenols.

CPP Distributions

The concentration distributions of the CPP compounds CL2D2, CL3D3, and CL4D2 are presented in Figures 9-11. The minimum detectable concentrations were an order of magnitude

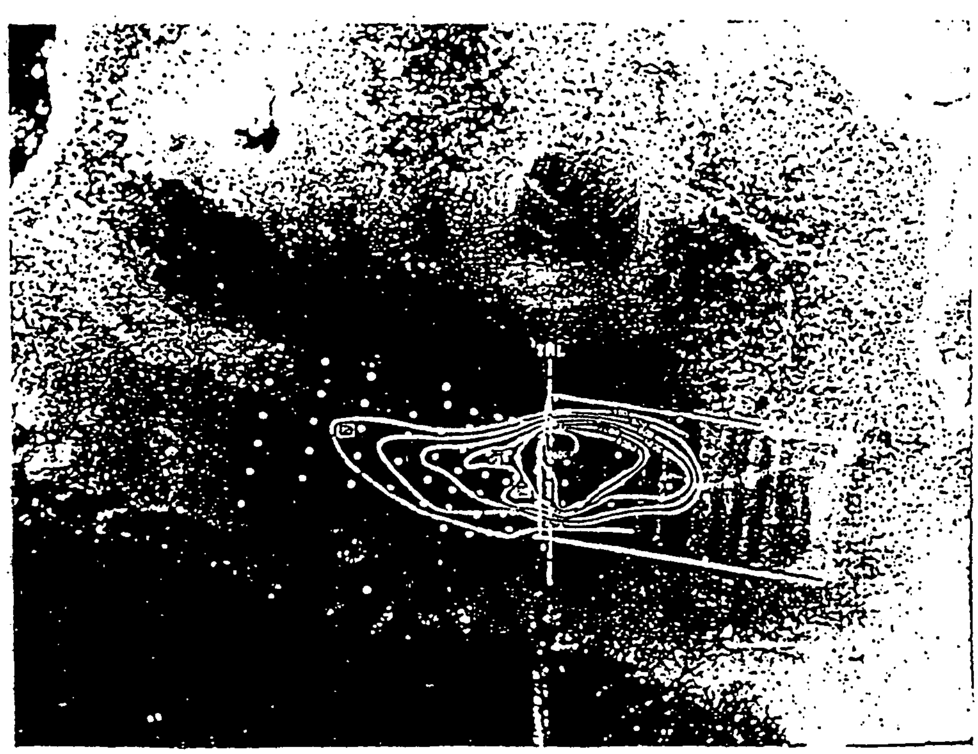

Fig. 9. Distribution of CL2D2. Contours are given in units of μg/l.

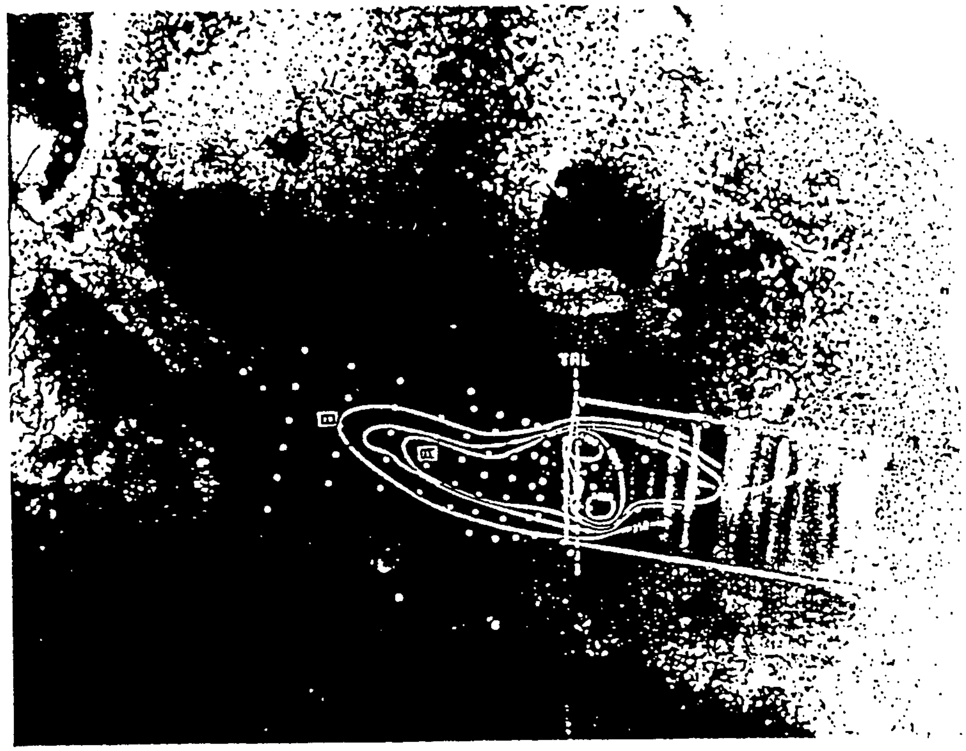

Fig. 10. Distribution of CL3D3. Contours are given in units of μg/l.

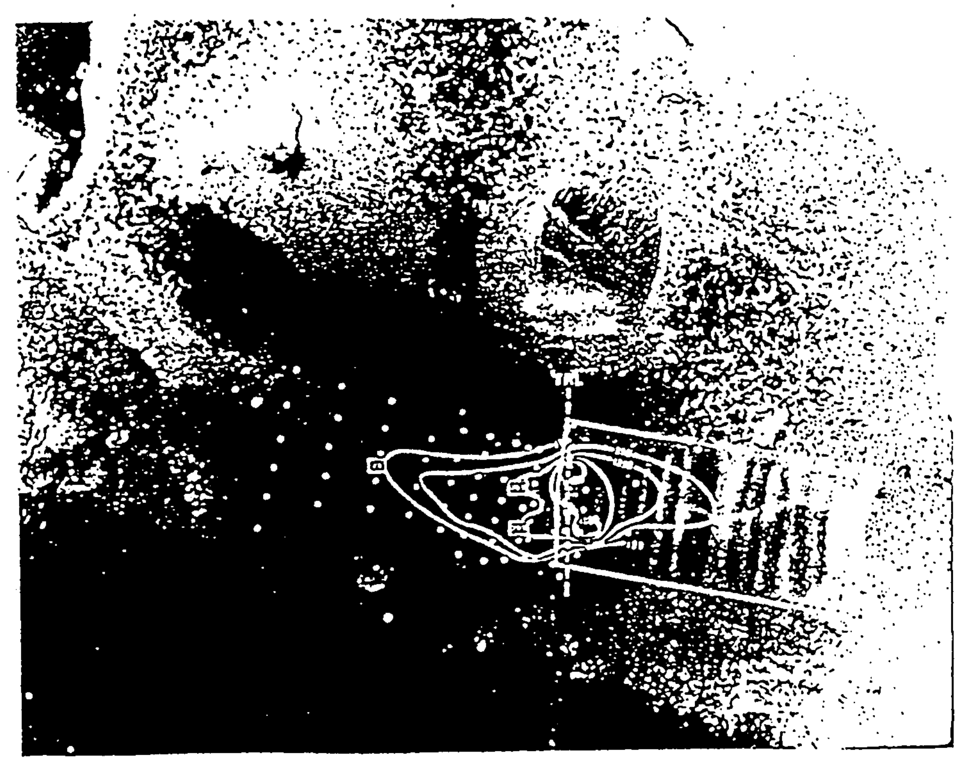

Fig. 11. Distribution of CL4D2. Contours are given in units of μg/l.

below the lowest values reported. The concentrations of these compounds dropped to 2% of their reference values at distances of approximately 230, 280, and 210 m, respectively (Table 1). These distances are less than those for most of the chlorophenols.

Porosity, Density, and Soil K_p and SOC Values

Values for the overall soil porosity (θ) of from 0.60 to 0.70 were obtained. The overall bulk mass density (ρ_b) values were in the range of 0.90 to 0.95.

For the concentration ranges studied, the results from the three batch equilibrium experiments indicated no significant dependencies of any of the K_p values on the concentration of sorbing analyte, or on the presence of 500 mg/l of added 2,4-DCP. The K_p values and the associated standard deviations presented in Table 2 were therefore calculated from the average of the results of the total of nine experiments. The K_p values for the chlorophenolics studied here ranged from 0.0 to 28. (Table 2). The control compound naphthalene gave a mean ±1s value for K_p of 16. ± 2.

The measured SOC values for the soil on a dry weight basis gave a mean ±1s value of 2.4 ± 0.3%. The number of replicates was 12. These determinations were complicated because of the high levels of carbonate present in the samples. The good precision suggests that the carbonate-removal step included in the SOC analysis procedure was effective, though the possibility of slightly high SOC values remains. The inclusion of the control compound naphthalene in the K_p experiments permitted an independent measure of the SOC content of the soil. Literature values for the K_{oc} for naphthalene are available. Karickhoff (1981) cites a value of 870, and Mabey *et al.* (1982) cite a value of 940. By equation (2), these K_{oc} values give SOC values of 1.8% and 1.7%, respectively. (The error in the K_p value for naphthalene has not been propagated into these SOC values since the available K_{oc} values are in any event averages for a number of different soils, and data on their corresponding statistical variability are not readily available.) The ratio of the average of these two values to the measured SOC value is 0.73, i.e., near 1.0.

Table 2. Measured K_p Values for Alkali Lake Soil/Water System (pH ≃ 10, T = 20°C), pK_a Values, and Literature K_{oc} Values for pH < pK_a

Compound	K_p	pK_a	K_{oc}
Naphthalene	16. ± 2.	–	870.[a]
2,4-DCP	0.0 ± 0.5	7.8	545.[b]
2,6-DCP	0.0 ± 0.5	6.8	NA
2,4,6-TCP	0.0 ± 0.5	6.2	1,070.[b]
TeCP	1.8 ± 1.0	5.4	6,640.[b]
PCP	9.5 ± 1.8	4.7	32,900.[b]
CL2D2	24. ± 5.	NA	NA
CL3D3	14. ± 3.	NA	NA
CL4D2	28. ± 5.	NA	NA

[a] Karickhoff, 1981.
[b] Schellenberg *et al.*, 1984.
NA = not available.

DISCUSSION

All of the chlorophenols and the CPPs demonstrated similar trends in areal distribution hydraulically downgradient from the site (Figures 4-11). The direction of transport is consistent with the previously reported slope of the water table (Pankow *et al.*, 1984). The transport distances for the di- and trichlorophenols were no doubt influenced greatly by their ionization in the high pH ground water. Indeed, as seen in Table 2, these compounds were found to have K_p values of ~0.0 for the soil and ground water taken from the site. These results are in agreement with those of Miller and Faust (1973) and Schellenberg *et al.* (1984). Both groups report that while the protonated forms of these phenols sorb (K_{oc} > 0 for pH < pK_a, see Table 2), their sorption to SOC decreases to zero when the pH exceeds their pK_a values by at least one unit. The pH ~10 ground water at the site is 2.2 to 3.8 units above the pK_a values for the di- and trichlorophenols (Table 2). It may therefore be concluded that the similarities of the di- and trichlorophenol distributions were indeed due in large part to the similarly nonsorbing natures of these three compounds at pH ≃ 10.

While also largely ionized at pH ≃ 10, TeCP and PCP demonstrated substantial sorption (Table 2). These results are also in agreement with results obtained by Schellenberg *et al.* (1984). Similarly, despite the fact that the CPPs will surely also be present largely as anions at pH ≃ 10, they demonstrated substantial sorption. Therefore, the fact that TeCP, PCP, and the CPPs demonstrated retardation relative to the di- and trichlorophenols may be understood in terms of their nonzero K_p values.

Of the three nonsorbing di- and trichlorophenols, it may be possible to treat 2,4-DCP, 2,6-DCP, and 2,4,6-TCP as approximately conservative. To evaluate the effect of sorption on the transport of TeCP, PCP, and the CPP, therefore. R_r values referenced to 2,6-DCP were: (1) calculated using the 2% and 25% transport distances [R_r(2%) and R_r(25%)] of the compound and those of 2,6-DCP; and (2) predicted using equation (3) and the experimental K_p values [R_r(pred)]. The results are presented in Table 1.

It should be pointed out that the most meaningful measured R_r values for the presumed constant source input function would have been the ones based on the 50% concentration fronts of the sorbed and nonsorbed compounds. R_r values based on the 2% or 25% fronts will be deflated relative to the 50% front due to differing relative effects of dispersion on the sorbed and nonsorbed compounds. Such differences will increase with increasing sorption and/or decreasing defined-frontal concentration. For TeCP, this effect could have caused a decrease in the R_r(2%) and R_r(25%) values of only ~9 and 15%, respectively (Johnson, 1984). For CL4D2, the most sorbed compound, this effect could have caused a decrease in the R_r(2%) and R_r(25%) values of ~30 and 45%, respectively (Johnson, 1984).

If the input function was not a constant, but rather decreased in time due to depletion of the finite mass of the source contaminants, that would lead to an inflation of the R_r(2%) and R_r(25%) values. This is the case because the nonsorbed compounds will tend to suffer relatively greater depletion at the source. This in turn requires that greater transport distances be inferred in order to reach 2% or 25% of the depleted source concentration values. Such inflation would tend to counteract deflation caused by the use of transport distances for contamination fronts defined at concentration values less than 50% of the source reference value.

Therefore, it may be concluded that only a small amount of deflation of the R_r values is possible. For the sorbing compounds ($K_p > 0$), however, the observed R_r(2%) and R_r(25%) values are in fact smaller than the R_r(pred) values by substantial amounts (Table 1). Indeed, had the sorption measurements been carried out at 10°C rather than 20°C, it may be expected that the R_r(pred) values in Table 1 would have been even larger.

The possible reasons remaining for the differences between the measured and predicted R_r values include: (1) cosolvent effects leading to a decreased retention of TeCP, PCP, and the CPPs; (2) nonuniform contaminant distributions at the time of the original burial, e.g., a time zero center of mass for 2,6-DCP further to the east than the time zero centers of masses of TeCP, PCP, and the CPPs; (3) the fractures in the aquifer; and/or (4) a decreasing ground-water velocity or irregularities in K_h with distance westward of the site.

Cosolvent effects could be due to either actual solvents in the contaminant plume and/or the high levels of di- and trichlorophenols. Large quantities of solvents are not believed to have been present in the waste, nor have any been detected in high concentrations. Since the batch equilibrium experiments demonstrated no changes of the K_p values with overall phenol concentration nor with the addition of 500 mg/l of 2,4-DCP, cosolvent effects due to the high concentrations of chlorophenols in the plume itself also do not appear important.

Figures 4-11 provide evidence that the various compounds were not distributed perfectly uniformly in the site. It does, however, appear that the trenches of waste near the selected transport reference line were the most contaminated in the compounds of interest to this study since the concentrations of the nonsorbed and sorbed compounds alike seem to be highest in that area. Most are more or less uniform in concentration along the TRL. (PCP is an exception with its locally very high concentrations in the northwest corner of the site (Figure 8). It is believed that this different character of the PCP distribution in the site artificially inflates its R_r(2%) and R_r(25%) values. Nevertheless, they are still substantially less than the R_r(pred) for this compound.) Moreover, when the data for all of the compounds are replotted after integrating along transects perpendicular to the direction of flow (a process which should remove dependence on the transverse irregularities in the source functions), the R_r(2%) and R_r(25%) values are still lower than the corresponding R_r(pred) values (Johnson, 1984).

The fact that the ground water moves in fractures in the soil is also not believed to be responsible for the reduced R_r(2%) and R_r(25%) values. It has been determined that diffusive equilibrium between the matrix and the fractures is approached within approximately two hours (Johnson, 1984). This short time period implies that matrix diffusion limitations are probably not responsible for the reduction of the R_r(2%) and R_r(25%) values, and that the Alkali Lake system behaves as an EPM.

Water-level measurements indicate that with increasing distance westward of the site, the hydraulic gradient first decreases, then increases, then decreases again as West Alkali Lake is approached (Johnson, 1984). The decrease and subsequent increase in the gradient is most likely due to a hydraulic conductivity-defined constriction located approximately 150 m west of the western edge of the site. This constriction is very likely the cause of the narrowing observed in the di- and trichlorophenol distributions. It appears from the contaminant distributions that all of the compounds have reached the constriction. The leading edges of the contaminant distributions of the nonsorbed compounds have largely stagnated on the downgradient side of the constriction. The leading edges of the contaminant distributions of the sorbed compounds, however, are still moving. The effect will be to reduce the measured $R_r(2\%)$ and $R_r(25\%)$ values. This is believed to be the primary reason why these values are lower than the $R_r(pred)$ values.

CONCLUSIONS

The areal distributions of eight chlorinated phenolics hydraulically downgradient from a chemical disposal site have been presented. These results show, for the first time, well-behaved concentration contours embodying compound-dependent retardation in the transport of sorbing and nonsorbing organic compounds from an existing waste disposal site. The trends in relative retardations of the compounds are consistent with the K_p values determined in batch equilibrium experiments carried out using samples of the native soil and ground water (pH $\simeq$ 10).

While the trend in observed retardations of the chlorophenolics is correct, the magnitudes of the relative retardations are less than those predicted using K_p values determined from the batch experiments. This is probably the result of irregularities in the K_h values downgradient of the site. Cosolvent effects due to the plume itself, nonuniform contaminant distributions, and the fractures in the aquifer are believed to have played only a minor role in this regard.

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TREATMENT TECHNOLOGY

Using the Properties of Organic Compounds to Help Design a Treatment System

by Evan Nyer, Gary Boettcher, and Bridget Morello

I have decided to provide the physical/chemical and treatability properties of 50 compounds in my column for this issue. The physical/chemical parameters of the compounds can be used to help evaluate data generated during remedial investigations. The treatability parameters can be used as a basis for the preliminary design of a treatment system that will remove organic compounds from ground water.

The biggest obstacle in designing a treatment system is where to begin. Typically, the two main starting points I have seen applied in designing a treatment system are laboratory treatability studies and "by-the-book" design. Neither of these methods are accurate or efficient. In laboratory treatability studies, the designer generally submits a ground water sample to the laboratory for purposes of simulating full-scale treatment units. Laboratory treatability studies, however, cannot be used as a direct simulation of most organic treatment processes. (This issue will be discussed in detail in my next column). Textbooks should never be used as "cookbooks" for the design of a treatment system. The cookbook recipe simply uses every treatment method available for removing organic compounds and sizes unit operations based on values supplied in the textbook. The final design uses all the treatment units in series. Textbooks, including my own, should be used for general knowledge and reference purposes only, not for design data.

The treatment system designs I have worked on have always been preceded by complete evaluation of the properties of the compounds. While I would not proceed directly to full-scale installation based strictly upon analysis of compound properties, they can provide several insights for final design. Most important, the properties of compounds can indicate critical points of a design and areas requiring further data. These areas can then be further evaluated in laboratory and field pilot tests.

The main physical/chemical properties that should be evaluated prior to design are solubility, specific gravity, and octanol/water coefficient. These properties mainly help us understand data generated during remedial investigations. However, they will have some input in the treatment system design as will be discussed.

Solubility

Solubility is one of the most important properties affecting the fate and transport of organic compounds. The solubility of a compound is described as the maximum dissolved quantity of compound in pure water at a specific temperature. Solubilities of most common organic compounds range from 1 to 100,000 ppm at ambient temperature. However, several compounds exhibit higher solubilities, and some are infinitely soluble. Highly soluble compounds are easily transported by the hydrologic cycle, and tend to have low adsorption coefficients for soils and low bioconcentration factors in aquatic life. Highly soluble compounds also tend to be more readily biodegradable.

Solubility usually decreases as temperature increases due to an increase in water vapor pressure at the liquid/gas interface. Escaping molecules then force larger numbers of gas molecules out of solution.

When reviewing the results from a ground water study, the concentrations of organic compounds should be related to the solubilities of those compounds. For example, high concentrations of a non-soluble compound may indicate the presence of a pure compound NAPL. Therefore, the treatment system should be designed with the capability to treat pure compounds. Table 1 presents the solubility values for 50 organic compounds.

Specific Gravity

Specific gravity is a dimensionless parameter derived from density. The specific gravity of a compound is defined as the ratio of the weight of a compound of a given volume and at a specified temperature to the weight of the same volume of water at a given temperature. The specific gravity of a water at 4 C is usually used as a basis because the density of water at 4 C is 1.000 g/mL.

In environmental analysis, the primary reason for knowing the specific gravity of a compound is to determine whether liquids will float or sink in water. Pure compounds that are lighter than water will form a layer on top of the water. Organic compounds that are heavier than water will move through the aquifer until they are

TABLE 1
Solubility for Specific Organic Compounds

	Compound	Solubility (mg/L)	Reference
1	Acenaphthene	3.42	2
2	Acetone	1×10^{6} *	
3	Aroclor 1254	1.2×10^{-2}	2
4	Benzene	1.75×10^{3}	1 (A)
5	Benzo(a)pyrene	1.2×10^{-3}	2
6	Benzo(g,h,i)perylene	7×10^{-4}	2
7	Benzoic acid	2.7×10^{3}	2
8	Bromodichloromethane	4.4×10^{3}	2
9	Bromoform	3.01×10^{3}	1 (B)
10	Carbon tetrachloride	7.57×10^{2}	1 (A)
11	Chlorobenzene	4.66×10^{2}	1 (A)
12	Chloroethane	5.74×10^{3}	2
13	Chloroform	8.2×10^{3}	1 (A)
14	2-Chlorophenol	2.9×10^{4}	2
15	p-Dichlorobenzene (1,4)	7.9×10^{1}	2
16	1,1-Dichloroethane	5.5×10^{3}	1 (A)
17	1,2-Dichloroethane	8.52×10^{3}	1 (A)
18	1,1-Dichloroethylene	2.25×10^{3}	1 (A)
19	cis-1,2-Dichloroethylene	3.5×10^{3}	1 (A)
20	trans-1,2-Dichloroethylene	6.3×10^{3}	1 (A)
21	2,4-Dichlorophenoxyacetic acid	6.2×10^{2}	2
22	Dimethyl phthalate	4.32×10^{3}	2
23	2,6-Dinitrotoluene	1.32×10^{3}	2
24	1,4-Dioxane	4.31×10^{5}	2
25	Ethylbenzene	1.52×10^{2}	1 (A)
26	bis(2-Ethylhexyl)phthalate	2.85×10^{-1}	2
27	Heptachlor	1.8×10^{-1}	2
28	Hexachlorobenzene	6×10^{-3}	1 (A)
29	Hexachloroethane	5×10^{1}	2
30	2-Hexanone	1.4×10^{4}	2
31	Isophorone	1.2×10^{4}	2
32	Methylene chloride	2×10^{4}	1 (B)
33	Methyl ethyl ketone	2.68×10^{5}	1 (A)
34	Methyl naphthalene	2.54×10^{1}	2
35	Methyl tert-butyl ether	4.8	3
36	Naphthalene	3.2×10^{1}	2
37	Nitrobenzene	1.9×10^{3}	2
38	Pentachlorophenol	1.4×10^{1}	1 (B)
39	Phenol	9.3×10^{4}	1 (A)
40	1,1,2,2-Tetrachloroethane	2.9×10^{3}	2
41	Tetrachloroethylene	1.5×10^{2}	1 (A)
42	Tetrahydrofuran	3×10^{-1}	4
43	Toluene	5.35×10^{2}	1 (A)
44	1,2,4-Trichlorobenzene	3×10^{1}	2
45	1,1,1-Trichloroethane	1.5×10^{3}	1 (A)
46	1,1,2-Trichloroethane	4.5×10^{3}	1 (A)
47	Trichloroethylene	1.1×10^{3}	1 (A)
48	2,4,6-Trichlorophenol	8×10^{2}	2
49	Vinyl chloride	2.67×10^{3}	1 (A)
50	o-Xylene	1.75×10^{2}	1 (C)

* Solubility of 1,000,000 mg/L assigned because of reported "infinite solubility" in the literature.

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TABLE 2
Specific Gravity for Specific Organic Compounds

	Compound	Specific Gravity*	Reference
1	Acenaphthene	1.069 (95°/95°)	1
2	Acetone	.791	1
3	Aroclor 1254	1.5 (25°)	3
4	Benzene	.879	1
5	Benzo(a)pyrene	1.35 (25°)	4
6	Benzo(g,h,i)perylene	NA	
7	Benzoic acid	1.316 (28°/4°)	1
8	Bromodichloromethane	2.006 (15°/4°)	1
9	Bromoform	2.903 (15°)	1
10	Carbon tetrachloride	1.594	1
11	Chlorobenzene	1.106	1
12	Chloroethane	.903	1
13	Chloroform	1.49 (20°C liquid)	2
14	2-Chlorophenol	1.241 (18.2°/15°)	1
15	p-Dichlorobenzene (1,4)	1.458 (21°)	1
16	1,1-Dichloroethane	1.176	1
17	1,2-Dichloroethane	1.253	1
18	1,1-Dichloroethylene	1.250 (15°)	1
19	cis-1,2-Dichloroethylene	1.27 (25°C liquid)	2
20	trans-1,2-Dichloroethylene	1.27 (25°C liquid)	2
21	2,4-Dichlorophenoxyacetic acid	1.255	6
22	Dimethyl phthalate	1.189 (25°/25°)	1
23	2,6-Dinitrotoluene	1.283 (111°)	1
24	1,4-Dioxane	1.034	1
25	Ethylbenzene	.867	1
26	bis(2-Ethylhexyl)phthalate	.9843	1
27	Heptachlor	1.57	5
28	Hexachlorobenzene	2.044	1
29	Hexachloroethane	2.09	6
30	2-Hexanone	.815 (18°/4°)	1
31	Isophorone	.921 (25°)	2
32	Methylene chloride	1.366	1
33	Methyl ethyl ketone	.805	1
34	Methyl naphthalene	1.025 (14°/4°)	1
35	Methyl tert-butyl ether	.731	1
36	Naphthalene	1.145	1
37	Nitrobenzene	1.203	1
38	Pentachlorophenol	1.978 (22°)	1
39	Phenol	1.071 (25°/4°)	1
40	1,1,2,2-Tetrachloroethane	1.600	1
41	Tetrachloroethylene	1.631 (15°/4°)	1
42	Tetrahydrofuran	.888 (21°/4°)	1
43	Toluene	.866	1
44	1,2,4-Trichlorobenzene	1.446 (26°)	1
45	1,1,1-Trichloroethane	1.346 (15°/4°)	1
46	1,1,2-Trichloroethane	1.441 (25.5°/4°)	1
47	Trichloroethylene	1.466 (20°/20°)	1
48	2,4,6-Trichlorophenol	1.490 (75°/4°)	1
49	Vinyl chloride	.908 (25°/25°)	1
50	o-Xylene	.880	1

* Specific gravity of compound at 20°C referred to water at 4°C (20°/4°) unless otherwise specified.

NA = Not Available

1. *Lange's Handbook of Chemistry*, 11th edition, by John A. Dean, McGraw-Hill Book Co., New 1973.
2. *Hazardous Chemicals Data Book*, 2nd edition, by G. Weiss, Noyes Data Corp., New York, 1986.
3. U.S. Public Health Service Agency for Toxic Substances and Disease Registry, "Draft Toxicological Profile for Selected PCBs," November 1987.
4. U.S. Public Health Service Agency for Toxic Substances and Disease Registry, "Draft Toxicological Profile for Benzo(a)pyrene," October 1987.
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6. Merck Index, 9th edition, Merck and Co. Inc., New Jersey, 1976.

fully adsorbed by soil particles or until they encounter an impenetrable layer. Table 2 presents the specific gravities of 50 organic compounds.

Octanol/Water Partition Coefficient

The octanol/water partition coefficient (K_{ow}) is defined as the ratio of a compound's concentration in the octanol phase to its concentration in the aqueous phase of a two-phase system. Measured values for organic compounds range from 10^{-3} to 10^{7}. Low K_{ow} values (< 10) are considered hydrophilic and tend to have higher water solubility. High K_{ow} values (> 10^{4}) are very hydrophobic.

K_{ow} values for organic compounds are used to evaluate fate in the environment. The parameter can be related to solubility in water and bioconcentration effects, but it is mainly used to relate to soil/sediment adsorption. When combined with the organic content of the soil, K_{ow} values can be used to predict the amount of material adsorbed in the soil and the retardation factor for movement through the aquifer.

When pure compounds are lost to the environment, it is important to know where they are likely to be found. Soluble compounds will migrate with the surface water which will infiltrate the aquifer and migrate with the ground water. Non-soluble compounds will be adsorbed on the soil. However, if the mass of organic compounds exceeds the adsorptive capacity of the soil, the compounds will continue to migrate until they reach the aquifer. Compounds with low specific gravity will be retained at the surface of the aquifer, and compounds with high specific gravity will continue to move vertically through the aquifer. Table 3 presents K_{ow} values for 50 organic compounds.

The physical/chemical properties presented here will help the reader understand where compounds of concern might be in the ground and/or aquifer. These properties are also necessary for use in designing treatment systems such as oil/water separators and liquid/liquid extractors.

The main treatability parameters that should be used to help design a treatment system are strippability (Henry's law constant), adsorbability, and biodegradability.

Henry's Law Constant

Generally for non-ideal solutions, Henry's law states that the equilibrium partial pressure of a compound in the air above the air/water interface is proportional to the concentration of that compound in the water. Henry's law can be expressed as follows:

$$P_A = H_A x_A$$

where:

P_A = Partial pressure of a compound in liquid at equilibrium with gas (atm)

H_A = Henry's laws constant (atm)

x_A = Mole fraction of a compound in gas (mole/mole)

Therefore, Henry's law constant expresses the amount of chemical partitioning between air and water at equilibrium.

TABLE 3
Octanol Water Coefficients (K_{ow}) for Specific Organic Compounds

	Compound	K_{ow}	Reference
1	Acenaphthene	$1.0x10^{4}$	2
2	Acetone	$6x10^{-1}$	1 (D)
3	Aroclor 1254	$1.07x10^{6}$	2
4	Benzene	$1.3x10^{2}$	1 (A)
5	Benzo(a)pyrene	$1.15x10^{6}$	2
6	Benzo(g,h,i)perylene	$3.24x10^{6}$	2
7	Benzoic acid	$7.4x10^{1}$	2
8	Bromodichloromethane	$7.6x10^{1}$	2
9	Bromoform	$2.5x10^{2}$	1 (B)
10	Carbon tetrachloride	$4.4x10^{2}$	1 (A)
11	Chlorobenzene	$6.9x10^{2}$	1 (A)
12	Chloroethane	$3.5x10^{1}$	2
13	Chloroform	$9.3x10^{1}$	1 (A)
14	2-Chlorophenol	$1.5x10^{1}$	2
15	p-Dichlorobenzene (1,4)	$3.9x10^{3}$	2
16	1,1-Dichloroethane	$6.2x10^{1}$	1 (A)
17	1,2-Dichloroethane	$3.0x10^{1}$	1 (A)
18	1,1-Dichloroethylene	$6.9x10^{1}$	1 (A)
19	cis-1,2-Dichloroethylene	5.0	1 (A)
20	trans-1,2-Dichloroethylene	3.0	1 (A)
21	2,4-Dichlorophenoxyacetic acid	$6.5x10^{2}$	2
22	Dimethyl phthalate	$1.3x10^{2}$	2
23	2,6-Dinitrotoluene	$1.0x10^{2}$	2
24	1,4-Dioxane	1.02	2
25	Ethylbenzene	$1.4x10^{3}$	1 (A)
26	bis(2-Ethylhexyl)phthalate	$9.5x10^{3}$	2
27	Heptachlor	$2.51x10^{4}$	2
28	Hexachlorobenzene	$1.7x10^{5}$	1 (A)
29	Hexachloroethane	$3.98x10^{4}$	2
30	2-Hexanone	$2.5x10^{1}$	3
31	Isophorone	$5.0x10^{1}$	2
32	Methylene chloride	$1.9x10^{1}$	1 (B)
33	Methyl ethyl ketone	1.8	1 (A)
34	Methyl naphthalene	$1.3x10^{4}$	2
35	Methyl tert-butyl ether	NA	
36	Naphthalene	$2.8x10^{3}$	2
37	Nitrobenzene	$7.1x10^{1}$	2
38	Pentachlorophenol	$1.0x10^{5}$	1 (B)
39	Phenol	$2.9x10^{1}$	1 (A)
40	1,1,2,2-Tetrachloroethane	$2.5x10^{2}$	2
41	Tetrachloroethylene	$3.9x10^{2}$	1 (A)
42	Tetrahydrofuran	6.6	4
43	Toluene	$1.3x10^{2}$	1 (A)
44	1,2,4-Trichlorobenzene	$2.0x10^{4}$	2
45	1,1,1-Trichloroethane	$3.2x10^{2}$	1 (B)
46	1,1,2-Trichloroethane	$2.9x10^{2}$	1 (A)
47	Trichloroethylene	$2.4x10^{2}$	1 (A)
48	2,4,6-Trichlorophenol	$7.4x10^{1}$	2
49	Vinyl chloride	$2.4x10^{1}$	1 (A)
50	o-Xylene	$8.9x10^{2}$	1 (C)

NA = Not Available

1. *Superfund Public Health Evaluation Manual*, Office of Emergency and Remedial Response Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, 1986.
   A. Environmental Criteria and Assessment Office (ECAO), EPA, Health Effects Assessments for Specific Chemicals, 1985.
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   D. *Handbook of Environmental Data for Organic Chemicals*, Van Nostrand Reinhold Co., New York, 2nd Edition, 1983.
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TABLE 4
Henry's Law Constants for Specific Organic Compounds

	Compound	Henry's Law Constant* atm m³ water/m³ air	Reference
1	Acenaphthene	5.1	5
2	Acetone	0	1
3	Aroclor 1254	150	5
4	Benzene	230	1
5	Benzo(a)pyrene	.1	5
6	Benzo(g,h,i)perylene	0	5
7	Benzoic acid	0	5
8	Bromodichloromethane	127	1
9	Bromoform	35	3
10	Carbon tetrachloride	1282	1
11	Chlorobenzene	145	2
12	Chloroethane	34	5
13	Chloroform	171	1
14	2-Chlorophenol	0.93	2
15	p-Dichlorobenzene (1,4)	104	4
16	1,1-Dichloroethane	240	1
17	1,2-Dichloroethane	51	1
18	1,1-Dichloroethylene	1841	1
19	cis-1,2-Dichloroethylene	160	1
20	trans-1,2-Dichloroethylene	429	1
21	2,4-Dichlorophenoxyacetic acid	10	5
22	Dimethyl phthalate	0	5
23	2,6-Dinitrotoluene	.2	5
24	1,4-Dioxane	.6	5
25	Ethylbenzene	359	1
26	bis(2-Ethylhexyl)phthalate	0	5
27	Heptachlor	46	5
28	Hexachlorobenzene	37.8	2
29	Hexachloroethane	138	5
30	2-Hexanone	1.6	5
31	Isophorone	.3	5
32	Methylene chloride	89	1
33	Methyl ethyl ketone	1.16	2
34	Methyl naphthalene	3.2	2
35	Methyl tert-butyl ether	196	1
36	Naphthalene	20	4
37	Nitrobenzene	1.2	5
38	Pentachlorophenol	0.15	2
39	Phenol	0.017	2
40	1,1,2,2-Tetrachloroethane	21	5
41	Tetrachloroethylene	1035	1
42	Tetrahydrofuran	2	5
43	Toluene	217	1
44	1,2,4-Trichlorobenzene	128	5
45	1,1,1-Trichloroethane	390	1
46	1,1,2-Trichloroethane	41	2
47	Trichloroethylene	544	1
48	2,4,6-Trichlorophenol	.2	5
49	Vinyl chloride	355,000	3
50	o-Xylene	266	1

* = at water temperature of 68°F

1. per Hydro Group Inc., 1990.
2. Solubility and vapor phase pressure data from *Handbook of Environmental Data on Organic Chemicals*, 2nd Edition, by Karel Verschueren, 1983, Van Nostrand Reinhold Co.
3. Michael C. Kavanaugh and R. Rhodes Trussel, "Design of Aeration Towers to Strip Volatile Contaminants from Drinking Water" *Journal AWWA*, December 1980, p. 685.
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Aeration is a technology often employed in water treatment applications to strip the concentration of volatile organic compounds (VOCs) from water. The controlling factor in removal of VOCs from water is the rate of transfer from the liquid phase (water) to the gas phase (air) until equilibrium is established. The transfer rate of VOCs from water via aeration depends upon the temperature of both the water and the air, as well as the physical and chemical properties of the VOCs. Water temperature changes of as little as 10 C can result in threefold increases in Henry's law constants. In a gas-liquid system, the equilibrium vapor concentration of a VOC can be computed from the compound specific Henry's law constant and total system pressure.

Generally, the greater the Henry's law constant (i.e., greater than 160 atm), the more volatile a compound, and the more easily it can be removed from solution. Henry's laws constants can be computer modeled to develop a preliminary design and cost estimate for an air stripper. Table 4 presents Henry's law constants for 50 organic compounds.

Carbon Adsorption Capacity

Activated carbon has variable effectiveness adsorbing organic compounds. Low molecular weight, polar compounds are not well absorbed. High molecular weight, non-polar compounds such as pesticides, polychlorinated biphenyls, phthalates, and aromatics are readily adsorbed.

Activated carbon adsorption isotherm data can be used to evaluate the carbon adsorptive capacity for organic compounds. These data may be used to complete an initial estimate of the organic mass that carbon will adsorb. Since the main cost of carbon adsorption is carbon, this mass data can be used as a preliminary basis for cost estimation. Table 5 presents carbon adsorption capacity values for 50 organic compounds.

Biodegradability

Organic compounds are transformed by biochemical reactions in the environment and in engineered unit operations. Biodegradation of organic compounds occur aerobically and/or anaerobically depending on the molecular structure of the chemical and the environmental conditions. Engineered bioremediation is necessary to enhance natural processes that are usually less than optimal in the environment.

The first and most important parameter to evaluate before implementing bioremediation is determining whether the compound is degradable, the most effective biodegradation mechanism (aerobic vs. anaerobic), and the biodegradation rate. From an ecological point of view, chemicals that are completely degradable, but slow, can be persistent in the environment.

Biodegradation potential has been reviewed and can be categorized as degradable, persistent, and recalcitrant. Readily degradable refers to compounds that have passed biodegradability tests in a variety of aerobic environments. Degradable also refers to compounds that are normally degraded in tests but not necessarily in the environment.

TABLE 5
Adsorption Capacity for Specific Organic Compounds

	Compound	Adsorption Capacity (mg compound/g carbon) at 500 ppb	Reference
1	Acenaphthene	155	4
2	Acetone	43	1
3	Aroclor 1254	NA	
4	Benzene	80	1
5	Benzo(a)pyrene	24.8	4
6	Benzo(g,h,i)perylene	8.3	4
7	Benzoic acid	40 (at pH = 3)	4
8	Bromodichloromethane	5	4
9	Bromoform	13.6	4
10	Carbon tetrachloride	6.2	2
11	Chlorobenzene	45	3
12	Chloroethane	0.3	4
13	Chloroform	1.6	1
14	2-Chlorophenol	38	3
15	p-Dichlorobenzene (1,4)	87.3	4
16	1,1-Dichloroethane	1.2	4
17	1,2-Dichloroethane	2	2
18	1,1-Dichloroethylene	3.4	4
19	cis-1,2-Dichloroethylene	9	5
20	trans-1,2-Dichloroethylene	2.2	4
21	2,4-Dichlorophenoxyacetic acid	NA	
22	Dimethyl phthalate	91.2	4
23	2,6-Dinitrotoluene	116	4
24	1,4-Dioxane	0.5-1.0	5
25	Ethylbenzene	18	1
26	bis(2-Ethylhexyl)phthalate	3995	4
27	Heptachlor	631.5	4
28	Hexachlorobenzene	42	3
29	Hexachloroethane	74.2	4
30	2-Hexanone	<13	5
31	Isophorone	24.4	4
32	Methylene chloride	0.8	3
33	Methyl ethyl ketone	94	1
34	Methyl naphthalene	150	5
35	Methyl tert-butyl ether	6.5	5
36	Naphthalene	5.6	3
37	Nitrobenzene	50.5	4
38	Pentachlorophenol	100	3
39	Phenol	161	1
40	1,1,2,2-Tetrachloroethane	8.2	4
41	Tetrachloroethylene	34.5	2
42	Tetrahydrofuran	<0.5	5
43	Toluene	50	1
44	1,2,4-Trichlorobenzene	126.6	4
45	1,1,1-Trichloroethane	2	2
46	1,1,2-Trichloroethane	3.7	4
47	Trichloroethylene	18.2	2
48	2,4,6-Trichlorophenol	179 (at pH = 3)	4
49	Vinyl chloride	TRACE	3
50	o-Xylene	75	4

NA = Not Available

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5. Roy, Al. Calgon Carbon, 1991.

TABLE 6
Disappearance or Biodegradation Potential for Specific Organic Compounds

	Compound	Biodegradability	Reference
1	Acenaphthene	D	2
2	Acetone	D	
3	Aroclor 1254	P,D	2,3
4	Benzene	D	1
5	Benzo(a)pyrene	P,D	2,4
6	Benzo(g,h,i)perylene	P,D	2,4
7	Benzoic acid	D	2
8	Bromodichloromethane	P,D	1
9	Bromoform	P,D	1
10	Carbon tetrachloride	P,D	1
11	Chlorobenzene	D	1
12	Chloroethane	D	6
13	Chloroform	P,D	1
14	2-Chlorophenol	D	1
15	p-Dichlorobenzene (1,4)	P,D	1
16	1,1-Dichloroethane	P,D	1
17	1,2-Dichloroethane	P,D	1
18	1,1-Dichloroethylene	P,D	1
19	cis-1,2-Dichloroethylene	P,D	1
20	trans-1,2-Dichloroethylene	P,D	1
21	2,4-Dichlorophenoxyacetic acid	D	2
22	Dimethyl phthalate	D	5
23	2,6-Dinitrotoluene	D,P	2,5
24	1,4-Dioxane	P,R	8
25	Ethylbenzene	D	1
26	bis(2-Ethylhexyl)phthalate	P,D	2,5
27	Heptachlor	P,R	2
28	Hexachlorobenzene	P,R	1
29	Hexachloroethane	D	2
30	2-Hexanone	D	5
31	Isophorone	D	5
32	Methylene chloride	D	1
33	Methyl ethyl ketone	D	
34	Methyl naphthalene	D	1
35	Methyl tert-butyl ether	NA	
36	Naphthalene	D	1
37	Nitrobenzene	D	2
38	Pentachlorophenol	P,D	1
39	Phenol	D	1
40	1,1,2,2-Tetrachloroethane	P,D	2,5
41	Tetrachloroethylene	P,D	1
42	Tetrahydrofuran	D	7
43	Toluene	D	1
44	1,2,4-Trichlorobenzene	P,D	2
45	1,1,1-Trichloroethane	P,D	1
46	1,1,2-Trichloroethane	P,D	1
47	Trichloroethylene	P,D	1
48	2,4,6-Trichlorophenol	D	2
49	Vinyl chloride	P,D	1
50	o-Xylene	D	1

Notes: D = Degradable; P = Persistent; R = Recalcitrant; NA = Not Available

References:

1. Citations compiled in E.K. Nyer, *Groundwater Treatment Technology*, 2nd Ed., In Production.
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Persistent refers to chemicals that remain in the environment for long periods of time. These compounds are not necessarily "non-degradable," but degradation requires long periods of acclimation or modification of the environment to induce degradation. Recalcitrant refers to compounds that are non-degradable.

From the literature, each compound must be evaluated to determine the estimated time to complete the transformation of the chemical under optimal conditions. If the time period is acceptable, treatability and pilot plants can then be initiated. Table 6 presents biodegradation potential for 50 organic compounds.

We can combine these treatability properties with our experience in full-scale design and generate a theoretical preliminary design. This design can be used to generate a preliminary cost estimate. Based upon this data, we can eliminate the technologies that obviously will not work. This data will also show us which compounds are controlling the designs. We can then go back and confirm their concentrations in the field, and test the actual treatment in laboratory and pilot plant tests.

I hope you find these tables to be a convenient source of important information. I encourage you, however, not to use the data as a final basis for full-scale design.

Evan K. Nyer is an expert in the research and application of technology to ground water cleanups. As vice president with Geraghty & Miller Inc., he is responsible for engineering services including hazardous and solid waste management, environmental and natural resource management, remediation activities and designing treatment systems for contaminated sites throughout the United States and in foreign countries. He has designed more than 100 ground water treatment systems.

Nyer travels throughout the country teaching treatment techniques at seminars and universities. He has written numerous papers on ground water decontamination and other water and waste water cleanup techniques. He is responsible for bringing to the field many innovative techniques for biological treatment of water, soils, and in situ treatment and the application of existing technologies to ground water contamination. He is a member of the Water Pollution Control Federation, The National Water Well Association, The American Institute of Chemical Engineers, and The American Society of Civil Engineers.

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Section 8

GROUNDWATER FLOW RATES AND MODELING

PERFORMANCE OBJECTIVES

At the end of this lesson, participants will be able to:

- Describe the physical, chemical and biological processes that affect groundwater flow and contaminant transport
- List three factors that groundwater models can predict
- List three problems associated with groundwater models used in groundwater assessment
- Identify misuses of groundwater models.

NOTES

GROUNDWATER FLOW RATES AND MODELING

PHYSICAL PROCESSES

- Advection
- Hydrodynamic dispersion
- Molecular diffusion
- Density stratification
- Immiscible phase flow
- Fractured media flow

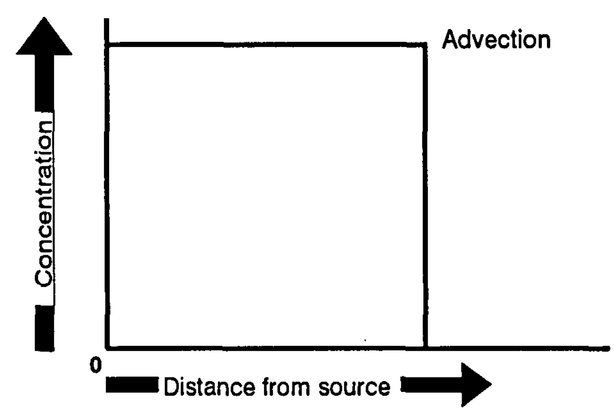
CHEMICAL PROCESSES

- Oxidation-reduction reactions
- Radionuclide decay
- Ion exchange
- Complexation
- Cosolvation
- Immiscible phase partitioning
- Sorption

NOTES

BIOLOGICAL PROCESSES

- Microbial population dynamics
- Substrate utilization
- Biotransformation
- Adaptation
- Cometabolism

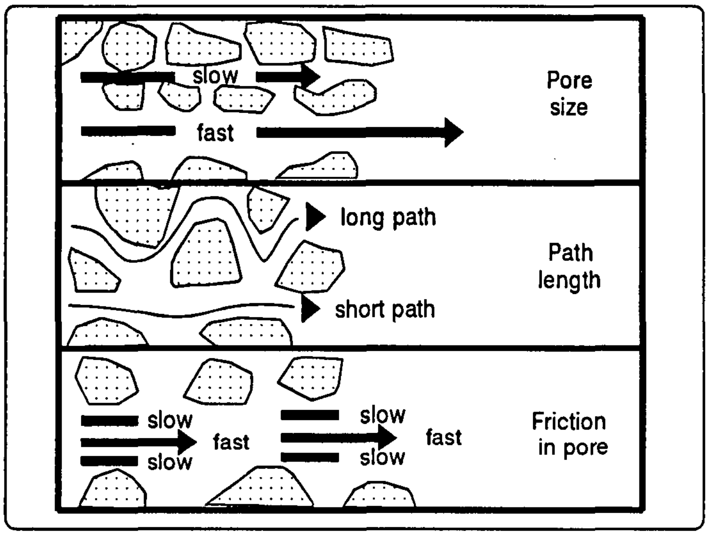


DARCY'S LAW

$$Q = KIA$$

- Q = discharge
- K = hydraulic conductivity
- I = hydraulic gradient
- A = area

NOTES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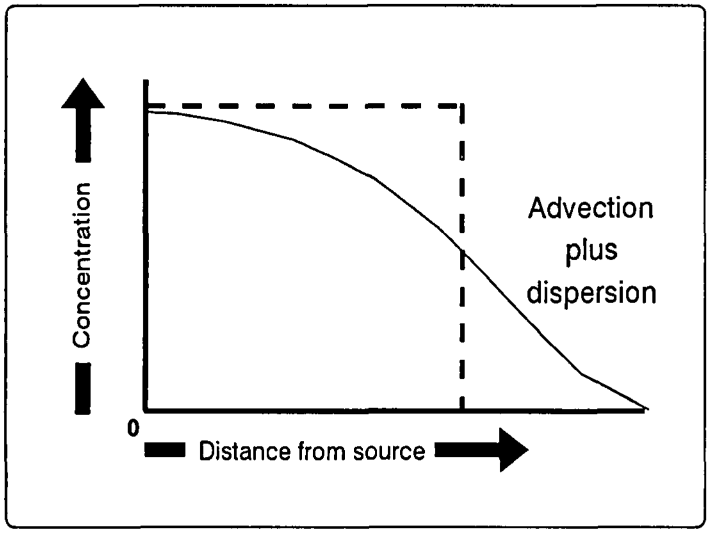
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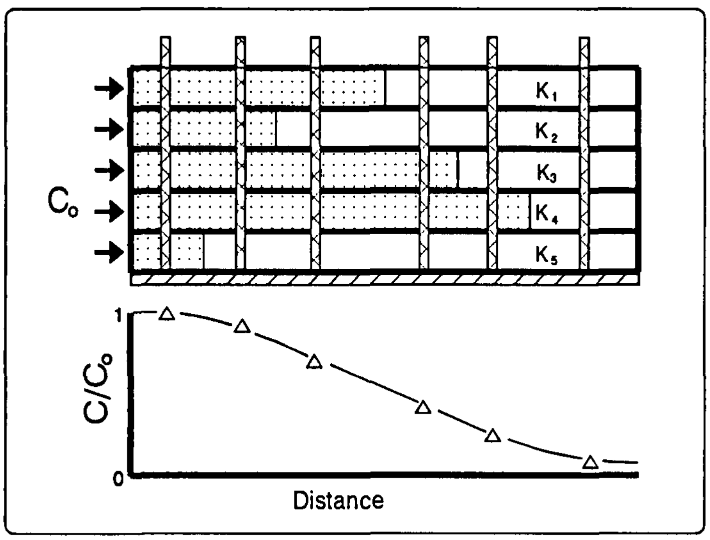
Advection plus dispersion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K_1
K_2
K_3
K_4
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Distance

NOTES

CONCENTRATION AT DISTANCE "L"

$$C = \frac{C_o}{2}\left[\operatorname{erfc}\left(\frac{L - vt}{2\sqrt{D_L t}}\right) + \exp\left(\frac{vL}{D_L}\right)\operatorname{erfc}\left(\frac{L + vt}{2\sqrt{D_L t}}\right)\right]$$

D_L = longitudinal dispersion coefficient

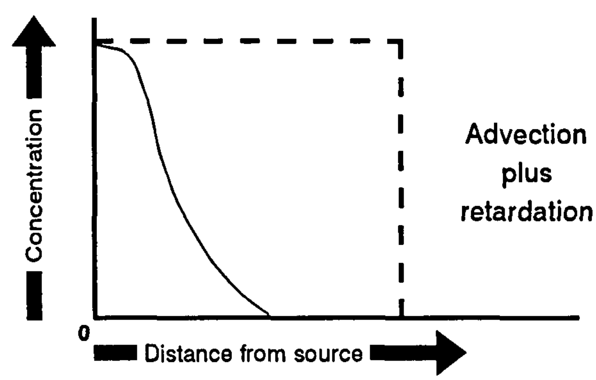
C_o = solute concentration at source

v = average linear velocity

L = distance

t = time

erfc = complementary error function



RETARDATION

$$R = 1 + \frac{\rho_b}{n} \times K_d$$

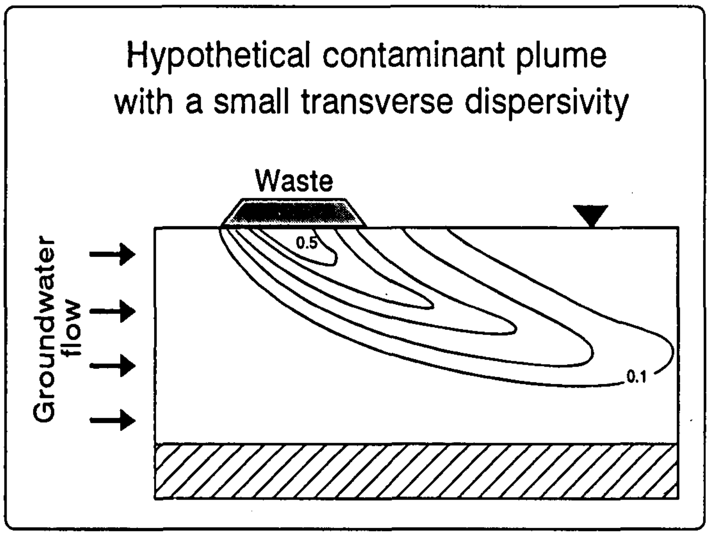
R = retardation factor
ρ_b = bulk density
K_d = distribution coefficient = $(K_{oc})(f_{oc})$
n = porosity

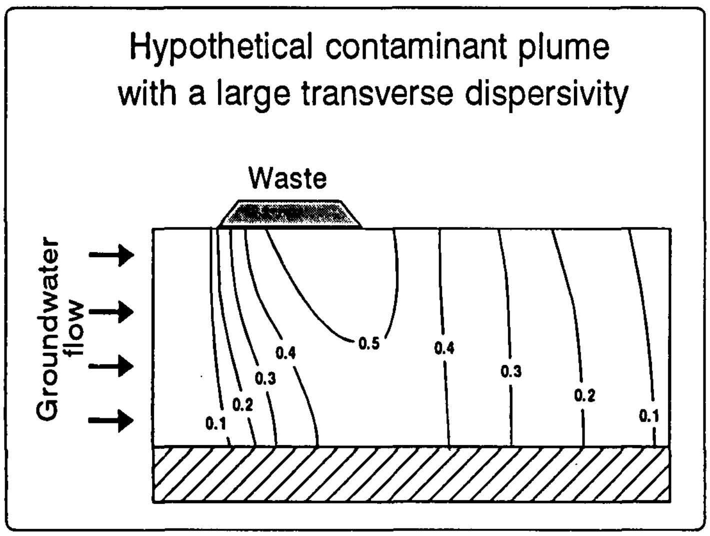
Contaminant Velocity:

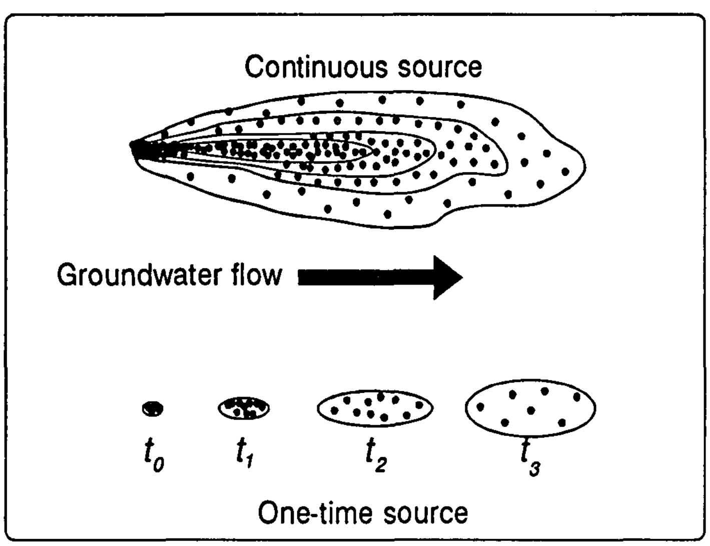
$$v_x = \frac{v}{R_x}$$

v_x = contaminant velocity
v = ground water flow velocity
R_x = retardation factor for contaminant x

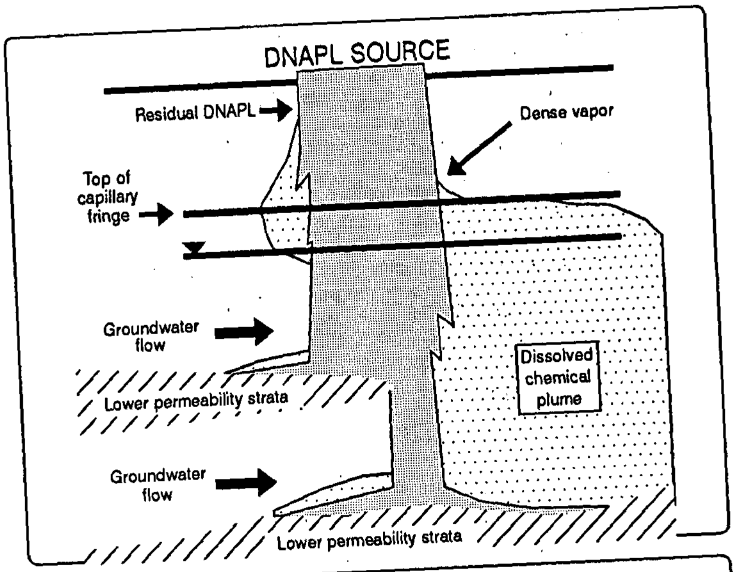
NOTES

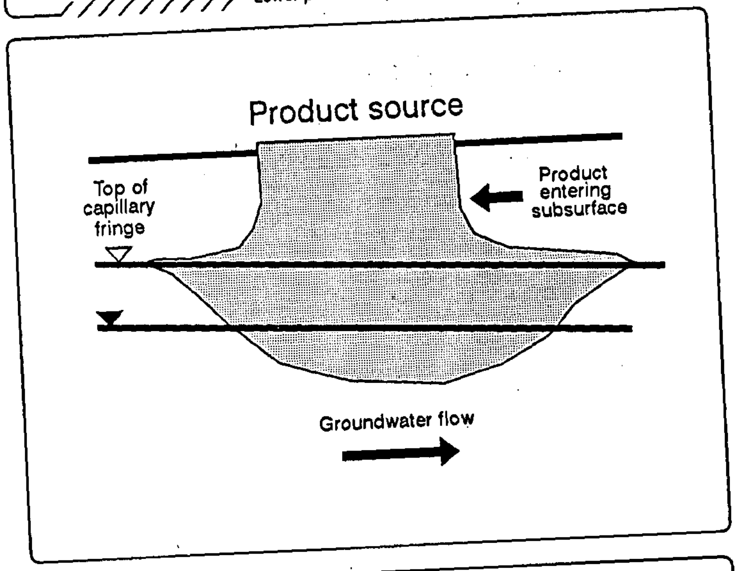

Hypothetical contaminant plume
with a small transverse dispersivity
Waste
Groundwater flow
0.5
0.1

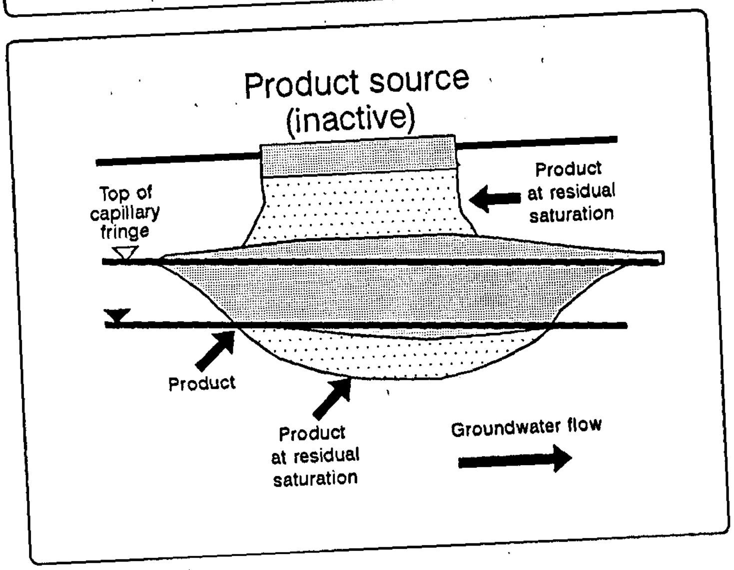

Hypothetical contaminant plume
with a large transverse dispersivity
Waste
Groundwater flow
0.5
0.4
0.3
0.2
0.1
0.4
0.3
0.2
0.1


Continuous source
Groundwater flow
t_0
t_1
t_2
t_3
One-time source

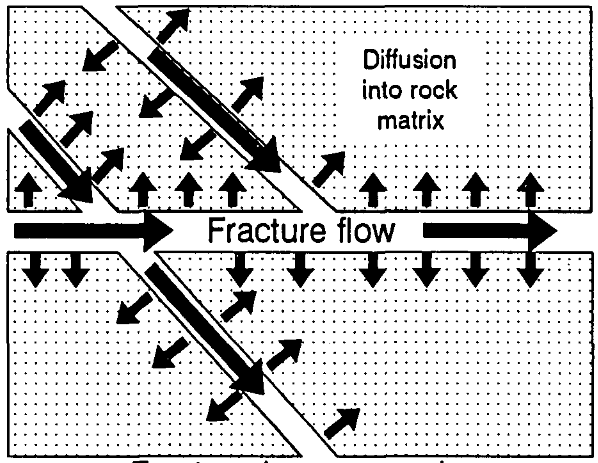
NOTES


DNAPL SOURCE
Residual DNAPL
Dense vapor
Top of capillary fringe
Groundwater flow
Dissolved chemical plume
Lower permeability strata
Groundwater flow
Lower permeability strata


Product source
Top of capillary fringe
Product entering subsurface
Groundwater flow


Product source (inactive)
Top of capillary fringe
Product at residual saturation
Product
Product at residual saturation
Groundwater flow

NOTES



Fractured porous rock

PRIMARY MODEL TYPES
Defined by Objective

- Screening models
- In-depth environmental fate models

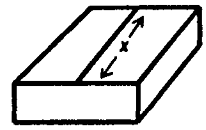
MODELS CAN PREDICT

- Spatial variation
- Temporal variation
- Parameter variation

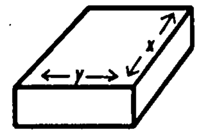
NOTES

MODEL DIMENSIONS

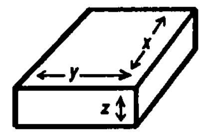
ONE-DIMENSIONAL

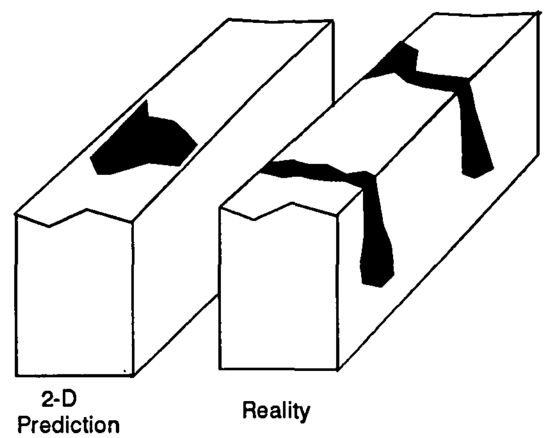


TWO-DIMENSIONAL



THREE-DIMENSIONAL





MODELING PROBLEMS

- Lack of appropriate modeling protocols and standards
- Insufficient technical support
- Inadequate education and training
- Widely used, but selection and use inconsistent

NOTES

MOST COMMON EPA MODELS

Name	Relative Use
MODFLOW	29
HELP	24
RANDOM WALK	21
USGS-2D	20
USGS-MOC	19

KEYS TO SUCCESSFUL USE OF MODELS

- Proper imput data and parameter estimates
- Effective communication
- Understanding the limitations of the model

G.I.G.O.

Garbage in = Garbage out

The first axiom of computer usage

NOTES

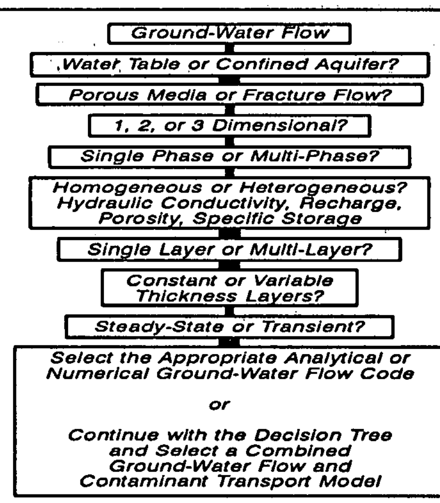
Selection Criteria for Mathematical Models Used in Exposure Assessments:

Ground-Water Models

U.S. EPA. 1988. EPA/600/8-88/075.

MODELING PROCESS

- Problem characterization
- Site characterization
- Model selection criteria
- Code installation
- Model application



NOTES

WATER TABLE OR CONFINED AQUIFER

- Water table
- Confined (majority)
- Combination of both

POROUS MEDIA/ FRACTURE FLOW

- Porous media (majority)
- Fractured media
- Combination of both

1, 2, OR 3 DIMENSIONAL

- 3 dimensional (preferred)
- Availability of data

NOTES

SINGLE PHASE OR MULTI-PHASE

- Few models available for multi-phase flow

HOMOGENEOUS OR HETEROGENEOUS

- Homogeneous if:
  - Conductivity values are within an order of magnitude
  - Recharge, porosity, and storage values vary less than 25%

SINGLE LAYER OR MULTI-LAYER

- Single layer aquifer if:
  - Hydraulic conductivities are within an order of magnitude
  - Hydraulic gradients and porosity are within 25%
  - Flow direction is same

NOTES

CONSTANT OR VARIABLE THICKNESS LAYERS

- Constant or uniform if thickness changes less than 10%

STEADY-STATE OR TRANSIENT

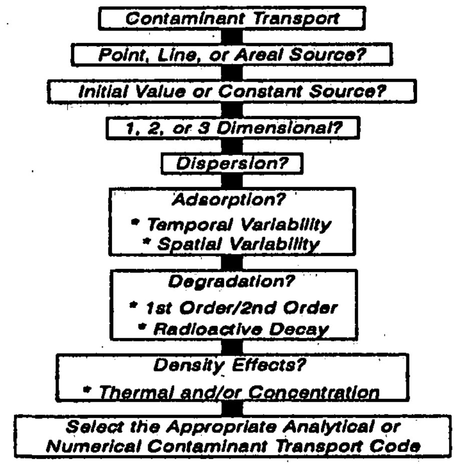
- Steady-state if water table fluctuations are less than 10%
- Transient is difficult to implement

- Select the appropriate analytical or numerical groundwater-flow code

or

- Continue with the decision tree and select a combined groundwater-flow and contaminant transport model
  - Compatible but separate models
  - Combined flow and transport model

NOTES



POINT, LINE, OR AREAL SOURCE

- Point source: pipe outflow or well
- Line source: trench
- Areal source: waste lagoon or agricultural field
- Volume source: volume in groundwater

INITIAL VALUE OR CONSTANT SOURCE

- Instantaneous pulse
- Continuous release
  - Constant
  - Variable

NOTES

1, 2, OR 3 DIMENSIONAL

- 3 dimensional unless lower dimension is justified
- 1 dimensional generally predicts higher concentrations

DISPERSION

- Represents spreading of solute caused by mechanical mixing
- Difficult to measure in the field
- Requires field calibration

ADSORPTION
Temporal/Spatial Variability

- Process whereby dissolved chemicals become attached to solids
- Current practice: lump chemical and biological processes into retardation

NOTES

DEGRADATION

1st/2nd Order - Radioactive Decay

- Degradation results from:
  - Biological transformations
  - Hydrolysis
  - Other chemical reactions

DENSITY EFFECTS

Thermal and/or Concentration

- Naturally occurring situations normally not affected by density
- Landfill leachates often affected by density

- Select the appropriate analytical or numerical contaminant transport code
  - Transport model compatible with groundwater-flow model
  - Combined groundwater-flow/ contaminant transport model

NOTES

SOURCES OF MODELS AND MODEL INFORMATION

Superfund Exposure Assessment Manual

Chapter 3 - Contaminant Fate Analysis (35 Models)

U.S. EPA. 1988. 540/1-88/001.

SOURCES OF MODELS AND MODEL INFORMATION

National Ground Water Association

6375 Riverside Drive
Dublin, Ohio 43017
614 761-1711
1-800-551-7379

SOURCES OF MODELS AND MODEL INFORMATION

International Groundwater Modeling Center (IGWMC)

Institute for Ground-Water Research and Education

Colorado School of Mines

Golden, Colorado 80401-1887

(303) 273-3103

Section 9

PROBLEM 1

Flow Net Construction

PROBLEM 1: FLOW NET CONSTRUCTION

GENERAL DISCUSSION

Groundwater-level data can be used to determine direction of groundwater flow by constructing groundwater contour maps and flow nets. A minimum of three observation points are needed to calculate a flow direction. The procedure is first to relate the groundwater field levels to a common datum - map datum is usually best - and then accurately plot their position on a scale plan, as in **Figure 1**. Next draw a pencil line between each of the observation points, and divide each line into a number of short, equal lengths in proportion to the difference in elevation at each end of the line.

The next step is to join points of equal height on each of the lines to form contour lines (lines of equal head). Select a contour interval which is appropriate to the overall variation in water levels in the study area. The direction of groundwater flow is at right angles to the contour lines from points of higher head to points of lower head.

This simple procedure can be applied to a much larger number of water-level values to construct a groundwater-level contour map such as the one in the example. First, locate the position of each observation point on a base map of suitable scale, and write the water level against each well's position. Study these water-level values to decide which contour lines would cross the center of the map. Select one or two key contours to draw in first.

Once the contour map is complete, flow lines can be drawn by first dividing a selected contour line into equal lengths. Flow lines are drawn at right angles from this contour, at each point marked on it. The flow line are extended until the next contour line is intercepted, and are then continued at right angles to this new contour line. Always select a contour which will enable you to draw the flow lines in a downgradient direction.

PROBLEM 1: THE THREE-POINT PROBLEM

Groundwater-flow direction will be determined from water-level measurements made on three wells at a site as depicted in **Figure 1**:

A. Given:

Well Number	Head (meters)
1	26.26
2	26.20
3	26.08

B. Procedure

1. Select water-level elevations (head) for three wells as depicted in **Figure 1**.

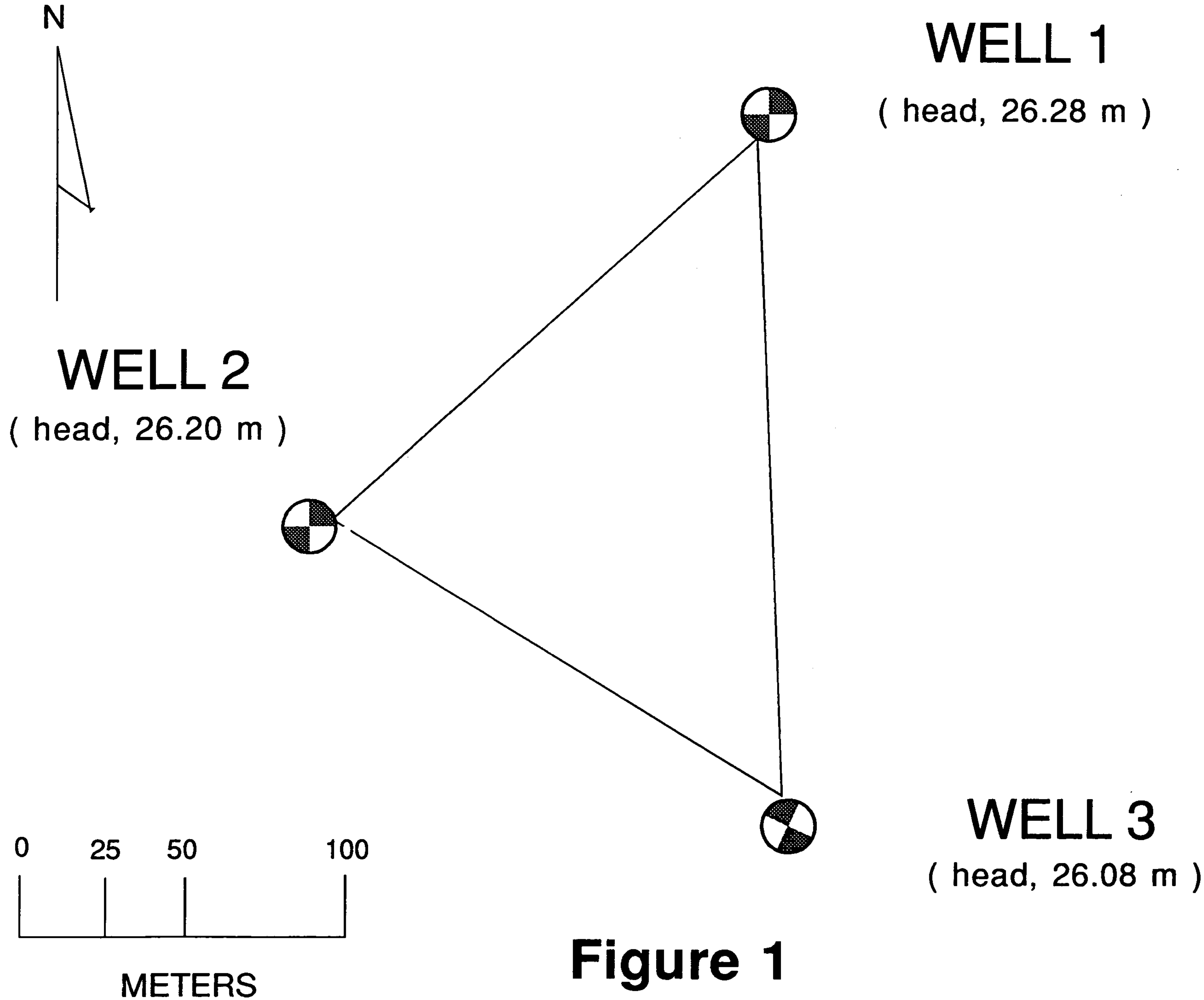

N
WELL 1
(head, 26.28 m)
WELL 2
(head, 26.20 m)
WELL 3
(head, 26.08 m)
0
25
50
100
METERS

Figure 1

2. Select the well with water-level elevation between the other wells (Well 2)

3. Draw a line between Wells 1 and 3. Note that somewhere between these wells is a point, labeled A in **Figure 2**, where the water-level elevation at this point is equal to Well 2 (26.20 m).

4. To determine the distance x from Well 1 to point A the following equation must be solved (see **Figures 3, 4, and 5**):

$$\frac{H_1 - H_3}{Y} = \frac{H_1 - H_2}{X}$$

5. Distance Y is measured directly from the map (200 m) on **Figure 3**. H_1, H_2, and H_3 represent head or water-level elevations from their respectively numbered wells.

6. After the x distance is calculated, groundwater-flow direction based on the water-level elevations can be constructed 90° to the line representing equipotential elevation of 26.20 m as depicted on **Figure 6**.

C. Problem:

Based on the previous instructions for the three point solution use the three head or water-level elevations depicted on **Figure 7** and determine the groundwater-flow direction for this site.

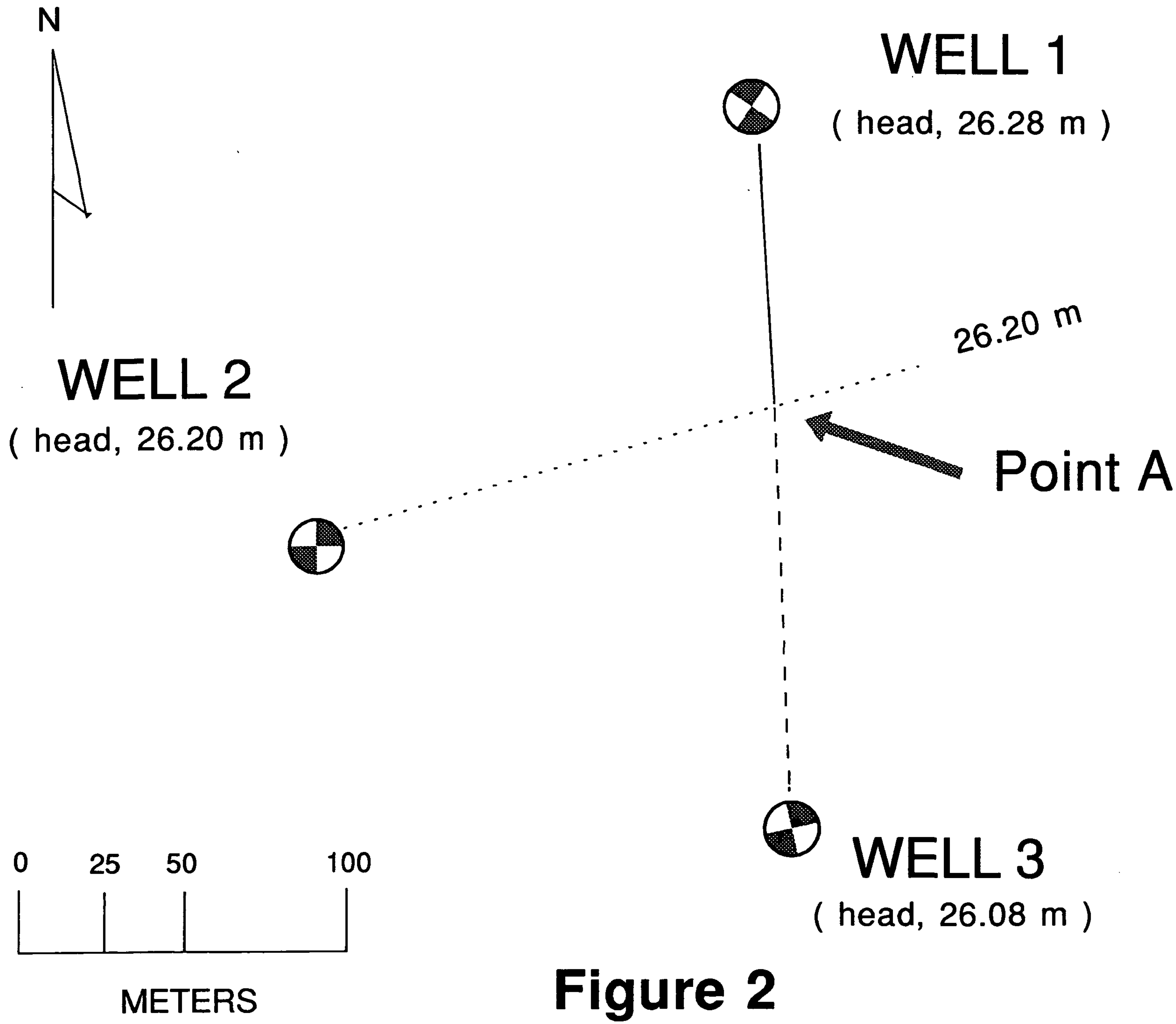

N
WELL 1
(head, 26.28 m)
26.20 m
WELL 2
(head, 26.20 m)
Point A
WELL 3
(head, 26.08 m)
0
25
50
100
METERS

Figure 2

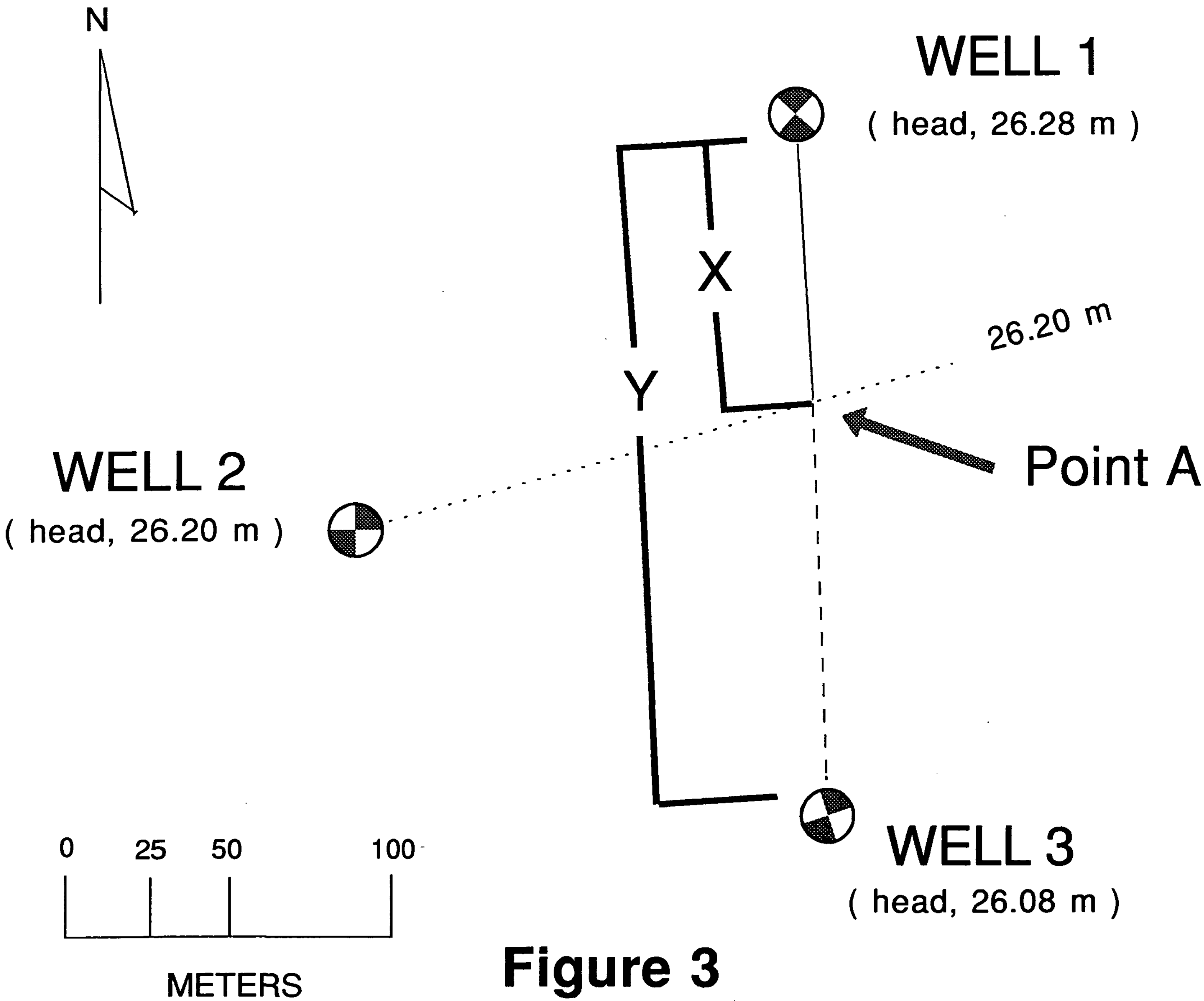

N
WELL 1
(head, 26.28 m)
X
Y
26.20 m
Point A
WELL 2
(head, 26.20 m)
WELL 3
(head, 26.08 m)
0
25
50
100
METERS

Figure 3

$$\frac{(26.28 - 26.20)}{X} = \frac{(26.28 - 26.08)}{200}$$

$$X = 80$$

Figure 4

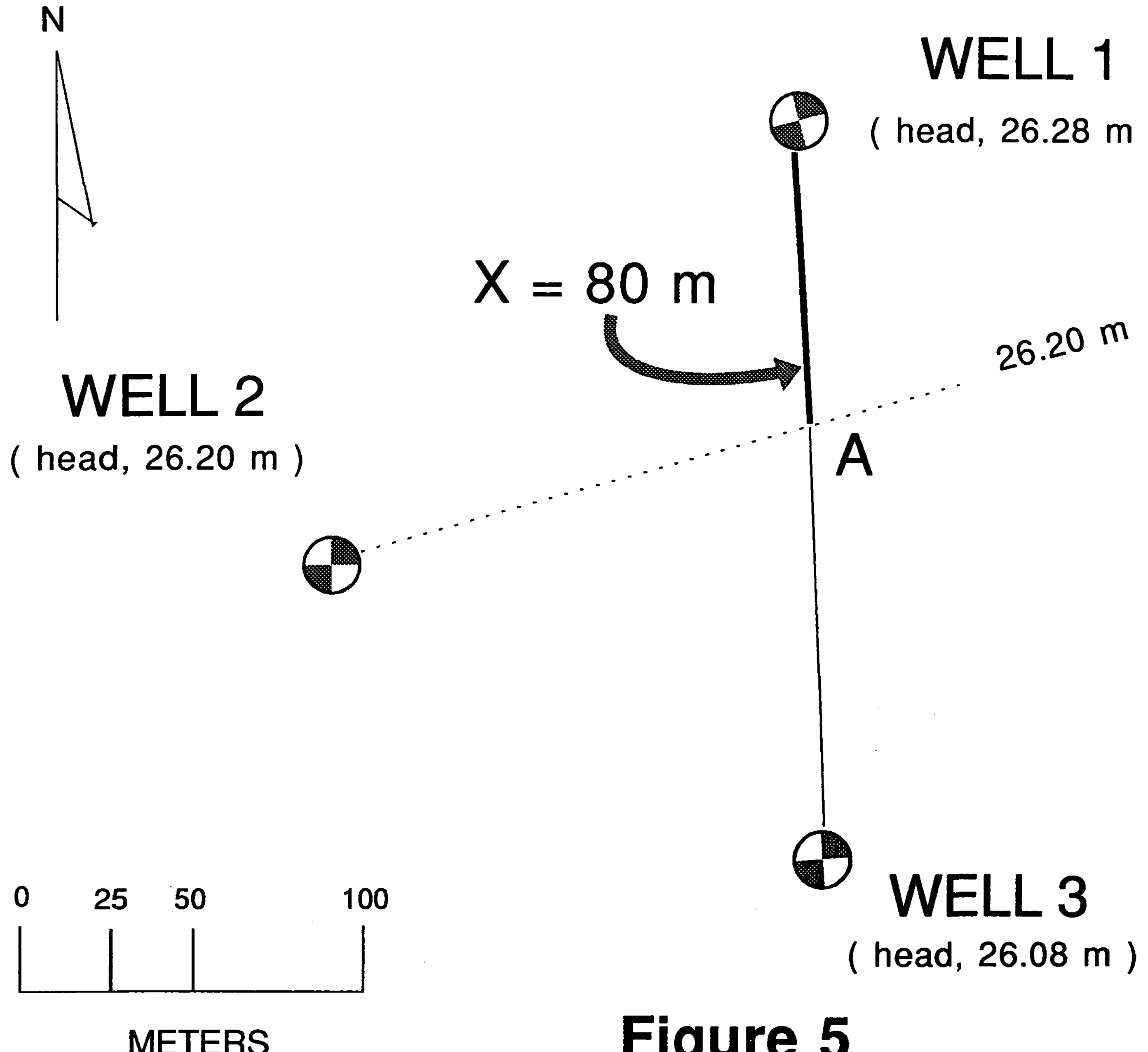

N
WELL 1
(head, 26.28 m)
X = 80 m
26.20 m
WELL 2
(head, 26.20 m)
A
WELL 3
(head, 26.08 m)
0
25
50
100
METERS

Figure 5

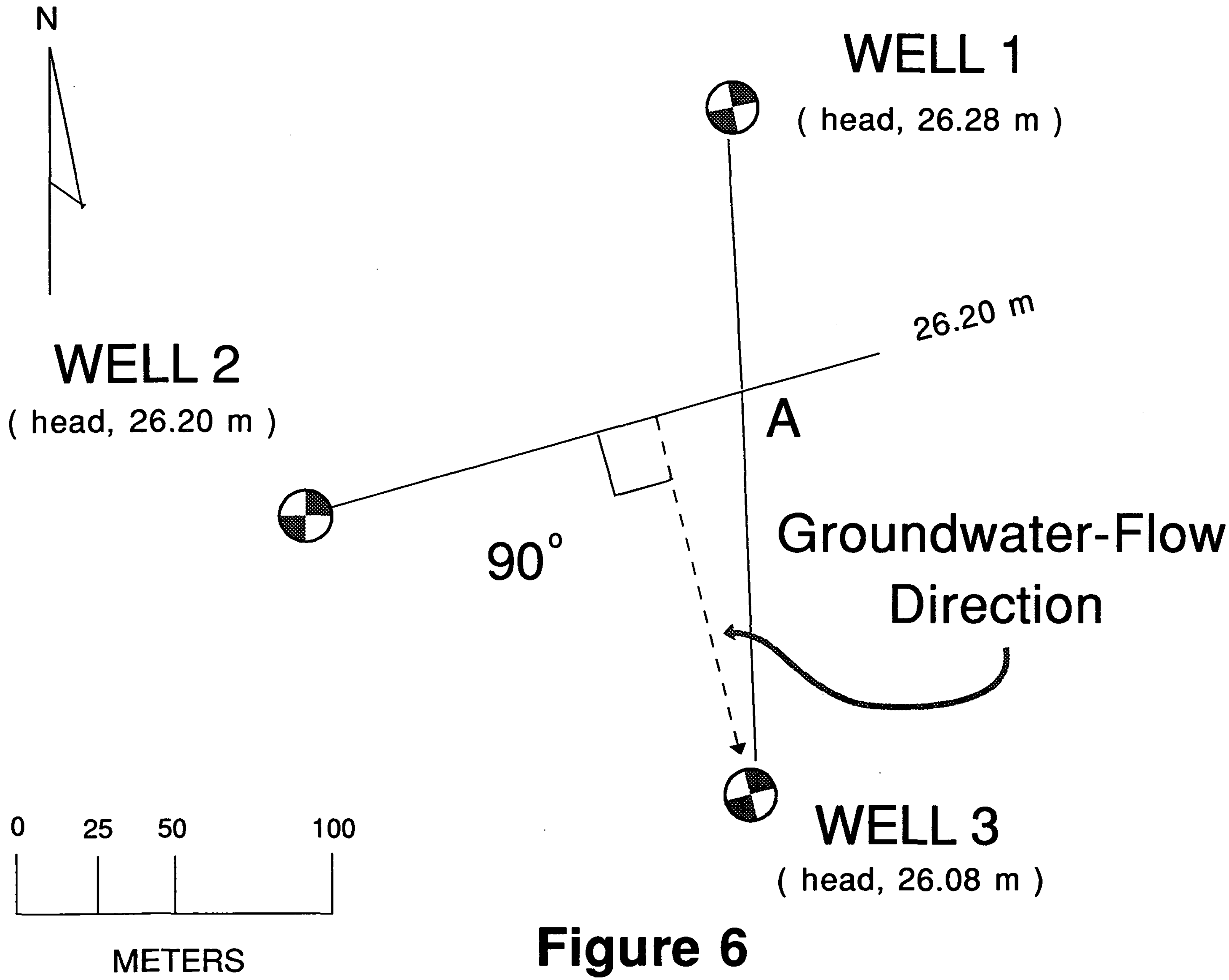

N
WELL 1
(head, 26.28 m)
WELL 2
(head, 26.20 m)
26.20 m
A
90°
Groundwater-Flow Direction
WELL 3
(head, 26.08 m)
0
25
50
100
METERS

Figure 6

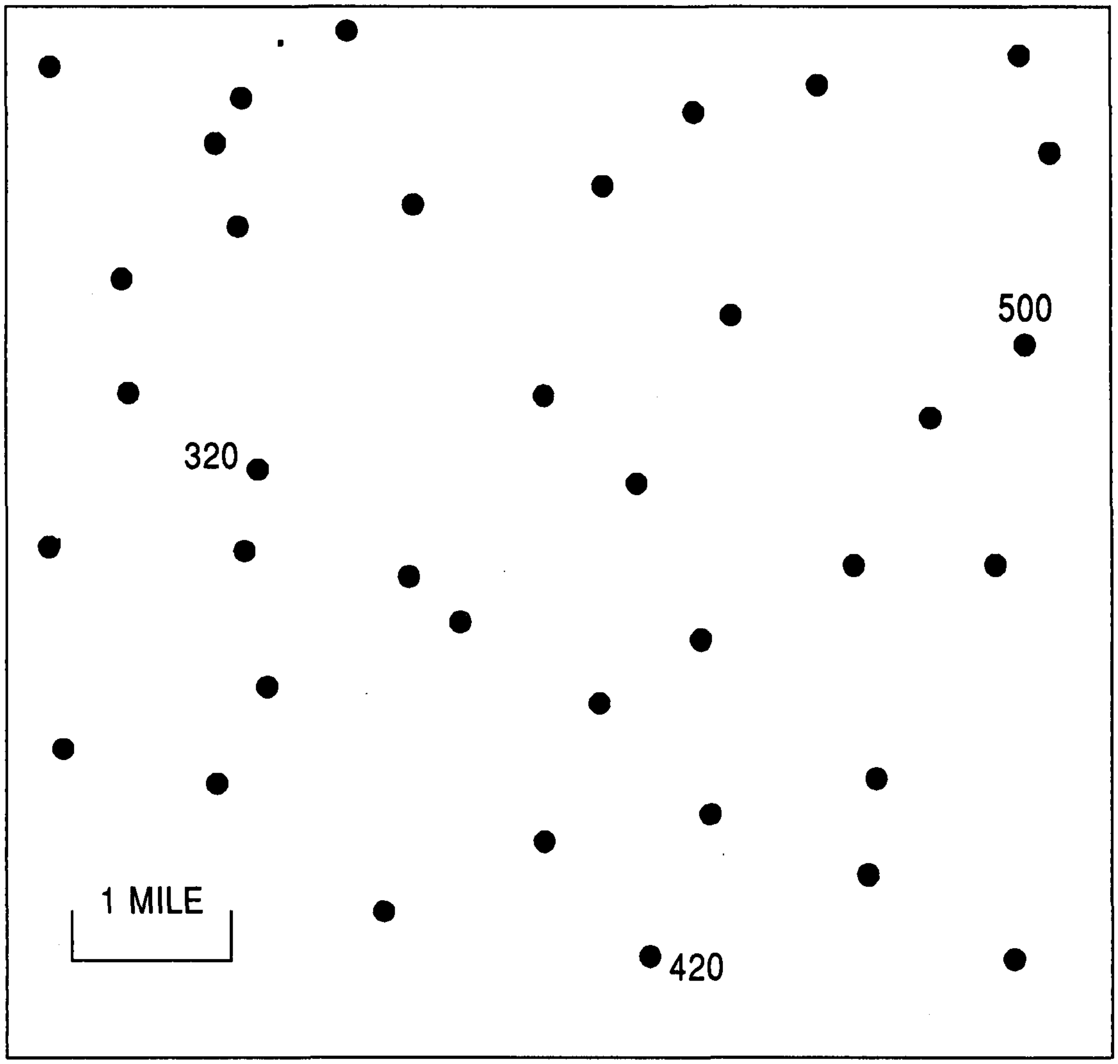


Figure 7

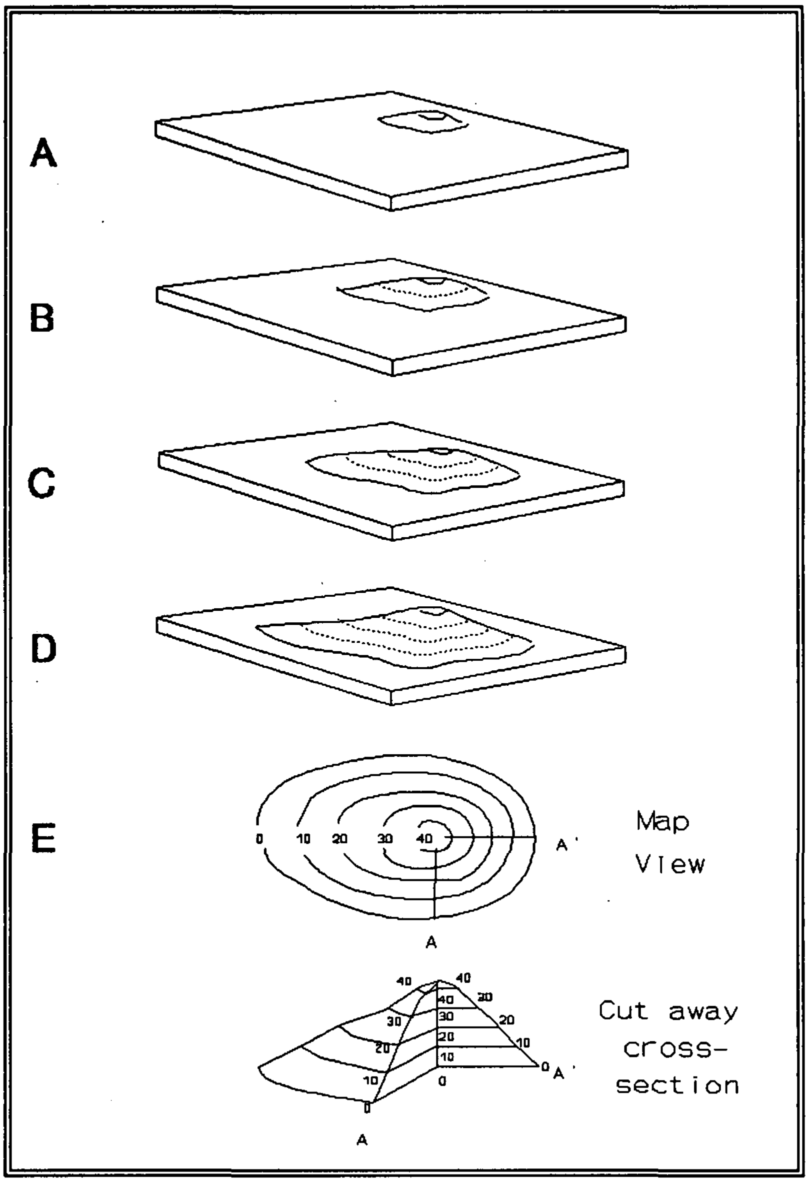


FIGURE 8
DEVELOPMENT OF CONTOUR LINES

Consider an island in a lake and the patterns made on it when the water level recedes. The shoreline represents the same elevation all around the island and is thus a contour line (**Figure 8A**). Suppose that the water level of the lake drops 10 ft and that the position of the former shoreline is marked by a gravel beach (**Figure 8B**). Now there are two contour lines, the new lake level and the old stranded beach, each depicting accurately the shape of the island at these two elevations. If the water level should continue to drop in increments of 10 ft, with each shoreline being marked by a beach, additional contour lines would be formed (**Figures 8C** and **8D**). A map of the raised beaches is in essence a contour map (**Figure 8E**), which represents graphically the configuration of the island.

PROBLEM 2: EXAMPLE OF FLOW NETS AND HYDRAULIC GRADIENTS

Purpose

The exercise will employ basic principles defined in the determination of groundwater-flow directions. Groundwater gradients (slope of the top of the groundwater table) will be calculated as shown in the three-point problem (problem 1) in this problem.

Key Terms

head—The energy contained in a water mass produced by elevation, pressure and/or velocity. It is a measure of the hydraulic potential due to pressure of the water column above the point of measurement and height of the measurement point above datum which is generally mean sea level. Head is usually expressed in feet or meters.

contour line—A line which represents the points of equal values, i.e. elevation, concentration, etc.

equipotential line—A line which represents the points of equal head of groundwater in an aquifer.

flow lines—Lines indicating the flow direction followed by groundwater toward points of discharge. Flow lines are always perpendicular to equipotential lines. They also indicate direction of maximum potential gradient.

Procedure

1. Review **Figures 8–11**.

2. Select an appropriate contour interval that fits the water-levels available and the size of the map on **Figure 9**. (Twenty-foot contour intervals should be appropriate for this problem.)

3. Draw the equipotential lines on the map (**Figure 10**) interpolating between water-level measurements in a similar manner as in problem 1.

4. Construct flow lines perpendicular to the equipotential lines drawn in step 3 (see **Figure 11**.)

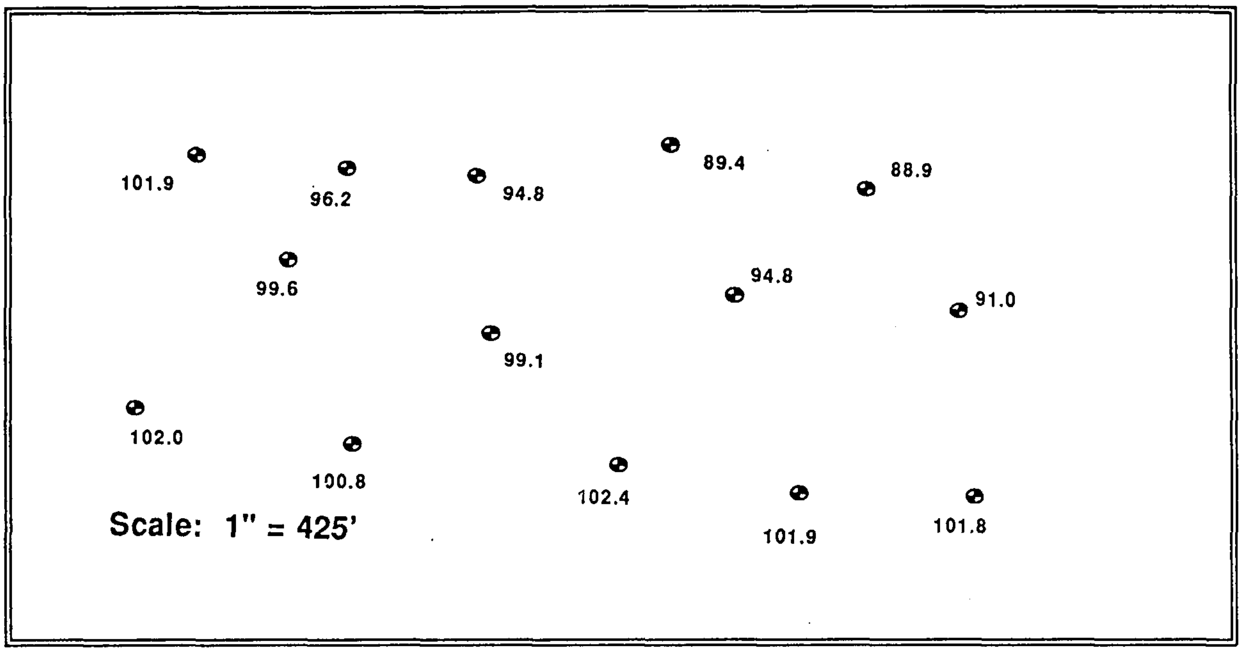


FIGURE 9
WELL LOCATIONS AND HEAD MEASUREMENTS

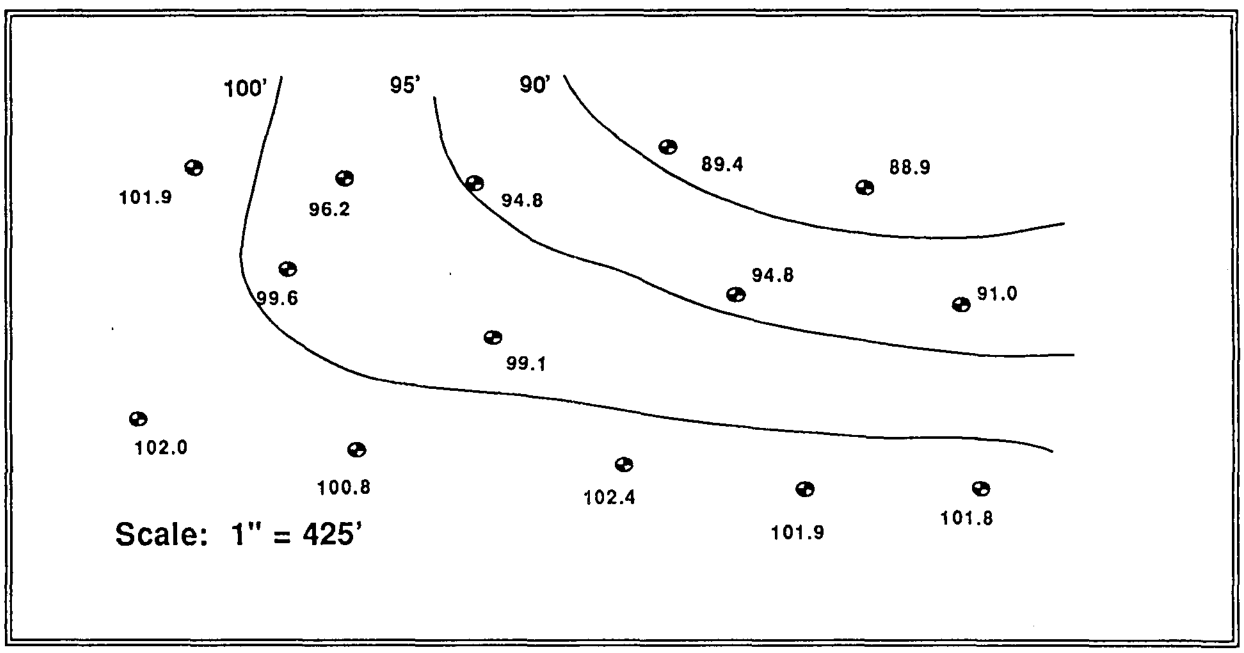


FIGURE 10
EQUIPOTENTIAL LINES WITH WELL HEAD MEASUREMENTS

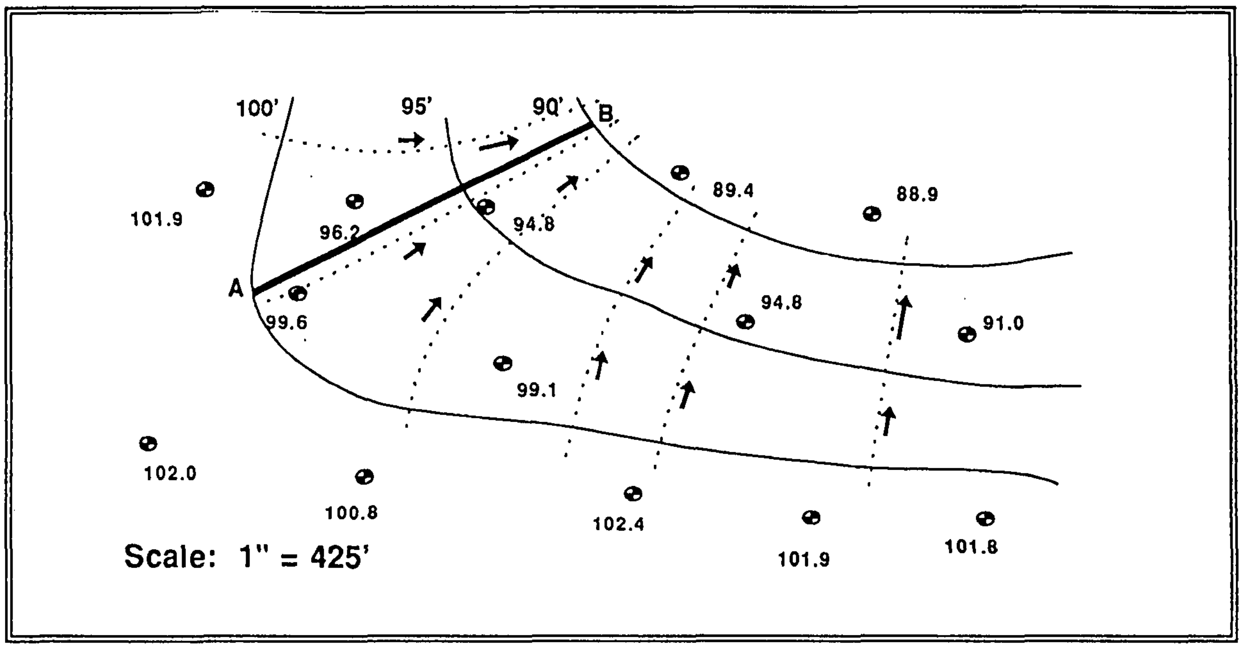


FIGURE 11
FLOW LINES ADDED TO EQUIPOTENTIAL LINES AND CALCULATION OF HYDRAULIC GRADIENT

5. The hydraulic gradient is calculated by measuring the scale distance between equipotential lines along a flow line that crosses the site, and dividing that value into the calculated change in head across the same distance (H_2 - H_1)

$$\frac{H_1 - H_2}{L} = \frac{\Delta H}{L}$$

For example (see **Figure 11**):

Head at A = 100' (H_1)

Head at B = 90' (H_2)

Measured distance between the points is 1200' (L)

Head at point A minus head at point B divided by the distance between the points equals hydraulic gradient (slope from point A to point B).

$$\frac{100\ feet - 90\ feet}{1200\ feet} = \frac{10}{1200} = 8.3 \times 10^{-3}\ feet/foot$$

Select a distance on your contour map between two contour lines and compute the gradient.

PROBLEM 3: FLOW NET CONSTRUCTION

After completing the contour map in Problem 2, plot a profile of the site's groundwater surface at Y-Y' on **Figure 12**.

Procedure

- Vertically project the contour lines that intersect line Y - Y' on map in **Figure 12**, to the dashed line labeled Y - Y' below this map and above the graph for the site's profile.
- Be sure to label each mark on this line with it's respective elevation.
- Plot each elevation point on the graph using the vertical scale given.
- Connect the points on the graph. You have now constructed the site's groundwater-surface profile. This profile also represents a cross section.

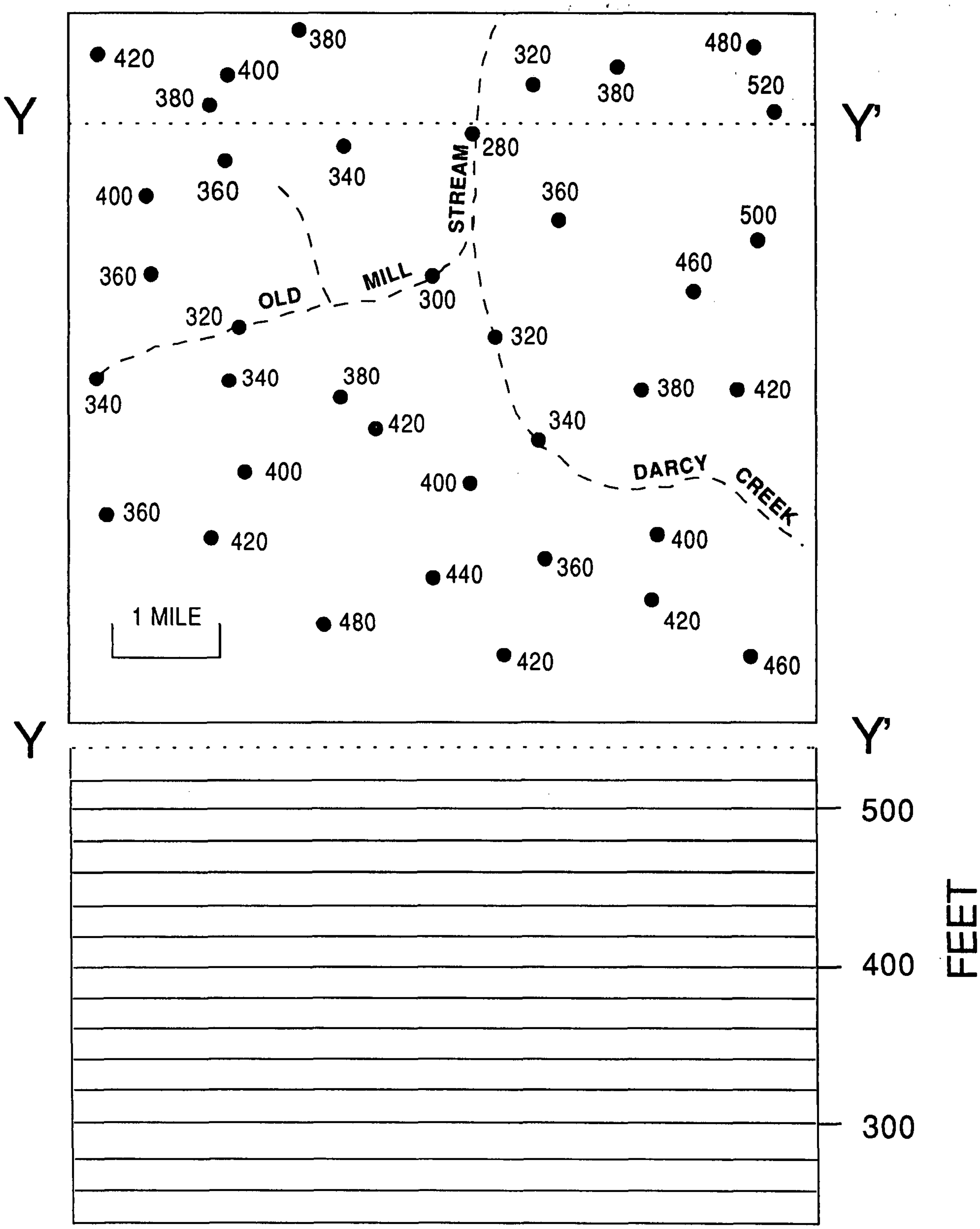

Y
Y'
420
380
400
380
320
380
480
520
280
STREAM
400
360
340
360
500
360
OLD
MILL
300
460
320
320
340
340
380
380
420
420
340
DARCY
CREEK
400
400
360
420
400
440
360
1 MILE
480
420
420
460
Y
Y'
500
400
300
FEET

Figure 12

PROBLEM 4: FLOW NET CONSTRUCTION

Site Name: Bakers Quarry

Location: Tippersville, Maine

SITE HISTORY/OPERATION

The quarry operation began in 1905 providing construction grade granite locally and was closed in 1928 when the volumes of groundwater seeping into the pit made it economically unfeasible to continue mining (**Figure 13**). The site was abandoned and the pit filled with water. The owners of the quarry declared bankruptcy and ownership fell to the city of Tippersville in lieu of delinquent tax payments.

The quarry was used as a swimming hole and occasional dump site for locals until 1958, when several children drowned. The site was fenced and patrolled to prevent swimming. Uncontrolled dumping by individuals and local industry increased dramatically with the swimming ban. Dumping took place around the rim of the quarry and periodically the bulldozer from the town landfill was used to push material into the pit. Gradually the pit was filled and several fires forced the town to terminate dumping in 1971. The surface of the site was covered with local material, primarily sand and gravel.

The site gained notoriety when an area-wide survey identified it as a potential industrial dump site. A preliminary site investigation, started on 4/14/82, including sampling a spring located approximately 25 feet from the limits of quarrying. Priority pollutant analysis of this sample identified ppm levels of polychlorinated biphenyls and trichloroethylene. Results from this preliminary investigation were used to justify a more extensive hydrogeologic study of the site.

ELEMENTS OF THE HYDROGEOLOGIC INVESTIGATION

The first step of this investigation was to do a literature review of geologic information. A discussion with a local amateur geologist revealed a paper from a geologic investigation performed during active quarrying. Information from this study and observations at an outcrop on-site provided a geologic background for the investigation. The quarry material is a slightly gneissoid biotite-muscovite granite. Several dikes were identified in the quarry wall.

The probable high permeability and infiltration rate of the less consolidated waste material compared to that of the granite, could cause groundwater mounding in the pit area. Potential mounding, and inadequate information about groundwater flow direction dictated a ringing of the site with monitoring wells.

Twenty-two monitoring wells were planned and installed at the site from 10/1 to 11/14/82. Eleven were installed in bedrock, the unconsolidated zone sealed with steel casing and grouted. Eleven monitoring wells were installed in the unconsolidated heavily weathered bedrock or unconsolidated zones. For the purpose of this problem set you will only be using data from the eleven wells listed in **Table 1**. An explanation of this data is depicted in **Figure 14**.

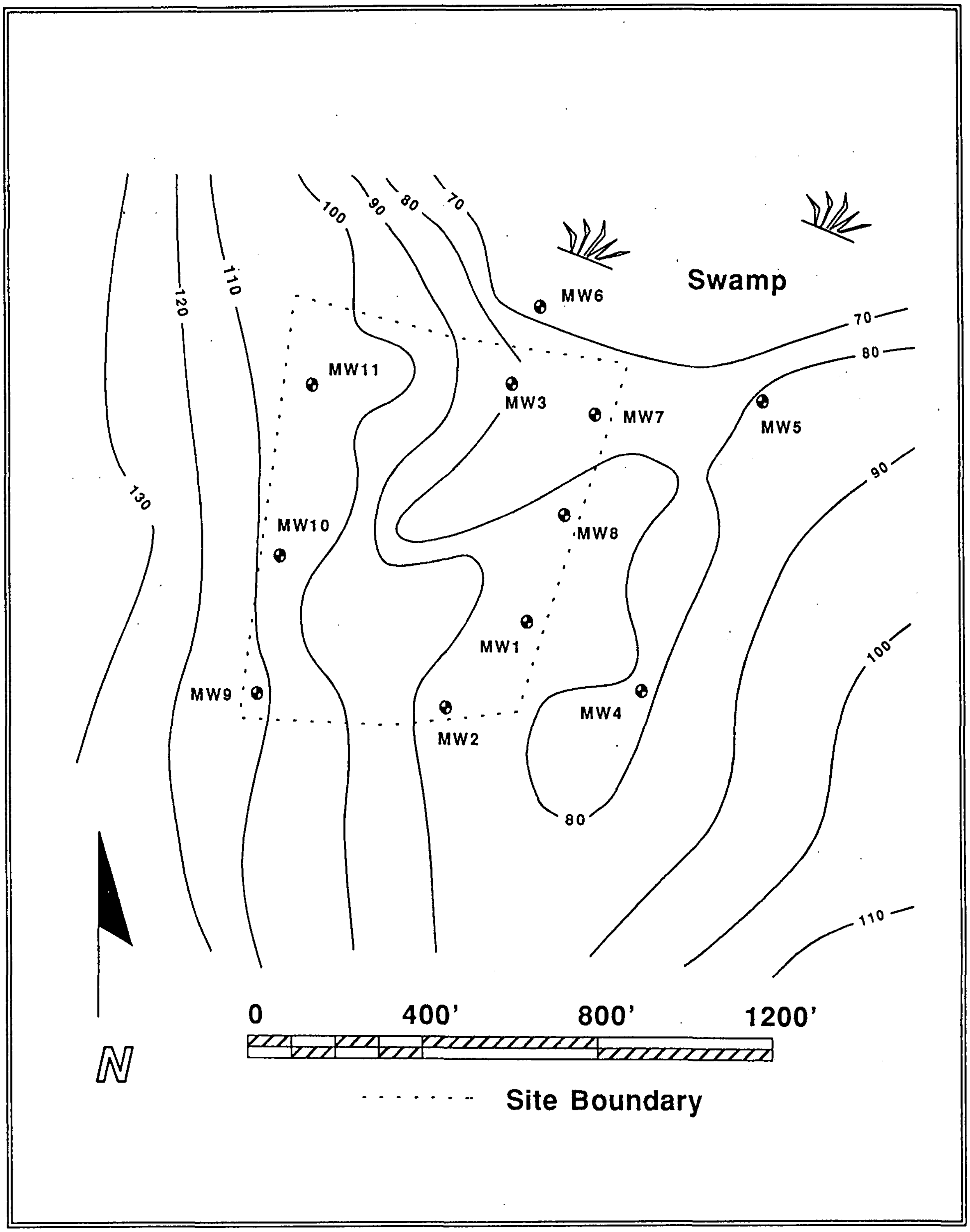


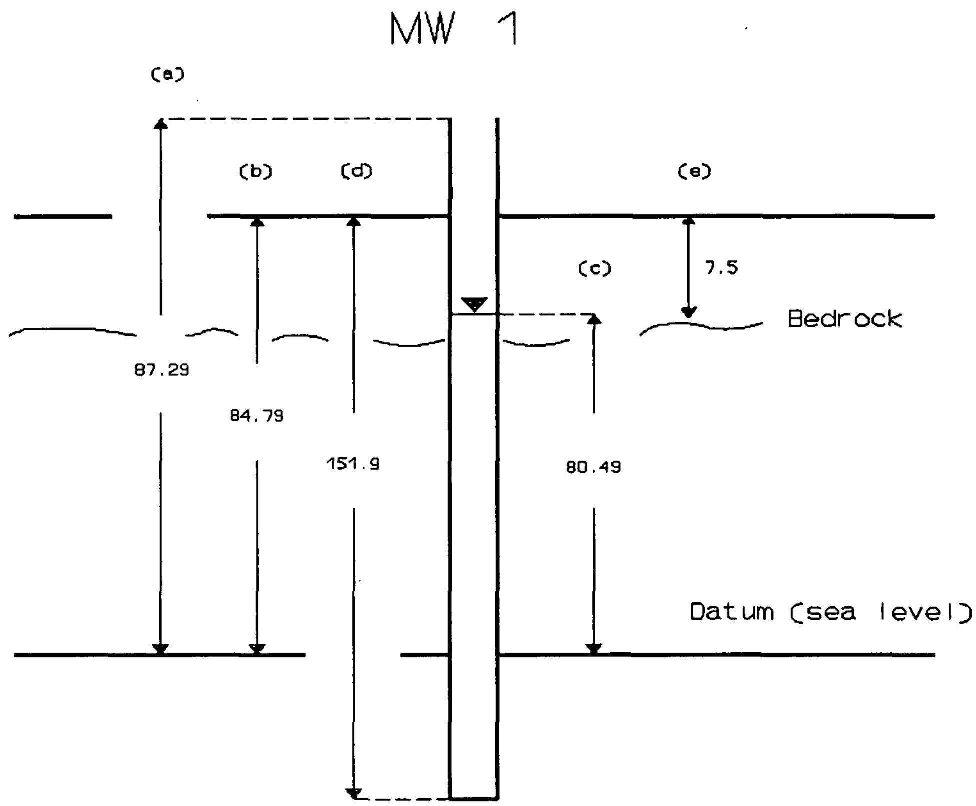
FIGURE 13
SITE MAP - BAKERS QUARRY, TIPPERSVILLE, MAINE

TABLE 1

MONITORING WELL DATA

WELL NUMBER	(a) TOP OF CASING ELEV. (feet)*	(b) GROUND SURFACE (GS) ELEV. (feet)*	(c) GROUND-WATER ELEV. (feet)*	(d) WELL DEPTH (feet below GS)	BOTTOM OF WELL ELEV. (feet)*	(e) BED-ROCK DEPTH (feet below GS)
MW 1	87.29	84.79	80.49	151.9	-67.11	7.5
MW 2	89.94	87.99	84.69	103.05	-15.06	7.5
MW 3	88.04	85.44	75.29	103.1	-17.66	2.0
MW 4	82.50	79.80	72.40	102.3	-22.50	14.0
MW 5	82.50	80.05	73.40	102.45	-22.40	8.5
MW 6	72.50	69.50	67.50	99.6	-30.10	9.0
MW 7	80.58	78.28	74.78	99.5	-21.22	8.0
MW 8	86.03	83.53	76.93	99.2	-15.67	8.5
MW 9	114.01	111.21	92.36	99.9	11.31	10.5
MW 10	108.67	106.67	93.97	98.7	7.97	10.8
MW 11	105.07	103.37	94.97	102.1	1.27	2.5

* Datum: mean sea level



(a) Top of casing elevation (feet)
(b) Ground surface elevation (feet)
(c) Groundwater elevation (feet)
(d) Well depth below ground surface (feet)
(e) Bedrock depth (feet)

FIGURE 14
MONITORING WELL ELEVATIONS

DEVELOPMENT OF SITE PROFILES

Purpose

The development and comparison of topographic profiles across the site will help the student to understand the variability of the surface terrain usually found on most of the larger sites. The water-table profile will also be constructed. These profiles will be useful during the next problem, "Flow Nets and Determination of Hydraulic Gradients."

Procedure

1. To construct cross-section lines, lay the edge of a piece of paper along the cross-section line selected and draw a straight line. Mark the location of the monitoring wells along the edge of the paper. (The placement of some wells may need to be projected, as not all of the wells lie along a straight line.)

A - A' MW 9, MW 2, and MW 4 (in that order)

B - B' MW 1, MW 8, and MW 7

C - C' MW 11, MW 3, MW 7, and MW 5

NOTE: One should be aware that projection of wells to a cross-section line could cause distortions which might affect interpretation of the distribution of subsurface geology or soil.

2. Using the graph paper provided, transfer these well locations to the bottom of the page along the horizontal axis.

3. The vertical axis will represent elevation in feet. Mark off the elevations in ten foot increments. Each division of the graph will represent an elevation increase of two feet.

4. Graph the ground surface elevation for each of the chosen monitoring wells. (This information is found in the monitoring well data, **Table 1**.)

5. Graph the groundwater elevations for these same locations.

6. Repeat this procedure for the other cross-sections lines.

7. Compare the topographic profile to the water table-profile. Are they identical? After looking at this data, are there any conclusions that can be drawn?

PROBLEM 2

Geologic Cross-Section Construction

PROBLEM 2: GEOLOGIC CROSS-SECTION CONSTRUCTION

Materials necessary to construct cross section:

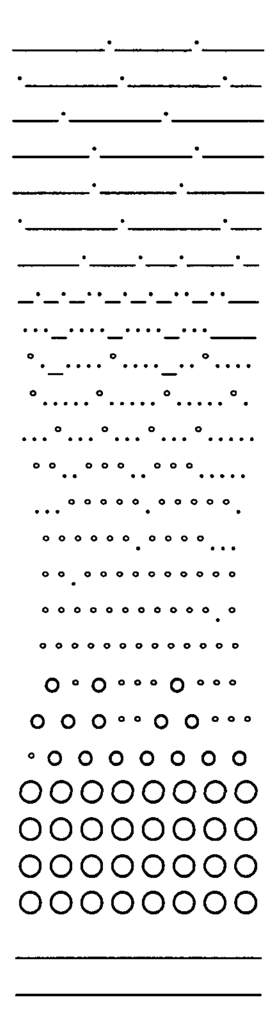
- Graph paper. Use vertical scale of one graph paper division per 20 feet.
- Colored geologic map from geologic report that covers the area surrounding the location of the cross section. The cross section is labeled on the map as A - A'.
- Description of major geologic units from a geologic report.
- Six water well logs which include a driller's description of the sediments and rocks encountered during the drilling of each well. Location of the wells are depicted on the geologic map and the following topographic quadrangle map. These logs will be used to construct the geologic cross section.
- Topographic quadrangle map depicting the ground surface elevation along this cross section. This map will be used to construct the surface profile at the cross section.
- Ruler and colored pencils will be supplied upon request.

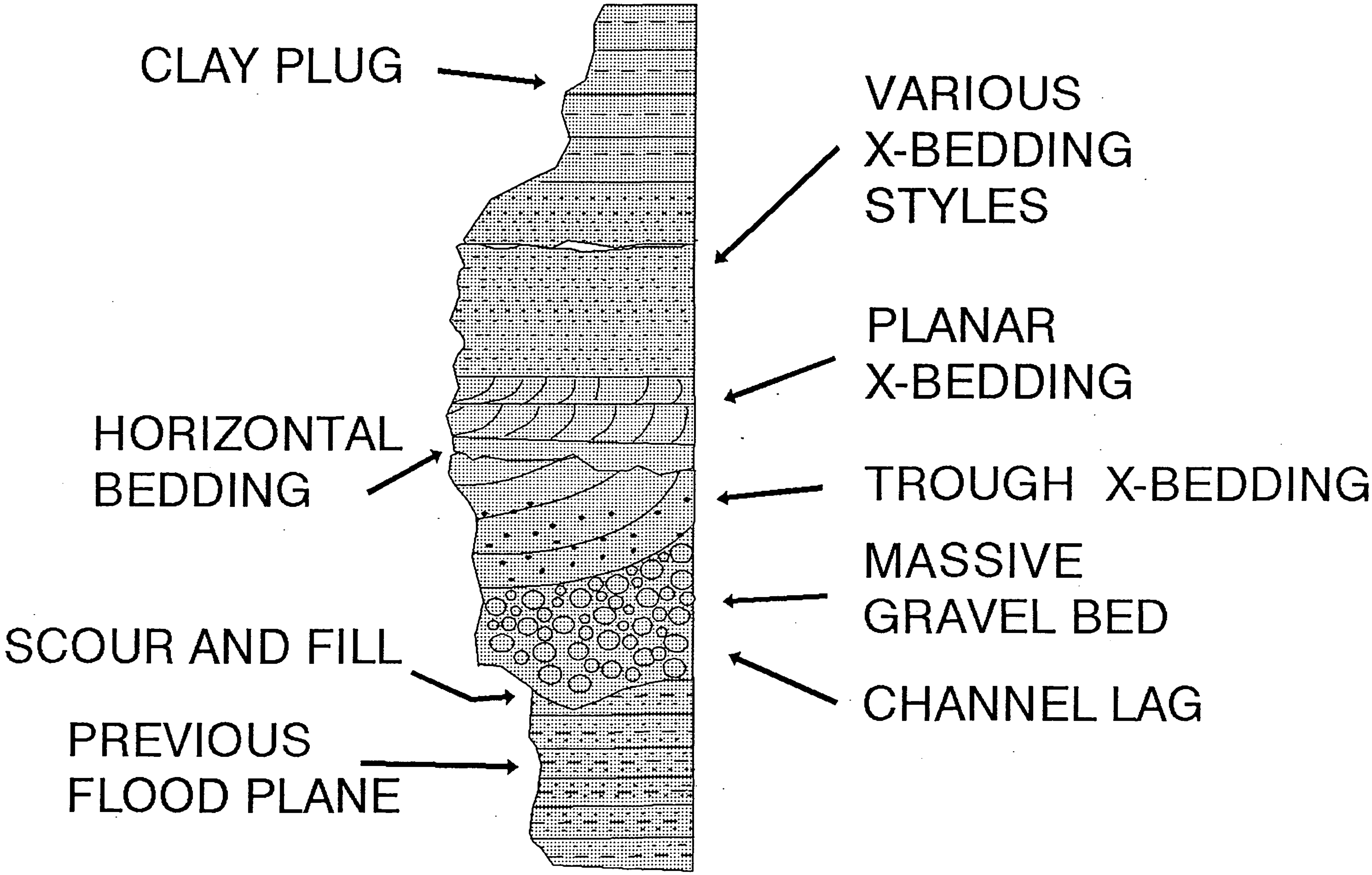
Procedure to follow in the construction of this cross section:

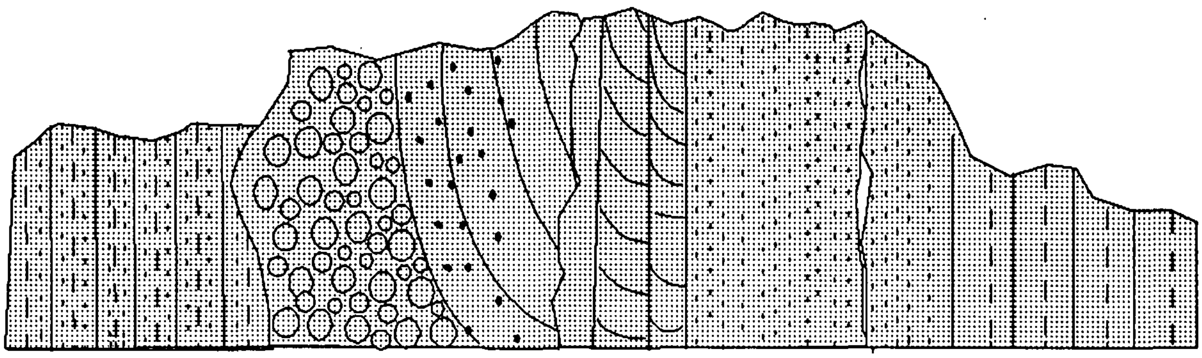
- The instructor will divide the students into groups after discussing the materials included with this exercise.
- Each group will first select an individual to construct a common surface profile that the other students will use to put their soil boring interpretation for each well on the cross section. This person will use the same procedure employed earlier to construct the profile in the flow net exercise.
- Each group will then determine who will evaluate the soil boring information from each well log and define which major geologic units are present. This interpretation will be based on the geologic information already provided. Hint: The geologic map indicates the major unit at the top of each soil boring.
- When the major unit intervals are defined on each boring, this information will be constructed on the graph paper provided using the vertical scale given above. It is suggested that one use the same symbols as those used to describe the major geologic units in the geologic report.
- After the surface profile is completed, the constructed boring log for each well will be transposed onto this profile. This is done by placing the top of each constructed well log at its appropriate surface location on the profile. This will eliminate the need

of calculating the elevation for the top of each major geologic unit found in each boring.

- Once this is accomplished each group will attempt to correlate these major geologic units between the six soil borings.

Depth of Soil Boring	Lithologic Description	Depth (ft)	Boring Log Example # 1	Boring Log Example # 2
0 - 5.0 ft	Tan, silty clay (SC)	0.0 -		SC
5.0 - 10.0 ft	Light brown, sandy silt (SS)	5.0 -		SS
10.0 - 15.0 ft	Brown, fine-grain sand (FS)	10.0 -		FS
15.0 - 17.5 ft	Dark brown, coarse-grain sand (CS)	15.0		CS
17.5 - 20.0 ft	Reddish brown gravel (G)	- 20.0		G
20.0 - 22.5 ft	Red Clay (C)	-		C


CLAY PLUG
VARIOUS
X-BEDDING
STYLES
PLANAR
X-BEDDING
HORIZONTAL
BEDDING
TROUGH X-BEDDING
MASSIVE
GRAVEL BED
SCOUR AND FILL
CHANNEL LAG
PREVIOUS
FLOOD PLANE



GRAIN SIZE DECREASES

→

FINING UPWARDS SEQUENCE

SORTING

POOR → GOOD

STREAM VELOCITY DECREASES

→

DESCRIPTION OF MAP UNITS

Symbol	*Description*
	Quaternary Sediments
Qa	Alluvium or stream deposits(Holocene)—Composed of silt-, sand-, and gravel-size sediment. These deposits are found in floodplains, river terraces, and valley bottoms. The vertical sequence of sediment grain size decreases from bottom to top. Locally the unit includes lacustrine (lake) and paludal (swamp or marsh) clays and silts, eolian (wind blown) sand deposits in depressions.
Qfg	Flood deposits (Pleistocene)—Poorly sorted, stratified mixture of boulders, cobbles, gravel, and sand resulting from multiple episodes of catastrophic outbursts from glacial-dammed lakes, such as glacial Lake Missoula. The Little Spokane River valley was one of the main channelways for outburst flood waters from this ancient lake. Each flood event is represented by a sequence of sediment grain size decreasing from bottom to top.
Qls	Alluvial fan deposits (Pleistocene)—Composed of unstratified and poorly sorted (heterogeneous and anisotropic) clay-, silt-,sand-, and gravel-size sediment. Some fan deposits contain large blocks of rock as much as 8 meters in diameter.
Ql	Loess (Pleistocene)—Composed of light- to medium-brown, unstratified eolian particles of clay, silt, sand, and volcanic ash. The loess mantles the Columbia River basalt and is most commonly found on the tops of low hills and plateaus where erosion by water has been minimal.
Qglf	Lacustrine and flood deposits (Pleistocene)—Composed of light-gray, friable, sediment of clay, silt, and fine sand near the top of this sequence of deposits. This sediment overlies flood deposits composed of stratified mixtures of boulders, cobbles, gravel, and sand. Each flood deposit is represented by a sequence of sediment grain size decreasing from bottom to top.
	Columbia River Basalt Group—Tertiary (Miocene)
Mv_{wp} & Mv_{gN2}	Wanapum basalt flows and upper flows of the Grande Ronde basalt.
Mc_l	Latah Formation—Gray to tan to yellow-orange siltstone, claystone, and minor sandstone of lacustrine and fluvial depositional environments.
	Intrusive Igneous Rock—Cretaceous
$Kiat_8$	The symbol represents all Cretaceous and Tertiary-age intrusive igneous rocks including the Mount Spokane granite.

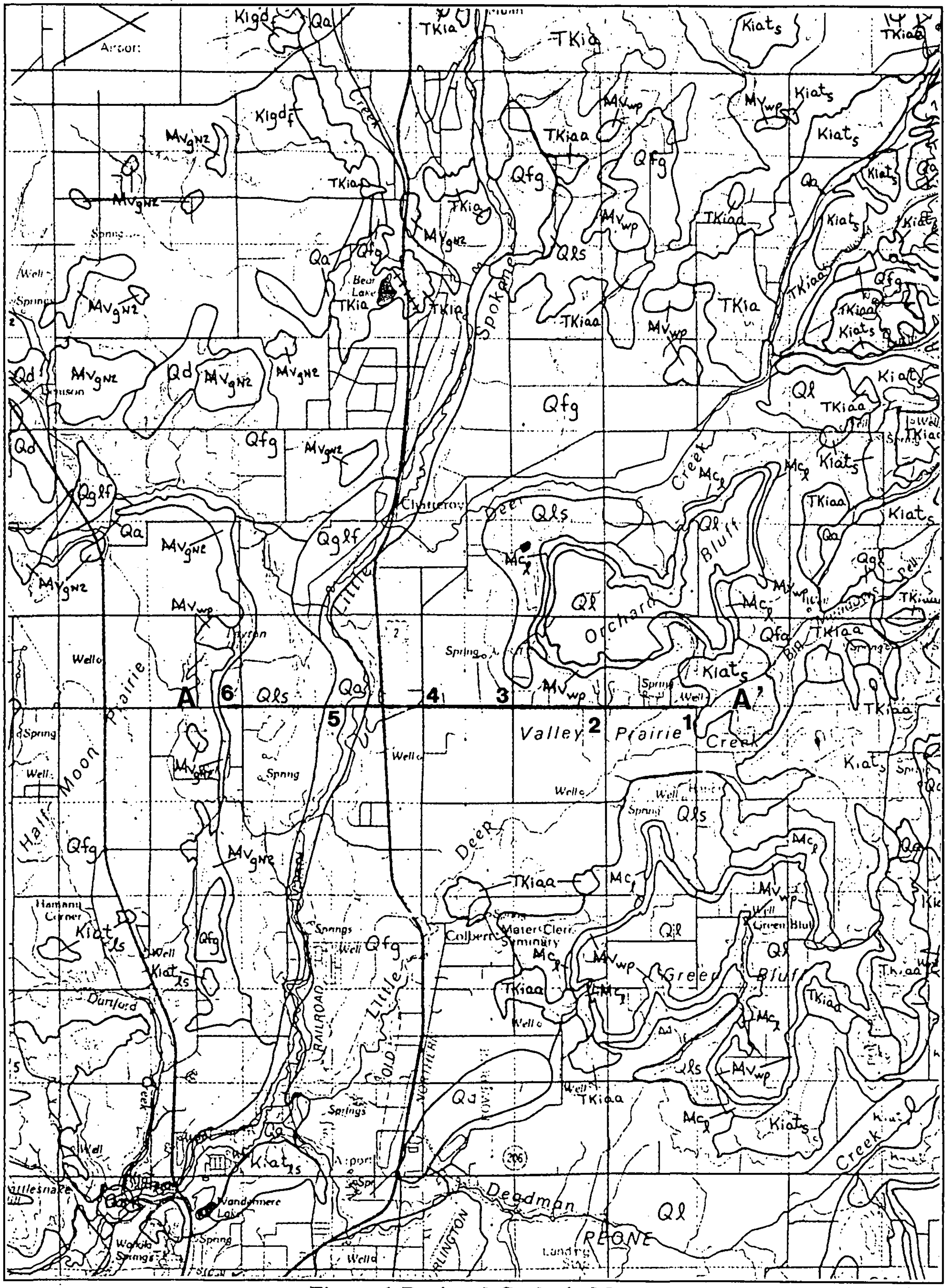


Figure 1 Regional Geologic Map
Mead Landfill Site

5000 0 5000 10000 15000 20000 25000
FEET

WATER WELL REPORT

STATE OF WASHINGTON

1) OWNER: Name ____ Address ____

2) LOCATION OF WELL: County Spokane NE SW SW ¼ SW ¼ Sec. 5 T. 27 N., R. 44 E.W.M.

Bearing and distance from section or subdivision corner

(3) PROPOSED USE: Domestic ☒ Industrial ☐ Municipal ☐ Irrigation ☐ Test Well ☐ Other ☐

(4) TYPE OF WORK: Owner's number of well (if more than one) 1

New well ☒ Method: Dug ☐ Bored ☐
Deepened ☐ Cable ☐ Driven ☐
Reconditioned ☐ Air Rotary ☒ Jetted ☐

(5) DIMENSIONS: Diameter of well 8.0 inches.
Drilled 100 ft. Depth of completed well 80 ft.

(6) CONSTRUCTION DETAILS:

Casing installed: 4.0" Diam. from 0 ft. to 60 ft.
Threaded ☒ ____" Diam. from ____ ft. to ____ ft.
Welded ☐ ____" Diam. from ____ ft. to ____ ft.

Perforations: Yes ☐ No ☒
Type of perforator used ____
SIZE of perforations ____ in. by ____ in.
____ perforations from ____ ft. to ____ ft.
____ perforations from ____ ft. to ____ ft.
____ perforations from ____ ft. to ____ ft.

Screens: Yes ☐ No ☐
Manufacturer's Name Johnson Well Screen
Type PVC Sch 80 Model No. ____
Diam. 4" Slot size 10 from 60 ft. to 80 ft.
Diam. ____ Slot size ____ from ____ ft. to ____ ft.

Gravel packed: Yes ☒ No ☐ Size of gravel: Sime 10-20
Gravel placed from 80 ft. to 55 ft.

Surface seal: Yes ☒ No ☐ To what depth? ____ ft.
Material used in seal Cement grout
Did any strata contain unusable water? Yes ☐ No ☒
Type of water? ____ Depth of strata ____
Method of sealing strata off ____

(7) PUMP: Manufacturer's Name Grundfos
Type: Submersible H.P. 5

(8) WATER LEVELS: Land-surface elevation above mean sea level 1922 ft.
Static level 1900 ft. below top of well Date ____
Artesian pressure ____ lbs. per square inch Date ____
Artesian water is controlled by ____ (Cap, valve, etc.)

(9) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☒ If yes, by whom? ____
Yield: 20 gal./min. with ____ ft. drawdown after 30 min hrs.
" " " "
" " " "

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ____
Bailer test ____ gal./min. with ____ ft. drawdown after ____ hrs.
Artesian flow ____ g.p.m. Date ____
Temperature of water ____ Was a chemical analysis made? Yes ☐ No ☐

(10) WELL LOG:

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation.

MATERIAL	FROM	TO
Sand; Coarse grained	0	5'
Gravel w/some boulders	5'	10'
Siltstone interbedded w/claystone	10	20'
Weathered Granite; easily broken sample cuttings	20	40'
Granite; hard dense	40	100'

Work started Aug 10 19 61 Completed Aug 18 19 61

WELL DRILLER'S STATEMENT:

This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

NAME ____ (Person, firm, or corporation) (Type or print)

Address ____

(Signed) ____ (Well Driller)

License No. ____ Date ____, 19____

(USE ADDITIONAL SHEETS IF NECESSARY)

ECY 050-1-20

WATER WELL REPORT

STATE OF WASHINGTON

1) OWNER: Name ______ Address ______

2) LOCATION OF WELL: County Spokane NW - NW 1/4 NW 1/4 Sec. 7 T. 27 N., R. 44 E W.M.

Bearing and distance from section or subdivision corner

(3) PROPOSED USE: Domestic ☒ Industrial ☐ Municipal ☐ Irrigation ☐ Test Well ☐ Other ☐

(4) TYPE OF WORK: Owner's number of well (if more than one) 2
New well ☒ Method: Dug ☐ Bored ☐
Deepened ☐ Cable ☐ Driven ☐
Reconditioned ☐ Air Rotary ☒ Jetted ☐

(5) DIMENSIONS: Diameter of well 8.0 inches.
Drilled 300 ft. Depth of completed well 220 ft.

(6) CONSTRUCTION DETAILS:

Casing installed: 4.0" Diam. from 0 ft. to 200 ft.
Threaded ☐ ___" Diam. from ___ ft. to ___ ft.
Welded ☐ ___" Diam. from ___ ft. to ___ ft.

Perforations: Yes ☐ No ☒
Type of perforator used ______
SIZE of perforations ___ in. by ___ in.
___ perforations from ___ ft. to ___ ft.
___ perforations from ___ ft. to ___ ft.
___ perforations from ___ ft. to ___ ft.

Screens: Yes ☒ No ☐
Manufacturer's Name Johnson Well Screen
Type PVC Sch 80 Model No. ______
Diam. 4" Slot size 10 from 220 ft. to 200 ft.
Diam. ___ Slot size ___ from ___ ft. to ___ ft.

Gravel packed: Yes ☒ No ☐ Size of gravel: Sieve size 10-20
Gravel placed from ___ ft. to ___ ft.

Surface seal: Yes ☒ No ☐ To what depth? ___ ft.
Material used in seal cement grout
Did any strata contain unusable water? Yes ☐ No ☐
Type of water? ___ Depth of strata ___
Method of sealing strata off ______

(7) PUMP: Manufacturer's Name Grundfos
Type: Submersible H.P. 10

(8) WATER LEVELS: Land-surface elevation above mean sea level.... 1960 ft.
Static level 180 ft. below top of well Date ______
Artesian pressure ___ lbs. per square inch Date ______
Artesian water is controlled by ______ (Cap, valve, etc.)

(9) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☒ If yes, by whom? ______
Yield: 25 gal./min. with ___ ft. drawdown after 30 min hrs.
" " "
" " "

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ______
Bailer test ___ gal./min. with ___ ft. drawdown after ___ hrs.
Artesian flow ___ g.p.m. Date ___
Temperature of water ___ Was a chemical analysis made? Yes ☐ No ☐

(10) WELL LOG:

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation.

MATERIAL	FROM	TO
Sand coarse grained	0	5
Sand medium to coarse w/gravel	5	10
gravel w/ boulders	10	15
boulders rounded	15	20
Sand coarse grained	20	25
clay gray to brown color	25	30
sand coarse grained	30	35
boulders & cobbles →	35	40
Clay and silt brown	45	50
silt and fine grain sand	50	55
basalt fragments/clay	55	60
↓	60	65
rounded basalt boulders	65	70
w/clay	70	75
	75	80
clay w/ boulders composed of	80	85
siltstone and claystone	85	90
↓	90	95
→	95	100
siltstone interbedded w/claystone	100	200
w/some basalt flows 75' thick →		
Weathered granite →	200	230
granite hard & dense	230	300
fractured & exfoliated		

Work started Sept 10, 19 63 Completed Sept 28, 19 63

WELL DRILLER'S STATEMENT:

This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

NAME ______ (Person, firm, or corporation) (Type or print)

Address ______

[Signed] ______ (Well Driller)

License No. ______ Date ______, 19___

(USE ADDITIONAL SHEETS IF NECESSARY)

ECY 050-1-20

WATER WELL REPORT

STATE OF WASHINGTON

1) OWNER: Name ________ Address ________

2) LOCATION OF WELL: County Spokane N/2 NW - NW ¼ NW ¼ Sec. 12 T. 27 N., R. 43 E.W.M.

Bearing and distance from section or subdivision corner

(3) PROPOSED USE: Domestic ☒ Industrial ☐ Municipal ☐ Irrigation ☐ Test Well ☐ Other ☐

(4) TYPE OF WORK: Owner's number of well (if more than one) 3

New well ☒ Method: Dug ☐ Bored ☐
Deepened ☐ Cable ☐ Driven ☐
Reconditioned ☐ Air Rotary ☒ Jetted ☐

(5) DIMENSIONS: Diameter of well 8.0 inches.
Drilled 350 ft. Depth of completed well 310 ft.

(6) CONSTRUCTION DETAILS:

Casing installed: 40 " Diam. from ____ ft. to ____ ft.
Threaded ☐ ____" Diam. from ____ ft. to ____ ft.
Welded ☐ ____" Diam. from ____ ft. to ____ ft.

Perforations: Yes ☐ No ☒
Type of perforator used ____
SIZE of perforations ____ in. by ____ in.
____ perforations from ____ ft. to ____ ft.
____ perforations from ____ ft. to ____ ft.
____ perforations from ____ ft. to ____ ft.

Screens: Yes ☒ No ☐
Manufacturer's Name Johnson Well Screen
Type PVC Sch 80 Model No. ____
Diam. 4.0" Slot size 20 from 290 ft. to 310 ft.
Diam. ____ Slot size ____ from ____ ft. to ____ ft.

Gravel packed: Yes ☒ No ☐ Size of gravel: sieve size 10-20
Gravel placed from ____ ft. to ____ ft.

Surface seal: Yes ☒ No ☐ To what depth? ____ ft.
Material used in seal cement grout
Did any strata contain unusable water? Yes ☐ No ☐
Type of water? ____ Depth of strata ____
Method of sealing strata off ____

(7) PUMP: Manufacturer's Name Grundfos
Type: Submersible H.P. 5

(8) WATER LEVELS: Land-surface elevation above mean sea level.... 1930 ft.
Static level 100 ft. below top of well Date ____
Artesian pressure ____ lbs. per square inch Date ____
Artesian water is controlled by ____ (Cap, valve, etc.)

(9) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☒ If yes, by whom? ____
Yield: 5.0 gal./min. with ____ ft. drawdown after 2.0 hrs.
" " "
" " "

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ____
Bailer test ____ gal./min. with ____ ft. drawdown after ____ hrs.
Artesian flow ____ g.p.m. Date ____
Temperature of water ____ Was a chemical analysis made? Yes ☐ No ☐

(10) WELL LOG:

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation

MATERIAL	FROM	TO
gravel & coarse sand	0	10
same as above	10	20
↓	20	30
	30	40
	40	50
	50	60
	60	70
	70	80
boulders of basalt & granite w/	80	90
sand & gravel and silt & clay	90	100
same as above	100	110
↓	110	120
	120	130
	130	140
	140	150
	150	160
siltstone and claystone grey to	160	260
brown in color		
vesicular basalt flow, fractured	260	290
granite, salt and pepper	290	350
appearance; rubbly at surface		
w/ increasing hardness w/		
depth.		

Work started June 5 1960 Completed June 30 1960

WELL DRILLER'S STATEMENT:

This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

NAME ____ (Person, firm, or corporation) (Type or print)

Address ____

[Signed] ____ (Well Driller)

License No. ____ Date ____, 19____

(USE ADDITIONAL SHEETS IF NECESSARY)

ECY 050-1-20

WATER WELL REPORT
STATE OF WASHINGTON

1) OWNER: Name ____ Address ____

2) LOCATION OF WELL: County Spokane SW - SW ¼ SW ¼ Sec. 2 T. 27 N., R. 43 E W.M.

Bearing and distance from section or subdivision corner

(3) PROPOSED USE: Domestic ☒ Industrial ☐ Municipal ☐ Irrigation ☐ Test Well ☐ Other ☐

(4) TYPE OF WORK: Owner's number of well (if more than one) 4
New well ☒ Method: Dug ☐ Bored ☐
Deepened ☐ Cable ☐ Driven ☐
Reconditioned ☐ Air Rotary ☒ Jetted ☐

(5) DIMENSIONS: Diameter of well 8.0 inches.
Drilled ____ ft. Depth of completed well ____ ft.

(6) CONSTRUCTION DETAILS:
Casing installed: 4.0" Diam. from 0 ft. to 170 ft.
Threaded ☐ ____" Diam. from ____ ft. to ____ ft.
Welded ☐ ____" Diam. from ____ ft. to ____ ft.

Perforations: Yes ☐ No ☒
Type of perforator used ____
SIZE of perforations ____ in. by ____ in.
____ perforations from ____ ft. to ____ ft.
____ perforations from ____ ft. to ____ ft.
____ perforations from ____ ft. to ____ ft.

Screens: Yes ☒ No ☐
Manufacturer's Name Johnson Well Screen
Type PVC Sch 80 Model No. ____
Diam. 4" Slot size .10 from 170 ft. to 200 ft.
Diam. ____ Slot size ____ from ____ ft. to ____ ft.

Gravel packed: Yes ☒ No ☐ Size of gravel: Sieve Size 10-20
Gravel placed from ____ ft. to ____ ft.

Surface seal: Yes ☒ No ☐ To what depth? ____ ft.
Material used in seal Concrete
Did any strata contain unusable water? Yes ☐ No ☒
Type of water? ____ Depth of strata ____
Method of sealing strata off ____

(7) PUMP: Manufacturer's Name Grundfos
Type: Submersible HP 10

(8) WATER LEVELS: Land-surface elevation above mean sea level.... 1864 ft.
Static level 1740 ft. below top of well Date ____
Artesian pressure ____ lbs. per square inch Date ____
Artesian water is controlled by ____ (Cap, valve, etc.)

(9) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☒ If yes, by whom? ____
Yield: 110.0 gal./min. with ____ ft. drawdown after 15 min
" " " "
" " " "

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ____
Bailer test ____ gal./min. with ____ ft. drawdown after ____ hrs.
Artesian flow ____ g.p.m. Date ____
Temperature of water ____ Was a chemical analysis made? Yes ☐ No ☐

(10) WELL LOG:

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation.

MATERIAL	FROM	TO
Sand w/gravel & boulders	0	10
same as above	10	20
gravel w/ boulders and sand	20	30
same as above	30	40
boulders w/ sand & gravel	40	50
same as above	50	60
same as above	60	70
sand w/ some gravel	70	80
same as above	80	90
boulders, w/ gravel and sand	90	100
interbedded silt and clay	100	110
yellow brown color	110	120
	120	130
Same as above w/ red brown	130	140
color abundant iron cement	140	150
	150	160
Same as above w/red color	160	170
Sand	170	180
sand w/ some gravel	180	190
gravel	190	200
Weathered vesicular basalt	200	210
claystone/siltstone color is	210	320
gray to brown		
weathered granite, very	320	350
crumbly or friable & very fract.		
dense granite gray in	350	380
color w/ less fractures		

Work started Aug 1, 19 61. Completed Sept 2, 19 61

WELL DRILLER'S STATEMENT:

This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

NAME ____ (Person, firm, or corporation) (Type or print)

Address ____

[Signed] ____ (Well Driller)

License No. ____ Date ____, 19____

(USE ADDITIONAL SHEETS IF NECESSARY)

ECY 050-1-20

WATER WELL REPORT

STATE OF WASHINGTON

(1) OWNER: Name .... Address ....

(2) LOCATION OF WELL: County Spokane SE SE SE - SE 1/4 SE 1/4 Sec. 4 T. 27 N., R. 43 E W.M.

Bearing and distance from section or subdivision corner

(3) PROPOSED USE: Domestic ☒ Industrial ☐ Municipal ☐ Irrigation ☐ Test Well ☐ Other ☐

(4) TYPE OF WORK: Owner's number of well (if more than one) 5

New well ☒ Method: Dug ☐ Bored ☐
Deepened ☐ Cable ☐ Driven ☐
Reconditioned ☐ Air Rotary ☒ Jetted ☐

(5) DIMENSIONS: Diameter of well 8.0 inches.
Drilled 300 ft. Depth of completed well 180 ft.

(6) CONSTRUCTION DETAILS:

Casing installed: 4.0" Diam. from 0 ft. to 150 ft.
Threaded ☐ ....." Diam. from ..... ft. to ..... ft.
Welded ☐ ....." Diam. from ..... ft. to ..... ft.

Perforations: Yes ☐ No ☒
Type of perforator used ....
SIZE of perforations ..... in. by ..... in.
..... perforations from ..... ft. to ..... ft.
..... perforations from ..... ft. to ..... ft.
..... perforations from ..... ft. to ..... ft.

Screens: Yes ☒ No ☐
Manufacturer's Name Johnson Well Screen
Type PVC Schedule 80 Model No. .....
Diam. 4" Slot size 20 from 150 ft. to 180 ft.
Diam. ..... Slot size ..... from ..... ft. to ..... ft.

Gravel packed: Yes ☒ No ☐ Size of gravel: Same size 10-20
Gravel placed from ..... ft. to ..... ft.

Surface seal: Yes ☒ No ☐ To what depth? ..... ft.
Material used in seal cement
Did any strata contain unusable water? Yes ☐ No ☐
Type of water? ..... Depth of strata .....
Method of sealing strata off .....

(7) PUMP: Manufacturer's Name Grundfos
Type: Submersible H.P. 10

(8) WATER LEVELS: Land-surface elevation above mean sea level.... 1680 ft.
Static level 1640 ft. below top of well Date .....
Artesian pressure ..... lbs. per square inch Date .....
Artesian water is controlled by ..... (Cap, valve, etc.)

(9) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☒ If yes, by whom? .....
Yield: 250 gal./min. with ..... ft. drawdown after 1.0 hrs.
" " " "
" " " "

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test .....
Bailer test ..... gal./min. with ..... ft. drawdown after ..... hrs.
Artesian flow ..... g.p.m. Date .....
Temperature of water ..... Was a chemical analysis made? Yes ☐ No ☐

(10) WELL LOG:

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation.

MATERIAL	FROM	TO
Silt and sand	0	10
sand and silt	10	20
Sand and silt w/ some gravel →	20	30
Clay and silt yellow brown	30	40
in color	40	50
Same as above	50	60
Same as above →	60	70
gravel and sand	70	80
gravel and sand	80	90
gravel	90	100
Gravel	100	110
sand w/gravel + silt	110	120
Sand and silt	120	130
Sand w/some silt	130	140
Sand	140	150
Sand w/gravel	150	160
gravel	160	170
Gravel →	170	180
weathered granite, very	180	250
broken w/extensive fractures →		
dense granite w/ some	250	300
fractures		

Work started June 30 1958 Completed July 27 1958

WELL DRILLER'S STATEMENT:

This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

NAME ..... (Person, firm, or corporation) (Type or print)

Address .....

[Signed] ..... (Well Driller)

License No. ..... Date ....., 19.....

(USE ADDITIONAL SHEETS IF NECESSARY)

ECY 050-1-20

WATER WELL REPORT

STATE OF WASHINGTON

(1) OWNER: Name .... Address ....

(2) LOCATION OF WELL: County Spokane N/2 NW - NE ¼ NE ¼ Sec. 8 T. 27 N., R. 43 E W.M.

Bearing and distance from section or subdivision corner

(3) PROPOSED USE: Domestic ☒ Industrial ☐ Municipal ☐ Irrigation ☐ Test Well ☐ Other ☐

(4) TYPE OF WORK: Owner's number of well (if more than one) 6
New well ☒ Deepened ☐ Reconditioned ☐
Method: Dug ☐ Bored ☐ Cable ☐ Driven ☐ Air Rotary ☒ Jetted ☐

(5) DIMENSIONS: Diameter of well 8.0 inches.
Drilled 350 ft. Depth of completed well 300 ft.

(6) CONSTRUCTION DETAILS:
Casing installed: 4.0" Diam. from 0 ft. to 280 ft.
Threaded ☐ ....." Diam. from ..... ft. to ..... ft.
Welded ☐ ....." Diam. from ..... ft. to ..... ft.

Perforations: Yes ☐ No ☒
Type of perforator used .....
SIZE of perforations ..... in. by ..... in.
..... perforations from ..... ft. to ..... ft.
..... perforations from ..... ft. to ..... ft.
..... perforations from ..... ft. to ..... ft.

Screens: Yes ☒ No ☐
Manufacturer's Name Johnson Well Screen
Type PVC Sch 80 Model No. .....
Diam. 4" Slot size 20 from 280 ft. to 300 ft.
Diam. ..... Slot size ..... from ..... ft. to ..... ft.

Gravel packed: Yes ☒ No ☐ Size of gravel: Sieve Size 10-20
Gravel placed from ..... ft. to ..... ft.

Surface seal: Yes ☒ No ☐ To what depth? ..... ft.
Material used in seal Concrete
Did any strata contain unusable water? Yes ☐ No ☐
Type of water? ..... Depth of strata .....
Method of sealing strata off .....

(7) PUMP: Manufacturer's Name Grundfos
Type: Submersible H.P. 5

(8) WATER LEVELS: Land-surface elevation above mean sea level.... 2000 ft.
Static level 1840 ft. below top of well Date .....
Artesian pressure ..... lbs. per square inch Date .....
Artesian water is controlled by ..... (Cap, valve, etc.)

(9) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☒ If yes, by whom? .....
Yield: 20 gal./min. with ..... ft. drawdown after 1.0 hrs.
" " " "
" " " "

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test .....
Bailer test ..... gal./min. with ..... ft. drawdown after ..... hrs.
Artesian flow ..... g.p.m. Date .....
Temperature of water ..... Was a chemical analysis made? Yes ☐ No ☐

(10) WELL LOG:

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of formation.

MATERIAL	FROM	TO
boulders of basalt w/ sand & gravel and silt/clay	0	90
claystone and siltstone gray to brown in color	90	280
weathered granite, very friable or rubbly, fractured	280	310
dense gray granite w/ less fracturing than above	310	350

Work started May 17, 1959. Completed June 17, 1959

WELL DRILLER'S STATEMENT:

This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

NAME ..... (Person, firm, or corporation) (Type or print)

Address .....

[Signed] ..... (Well Driller)

License No. ..... Date ....., 19.....

(USE ADDITIONAL SHEETS IF NECESSARY)

ECY 050-1-20

PROBLEM 3

Aquifer Tests

NOTES

AQUIFER TESTS

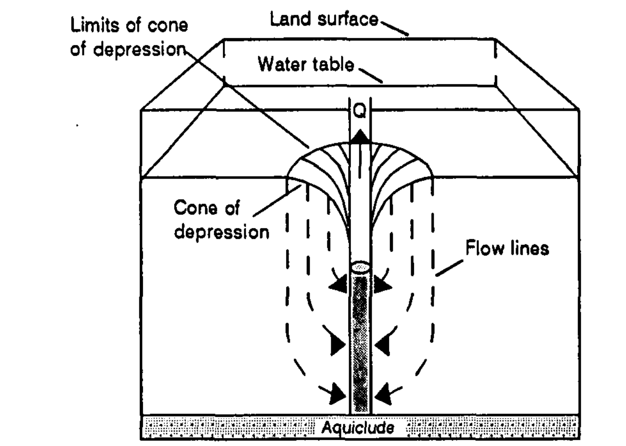
GROUNDWATER AND CONTAMINANT MOVEMENT

- Position and thickness of aquifers and aquitards
- Transmissivity and storage coefficient
- Hydraulic characteristics of aquitard
- Position and nature of boundaries
- Location and amounts of groundwater withdrawals
- Locations, kinds, and amounts of pollutants

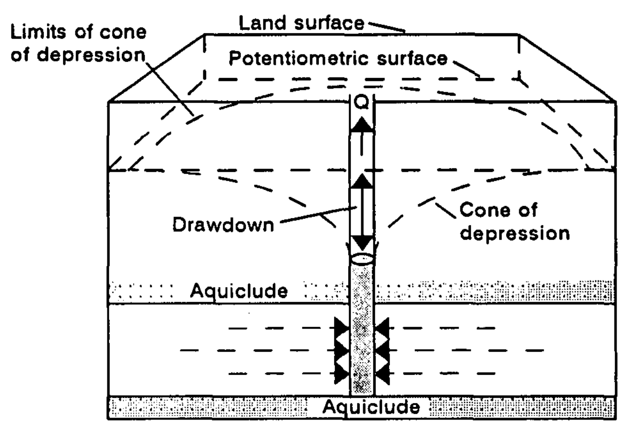
AQUIFER RESPONSE DEPENDS ON:

- Rate of expansion of cone of depression
  - Transmissivity of aquifer
  - Storage coefficient of aquifer
- Distance to boundaries
  - Recharge
  - Impermeable

NOTES



Unconfined Aquifer



Confined Aquifer

AQUIFER TEST METHODS

- Step drawdown/well recovery tests
- Slug tests
- Distance-drawdown tests
- Time-drawdown tests

NOTES

STEP DRAWDOWN
Well Recovery Tests

- Well is pumped at several successively higher rates and drawdown is recorded
- Purpose
  - Estimate transmissivity
  - Select optimum pump rate for aquifer tests
  - Identify hydraulically connected wells
- Advantages
  - Short time required
  - One well required

SLUG TESTS

- Water level is abruptly raised or lowered
- Used in low yield aquifers (<0.01 cm/s)

SLUG TESTS
Advantages

- Can use small-diameter well
- No pumping - no discharge
- Inexpensive - less equipment required
- Estimates made *in situ*
- Interpretation/reporting time shortened

NOTES

SLUG TESTS
Disadvantages

- Very small volume of aquifer tested
- Only apply to low conductivities (0.0000001 to 0.01 cm/s)
- Transmissivity and conductivity only estimates
- Not applicable to large-diameter wells
- Large errors if well not properly developed
- Do not give storativity

DISTANCE-DRAWDOWN TESTS
Advantages

- Can also use time-drawdown
- Results more accurate than single well test
- Represent more of aquifer
- Can locate boundary effects

DISTANCE-DRAWDOWN TESTS
Disadvantages

- Requires multiple piezometers or monitoring wells (at least 3 wells)
- More expensive than single well test
- Must handle discharge water
- Requires conductivities above 0.01 cm/s

NOTES

TIME-DRAWDOWN TESTS
Advantages

- Only one well required
- Tests larger aquifer volume than slug test
- Less expensive than multiple-well test

TIME-DRAWDOWN TESTS
Disadvantages

- Pump turbulence may interfere with water-level measurements
- Tests smaller aquifer volume than multiple-well test
- Must handle discharge water
- Requires conductivities above 0.01 cm/s

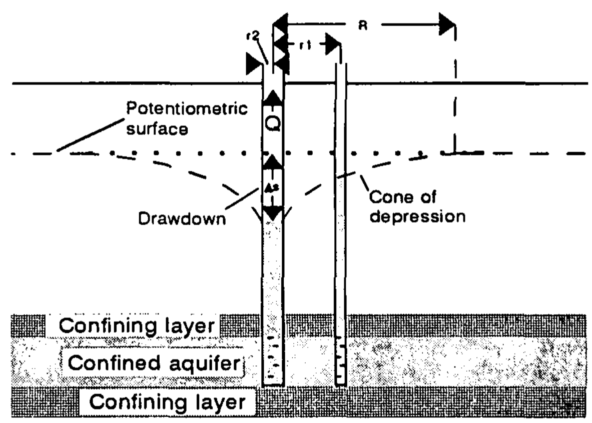
THEIS METHOD

- First formula for unsteady-state flow
  - Time factor
  - Storativity
- Derived from analogy between groundwater flow and heat flow
- Laborious method
  - Log-log paper
  - Curve matching
- More accurate than Jacob method

NOTES

THEIS'S ASSUMPTIONS

- Aquifer is confined
- Aquifer has infinite areal extent
- Aquifer is homogeneous and isotropic
- Piezometric surface is horizontal
- Carefully controlled constant pump rate
- Well penetrates aquifer entirely
- Flow to well is in unsteady state



THEIS EQUATION

$$T = \frac{QW(u)}{4\pi s}$$

$$S = \frac{4Ttu}{r^2}$$

T = transmissivity

Q = discharge (pumping rate)

W(u) = well function

s = drawdown

S = storage coefficient

t = time

r = radial distance

NOTES

WELL FUNCTION - W(u)

$$W(u) = -0.577216 - \log_e u + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \frac{u^4}{4 \times 4!} + \ldots$$

$$\text{and } u = \frac{r^2 S}{4Tt}$$

S = storage coefficient

r = distance

t = time

T = transmissivity

- W(u) is an infinite exponential series and cannot be solved directly

JACOB METHOD

- Somewhat more convenient than Theis's method
  - Semilogarithmic paper
  - Straight line plot
  - Eliminates need to solve well function W(u)
  - No curve matching
- Applicable to:
  - Zone of steady-shape
  - Entire zone if steady-state

JACOB'S FORMULA

$$T = \frac{2.3\,Q}{4\pi \Delta s}$$

T = transmissivity (ft^2/day)

Q = pump rate (ft^3/min)

Δs = change in drawdown (ft/log cycle)

$$T = \frac{2.3\,Q}{4\pi \Delta s} = \frac{2.3}{4\pi} \times \frac{\text{gal}}{\text{min}} \times \frac{1{,}440\ \text{min}}{\text{day}} \times \frac{\text{ft}^3}{7.48\ \text{gal}} \times \frac{1}{\text{ft}}$$

$$= \frac{35\,Q}{\Delta s}$$

so that Q is now expressed in units of in gallons per minute

NOTES

JACOB DERIVATION

$$T = \frac{35Q}{\Delta s} \qquad K = \frac{T}{b}$$

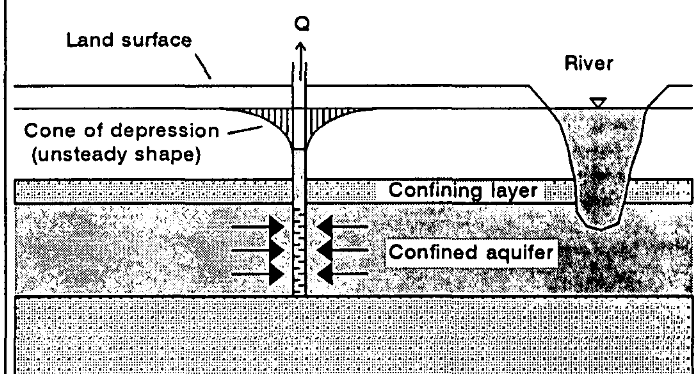
T = transmissivity is square feet per day

Q = pump rate in gallons per minute

Δs = change in drawdown in feet over one log cycle

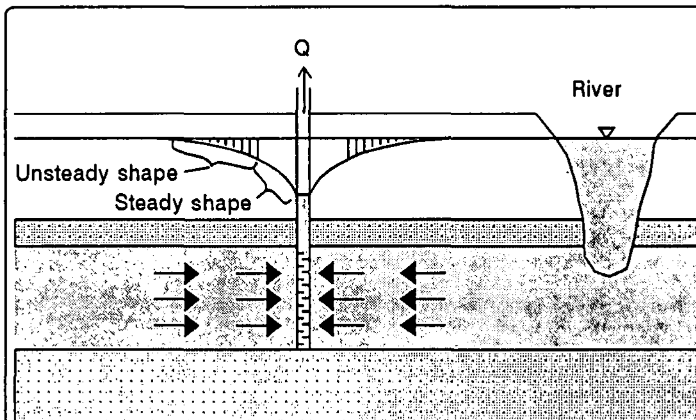
K = hydraulic conductivity in feet per day

b = aquifer thickness in feet



(1)

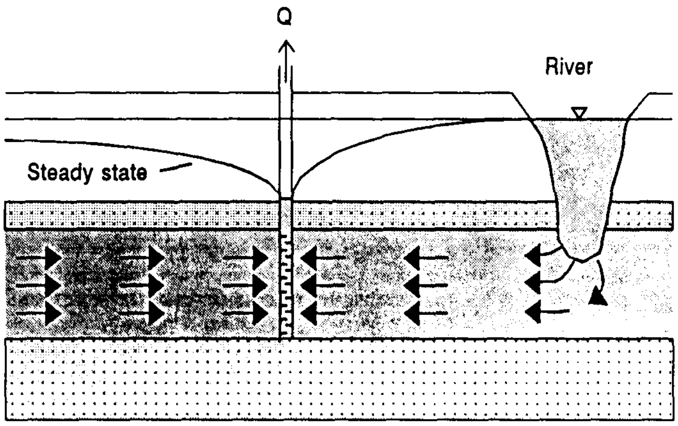
NONEQUILIBRIUM



(2)

NONEQUILIBRIUM

NOTES



(3)

EQUILIBRIUM

TABLE 1 PUMPING TEST DATA	
Q = 109 GPM	b = 20 feet
Pumping Time (minutes)	Drawdown measured from top of casing (feet)
0	6.1
1	6.5
2	7.5
3	8.0
4	8.6
5	9.5
6	10.5
7	11.2
8	12.0
9	13.0
10	14.0
11	15.5
12	17.0
13	18.0
14	19.3
15	20.5
18	23.5
20	25.2
22	26.7
24	28.2
26	29.5
28	30.5
32	32.0
35	34.5
40	36.6
45	38.5
50	40.5
55	42.0
60	43.5
90	50.1
120	54.8

PROBLEM 4

Groundwater Investigation

PROBLEM 4: GROUNDWATER INVESTIGATION

LEAVINGS RESIDENCE

On October 12, 1982, the Bettendorf, Iowa, Fire Department was called to the Leavings residence with complaints of gasoline vapors in the basement of the home.

October 16, 1982, the Leavings were required to evacuate their home on an indefinite basis until the residence could be made safe for habitation.

PERTINENT KNOWN FACTS

The site of contamination is a residential neighborhood in Bettendorf, Iowa.

It backs on commercially zoned property, which has only been partially developed to date. The residential area is about 10 years old, and contains homes in the $40,000 to $70,000 range. There was apparently some cutting and filling activity at the time it was developed.

Within 1/4 mile to the northwest and southwest, eleven reported underground storage tanks are in use, or have only recently been abandoned.

- 1000 feet northwest to two tanks owned and operated by the Iowa Department of Transportation (IDOT)

- 700 feet southwest to three in-place tanks owned initially by Continental Oil and now by U-Haul. One reportedly leaked. (Bettendorf Fire Department (BFD))

- 1200 feet southwest to three tanks owned and operated by an Amoco service station, no reported leaks (BFD)

- 1200 feet southwest to three tanks owned and operated by a Mobil Oil service station, no reported leaks (BFD)

Adjoining neighbors have complained about several trees dying at the back of their lots (8 and 10). No previous problem of gasoline vapors reported at these locations.

The general geologic setting is Wisconsin age loess soils mantling Kansan and Nebraskan age glacial till. Valleys may expose the till surface on the side slope. Valley soils typically consist of the colluvial and alluvial silts.

Your previous experience in this area includes a geotechnical investigation of the hotel complex located west of Utica Ridge Road and northwest of the Amoco service station. Loess soils ranged from twenty-two feet thick on the higher elevations of the property (western half) to 10 feet thick on the side slope. Some silt fill was noted (five to seven feet) at the east end of the hotel property. Loess soils were underlain by a gray lean clay glacial till which apparently had groundwater perched on it. Groundwater was typically within ten to fifteen feet of ground surface. This investigation was performed eight years ago and nothing in the boring logs noted hydrocarbon vapors observed. It should be noted that these observations were not routinely reported at that time.

Other projects in the area include a maintenance yard pavement design and construction phase testing project at the IDOT facility located northwest of the Leavings residence. Loess soils were also encountered in the shallow pavement sub-grade project completed three years ago. It was noted in the firm's records that the facility manager had a minor gasoline spill a year before and that it had been cleaned up when the tank was removed and replaced with a new steel tank. The second tank apparently was not replaced at that time.

In the Leavings residence, vapors are very strong and the power has been shut off. Basement windows have been left open to reduce the explosion potential.

OBJECTIVE

Your consulting geoenvironmental engineering firm has been retained by the attorney representing the Leavings to:

1. Determine the source of the hydrocarbon contamination. **This is not an emergency response action.**

2. Be prepared to defend the data you obtain and the conclusions you draw by means of litigation.

3. Consider possible site remediation plans and recommendations that will make the home habitable again.

BUDGET

The allowable budget to develop the field exploration is $25,000.

INFORMATION AVAILABLE

Interviews of neighbors, IDOT, station managers, and U-Haul

Lot 9: The trees are in pretty good condition. The house was vacant. Mrs. Leavings let you in and asked you to put any cigarettes out before entering, just in case. She wanted to have a house, not a hole, to come back to. You observe six inches of free product that looks and smells like gasoline in the open sump pit in the basement. The power was cut so the water level in the sump was allowed to rise. The fluid level in the sump was about three feet below the basement floor level.

Neighbors: They lost several trees in back yards during the past spring. They contacted the commercial developer behind their homes and complained that the fill that was placed there several years ago has finally killed their trees. They got no satisfaction from the developer. Both said that when you find out where the gas came from let them know so they can sue someone too. They noted that this past September and October were unusually wet (lots of rainfall).

IDOT: The manager remembers your people testing his parking pad. Says the one underground storage tank (UST) was replaced in 1979 while the second tank was installed when the facility was first built in 1967. Both the original tanks were bare metal tanks. The old one has always had gasoline while the newer one was the diesel tank. There are no inventory records or leak testing records. He has never had any water in his tanks. He will check with his supervisor to have the USTs precision leak tested.

U-Haul: The manager says the station used to be a Continental Oil station with three USTs. One 6000 gal UST unleaded was kept in service for their fleet. It was found to be leaking a month ago. They had originally been installed by Continental in 1970 when the station was built. He has no idea how much was lost.

Mobil: The manager was pleasant until he found out what you wanted. You did learn that he built the station in 1970 and installed three USTs at that time. The manager would not answer any further questions.

Amoco: The manager wasn't in, but you talked to an assistant and got his phone number. When you called later the manager said he was aware of the leaking tank at U-Haul and was anxious to prove the product was not from his station. He said they installed three USTs for unleaded, premium and regular in 1972. A diesel UST was installed in 1978. The tanks are tested every two years using the Kent Moore (now Petrotite) test method. The tanks have always tested tight. No inventory control system is being used at present. If you want to put monitoring wells on his property, just let him know and he'd be happy to help out.

<u>Review of Bettendorf City Hall records</u>

An existing topographic map and scaled land use map are available.

Ownership records indicate the land was previously owned by Mr. and Mrs. Ralph Luckless. Zoning at that time was agricultural only. The clerk said she had known them prior to the farm sale in 1964. That section was used mostly for grazing cattle. It was too steep for crops. She said she remembered a couple wooded valleys in that field. A stream used to run along where Golden Valley Drive is now and that kids used to swim in it (get muddy in it). The other valley was between Golden Valley Drive and where all that fill is now near U-Haul and Amoco. You may want to talk to the current property owner about that.

The current owner of the undeveloped property is Mr. M. Forester (developer) with an Iowa City, IA address.

There is no record of storm or sanitary sewer lines along Utica Ridge Road south of Golden Valley Drive. Storm and sanitary sewer lines run along Spruce Hills Drive.

Iowa Geological Survey

There are no records of any wells in the section.

Adjoining section wells indicate top of bedrock at about 650 feet mean sea level (MSL). The uppermost useable aquifer is the Mississippian for elevation 350 feet to 570 feet MSL. The materials overlying the Mississippian are Pennsylvanian shales and limestone.

Soil Conservation Survey maps

The 1974 edition indicates "Made Land" over nearly all of the area not designated as commercial zone. "Made Land" normally indicated areas of cut or fill.

Interview with developer - Mr. M. Forester

He bought the property in question in the 1960's. He developed the residential area first and some of the commercial development followed. About forty acres remain undeveloped to date. He is looking to locate a shopping center there if the economy ever turns back around.

He remembers getting a lot of cheap dirt and fill when the interstate cut went through about one half mile west in the late 1960's. He filled in a couple of good sized valleys at that time. He has a topographic map of the area after it was filled.

He would be more than happy to help out in any way possible. If you need to put any wells on the property just let him know ahead of time. There are no buried utilities on the property except behind the residential property.

ASSIGNMENT: PHASE 1 FIELD INVESTIGATION

TABULATION OF FEES FOR PHASE 1 FIELD INVESTIGATION GROUP ____

WORK SHEET #1	# UNITS	COST	TOTAL
Recommendation for making residence habitable		$500 LS (lump sum)	$
Field Exploration - mobilization		$500 LS	$
seismic refraction survey		not available	$--------
earth resistivity survey		not available	$--------
terrain conductivity		not available	$--------
soil gas survey		$1500 /ac	$
soil boring with photo ionization detector - 25 feet deep max - grouted shut		$500 ea	$
Monitoring wells			
2" PVC 15 ft screen - 25 ft deep		$1200 ea	$
2" stainless steel 15 ft screen - 25 ft deep		$1700 ea	$
well security - locking protector pipe		$300 ea	$
Aquifer testing:			
lab permeabilities		not available	$--------
slug test w/interpretation		not available	$--------
pump test w/interpretation 24 - 36 hr test		not available	$--------
Chemical analysis (under C-O-C procedures)			
priority pollutants		not available	$--------
total hydrocarbons by IR BTEX by GC		not available	$--------
Field investigation engineering analysis and report		15% $2000 min	$
TOTAL COST:			

SCHEDULE OF FEES AND ESTIMATE OF COSTS*

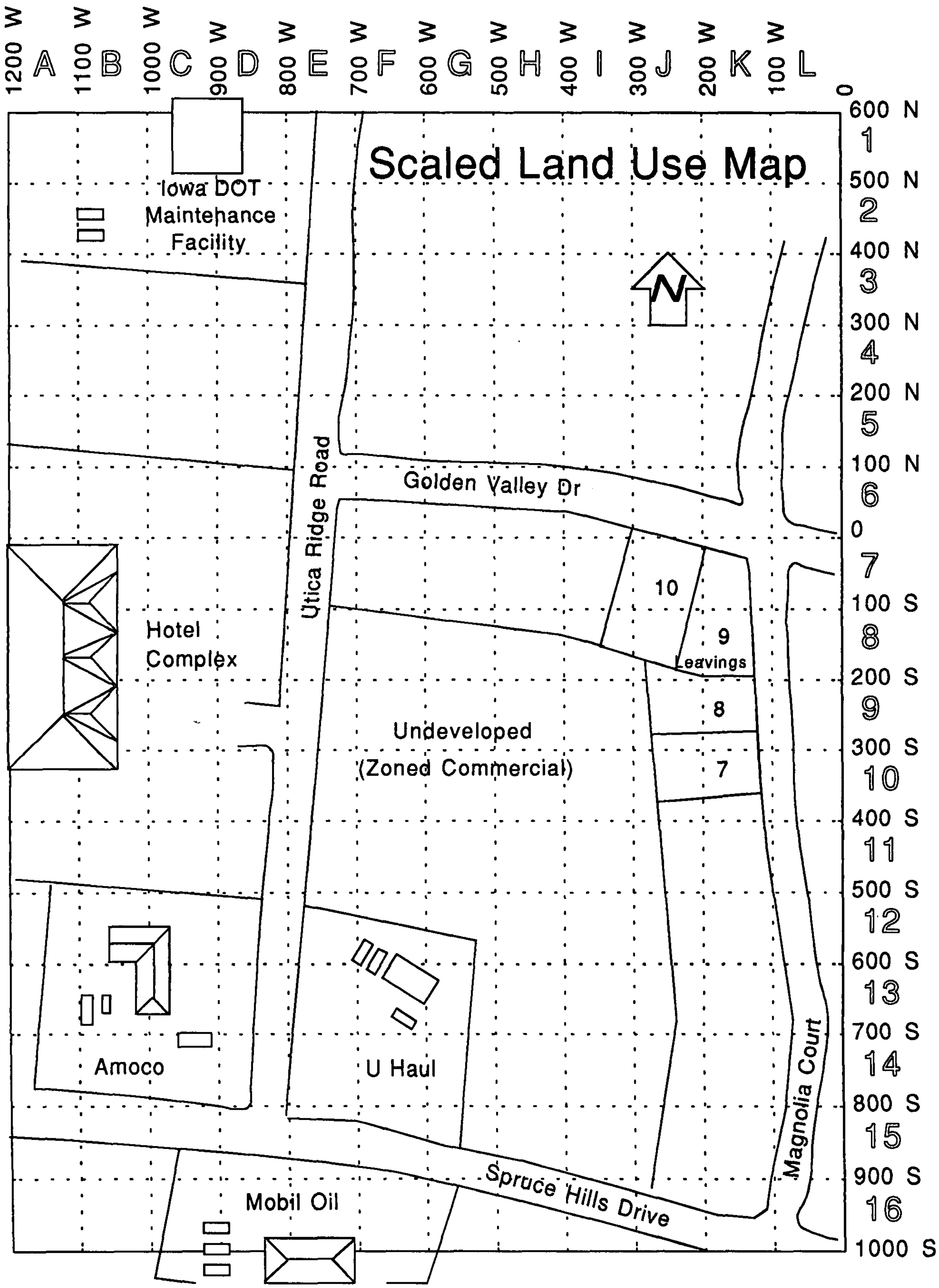
Recommendations for making residence habitable		$500	LS
Field Exploration:	mobilization	$500	LS
	seismic refraction survey	$2,500	/acre
	earth resistivity survey	$2,500	/acre
	terrain conductivity	$1,000	/acre
	soil gas survey	$1,500	/acre
	soil boring with PID		
	25 ft deep - grouted	$500	ea
	monitoring well - 2" PVC		
	15 ft screen - 25 ft deep	$1,200	ea
	monitoring well - 2" stainless steel		
	15 ft screen - 25 ft deep	$1,700	ea
	well security - locking protector pipe	$300	ea
	aquifer testing		
	lab permeabilities	$200	ea
	slug test with interpretation	$300	ea
	pump test with interpretation		
	(24 - 36 hr test)	$5,000	ea
	chemical analysis (C-O-C procedures)		
	priority pollutants	$1,000	ea
	total hydrocarbons by IR		
	BTEX by GC	$100	ea
	field investigation engineering analysis		
	and report	$2,000 (minimum)	LS
Remediation Study:			
	remedial option evaluation	$8,000 (minimum)	LS
	report preparation	$2,000	LS
	agency coordination	$2,000	LS

* fees and cost estimates are for classroom purposes only.

Remediation implementation and operation

excavate and dispose	$150	cubic yard
air stripper		
install winterized system	$45,000	ea
operation for one year	$5,000	ea
carbon adsorption unit		
water phase installation	$15,000	ea
operation for one year	$10,000	year
recovery system (20 - 25 ft trench)		
trench installation	$75	linear ft
operation for one year	$2,000	ea
well point		
installation	$2,000	ea
operation for one year	$2,000	year
construction observation and testing	20%*	
analytical costs (total hydrocarbons by IR, BTEX by GC)		
recovery system	$2,400	month
monitoring well system (quarterly)	$150	well

* This is based on the remediation system construction and installation costs, not operational costs.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Scaled Land Use Map
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Iowa DOT
Maintenance
Facility
Utica Ridge Road
Golden Valley Dr
Hotel
Complex
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Leavings
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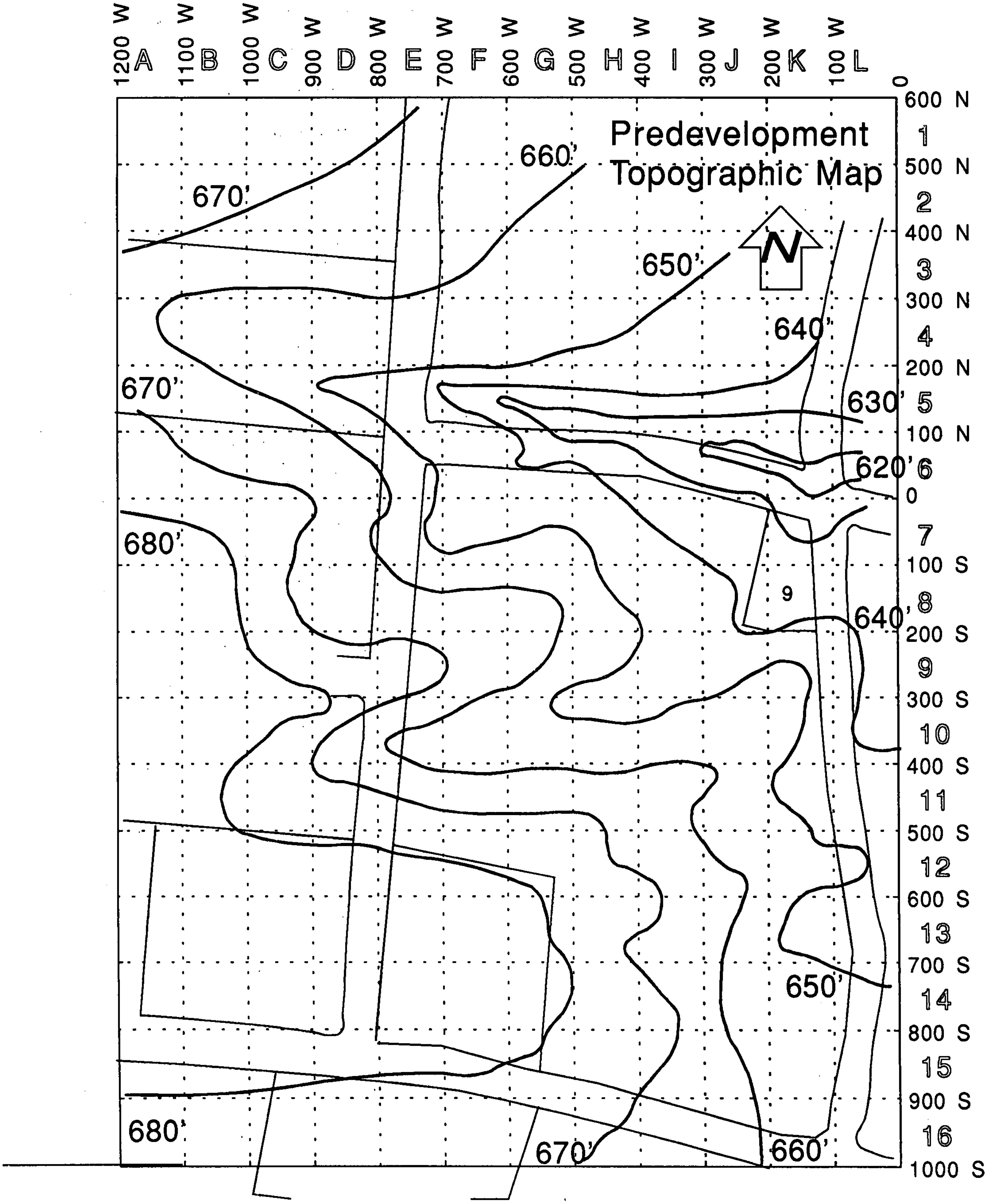
7
Undeveloped
(Zoned Commercial)
Amoco
U Haul
Magnolia Court
Spruce Hills Drive
Mobil Oil


Predevelopment
Topographic Map
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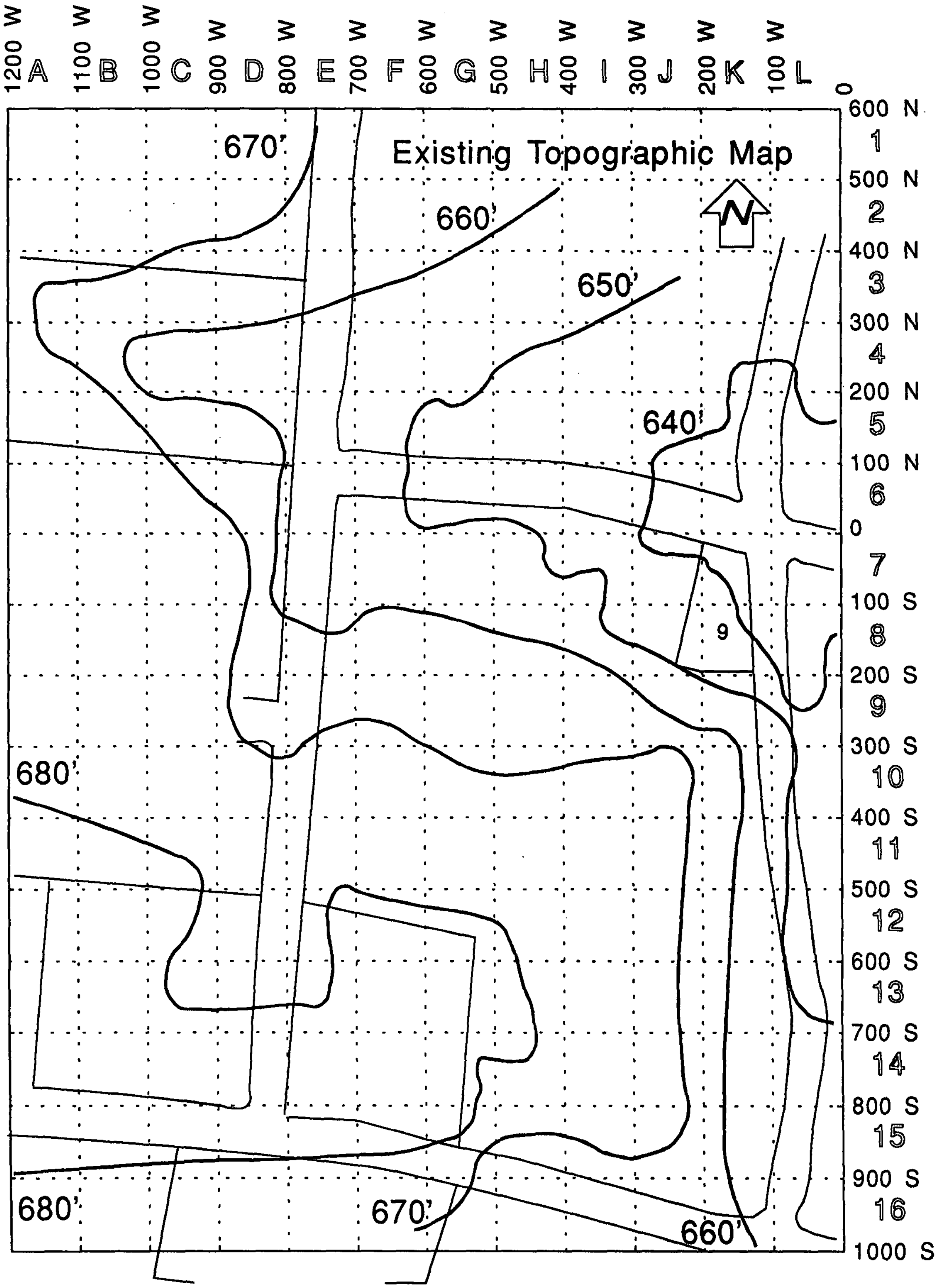
Existing Topographic Map
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660'
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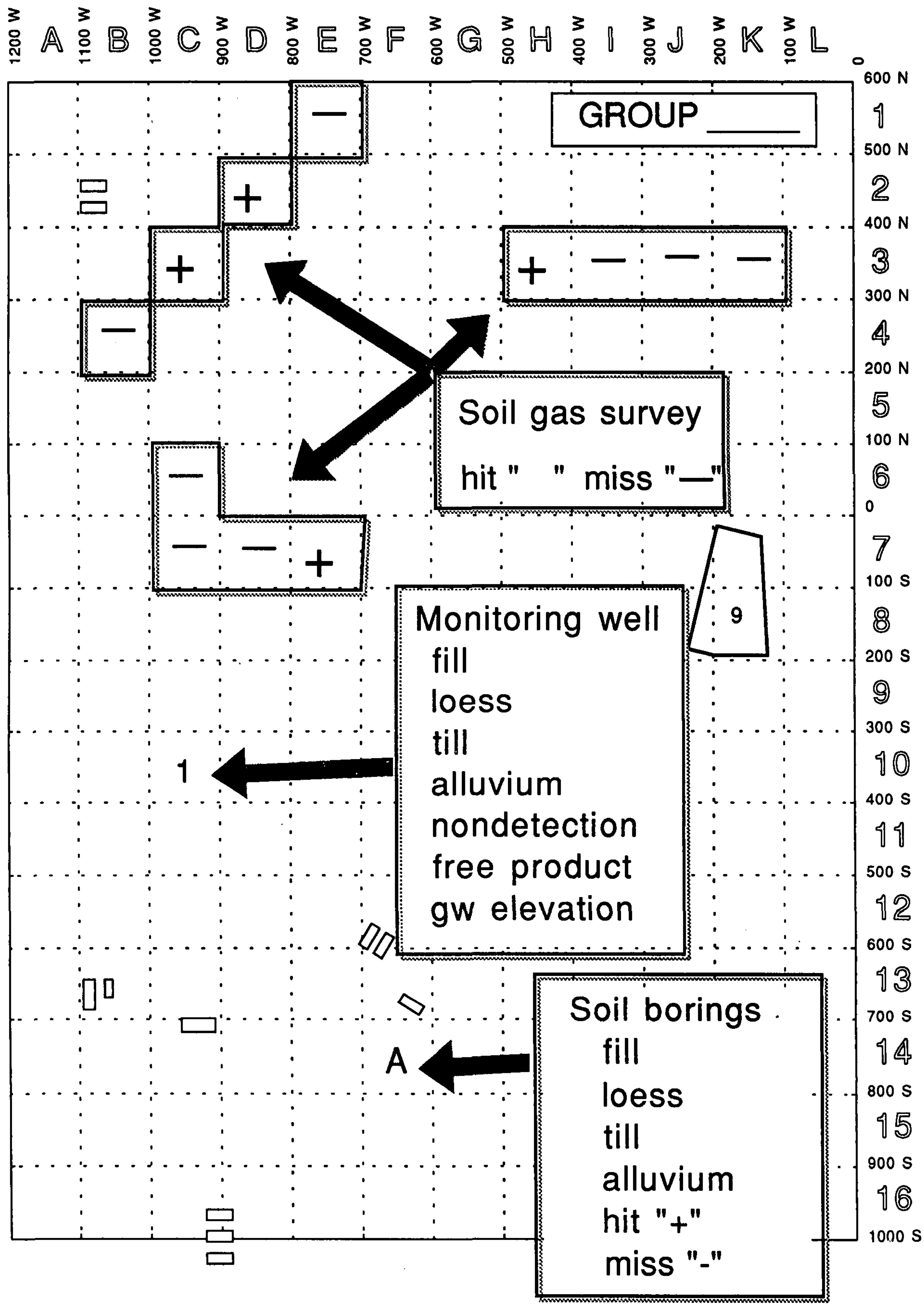
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7
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9
300 S
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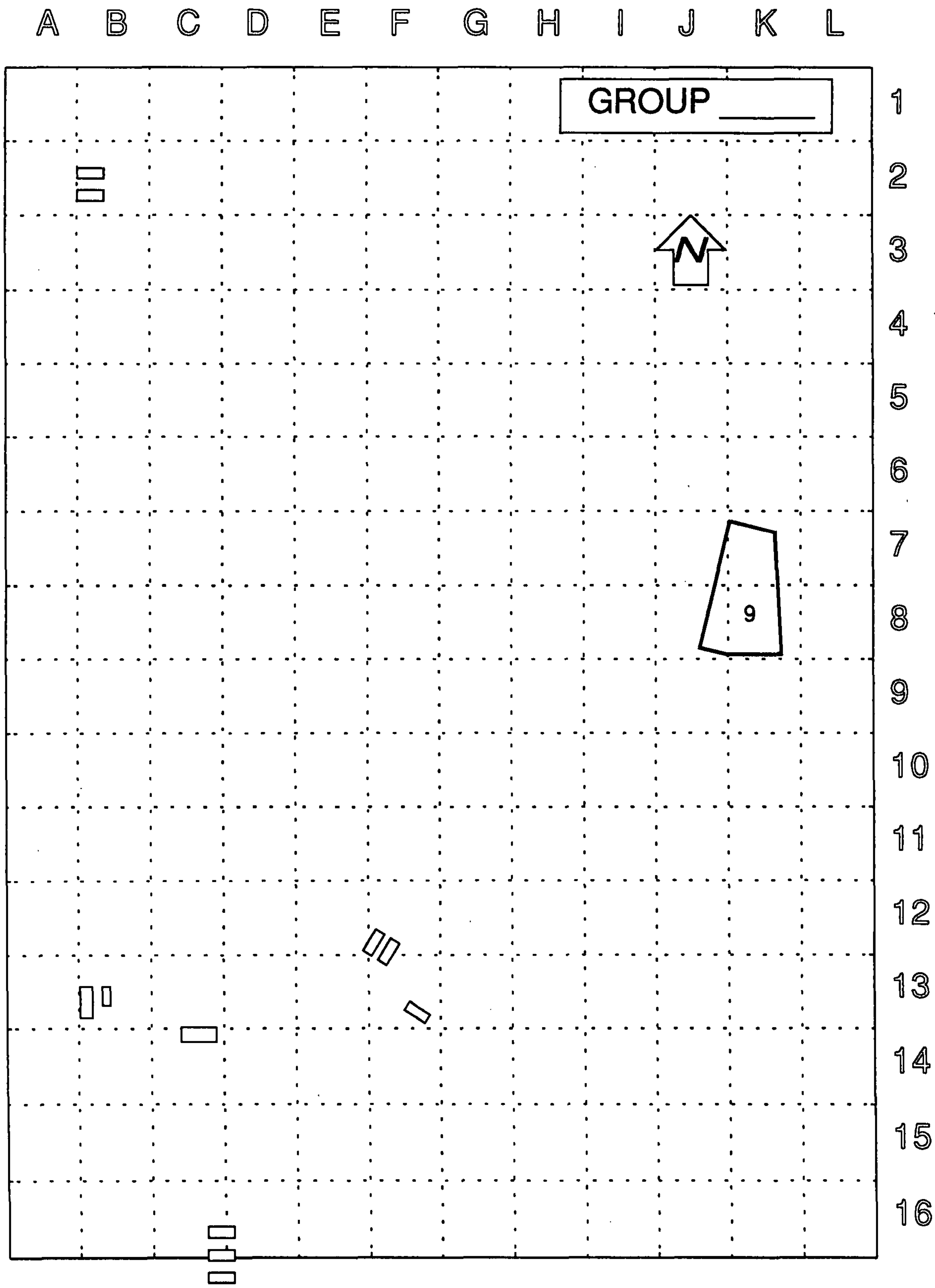
400 S
11
500 S
12
600 S
13
700 S
14
800 S
15
900 S
16
1000 S
GROUP _____
Soil gas survey
hit " " miss "—"
Monitoring well
fill
loess
till
alluvium
nondetection
free product
gw elevation
1
9
Soil borings
fill
loess
till
alluvium
hit "+"
miss "-"
A



A B C D E F G H I J K L
GROUP ______
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15
16

GROUP _____

MONITORING WELLS

	1	2	3	4	5	6	7	8	9	10
FILL										
LOESS										
ALLUVIUM										
TILL										
NON DETECTED										
DISSOLVED PRODUCT										
FREE PRODUCT										
WATER ELEVATION										

SOIL BORINGS

	A	B	C	D	E	F	G	H	I	J
FILL										
LOESS										
ALLUVIUM										
TILL										
HIT (+)										
MISS (-)										

PROBLEM 5

Nomograph

The information in *Problem 5: Nomograph* is reproduced or adapted from the following article:

> Kent, D.C., W.A. Pettyjohn, and F.E. Witz. 1982. Methods for the Prediction of Leachate Plume Migration. pp. 246-261. *In:* Proceedings of the Second National Symposium on Aquifer Restoration and Ground Water Monitoring. May 26-28, 1982, The Fawcett Center, Columbus, Ohio. D.M. Nielsen (ed).

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Table 1
Definition of Terms

Primary Variables:		Units
C	= Concentration of leachate at a specified time and distance	(M/L^3)
X	= Distance from source where concentration of leachate is computed. Distance is measured in direction of ground-water flow (perpendicular to gradient)	(L)
y	= Transverse distance measured from the centerline of ground-water flow (Assumed to be zero in the nomograph)	(L)
t	= Sample time from beginning of leachate source flow	(T)
Aquifer Parameters:		
m	= Effective aquifer thickness or zone of mixing	(L)
n	= Effective porosity of aquifer or zone of mixing	(Dimensionless)
V	= Velocity of ground-water flow within voids: estimated directly or from: $V = \frac{KI}{n}$	
	where:	
	K = Coefficient of permeability or hydraulic conductivity of aquifer or zone of mixing: $K = \frac{T}{m}$	
	I = Gradient of ground-water flow	(Dimensionless)
Transport Parameters:		
D_x	= Longitudinal dispersion coefficient (mixing rate) with respect to distance in x direction and time: estimated directly or from: $D_x = \alpha_x V + D^*$	(L^2/T)
	where:	
	α_x = Longitudinal dispersivity	(L)
	D^* = Molecular diffusion coefficient, which is assumed to be negligible for velocities typical of permeable aquifers. D^* may be the dominant process in aquitards where $\alpha_x V$ would be negligible.	(L^2/T)
Dy	= Transverse dispersion coefficient (mixing rate) with respect to distance in the y direction and time: estimated directly or from:	(L^2/T)
	$D_y = \alpha_y V + D^*$	
	where:	
	α_y = Transverse dispersivity	(L)
	or estimated as:	
	$D_y = D_x$ divided by a ratio, which commonly ranges between 5 and 10 for medium to coarse sand aquifers.	

Table 1
Definition of Terms
(Continued)

R_d = Retardation factor estimated directly or from: (Dimensionless)

$$R_d = 1 + \frac{\rho b\,(Kd)}{n_t} \quad \text{(or)} \quad R_d = \frac{V}{Vd}$$

where:

ρ_b = Bulk density of aquifer medium (M/L^3)

n_t = Total porosity (Dimensionless)

K_d = Distribution factor for sorption on aquifer medium (from sorption isotherm column studies) (L^3/M)

V = Velocity of ground water (L/T)

V_d = Observed velocity of leachate for a given concentration and chemical species (L/T)

γ = Coefficient for radioactive or biological decay. For no decay, the value of γ is one. (Assumed to be one in the nomograph.) Calculated from: (Dimensionless)

$$\gamma = + \left(\frac{4D_x}{V^2}\right) \lambda = 1 + \frac{4D_x \log(2)}{V^2\, t_{1/2}}$$

where:

$$\lambda = \text{Decay constant} = \frac{\log(2)}{t_{1/2}}$$ $(1/T)$

$t_{1/2}$ = Halflife: time when half of the original mass remains (T)

Source Rate of Leachate:

QC_0 = Mass flow rate estimated directly or obtained from the product of: (M/T)

Q = Volume flow rate estimated directly or from: (L^3/T)

$$Q = Aq$$

where:

A = area of source (L^2)

q = recharge rate (L/T)

C_0 = Initial concentration (M/L^3)

Intermediate Variables (Used for Nomograph only):

X_D = A characteristic dispersion length or scale factor given by: (L)

$$X_D = \frac{D_x}{\sqrt{\gamma V}}$$

T_D = A characteristic dispersion time or scale factor given by: (T)

$$T_D = \frac{R_d D_x}{\gamma V^2}$$

Q_D = A characteristic dilution-dispersion flow (L^3/T)

$$Q_D = n\ m\ \sqrt{D_x D_y}$$

PROBLEM 5: NOMOGRAPH

A SIMPLE GROUNDWATER MODEL TO EVALUATE CONTAMINANT PLUME MIGRATION

INTRODUCTION

Groundwater models are used to evaluate the fate of contaminant migration in groundwater. Typically this migration is depicted as a plume. The size and shape of the plume is dependent on many interactive factors such as the hydraulic parameters of the aquifer, the compositional complexities and concentrations of the contaminants, the length of time contaminants were injected into the groundwater, and the heterogeneity and compositon of the aquifer's geologic framework. More complicated models are capable of assimilating on a grid or other data distribution system, which covers the potential area of concern, the interaction of these factors in order to predict the plume's geometry. Obviously, the more data available to input into the model, the more time required to compute this information and to evaluate the extent of migration. Of course this also requires more money for lengthy computations. Fortunately there are less complex models available that are not as costly and time consuming. Unfortunately these models are less sensitive to the variance of factors that control plume migration. They are considered more of an approximation or screening device to quickly evaluate the extent of contamination.

The nomograph is one such model. It has the capability of quickly estimating the potential distance and time a contaminant plume migrates downgradient from the source. Other benefits include quickly evaluating the placement of monitoring wells to further characterize the plume and possibly controlling migration offsite, and providing an inexpensive predictive method. However, it can only evaluate the concentration of one chemical component within this plume. When there are many contaminants found at a site it is suggested that the most mobile or conservative contaminant should be considered first. This should provide a worst case senario in evaluating the maximum length the plume has migrated from the source.

Computer models are based on an attempt to define the interaction of physical properties of the aquifer and the contaminant in terms of mathematical formulas. The nomograph is not different in this respect. It utilizes a variance to the Wilson-Miller equation (Wilson and Miller, 1978) as shown below:

$$C = \frac{QC_o}{4Q_D\sqrt{\pi x/X_D}} \exp\left[x/X_D\left(\frac{\sqrt{\Upsilon} - x/X_D}{2}\right) erfc\ (\phi)\right]$$

where:

$$\phi = \frac{(x/X_D - t/T_D)}{2\sqrt{t/T_D}}$$

The Wilson-Miller equation was formulated to predict a two dimensional plume in a uniform groundwater-flow environment. The equation shown above provides scale factors based on physical parameters which are known or can be calculated. The scale factors in this equation are used as ratios with the primary parameters of time (t), distance (x), and the mass flow rate from the source or the product of volume flow rate (Q) times the initial concentration of the contaminant (C_o). These ratios are expressed as t/T_D, x/X_D, and QC_o/Q_D. These scale factors are defined below as:

$$T_D = \frac{R_d D_x}{V^2}$$

$$X_D = \frac{D_x}{V}$$

$$Q_D = nm\sqrt{D_x D_y}$$

where:

D_x = longitudinal dispersion coefficient or dispersion in the downgradient direction (i.e., x direction),

D_y = transverse dispersion coefficient or dispersion in the crossgradient direction (i.e., y direction),

V = seepage velocity of the groundwater,

R_d = retardation of the contaminant,

n = effective porosity of the aquifer, and

m = total aquifer thickness.

It is important to note that the y distance of contaminant migration is ignored in the nomograph model.

Values of D_x and D_y are site-specific parameters and are dependent on the homogeneity and isotropism of the aquifer, advection rate of the contaminants, hydrodynamic dispersion, and the reaction potential of the contaminants to the aquifer's matrix or geology. Therefore these values are difficult to determine. Typically values can be obtained through laboratory experiments but are usually underestimates due to the size of the aquifer sample. There are also field methods which can be used to determine these coefficients, but are beyond the scope of this discussion. If the reader is interested in further discussion on this matter he/she should review the modeling section of this manual, Freeze and Cherry (1979), Fetter (1988), and Driscoll (1986).

Seepage velocity (V) is calculated if hydraulic conductivity (K), hydraulic gradient (I), and effective porosity are known for the aquifer using the formula as shown below:

$$V = \frac{K\,I}{n}$$

Retardation coefficient (Rd) can also be calculated using the following formula:

$$R_d = 1 + \frac{\rho_B\,K_d}{\theta}$$

where:

K_d = distribution coefficient of the contaminant between the groundwater and aquifer,

ρ_B = bulk density of the aquifer matrix, and

Θ = the total porosity within in the aquifer which is typically a higher value than the effective porosity used earlier.

Distribution coefficient is also further explained in the modeling references given earlier in this discussion.

APPLICATIONS

As stated earlier, the nomograph is designed to provide a simple technique to estimate one of the following problems:

1a. *The concentration (C) is determined from a given distance (x) and for a specified time (t),*

1b. *The maximum concentration (C) that might occur over a long period of time usually defined as steady state conditions,*

2a. *The distance (x) where a specified concentration of contaminant will exist given some time interval (t),*

2b. *The maximum distance (x) a contaminant might migrate under steady state conditions, or*

3. *The time (t) when a known or specified concentration (C) of a contaminant will migrate to a selected location downgradient of the source.*

EXAMPLE

A disposal facility in South Farmingdale, Nassau County, New York began receiving cadmium- and hexavalent chromium-enriched electroplating wastes in 1941. The waste was dumped into three pits on location and immediately began infiltrating into an unconfined, shallow glacial aquifer. By early 1960 the migrating plume had reached 4,200 feet (ft) downgradient (x), 1,000 ft crossgradient (y), and 70 ft into the aquifer. The thickness of the aquifer (m) in this area varied according to soil borings from 100 to 140 ft with an average of 110 ft. Groundwater velocity was estimated between 0.5 and 1.5 feet per day (ft/dy). Specific yield (S_y) of the aquifer was estimated at 35. According to site records it was reported that 200,000 to 300,000 gallons per day (gpd) of waste fluids were discharged into the three pits. Infiltration rate (q) was estimated at a rate of 7,600 inches per year (in/yr). Chromium concentration in the waste averaged 31 milligrams per liter (mg/l). The combined area of these pits was measured at approximately 15,470 square feet (ft^2). Retardation of the contaminants was not a factor at this site due to the lack of free clay and organic matter within the surficial aquifer. Based on experimental data obtained from similar sites in the area, longitudinal or downgradient dispersivity (α_x) and transverse or crossgradient dispersivity (α_y) were assumed to be 70 ft and 14 ft respectively. A summary of this information is provided in Table 1 below:

TABLE 1

m = thickness of aquifer	110.0 ft
S_y = specific yield	35.0
V = groundwater velocity	1.5 ft/dy
α_x = longitudinal dispersivity	70.0 ft
α_y = transverse dispersivity	14.0 ft
R_d = retardation coefficient	1.0
C_o = initial concentration of contaminant	31.0 mg/l
A = area of discharge of contaminant	15,470.0 ft^2
q = infiltration rate of contaminant	7,600.0 in/yr

Before using the nomograph some basic assumptions and calculations are necessary. First, effective porosity (n) of the aquifer is not known for this site. However S_y was reported as 35. Without further information one will estimate n at 35% based on the S_y value. Dispersion coefficients can be calculated from dispersivity values already given in Table 1 using the following formulas of $D_x = \alpha_x V$ and $D_y = \alpha_y V$ where V is velocity of the groundwater found in Table 1.The results of these calculations are 105 ft^2/dy and 21 ft^2/dy, respectively.

For a nonpoint source for contaminants, such as at this site, the volume flow rate is estimated using the formula Q = Aq. Values of A and q are given above in Table 1. Converting units of q from in/yr to ft/dy requires the following calculation:

$$q = \left(\frac{7{,}600\,in}{yr}\right)\left(\frac{1ft}{12\,in}\right)\left(\frac{1\,yr}{365\,dy}\right) = 1.73\frac{ft}{dy}$$

The value for Q can now be calculated as 26,763 ft^3/dy using the above formula Q = Aq. The value of Q can also be computed from the discharge rate of 200,000 gpd of waste in the pits by using the conversion formula of 1 ft^3/7.48 gallons to change the units of gpd to ft^3/dy. The result of this conversion yields a value for Q of 26,738 ft^3/dy which is similar to the previous value of Q.

Now the mass flow rate, expressed as QC_o, is (26,763 ft^3/dy)(31 mg/l). Changing the units of mg/l to pounds per cubic feet (lb/ft^3) requires the following conversion:

$$\frac{31mg}{l} = \left(\frac{31mg}{l}\right)\left(\frac{1kg}{10^6 mg}\right)\left(\frac{2.2lb}{1kg}\right)\left(\frac{10^3 l}{1m^3}\right)\left(\frac{1m^3}{35ft^3}\right) = \frac{0.00195lb}{ft^3}$$

The mass flow rate (QC_o) of (26,763 ft^3/dy)(31 mg/l) is equivalent to 52 lb/dy.

From the above computations and assumptions we now have sufficient information to calculate the scale factors for the previously decribed applications for the nomograph as shown below:

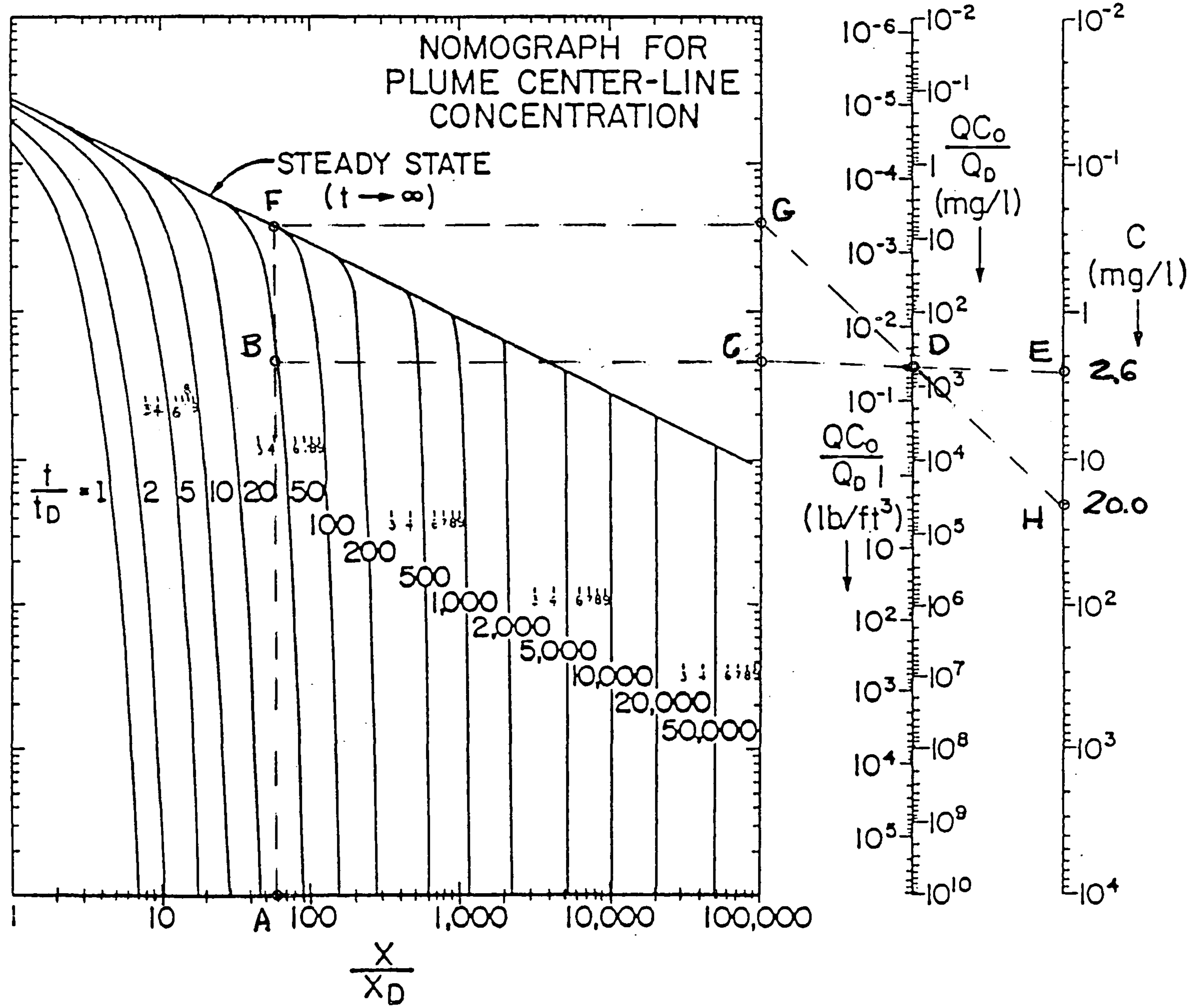
$$X_D = \frac{D_x}{V} = \frac{105ft^2/dy}{1.5ft/dy} = 70ft$$

$$T_D = \frac{R_d D_x}{V^2} = \frac{1.0x105ft^2/dy}{(1.5ft/dy)^2} = 46.67dy$$

$$Q_D = nm\sqrt{D_x D_y} = (0.35)(110ft)\sqrt{(105ft^2/dy)(21ft^2/dy)} = 1,808ft^3/dy$$

Now consider the three applications of the nomograph. In order to use the nomograph, the ratios used in the nomograph must be calculated as shown in **Figure 1**.

Figure : Application a & b



Application 1a and 1b

1a. Find the concentration (C) of chromium at a known distance (x) downgradient and time (t). Assume for this example x = 4,200 ft and t = 2,300 dy. Follow **Figure 1** for the solution to this problem.

$$\frac{x}{X_D} = \frac{4{,}200ft}{70ft} = 60 \quad \textit{(This value is located at point A)}$$

$$\frac{t}{T_D} = \frac{2{,}300dy}{46.67dy} = 49.3 \quad \textit{(This value is located at point B)}$$

$$\frac{QC_o}{Q_D} = \left(\frac{(26{,}763ft^3/dy)(31mg/l)}{1{,}808ft^3/dy}\right) = 458.9mg/l \quad \textit{(This value is located at point D)}$$

To find the concentration (C) draw a line vertical from point A to the intersection with the t/T_D value of 49.3 located as point B on **Figure 1**. Then draw a line horizontally from point B to point C. Now from point C draw a straight line through the QC_o/Q_D value of 458.9 mg/l (point D) and intersecting the vertical bar graph representing the concentration (C) of the contaminant, in this case chromium, under these conditions (point E). The solution to the problem is 2.6 mg/l of hexavalent chromium found 4,200 ft downgradient after 2,300 days of migration from the disposal pits.

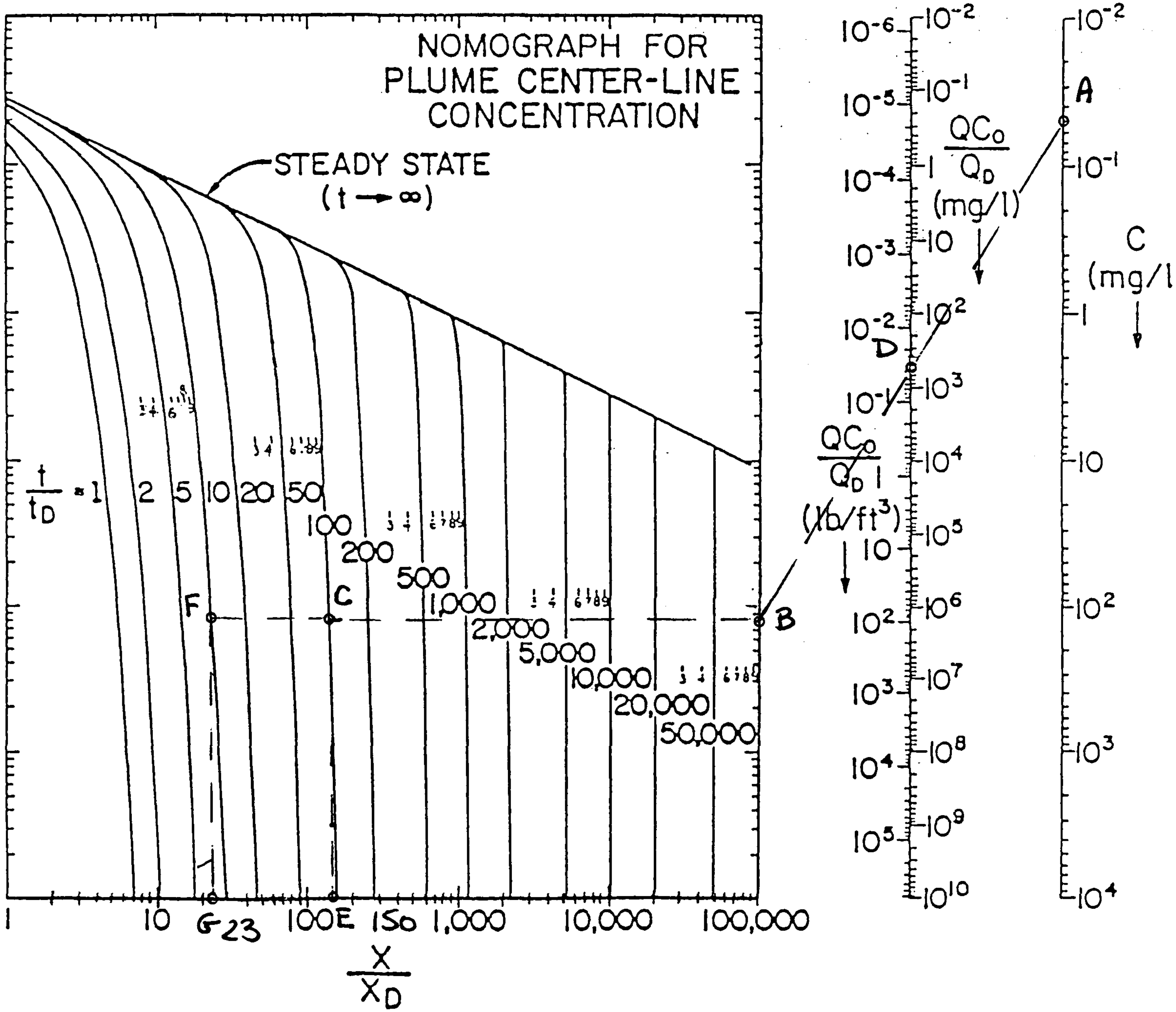
1b. Find the maximum concentration of hexavalent chromium for the same distance downgradient as given in application 1a but for a longer time period (greater than 10 years). In this solution, as depicted in **Figure 1** also, one must project the x/X_D value vertically to the steady state line which represents a time (t) approximately greater than 10 years. This is depicted as point F on **Figure 1**. The procedure is now similar to application 1a ultimately projecting a line through point D and intersecting the vertical concentration bar graph at point H. Under these conditions, 20 mg/l of hexavalent chromium is predicted.

Application 2a and 2b

2a. Determine the distance (x) downgradient where a selected concentration (C) of a contaminant, such as hexavalent chromium, will occur at a given time (t). This application is important if one is interested in evaluating chromium's breakthrough concentration above its MCL (maximum contaminant level) of 0.05 mg/l according to drinking water standards. Using the same value for QC_o/Q_D of 458.9 mg/l as represented as point D on **Figure 2** , one now locates the concentration of 0.05 mg/l on the vertical concentration bar graph. This is depicted as point A on **Figure 2**. Starting at point A project a straight line through point D to point B on the nomograph of **Figure 2**. From point B construct a line horizontally across the nomograph. Now one must determine the amount of time (t) the migration of the contaminant has occurred in order to determine the time ratio of t/T_D. For example, one might be interested in how far downgradient this concentration of 0.05 mg/l will occur after 4,667 days. The time ratio computes to 100 using the time scalor (T_D) of 46.67 days and is depicted as point C on **Figure 2**. Projecting a line vertically down from point C to the x/X_D value of 150 (point E), the distance (x) downgradient this concentration occurs after 4,667 days is computed as 10,500 ft or approximately 2 miles. For a shorter time (t) period , such as 466.7 days the ratio t/T_D equals 10 (point F), x/X_D is determined as 23. Therefore the concentration of 0.05 mg/l of hexavalent chromium is estimated at 1610 ft downgradient from the source after 466.7 days have passed.

2b. Find the distance downgradient the concentration of 0.05 mg/l will occur under steady state conditions. Unfortunately the steady state line on the nomograph is not intersected as depicted on **Figure 2**. For this scenario, one can only assume that the distance downgradient is greater than 7,000,000 ft according to the computation of 100,000 (x/X_D) times 70 ft (X_D). Let us hope your agency has remediated this site before steady state is ever achieved!

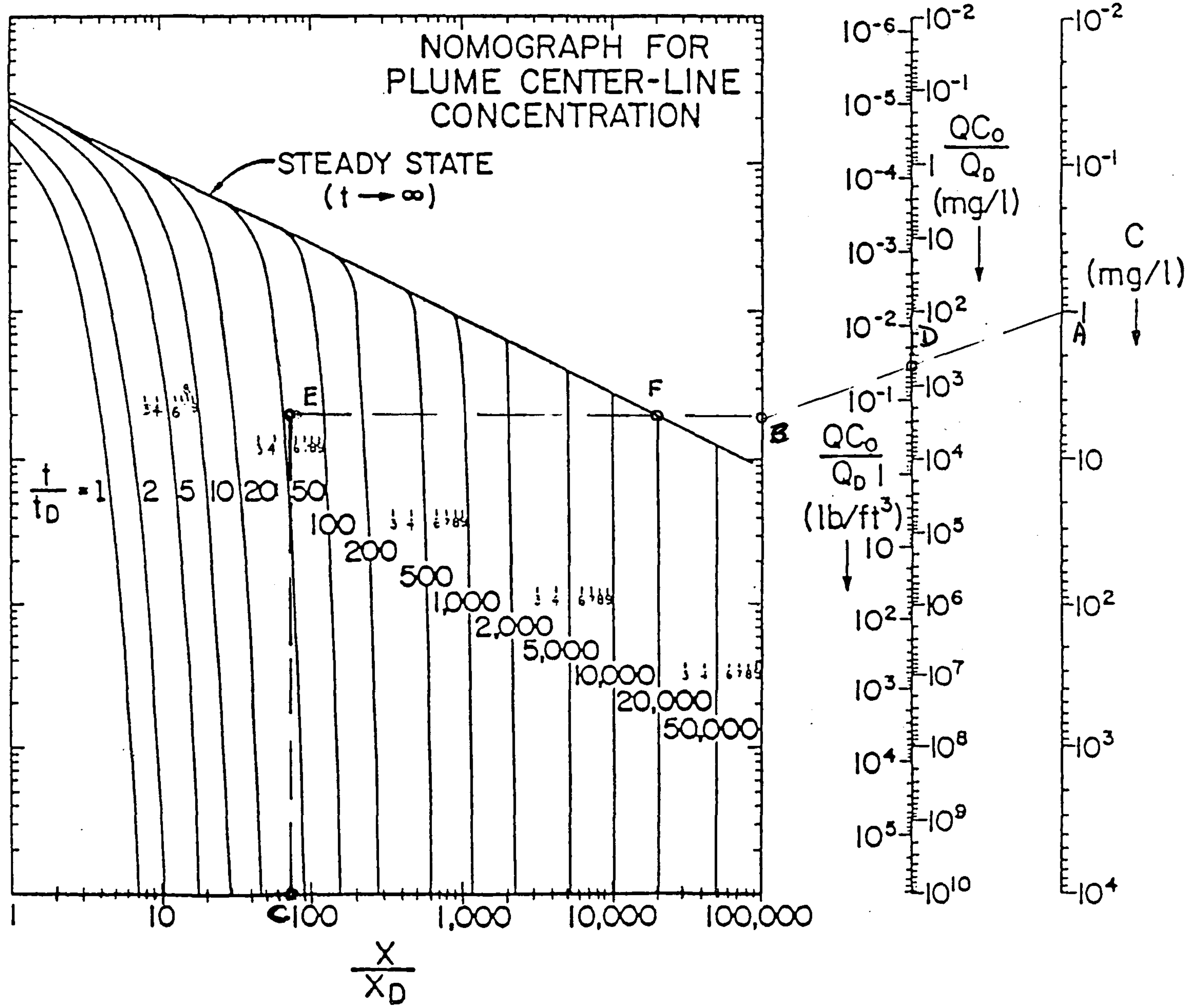
Figure 2 : Application 2a & 2b



Application 3

3. Find the time (t) required for a known concentration (C) to migrate to a specified distance (x) downgradient of the source. Let us consider how long it will take for 1 mg/l of hexavalent chromium to reach a private water supply well located 5280 ft (x) downgradient of the contaminant source. First one must locate the concentration (C) of 1 mg/l on the vertical concentration bar graph. This is depicted as point A on **Figure 3**. Using the same value of 458.7 mg/l for the ratio of QC_o/Q_D (point D), construct a straight line from point A through point D to the nomograph (point B). Then project a horizontal line from point B through the graph. Next project a vertical line from point C representing the value of 75.45 as computed for x/X_D = 5,280 ft/ 70 ft until it crosses the previously constructed horizontal line (point E) as shown on **Figure 3**. At this intersection the value of t/T_D is equal to 60 or t is 2,800 days according to the calculation T_D times 60 where T_D equals 46.67 days. It is important to note that should point E occur above the steady state line for the value x/X_D of 75.45 on the nomograph, the concentration (C) of 1 mg/l will not be found at this distance of 5,280 ft downgradient from the source.

Figure 3: Application 3



PROBLEM

The Alkali Lake chemical storage site in eastern Oregon became a chemical waste disposal site in November, 1983 when 25,000 55-gallon capacity drums were crushed and buried in 12 shallow (0.60 to 0.75 meters deep) unlined trenches, 130 meters (m) long and 20 m apart. The drums contained chlorophenolic "still bottoms" or distillation residues from the manufacturing of herbicides 2,4-D (2,4-Dichlorophenoxyacetic acid) and MCPA (4-Methyl-2-chlorophenoxyacetic acid) for the Vietnam War. The average concentration of 2,4-D in the drums was determined to be 200 mg/l. Burial of these drums injected this chemical waste directly into the groundwater system beneath this site at the rate of 8,313 gallons per day. A site investigation was conducted eight years later after many complaints concerning the strange odor and taste in the water from private wells. The results of the site investigation obtained the following aquifer parameters or properties:

m = aquifer thickness	30 m (98.43 ft)
n = effective porosity	5 % (0.05)
Θ = total porosity	65 % (0.65)
ρ_B = bulk density	0.95 g/cm^3
K = hydraulic conductivity	0.1 cm/sec (283 ft/dy)
I = hydraulic gradient	0.0002
V = seepage velocity	1.132 ft/dy
D_X = longitudinal dispersion coefficient	60 ft^2/dy
D_Y = transverse dispersion coefficient	12 ft^2/dy
QC_0 = mass injection rate	8,313 gpd x 200 mg/l
K_d = distribution coefficient	0.5 cm^3/g
R_d = retardation coefficient	1.73

Unfortunately this investigation was concluded and a site report submitted to the State Department of Environmental Protection before it was discovered that the well search was not complete. Somehow, a municipal water-supply well located 1,700 ft downgradient was overlooked on the initial well search for potentially impacted water-supply wells within a one-mile radius of the site. Since the water from this well was not sampled during the investigation, how can one estimate the concentration (C) of 2,4-D in this well given the following ratios for the nomograph:

$t/T_D = 36$, $x/X_D = 32$, and $QC_0/Q_D = 1{,}696$ mg/l.

PROBLEM

Calculations and Unit Conversions

AQUIFER THICKNESS (m)

$$m = \left[\frac{30\,m}{1.0}\right]\left[\frac{3.281\,ft}{1.0\,m}\right] = 98\,ft$$

HYDRAULIC CONDUCTIVITY (K)

$$K = \left[\frac{0.1\,cm}{\text{sec}}\right]\left[\frac{60.0\,\text{sec}}{1.0\,\text{min}}\right]\left[\frac{60.0\,\text{min}}{1.0\,hr}\right]\left[\frac{24.0\,hr}{1.0\,dy}\right]\left[\frac{1.0\,in}{2.54\,cm}\right]\left[\frac{1.0\,ft}{12.0\,in}\right]$$

$$K = \left[\frac{8{,}640\,ft}{30.38\,dy}\right] = 283\,\frac{ft}{dy}$$

SEEPAGE VELOCITY (V)

$$V = \frac{K\,I}{n} = \left[283\,\frac{ft}{dy}\right]\left[\frac{0.0002}{0.05}\right]$$

$$V = 1.132\,\frac{ft}{dy}$$

RETARDATION COEFFICIENT (R_d)

$$R_d = 1.0 + \left[\frac{K_d\,\rho_b}{\theta}\right]$$

$$R_d = 1.0 + \left[\frac{0.5\,cm^3}{g}\right]\left[\frac{0.95\,g}{cm^3}\right]\left[\frac{1.0}{0.65}\right]$$

TIME SCALE FACTOR (T_D)

$$R_d = 1.0 + 0.73 = 1.73$$

$$T_D = \frac{R_d\, D_X}{V^2}$$

$$T_D = \left[\frac{1.73}{1.0}\right]\left[\frac{60.0 ft^2}{dy}\right]\left[\frac{dy^2}{(1.132 ft)^2}\right]$$

$$T_D = \frac{103.8\ dy}{1.28} = 81\ dy$$

DISCHARGE RATE (Q)

$$Q = \left[\frac{8{,}313 gal}{dy}\right]\left[\frac{1.0 ft^3}{7.48 gal}\right] = 1{,}111 \frac{ft^3}{dy}$$

FLOW SCALE FACTOR (Q_D)

$$Q_D = n\ m\ \sqrt{D_X\, D_Y}$$

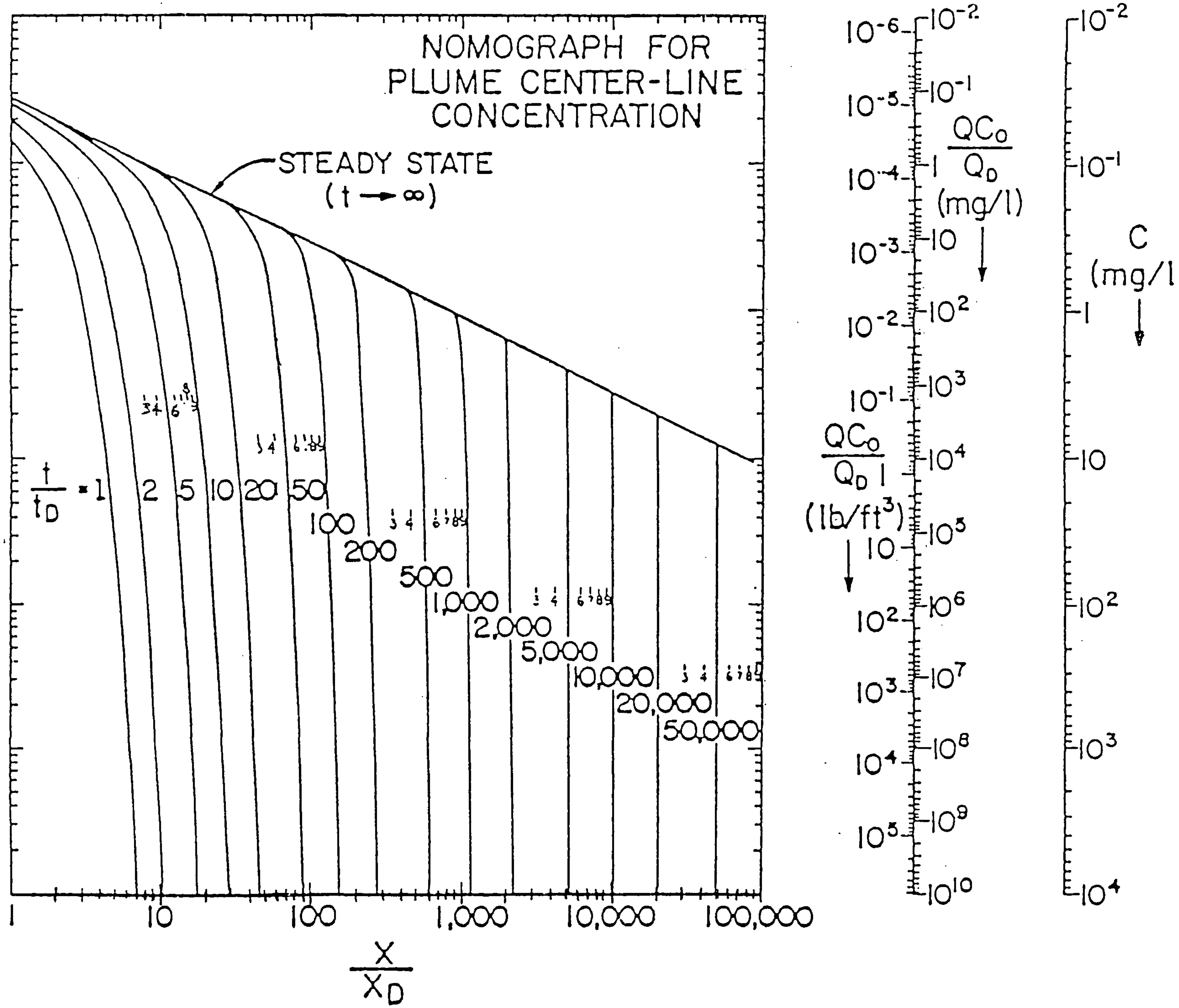
$$Q_D = (0.05)(98.0 ft)\sqrt{\left[\frac{60.0 ft^2}{dy}\right]\left[\frac{12.0 ft^2}{dy}\right]}$$

$$Q_D = 4.9 ft \sqrt{\frac{720 ft^4}{dy^2}} = 131 \frac{ft^3}{dy}$$

LENGTH SCALE FACTOR

$$X_D = \frac{D_X}{V}$$

$$X_D = \left[\frac{60.0 ft^2}{dy}\right]\left[\frac{dy}{1.132 ft}\right] = 53\ ft$$


NOMOGRAPH FOR PLUME CENTER-LINE CONCENTRATION
STEADY STATE (t → ∞)
t/tD = 1
2
5
10
20
50
100
200
500
1,000
2,000
5,000
10,000
20,000
50,000
1
10
100
1,000
10,000
100,000
X/XD
QCo/QD l (lb/ft3)
QCo/QD (mg/l)
C (mg/l)

APPENDIX A

Sampling Protocols

GENERALIZED GROUNDWATER SAMPLING PROTOCOL

Step	Goal	Recommendations
Hydrologic measurements	Establish nonpumping water level	Measure the water level to ±0.3 cm (±0.01 ft)
Well purging	Remove or isolate stagnant H_2O, which would otherwise bias representative sample	Pump water until well purging parameters (e.g., pH, T, Ω^{-1}, Eh) stabilize to ±10% over at least two successive well volumes pumped
Sample collection	Collect samples at land surface or in well bore with minimal disturbance of sample chemistry	Pumping rates should be limited to ~100 mL/min for volatile organics and gas-sensitive parameters
Filtration/preservation	Filtration permits determination of soluble constituents and is a form of preservation; it should be done in the field as soon as possible after sample collection	For trace metals, inorganic anions/cations, and alkalinity. Do not filter TOC, TOX, or other volatile organic compound samples; filter other organic compound samples only when required
Field determinations	Field analyses of samples will effectively avoid bias in determining parameters/constituents that do not store well (e.g., gases, alkalinity, and pH)	Samples for determining gases, alkalinity, and pH should be analyzed in the field if at all possible
Field blanks/standards	These blanks and standards will permit the correction of analytical results for changes that may occur after sample collection. Preserve, store, and transport with other samples.	At least one blank and one standard for each sensitive parameter should be made up in the field on each day of sampling. Spiked samples are also recommended for good QA/QC.
Sample storage, transportation, and chain of custody (COC)	Refrigerate and protect samples to minimize their chemical alteration prior to analysis. Document movement of samples from collector to laboratory.	Observe maximum sample holding or storage periods recommended by EPA. Documentation of actual holding periods should be carefully performed. Establish COC forms, which must accompany all samples during shipment.

Adapted from: U.S. EPA. 1985. Practical Guide for Ground-Water Sampling. EPA/600/2-85/104. Robert S. Kerr Environmental Research Laboratory, Ada, OK.

APPENDIX B

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APPENDIX C

Sources of Information

SOURCES OF INFORMATION

SOURCES OF U.S. ENVIRONMENTAL PROTECTION AGENCY DOCUMENTS

Center for Environmental Research Information (CERI) (no charge for documents)

Center for Environmental Research Information (CERI)
ORD Publications
26 West Martin Luther King Drive
Cincinnati, OH 45268
513 569-7562
FTS 8-684-7562

Public Information Center (PIC) (no charge for public domain documents)

Public Information Center (PIC)
U.S. Environmental Protection Agency
PM-211B
401 M Street, S.W.
Washington, DC 20460
202 382-2080
FTS 8-382-2080

Superfund Docket and Information Center (SDIC)

U.S. Environmental Protection Agency
Superfund Docket and Information Center (SDIC)
OS-245
401 M Street, S.W.
Washington, DC 20460
202 260-6940
FTS 8-382-6940

National Technical Information Services (NTIS) (cost varies)

National Technical Information Services (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
703 487-4650
1-800-553-NTIS(6847)

Superintendent of Documents

Government Printing Office
202 783-3238

SOURCES OF MODELS AND MODEL INFORMATION

Superfund Exposure Assessment Manual

EPA/540/1-88/001, April 1988
Chapter 3 "Contaminant Fate Analysis" - 35 models

National Ground Water Association

National Ground Water Association
6375 Riverside Dr.
Dublin, OH 43017
614 761-1711

International Groundwater Modeling Center (IGWMC)

Paul K. M. van der Heijde, Director IGWMC
Institute for Ground-Water Research and Education
Colorado School of Mines
Golden, CO 80401-1887
303 273-3103
303 273-3278 (fax)

Groundwater Flow Model

Soil and Water Conservation Society (SWCS) Student Chapter
Iowa State University
3510 Agronomy Hall
Ames, IA 50011
515 294-7850
Cost: $384.00 (including shipping)

UST Video: Groundwater Cleanup

Industrial Training Systems Corp.
20 West Stow Road
Marlton, NJ 08053
609 983-7300
Cost: $595.00

GEOPHYSICS ADVISOR EXPERT SYSTEM VERSION 2.0

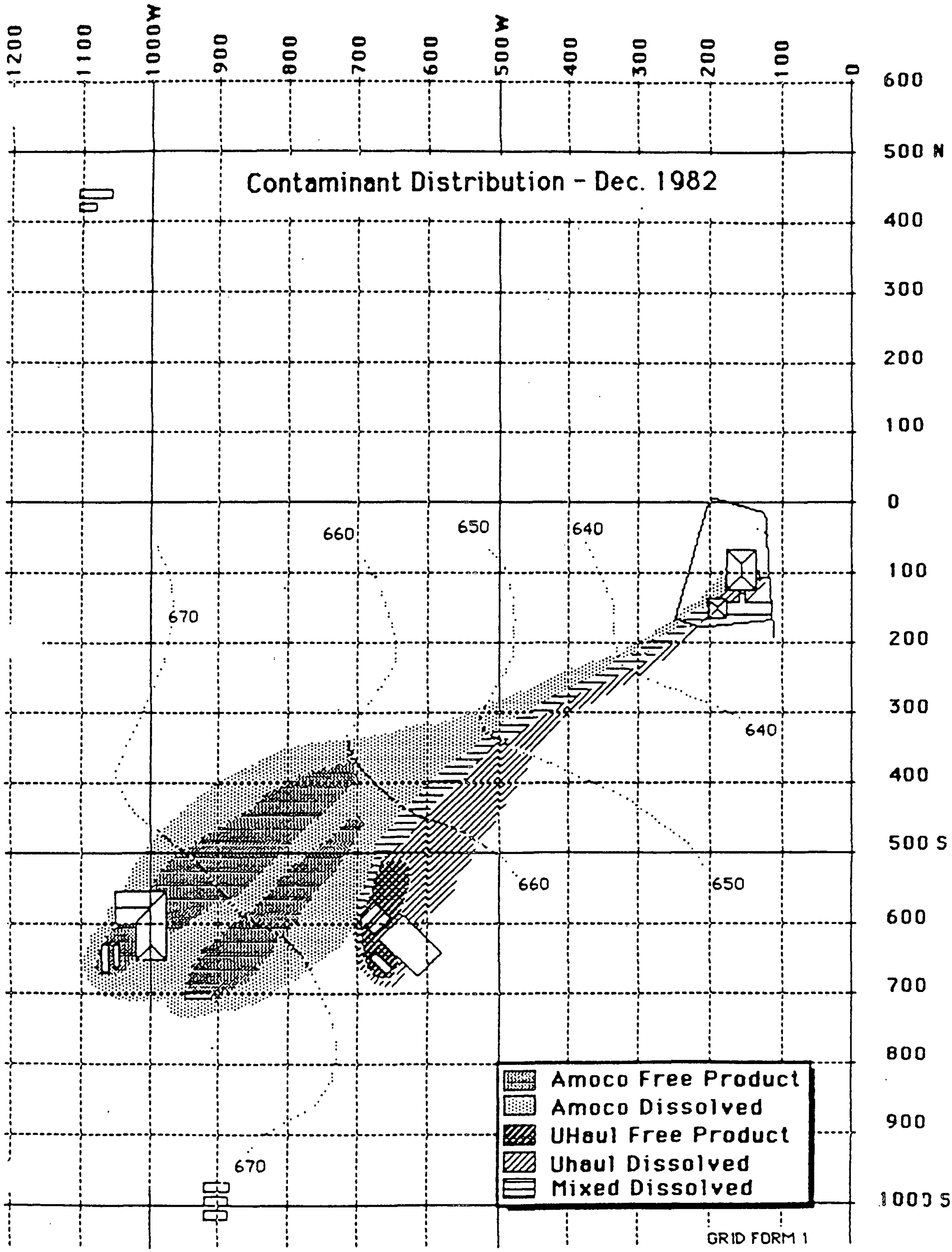
Gary R. Olhoeft, Jeff Lucius, Cathy Sanders
U.S. Geological Survey
Box 25046 DFC - Mail Stop 964
Denver, CO 80225
303 236-1413/1200

U.S. Geological Survey preliminary computer program for Geophysics Advisor Expert System. Distributed on 3.5" disk and written in True BASIC 2.01 to run under Microsoft MS-DOS 2.0 or later on IBM-PC or true compatible computers with 640k or greater memory available to the program. No source code is available.

This expert system program was created for the U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, Nevada. The expert system is designed to assist and educate non-geophysicists in the use of geophysics at hazardous waste sites. It is not meant to replace the expert advice of competent geophysicists.

COMPREHENSIVE LISTING OF AERIAL PHOTOGRAPHY

U.S. Department of Agriculture, ASCS
Aerial Photography Field Office
2222 West 2300 South
P.O. Box 30010
Salt Lake City, UT 84130-0010
801 524-5856


Contaminant Distribution - Dec. 1982
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900
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700
600
500W
400
300
200
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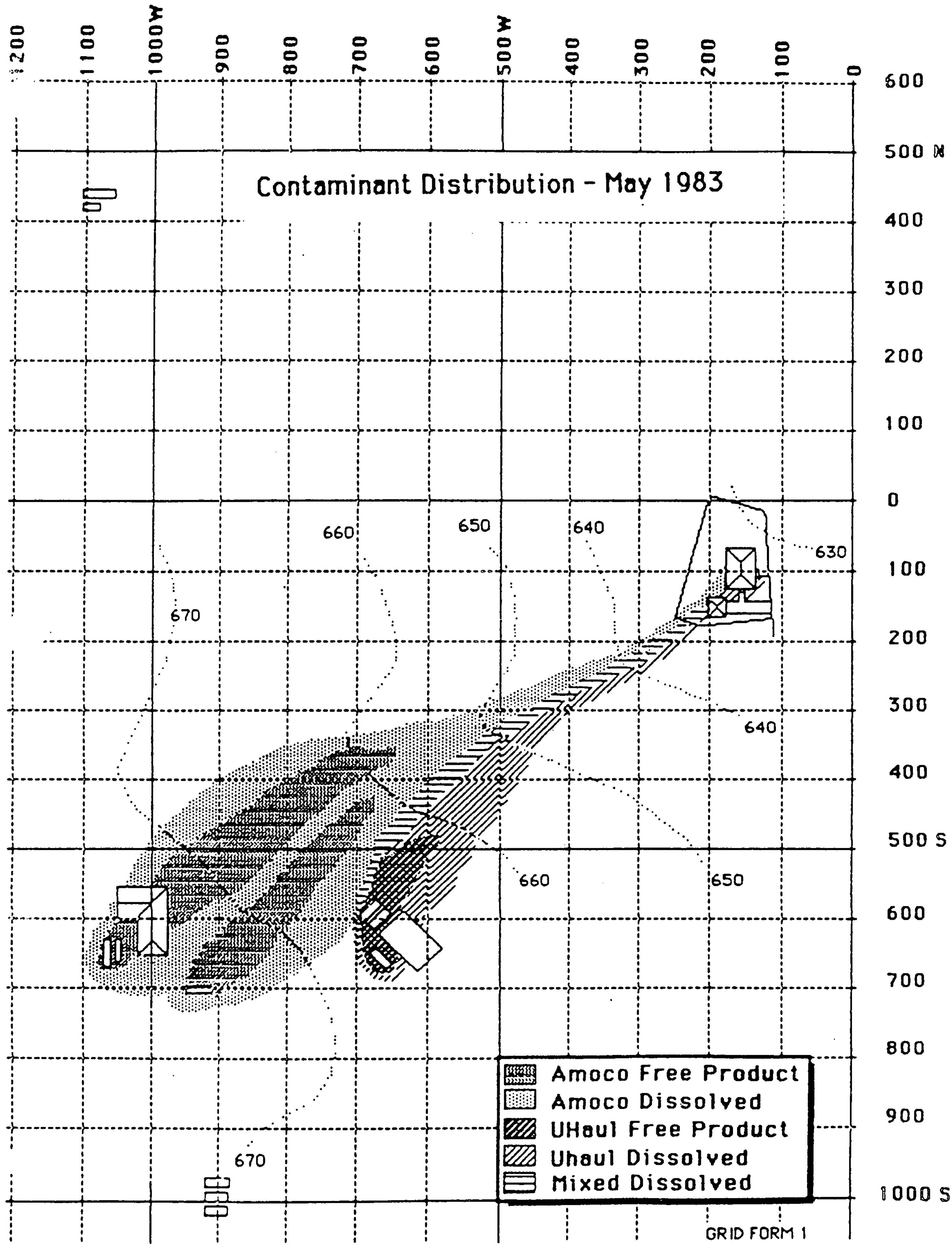
0
600
500 N
400
300
200
100
0
100
200
300
400
500 S
600
700
800
900
1000 S
660
650
640
670
640
660
650
670
Amoco Free Product
Amoco Dissolved
UHaul Free Product
Uhaul Dissolved
Mixed Dissolved
GRID FORM 1


Contaminant Distribution - May 1983
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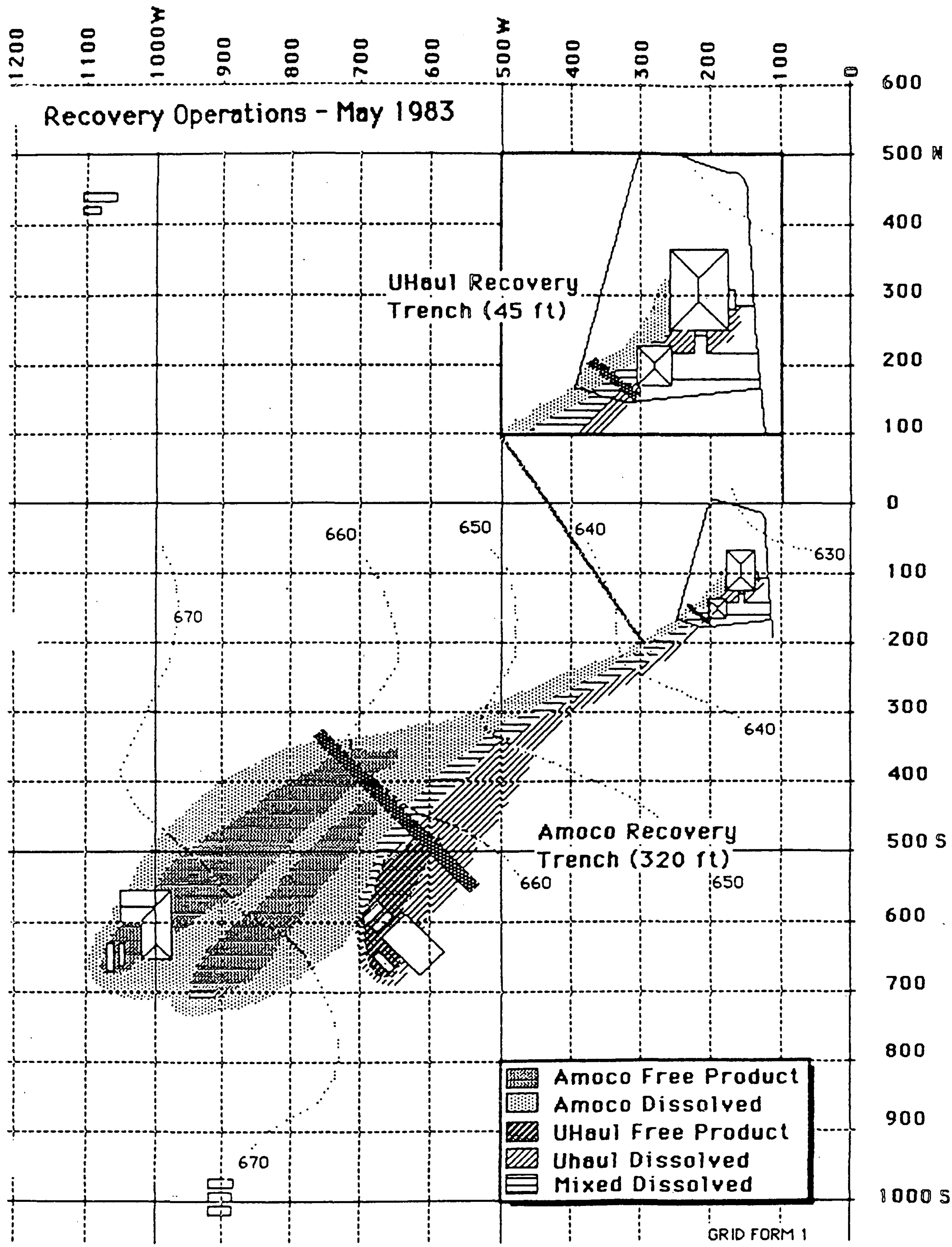
1100
1000W
900
800
700
600
500W
400
300
200
100
0
600
500 N
400
300
200
100
0
100
200
300
400
500 S
600
700
800
900
1000 S
660
650
640
630
670
640
660
650
670
Amoco Free Product
Amoco Dissolved
UHaul Free Product
Uhaul Dissolved
Mixed Dissolved
GRID FORM 1



Recovery Operations - May 1983
1200
1100
1000W
900
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700
600
500W
400
300
200
100
0
600
500 N
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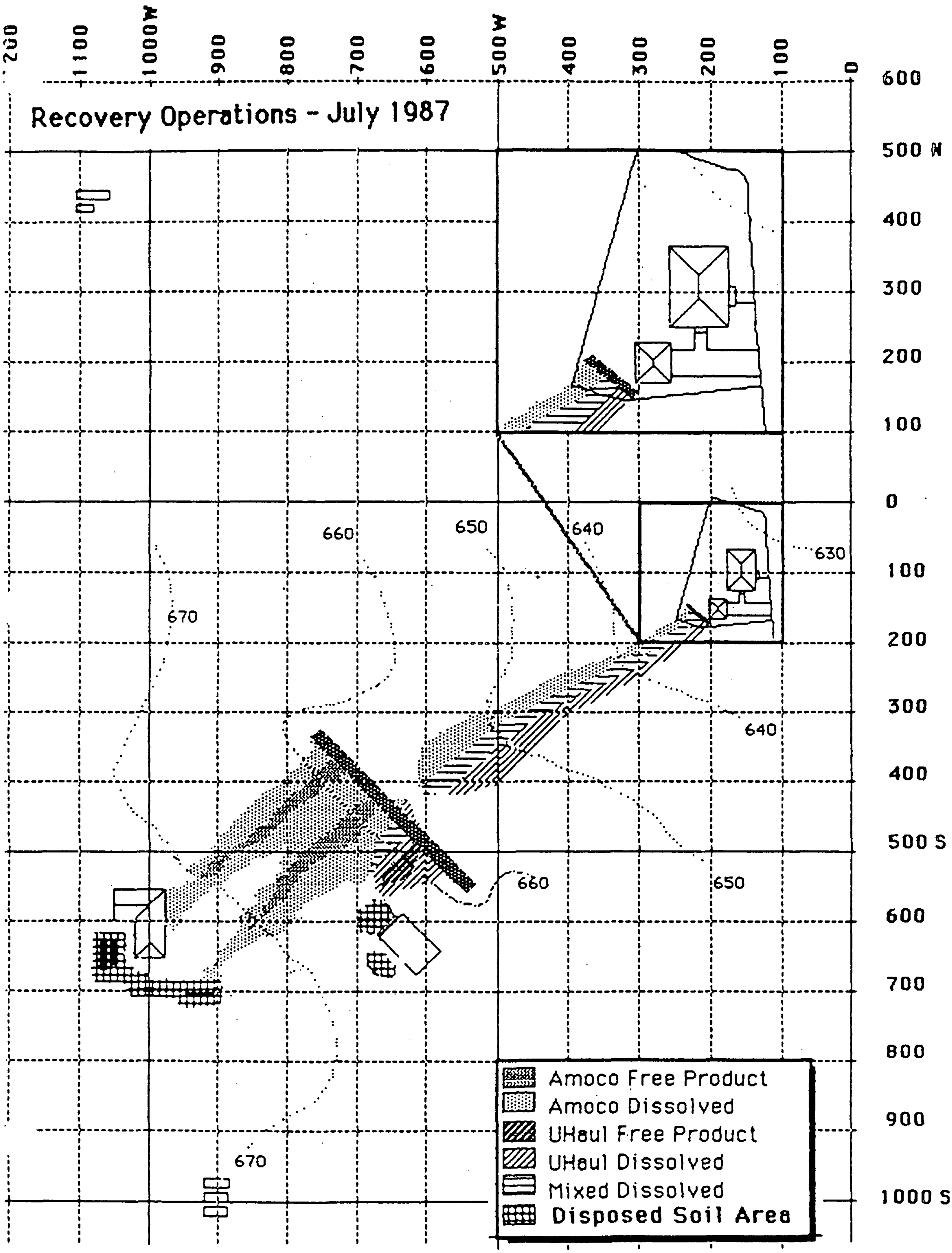
200
100
0
100
200
300
400
500 S
600
700
800
900
1000 S
UHaul Recovery
Trench (45 ft)
Amoco Recovery
Trench (320 ft)
660
650
640
630
670
640
660
650
670
Amoco Free Product
Amoco Dissolved
UHaul Free Product
Uhaul Dissolved
Mixed Dissolved
GRID FORM 1



Recovery Operations - July 1987
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1000W
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800
700
600
500W
400
300
200
100
0
600
500 N
400
300
200
100
0
100
200
300
400
500 S
600
700
800
900
1000 S
660
650
640
630
670
640
660
650
670
Amoco Free Product
Amoco Dissolved
UHaul Free Product
UHaul Dissolved
Mixed Dissolved
Disposed Soil Area

Table 2
Project No. 782563

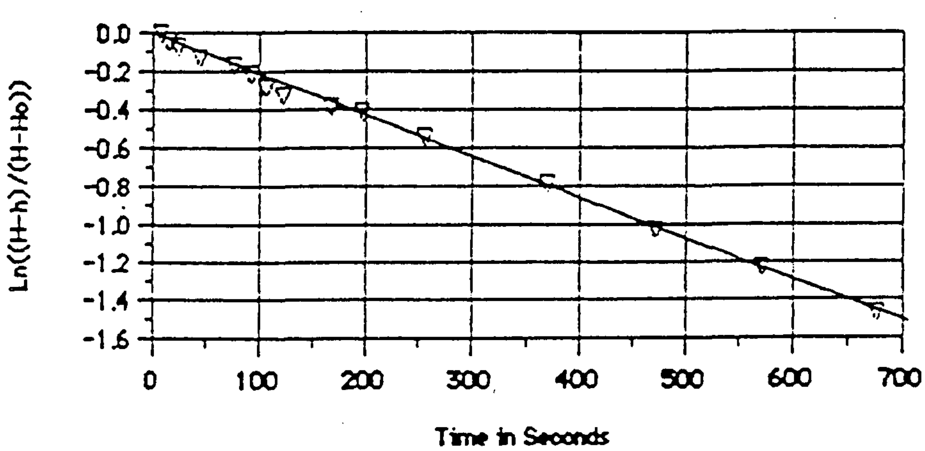
Slug-In Test Results

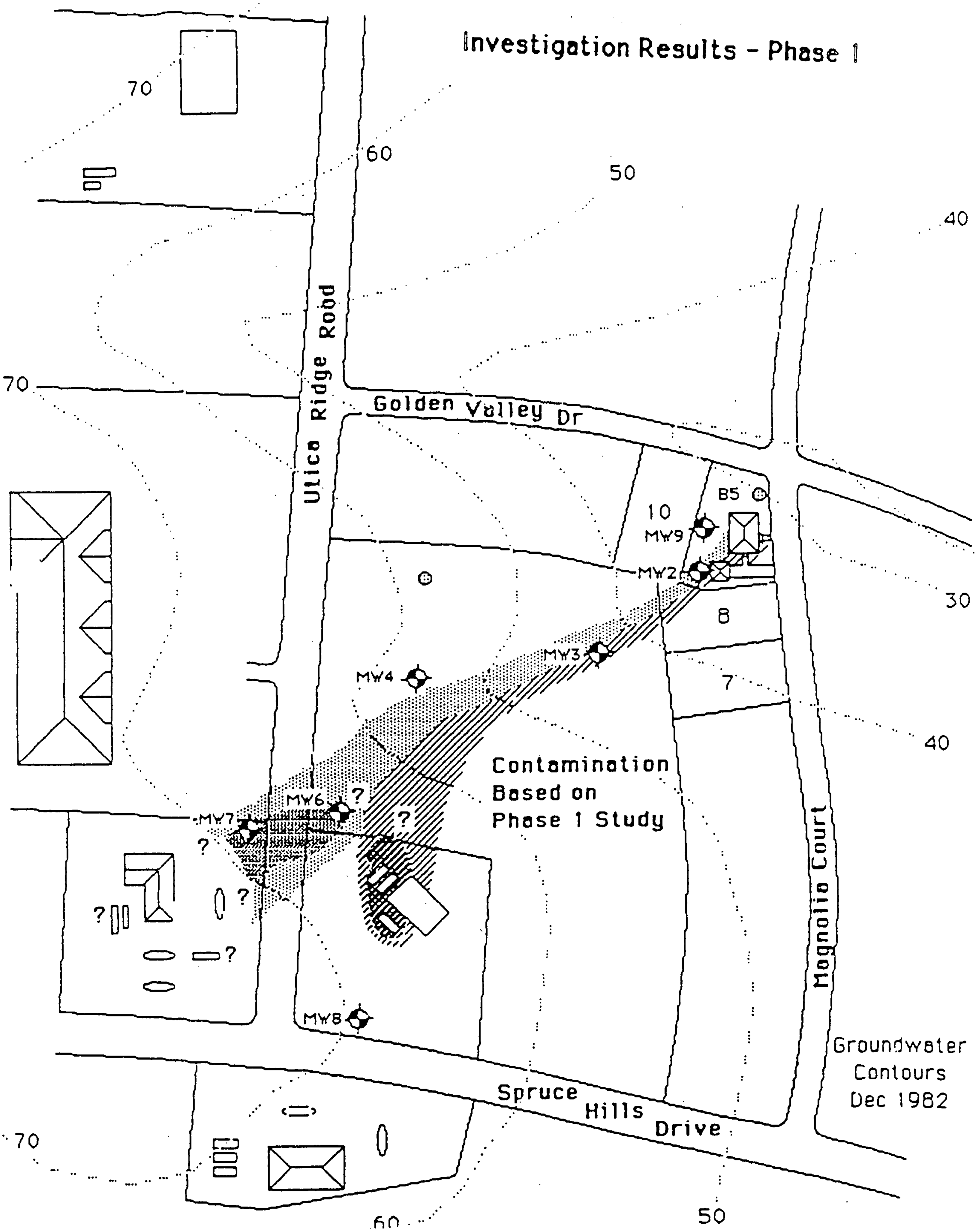
Monitoring Well MW-6
Test No. 1

Elapsed time Raw Min	Elapsed Ti.. Seconds	Water Depth Ft	h	(H-h)/(H-Ho)
0.12	7.2	2.09	19.91	1.00
0.24	14.4	2.51	19.49	0.96
0.36	21.6	2.76	19.24	0.93
0.72	43.2	3.23	18.77	0.88
1.25	75.0	3.61	18.39	0.84
1.5	90.0	3.95	18.05	0.80
1.75	105.0	4.39	17.61	0.76
2.01	120.6	4.72	17.28	0.72
2.75	165.0	5.07	16.93	0.68
3.25	195.0	5.32	16.68	0.66
4.25	255.0	6.06	15.94	0.58
6.14	368.4	7.24	14.76	0.45
7.83	469.8	8.12	13.88	0.36
9.51	570.6	8.76	13.24	0.29
11.24	674.4	9.35	12.65	0.23

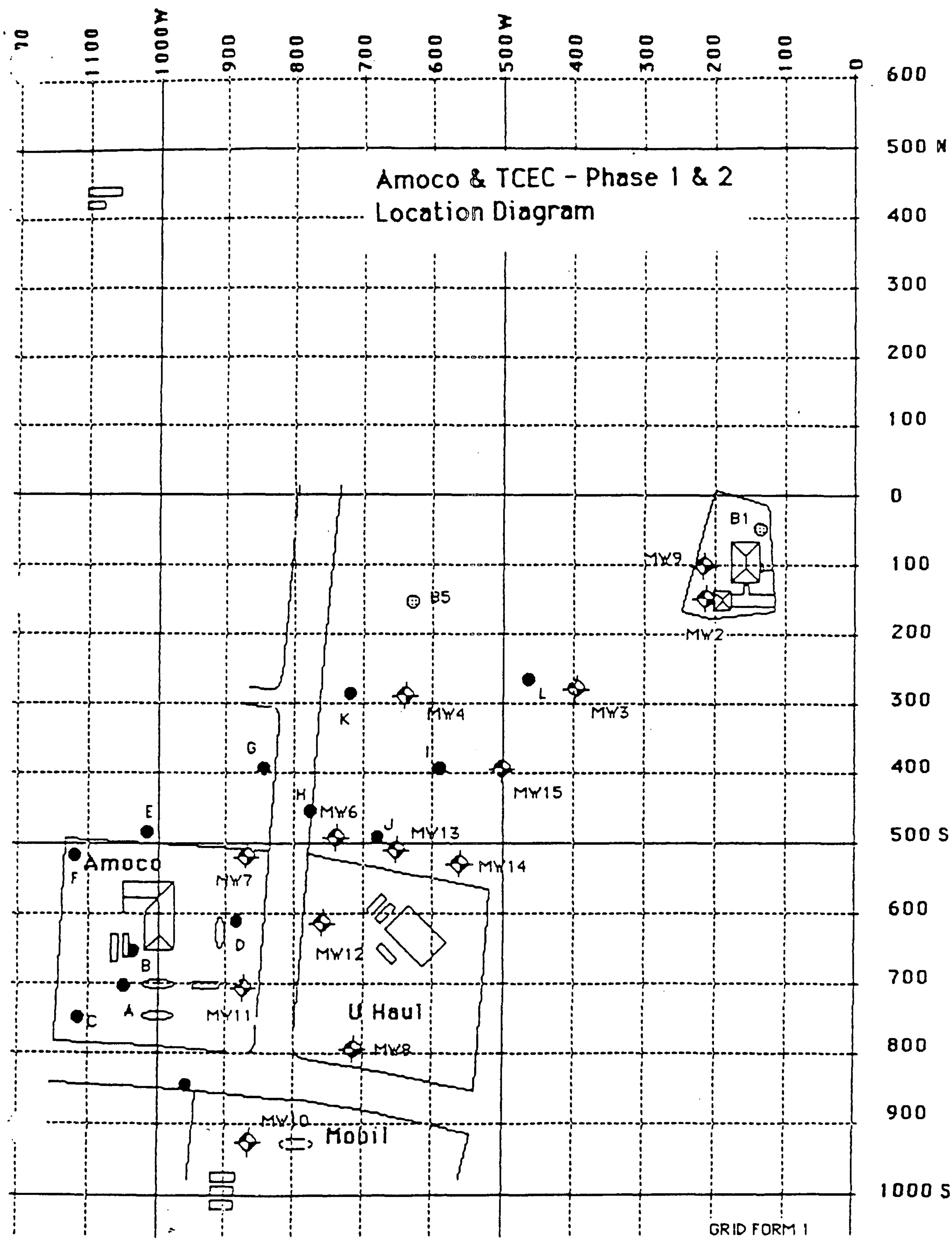
r = 1 in. K = 3.3E-6 ft/sec or 1.0E-4 cm/sec
L = 8.7 ft 2.8E-1 ft/day or 1.0E2 ft/yr
R = 2.25 in. To= 466.7 sec.

Note: K is calculated based on Hvorslev Method (1951)





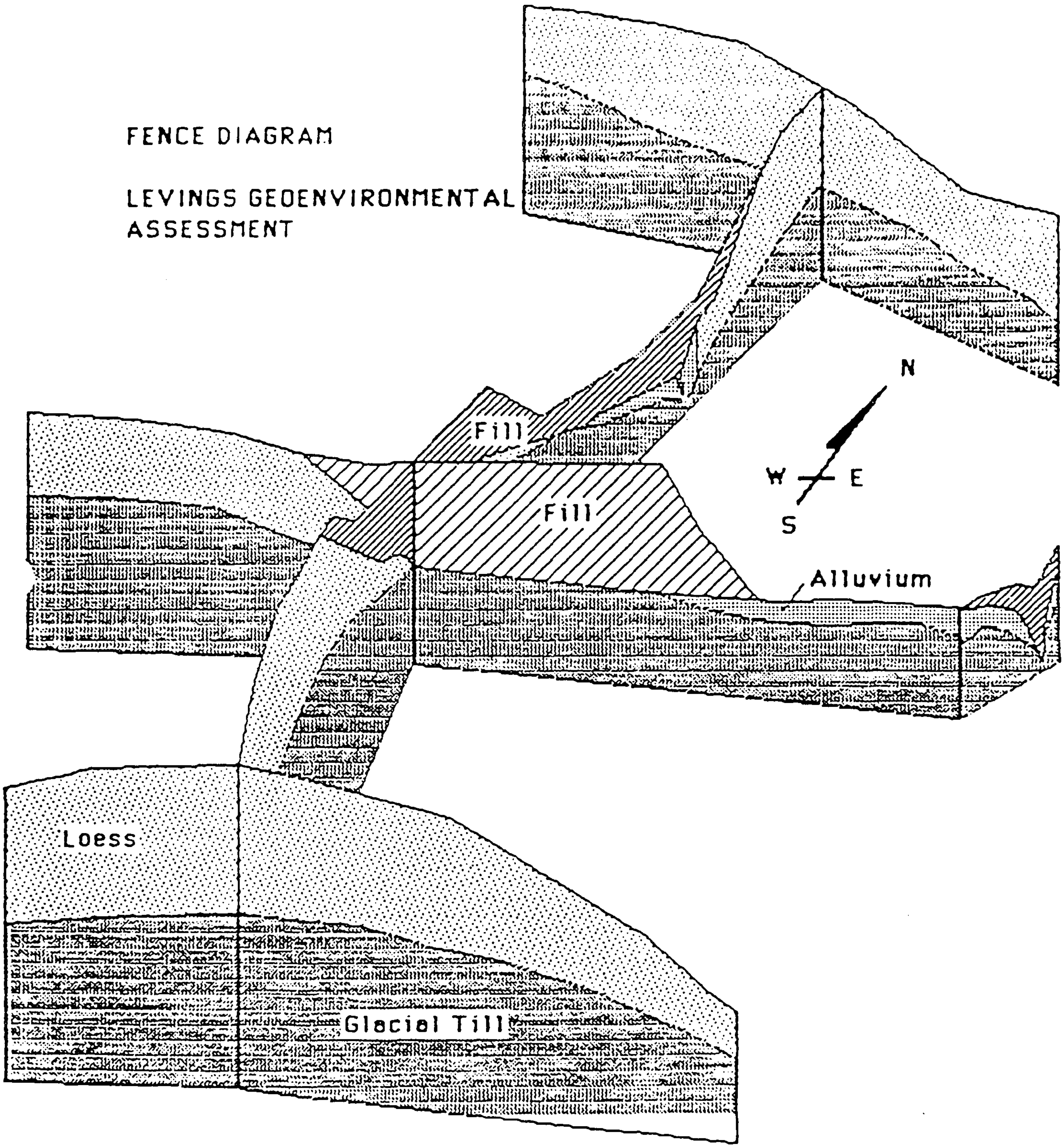
Investigation Results - Phase 1
70
60
50
40
30
70
Ulica Ridge Road
Golden Valley Dr
B5
10
MW9
MW2
8
MW3
7
MW4
40
Contamination
Based on
Phase 1 Study
MW6
MW7
?
MW8
Magnolia Court
Groundwater
Contours
Dec 1982
Spruce
Hills
Drive
70
60
50

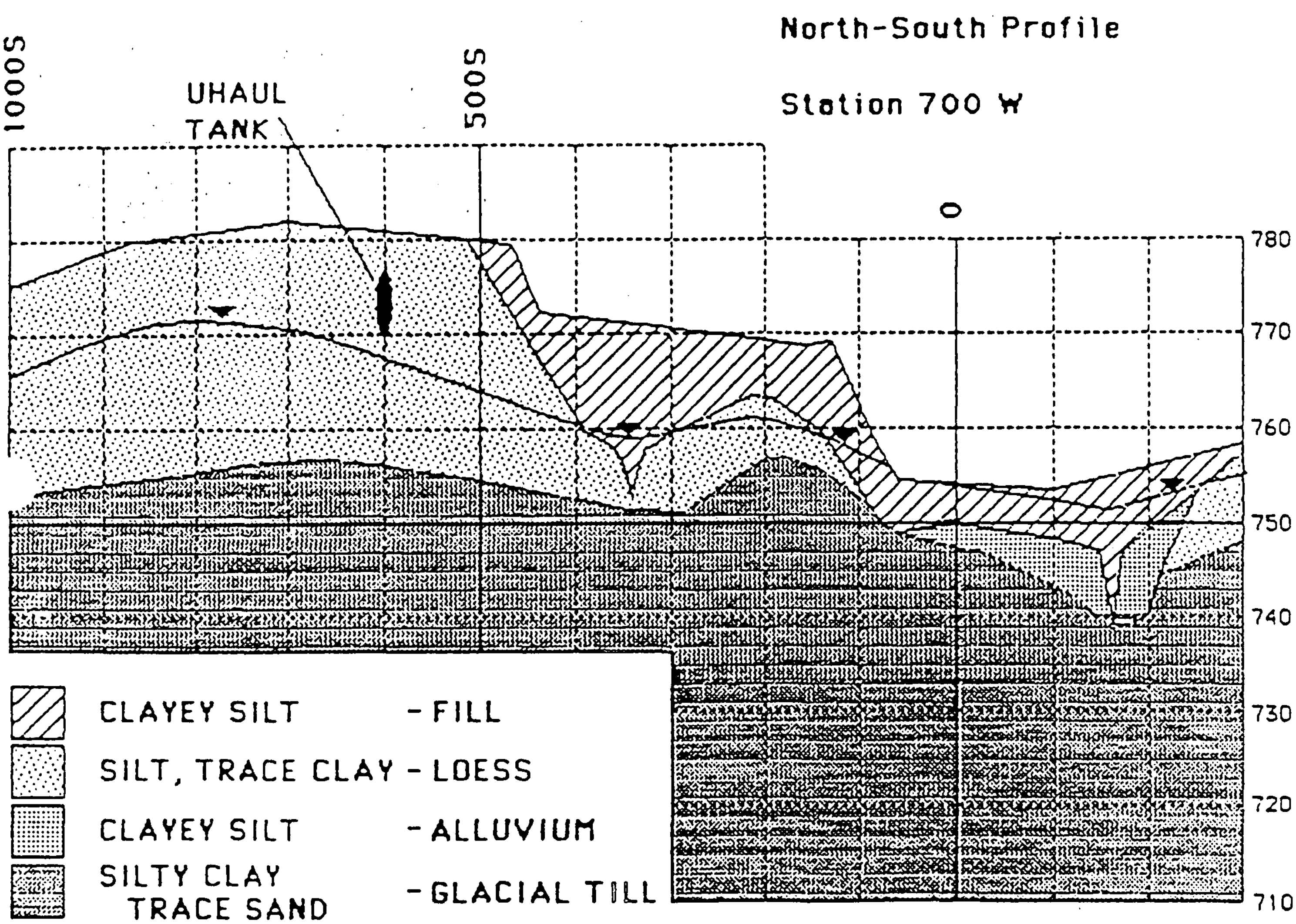


Amoco & TCEC - Phase 1 & 2
Location Diagram
1100
1000W
900
800
700
600
500W
400
300
200
100
0
600
500 N
400
300
200
100
0
100
200
300
400
500 S
600
700
800
900
1000 S
B1
MW9
MW2
B5
L
MW3
K
MW4
G
I
MW15
H
MW6
E
J
MW13
Amoco
F
MW7
MW14
D
MW12
B
A
MW11
C
U Haul
MW8
MW10
Mobil
GRID FORM 1

FENCE DIAGRAM

LEVINGS GEOENVIRONMENTAL
ASSESSMENT





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