SESSION 8

GROUNDWATER EXPLORATION I

Dr Amjad Aliewi

House of Water and Environment

Email: amjad.aliewi@hwe.org.ps , Website: www.hwe.org.ps

1 Introduction

Ground water exploration is the search for groundwater resources which can be exploited for the benefit of mankind.

Boreholes represent a large capital investment in a groundwater investigation; therefore, each borehole should be drilled to an optimum design and the location.

Optimum borehole design depends on a detailed knowledge of the geological functions and subsurface geometry in the area to be drilled.

This phased approach applies to both groundwater resource studies and to pollution investigations.

1 Introduction

The principles of groundwater exploration are:

- Desk Studies
- Remote Sensing
- Well Inventories
- Surface geophysics
- Exploration Drilling
- Groundwater Monitoring

2 Objectives of Groundwater Exploration

1. **Development/exploitation of groundwater resources**

   Select areas where groundwater resources can be exploited (aerial photo interpretation studies, hydrogeological mapping, well inventories, … etc)

   Determine the quantity and quality of the resources that can be exploited without depleting the groundwater basin

   Locate springs and identify sites suitable for the installation of individual production wells and/or wellfields

   Determine the depths of the wells to be drilled and the yield and the anticipated quality of the groundwater when production wells are installed.

2 Objectives of Groundwater Exploration

2. Protection of groundwater resources (control of hazards) (Contaminated Hydrogeology)

3 Desk Studies and Preliminary Field Reconnaissance

3.1 Topography and Geology

Topographical maps (Figure 3.1) showing topography, wadis, vegetation, roads and communities can give a good picture about the investigated area;

Scale of maps 1:100,000 – 1:250,000 regional review

1:25,000 – 1:50,000 detailed review

Springs and areas with shallow groundwater levels may be shown on the map indicating the presence of groundwater resources;

3 Desk Studies and Preliminary Field Reconnaissance

Topographical area like rivers, wadi intersection and coastal areas may indicate the presence of groundwater;

The slope of the terrain shown on the map usually indicates the direction of shallow groundwater flow.

Geological borehole logs are mainly compiled on the basis of rock samples (geotechnical assessments, oil and gas exploration, … etc) (see Figure 3.2)

The logs normally consist of written descriptions of the geology (lithological description of rock types) (see Figure 3.2)

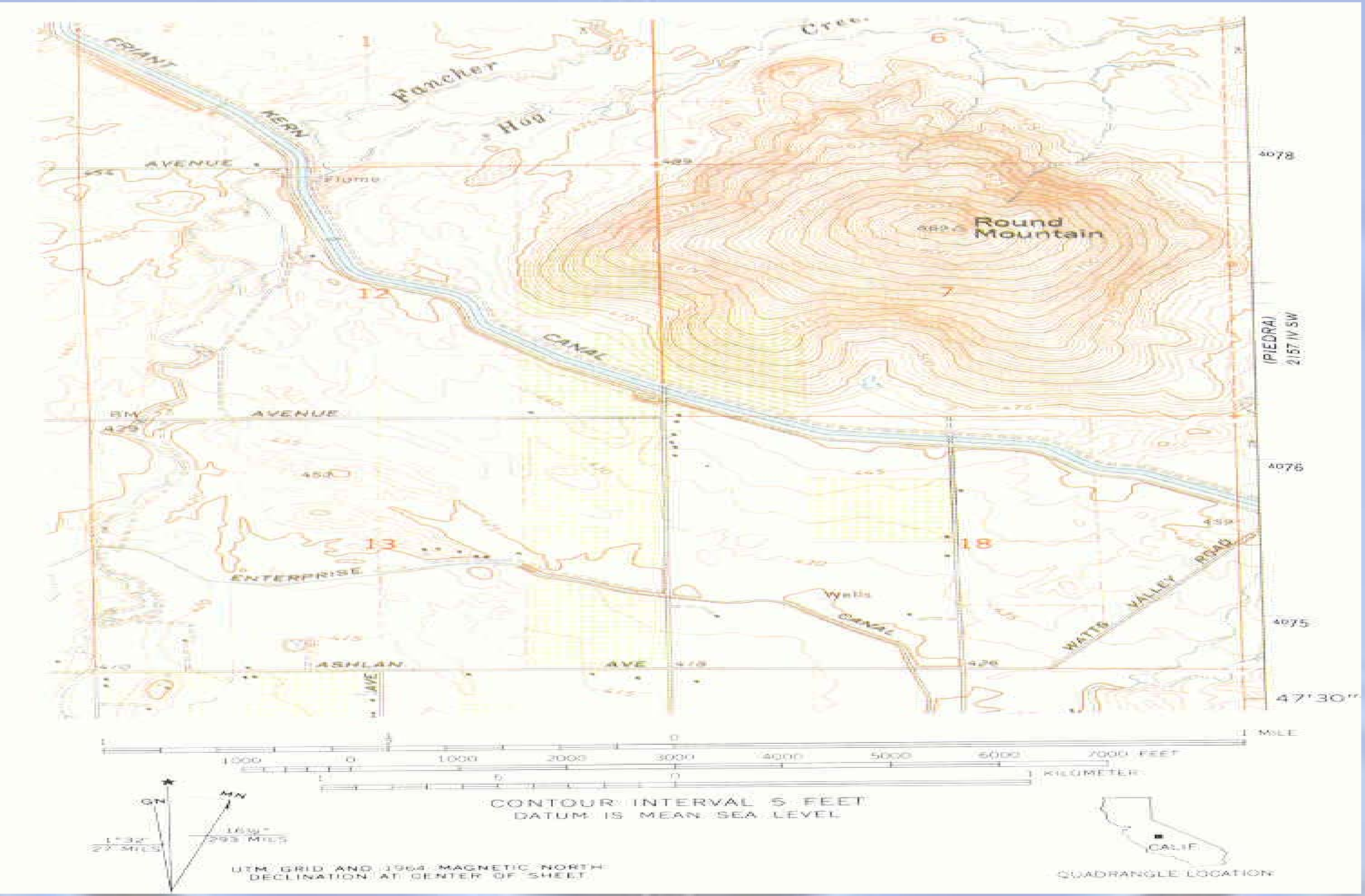


Figure 3.1: Topographic maps are useful to drilling contractors because they indicate the nature of the terrain, the presence of streams, and lakes, and the location of highways, buildings and railroads.

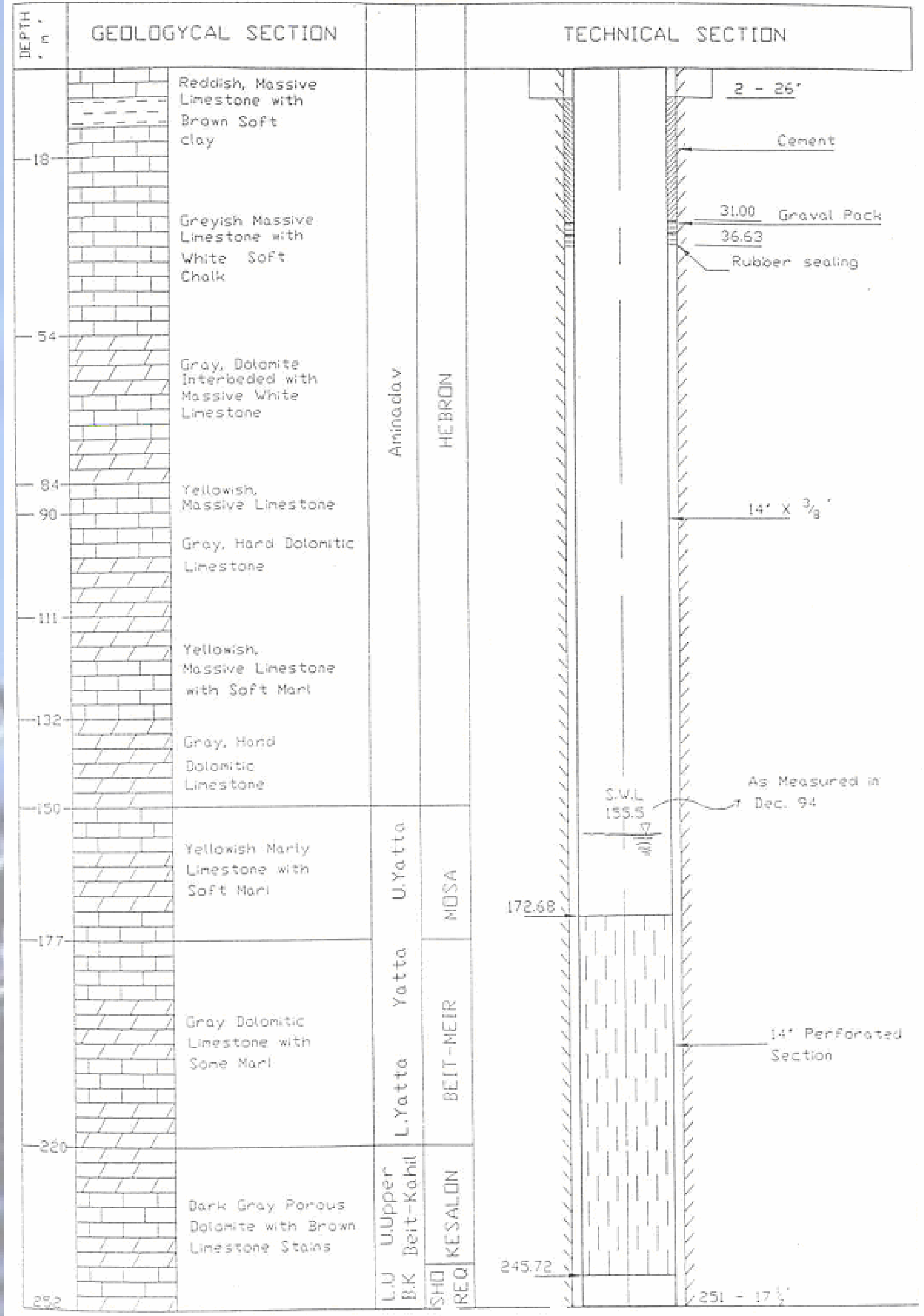


Figure 3.2 Vertical Geological section and technical section for Ein Samia Well (ESW2a)

3 Desk Studies and Preliminary Field Reconnaissance

Topographical area like rivers, wadi intersection and coastal areas may indicate the presence of groundwater;

The slope of the terrain shown on the map usually indicates the direction of shallow groundwater flow.

Geological borehole logs are mainly compiled on the basis of rock samples (geotechnical assessments, oil and gas exploration, … etc) (see Figure 3.2)

The logs normally consist of written descriptions of the geology (lithological description of rock types) (see Figure 3.2)

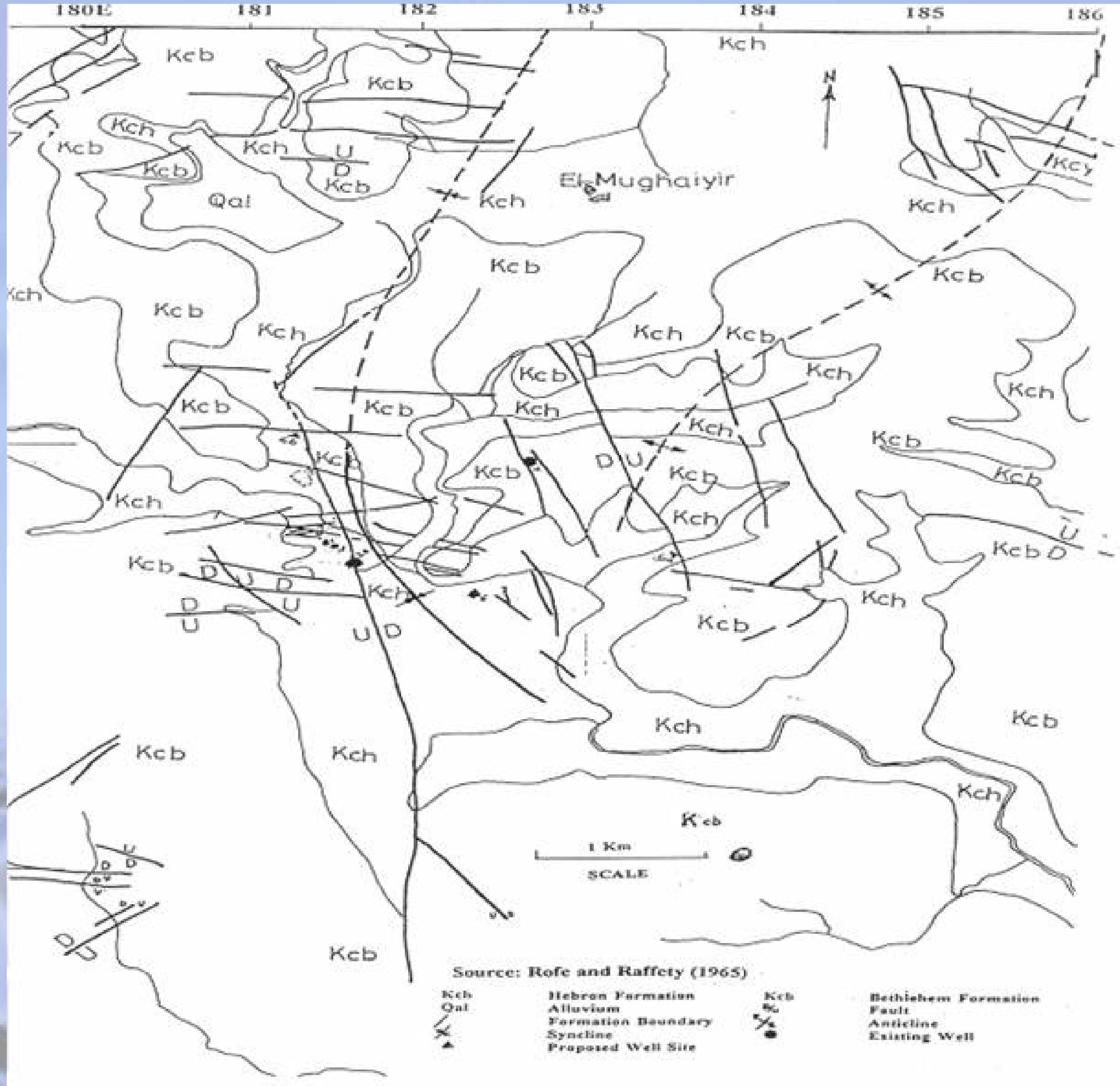


Figure 3.3 Geological Map of the Ein Samia Area

3 Desk Studies and Preliminary Field Reconnaissance

3.2 Hydrometeorological Methods

- When precipitation over evaporation is large then the recharge into the groundwater basin is large (that is when the geological formations area sufficiently permeable)

3 Desk Studies and Preliminary Field Reconnaissance

- **Springs indicate the presence of groundwater resources**

- Springs issue as a result of contact between limestone and chalk (or shale or marl) indicate that one rock type acts as the permeable groundwater supplying formations and the other as the impermeable rock forcing the water to land surface.
- Springs at fault zones: if the fault zone acts as an impermeable barrier, water levels upstream will rise (shallow water levels) and springs may issue upstream. This indicates that the water levels downstream are likely to be deep and thus reducing the possibility of groundwater exploitation.
- Springs flow is in fact groundwater discharge from related permeable formations. Depending on the amount of groundwater recharge one can generally state that the larger the spring the larger is the groundwater basin which contributes to spring flow.
- By considering a geological map together with spring flow records, the potential of the local aquifer in the investigated area can be identified.

3 Desk Studies and Preliminary Field Reconnaissance

- **Wadis and Discharges**

- If the pattern of a wadi runoff is dense, then the permeability of the (underneath) formations is low. Most of the precipitation will become surface runoff thereby creating this dense pattern.

- When the pattern is not very dense then the permeability of the formation is high: much of the precipitation will infiltrate and there will be hardly any surface runoff to create a dense pattern. Thus, these wadis are major sources of groundwater pollution should the wadis become contaminated

3 Desk Studies and Preliminary Field Reconnaissance

3.3 Available Groundwater Data

- **Geophysical reports**: identify sections with interpreted resistivities;

- **Well site reports**: you may find geological logs, geophysical logs, water sample analysis, well design, pumping test data, groundwater level records, pumping rate data … etc;

- Maps and sections;

- Groundwater assessment reports;

3 Desk Studies and Preliminary Field Reconnaissance

3.4 Satellite Imagery Studies

- Satellites circling around the earth take pictures of the earth surface (see **Figure 3.4**). The **full light spectrum** may be used when taking these pictures or certain wave lengths of the spectrum may be selected. Groundwater related features on satellite pictures can be detected by bare eye and by using a **stereoscope**.

- The best known picture are the **LANDSAT** images taken by satellites launched by the USA and the **SPOT** images produced by satellites brought into orbit by France.

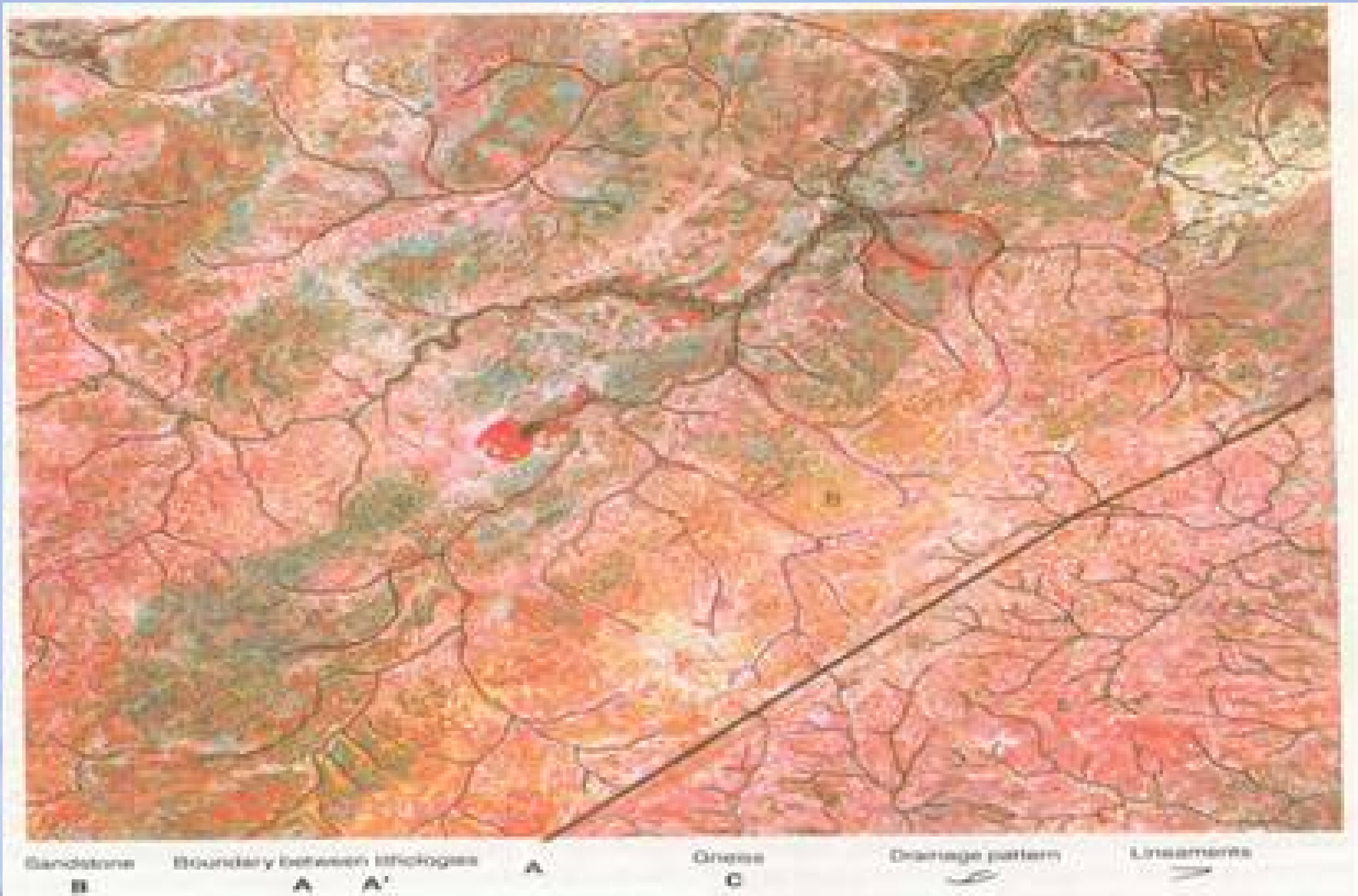


Figure 3.4 Computer-enhanced LANDSAT color composite of Bobo-Dioulasso Area, upper volta, West Africa. Acquired on March 31, 1976.

3 Desk Studies and Preliminary Field Reconnaissance

3.4 Satellite Imagery Studies

- **Interpretations**

- ✓ Satellite images are very handy tools to obtain a regional overview of the geology.
- ✓ The images can be used to get an impression on the regional drainage system.
- ✓ Combining the geological and surface water information, a hydrogeological assessment of the “imaged area” can be made.
- ✓ The images can be used to identify lineaments extending over several tens or even hundreds of kilometers.

3 Desk Studies and Preliminary Field Reconnaissance

3.5 Aerial Photography Analysis and Fracture Traces Technique for Sitting a Well

General Notes

- Aerial photos are taken from an aeroplane. The plane follows a flight path covering completely the selected area. The photos taken are partly overlapping each other in order to be able to obtain 3-dimensional view with a stereoscope. The instrument consists of two sets of mirrors and lenses which produce the three dimensional view (see Figure 3.5).

3 Desk Studies and Preliminary Field Reconnaissance

Figure 3.5 Groundwater related features on satellite picture can be detected by bare eye and by using a **Stereoscope**.

3 Desk Studies and Preliminary Field Reconnaissance

3.5 Aerial Photography Analysis and Fracture Traces Technique for Sitting a Well

- Stratgraphical layering of consolidated sedimentary rocks can be observed as ‘bands’ on the photos.
- Shales, mudstones and siltstones can be recognized by ‘bands’ of darkgrey to black tones.
- Not very permeable carbonate rocks such as limestone and dolomites can be identified by their massive banding and usually lighter tones.
- Permeable limestones and dolomites are often identified by the presence of karstic features including **sinkholes** (see **Figure 3.6**).

3 Desk Studies and Preliminary Field Reconnaissance

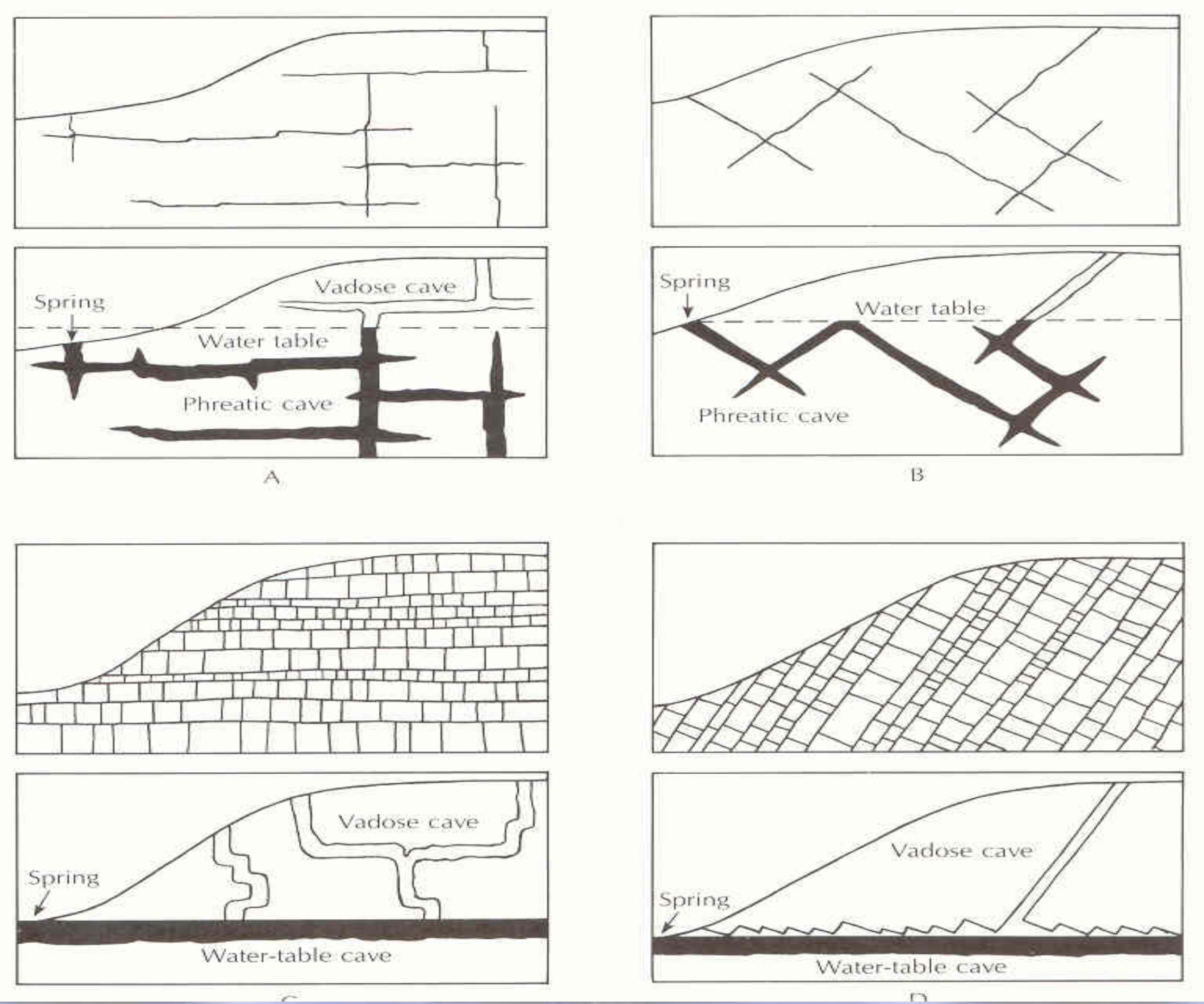


Figure 3.6 Effects of fissure density and orientation on the development of caverns

3 Desk Studies and Preliminary Field Reconnaissance

- River alluvial deposits (gravel, sands, clays and silt) can be recognized from the presence of river terraces.
- From above, the identified on the aerial photos can be classified as aquifers, aquitards, … etc.
- The type, location, and size of the aquifers present in the area give an indication of the groundwater potential.
- In the **saddles and crests of large folds**, fissures have often formed as a result of lateral issues.
- The presence of a spring is indicated by dense vegetation.
- Groundwater is known to be concentrated in fracture zone found in many different rock types (see **Figure 3.7**).

3 Desk Studies and Preliminary Field Reconnaissance

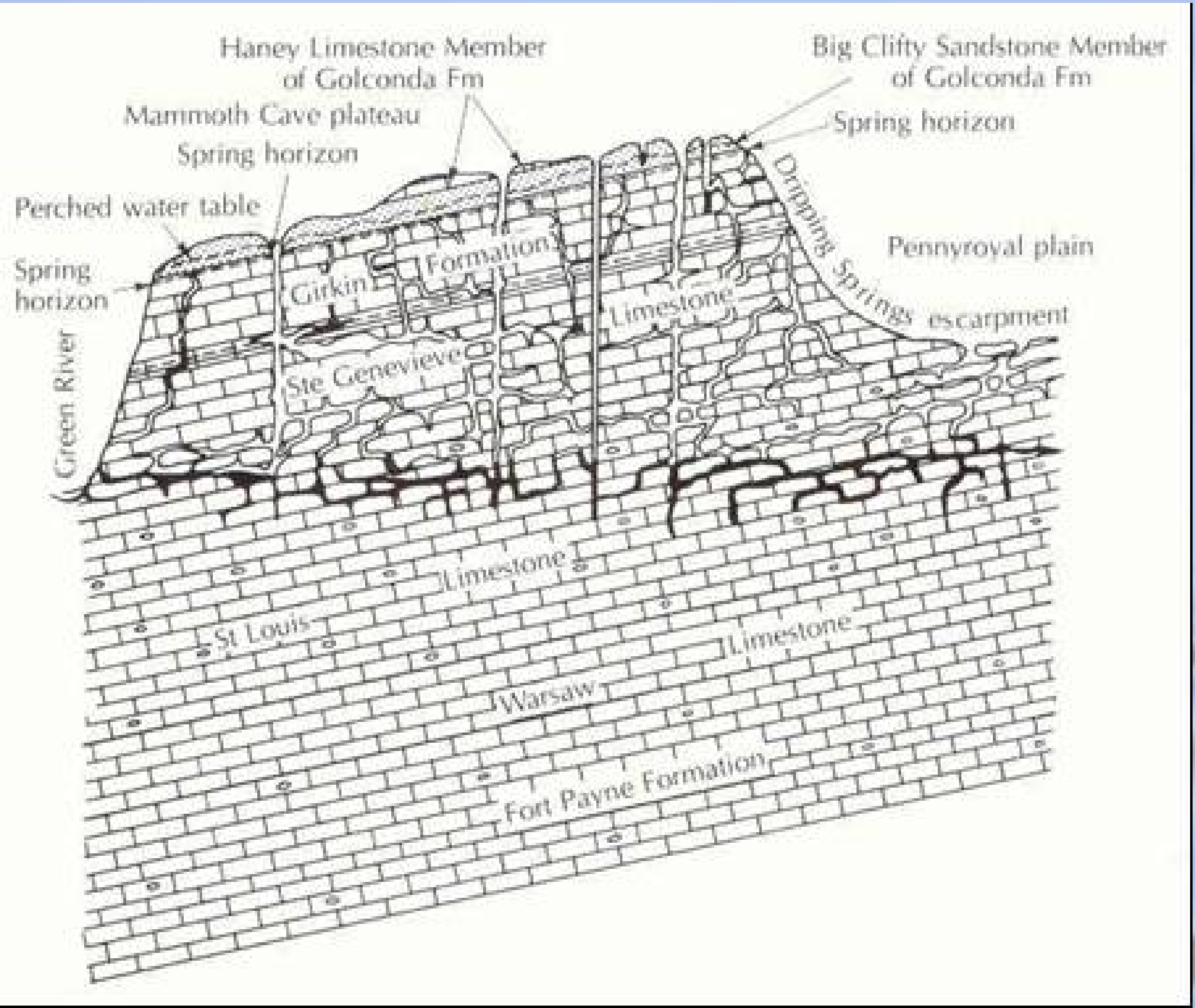


Figure 3.7 Groundwater flow in the carbonate aquifer is from south to north

3 Desk Studies and Preliminary Field Reconnaissance

- In the identification of fracture traces on aerial photographs, a low magnification stereoscope is generally used. (60% stereoscopic overlapping, 1:20,000 scale. 20% overlapping between flight lines).
- Possible fracture traces are indicated by drawing on the photograph. One problem in identification is the confusion of linear features of human origin (fences, roads, … etc.) with natural linear feature. Following the mapping of linear features on air photos, it is necessary to make a field check.

3 Desk Studies and Preliminary Field Reconnaissance

- In crystalline rock areas, high-yield wells are generally associated with fracture traces which may not be necessarily correspond to topographic lows.
- A **zig-zag** offsets in the regional valley alignment assure well developed fracture traces.
- Openings in the fault zones and at the weathered parts of joint systems may indicate exploitable groundwater resources.

Fracture Traces and Lineaments

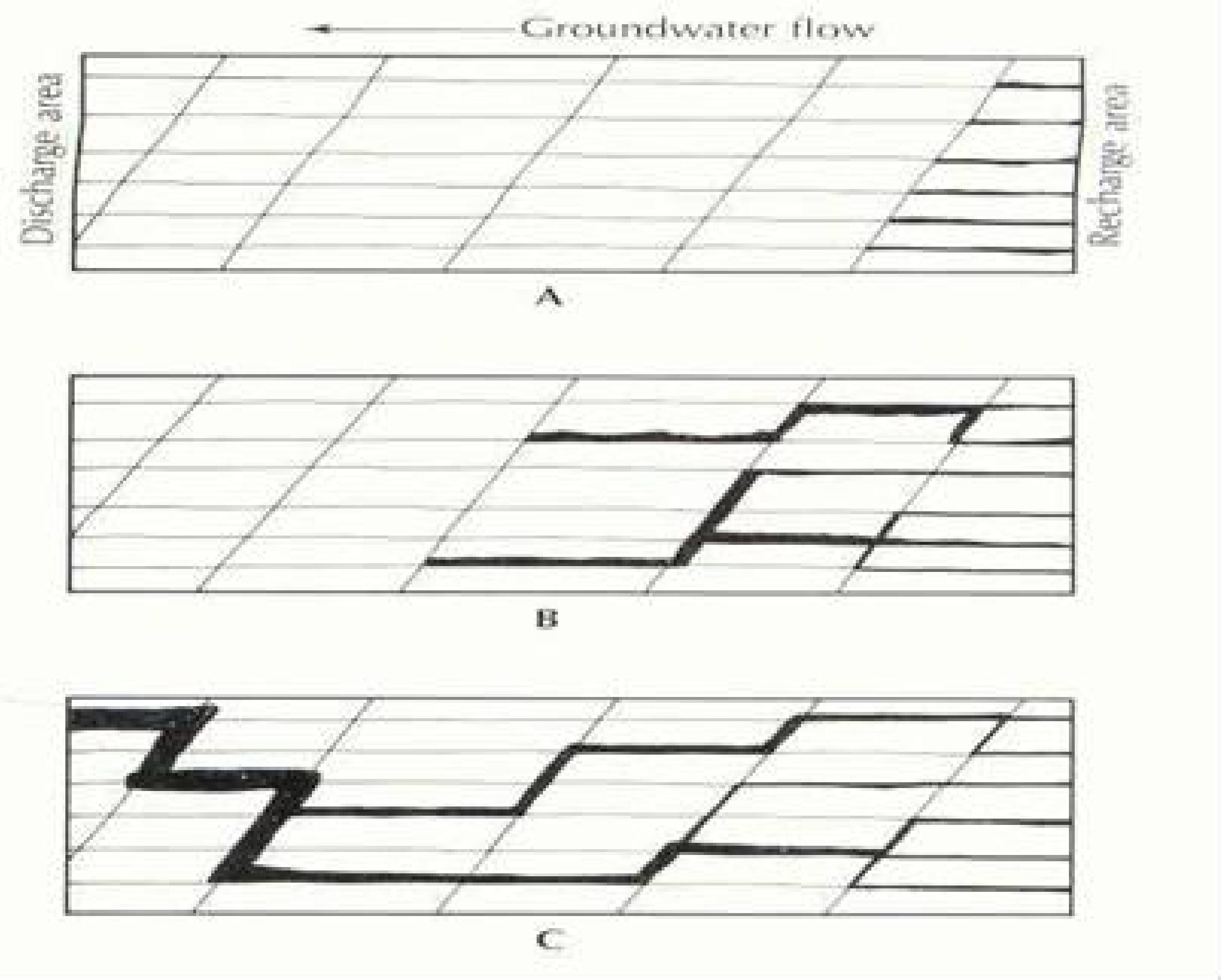
- **Fracture traces** are located by study of linear features on aerial or satellite photographs.
- Natural linear features from **300 m** to around **1500 m** in length are **fracture traces**.
- Natural linear features **greater than 1500 m** in length are termed **lineaments**. Some lineaments are up to 150 km long.
- **Fracture traces** are surface expressions of joints, zone of joint concentration or faults.

Fracture Traces and Lineaments

- On air photos, natural linear features consist tonal variation in soils:
  - Alignment of vegetation patterns;
  - Straight stream segments or valleys;
  - Aligned surface depressions;
  - Gaps in ridges;
- It is generally believed that the joint sets tend to be perpendicular. They are known to extend to a depth of 1000 m at one Arizona location as an example (see Figure 3.8).

Fracture Traces and Lineaments

Figure 3.8 Growth of a carbonate aquifer drainage system starting in the recharge area and growing toward the discharge area. **A.** At first, most joints in the recharge area undergo solution enlargement. **B.** As the solution passages grow, they join and become fewer. **C.** Eventually, one outlet appears at the discharge zone.

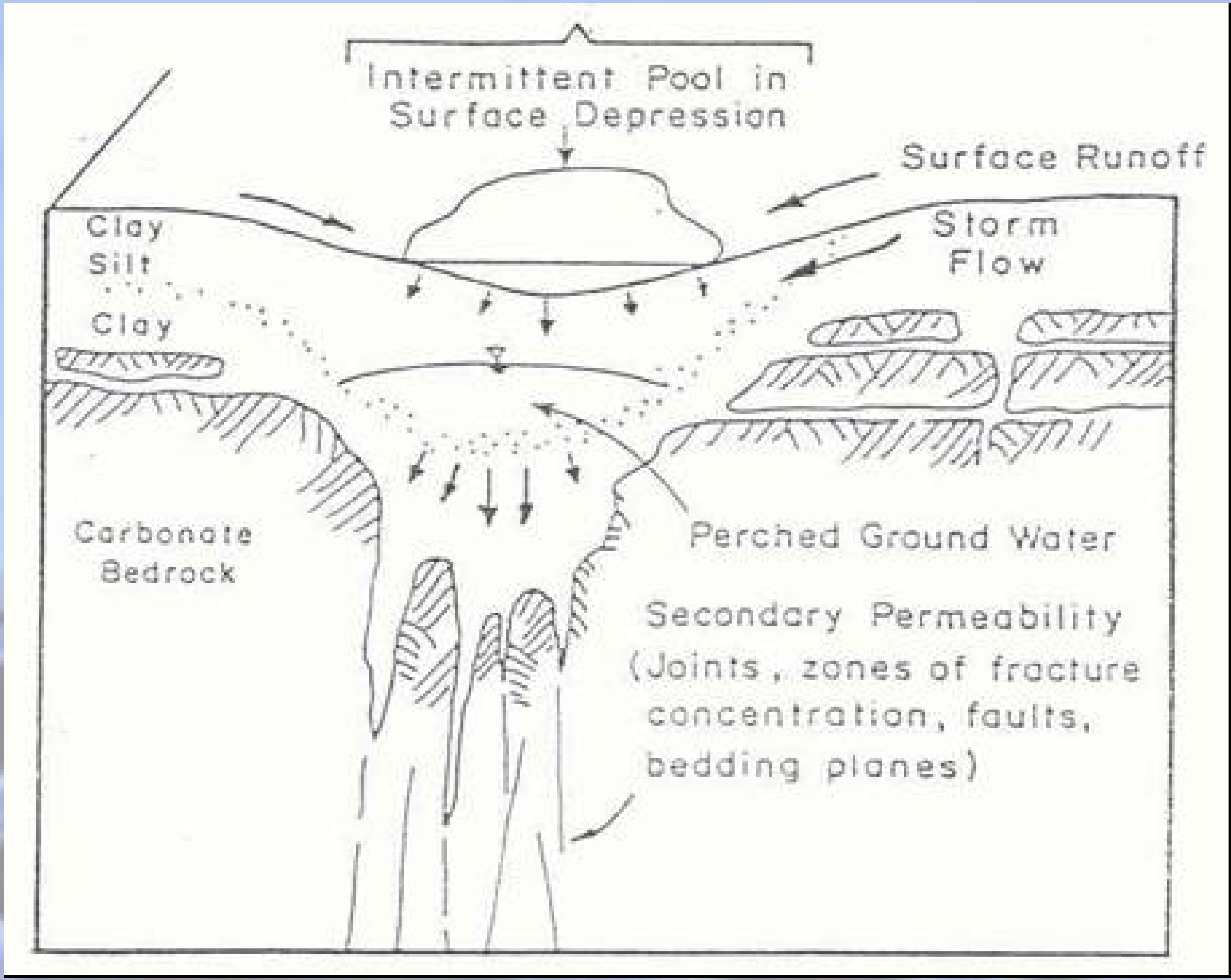


Fracture Traces and Lineaments

- **Fracture zones** are less resistant to erosion. Hence, valley and stream segments tend to run along fracture zone.
- **Fracture traces and lineaments** appear to have their greatest utility in rocks where secondary permeability and porosity dominate and where intergranular characteristics combine with secondary openings influencing weathering and soil water and groundwater movement. Fracture traces and lineaments are considered surface manifestations of vertical to near-vertical zone of fracture concentration.
- **Fracture traces** may be related to regional tectonic activity. They tend to be oriented at a constant angle to the regional structural trend. However, the orientation appears to be independent of local folds.
- **Fracture traces** in carbonate rocks are typically areas of solution. Aligned sinkhole or surface sags are typical surface expressions (see **Figure 3.9**).

Fracture Traces and Lineaments

Figure 3.9 Differential weathering along secondary openings in bedrock result in the surface sag and depressions that concentrate surface runoff perched ponds, groundwater lenses and increased infiltration and solution of bedrock.



Fracture Traces and Lineaments

- Lineaments are known to cut across rocks of many ages and cross folds and faults (see **Figure 3.10**).

Figure 3.10 Lineaments and fractures map of Ein Samia

Fracture Traces and Lineaments

- Lineaments have been observed to be parallel to the major joint sets in flat-lying or gently dipping strata, but this is not the case if the strata are steeply dipping.
- If surface area separated by major faults, the individual fault blocks may have fracture traces of different orientation.
- The majority of fracture traces control is evident have been described as having a “stair-step” pattern.

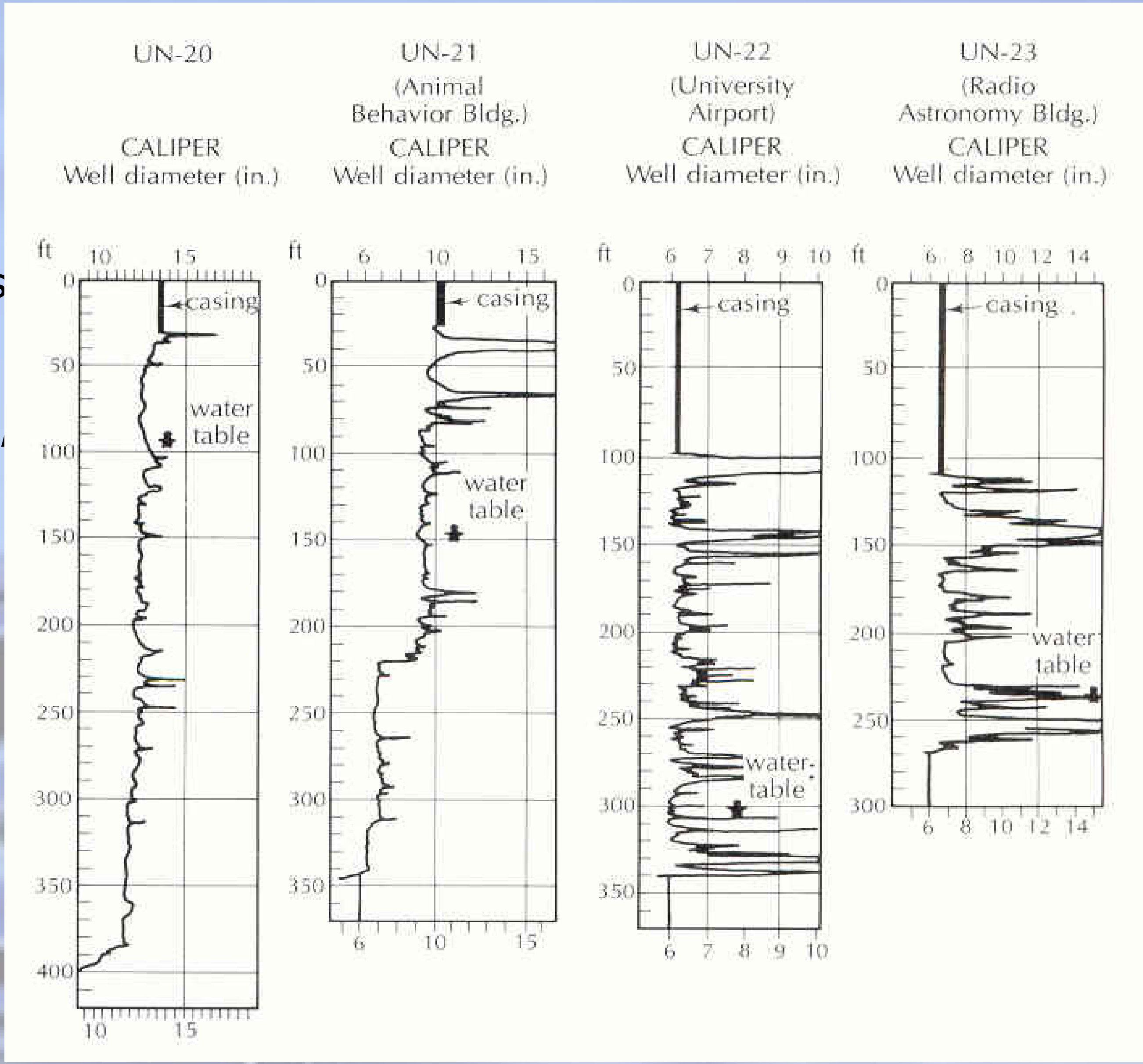
Fracture Traces and Lineaments

- Statistical studies of wells in carbonate terrane have shown that those located on fracture traces, either intentionally or accidentally have a greater yield than those not on fracture traces.
- Fracture traces are known to reveal narrow zones (2 to 20 m wide) suitable for groundwater prospecting, high permeability and porosity avenues 10 to 1000 times that of adjacent strata.
- Caliper logs of wells on fracture traces in carbonate-rock terrane showed many more cavernous opening and enlarged bedding planes than logs of those wells drilled in interfracture areas (see Figure 3.11).

Fracture Traces and Lineaments

Figure 3.11

Caliper logs of wells in an area of carbonate rocks in central Pennsylvania. Wells UN-20 and UN-21 were drilled in interfracture area, Wells UN-22 and UN-23 were located on fracture traces



Fracture Traces and Lineaments

- Fracture traces technique is used to locate high-yield wells (see **Figure 3.12**).

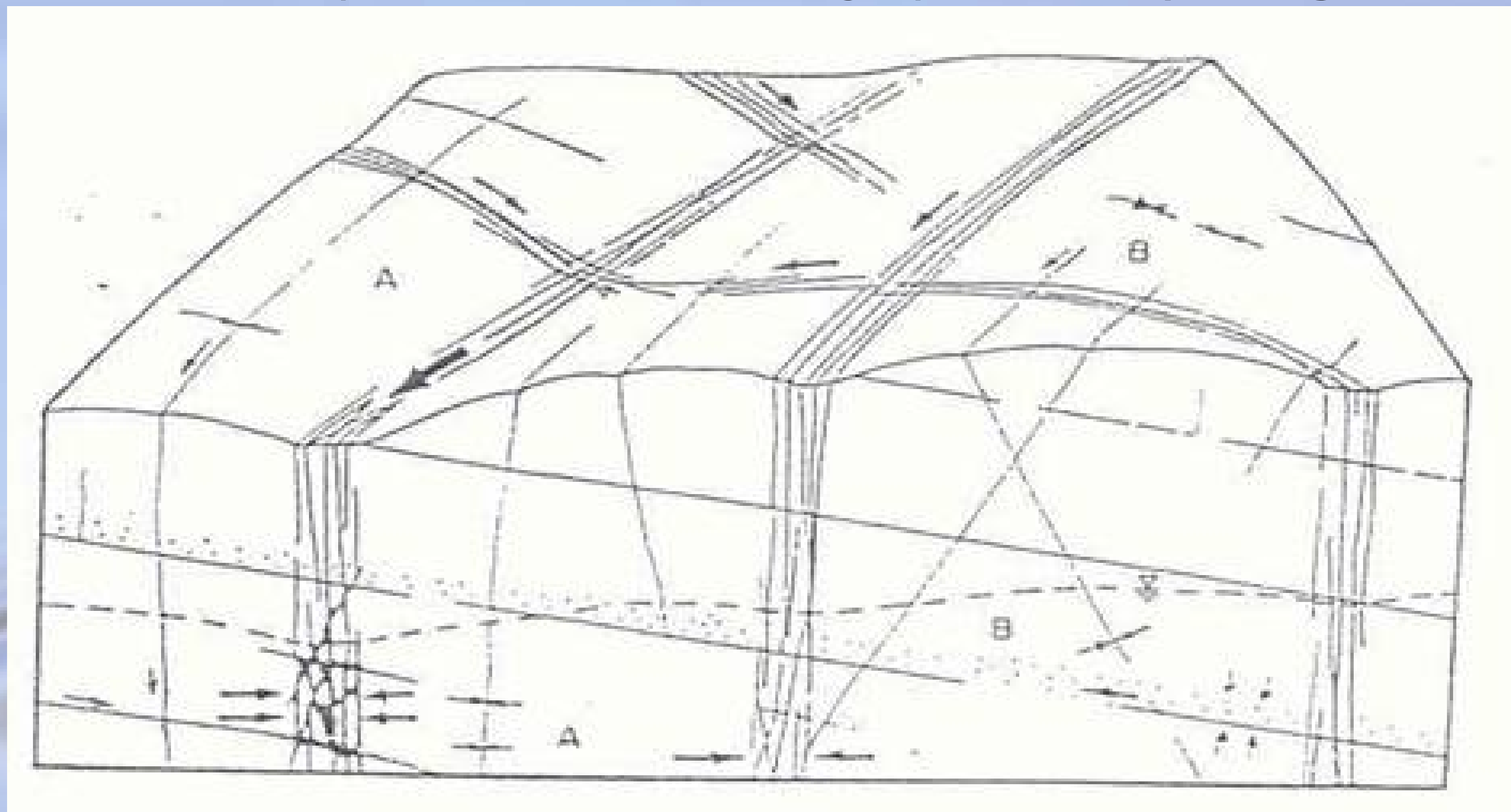


Figure 3.12 Massive bocks of carbonate rock interlaced with high avenues of permeability development along zones of fracture concentration. Transmission and storage properties afforded by intergranular and vugular openings within selected beds, bedding plane partings, joints and fault zones.

Fracture Traces and Lineaments

- **The problems with lineaments and fracture traces**:
  - ✓What are the depth and width of lineaments and fracture traces!!;
  - ✓Accurate location on the ground!;
  - ✓Well yield depends also on well radius, well depth and diameter, casing length, method of drilling, degree of well development, depth to water table, presence of various changes of rock type, dip of beds, topographical settings, rock type, type of fold structure, presence and type of joints, number and type of zones of fracture concentration, … etc.;
- If fracture traces are absent from a property on which water is required, the use of expert advice would not help except to point out the increased risk of obtaining a low yield.

Well Sitting

- Well sitting is important prior to any water resources development project.
- Site studies are necessary prior to construction of projects as sanitary landfills, land-treatment systems for wastewater, surface mines, power plants, artificial-recharge lagoons, nuclear-waste repositories, dams and reservoirs.
- The greatest yields come from wells located at the **intersection** of two fracture traces or more (see **Figure 3.13**).

Well Sitting

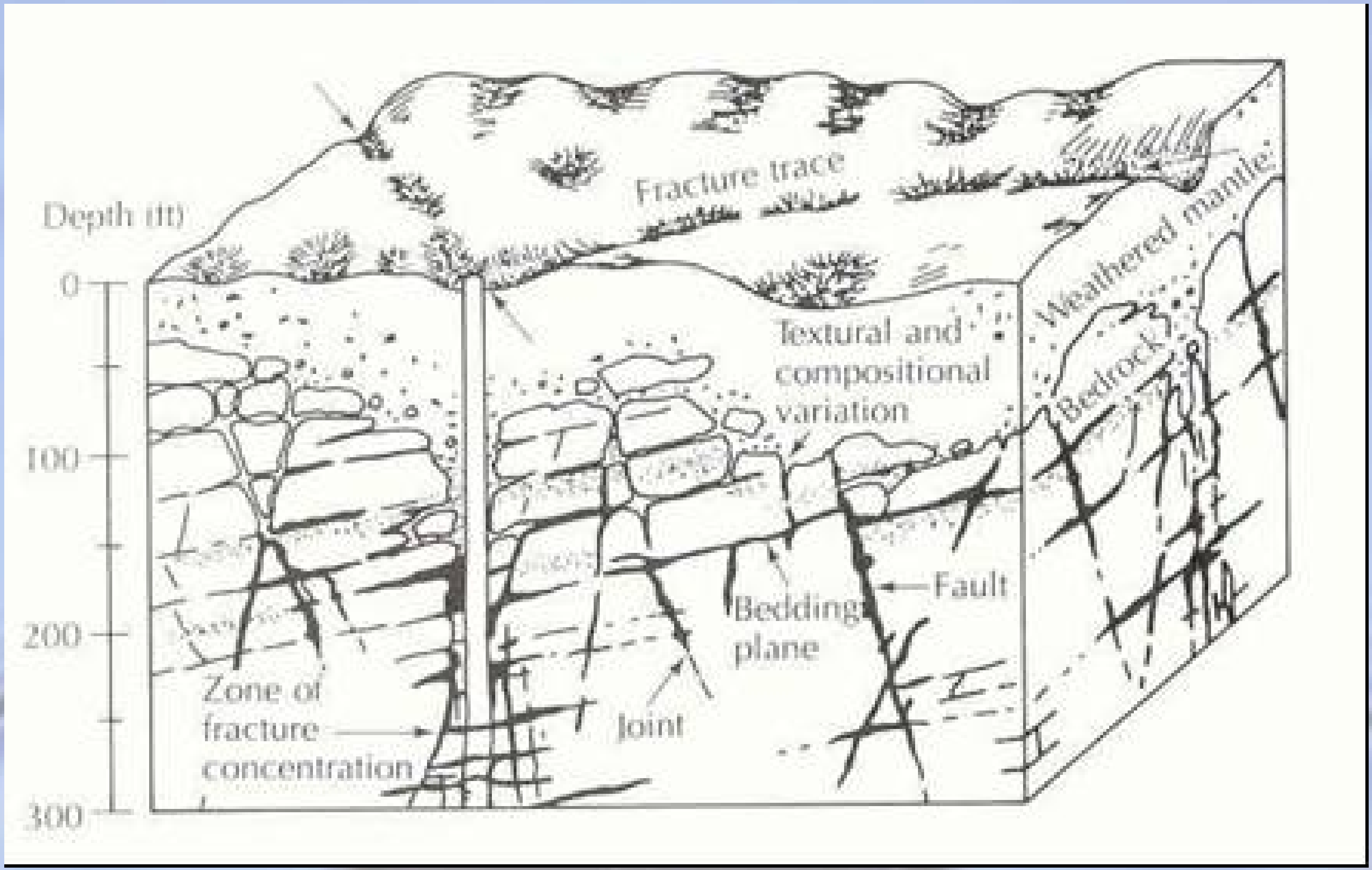


Figure 3.13 Concentration of ground water along zones of fracture concentrations in carbonate rock. Wells that don't intercept an enlargement fracture or a bedding plane may be dry, thus indicating a discontinuous water table.

Well Sitting

- Some investigations failed to correlate high well yields and well locations with respect to fracture traces sites in carbonate rocks because:

  - ✓ Fracture traces were not mapped correctly;
  - ✓ The width of influence of fracture trace was not known;
  - ✓ Wells did not hit the center lines of fracture traces;

Well Sitting

- Some variability in yield remains for wells located on lineaments due to the fact that joints, fractures, bedding plane partings and secondary weathering is not equally well developed beneath lineaments and an element of chance and variability of penetrating openings will always remain when drilling on fracture concentration. Variable fracture development has been observed in cross-sectional views.

- The same variability of fracture and joint development beneath lineaments has not been documented but it is recommend that all lineament well sites also located on fracture trace intersections or on single fracture traces to increase the probability of penetrating the maximum number of secondary openings.

Well Sitting

- Fracture-trace analysis is also very useful in determining the locations of groundwater monitoring wells. Because groundwater flow preferentially follows the most permeable pathway, monitoring wells should be located on fracture traces.

- It should be noted that wells located in valley bottom settings show higher yields than wells located on adjacent uplands (see **Figure 3.14**).

Well Sitting

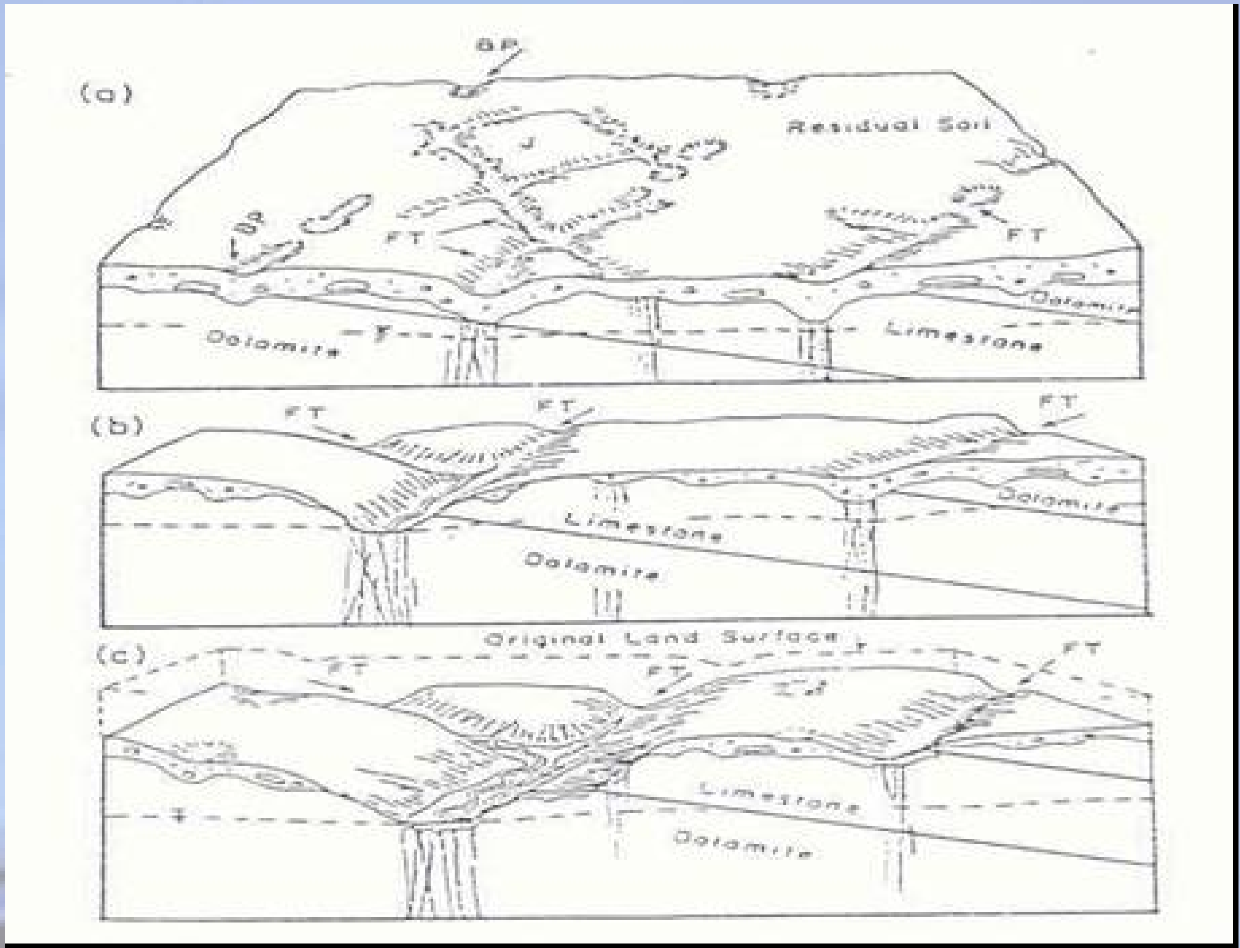


Figure 3.14 Valley development localized along strike of exposed limestone but later incised into underlying gently dipping dolomite. In **(a)** differential weathering along bedding planes (BP), joints (J), and zones of fracture concentration (FT) produce surface sags and depressions that concentrate surface runoff, facilitates infiltration and erosion of residual soils. In **(b)** weathering and erosion are enhanced along soluable limestone and a master drainage system is fixed in its position. Increased runoff facilitates erosion until groundwater drains are established. In **(c)** the land surface is lowered and the valley is incised into less soluable dolomite bedrock.

Well Sitting

- The **poorest sites** were expected within interfracture trace areas, on **upland**, on **synclinal troughts**, where bedrocks dips were **in excess of 30°**, the water table is deep and shale was exposed (see **Figure 3.15**).

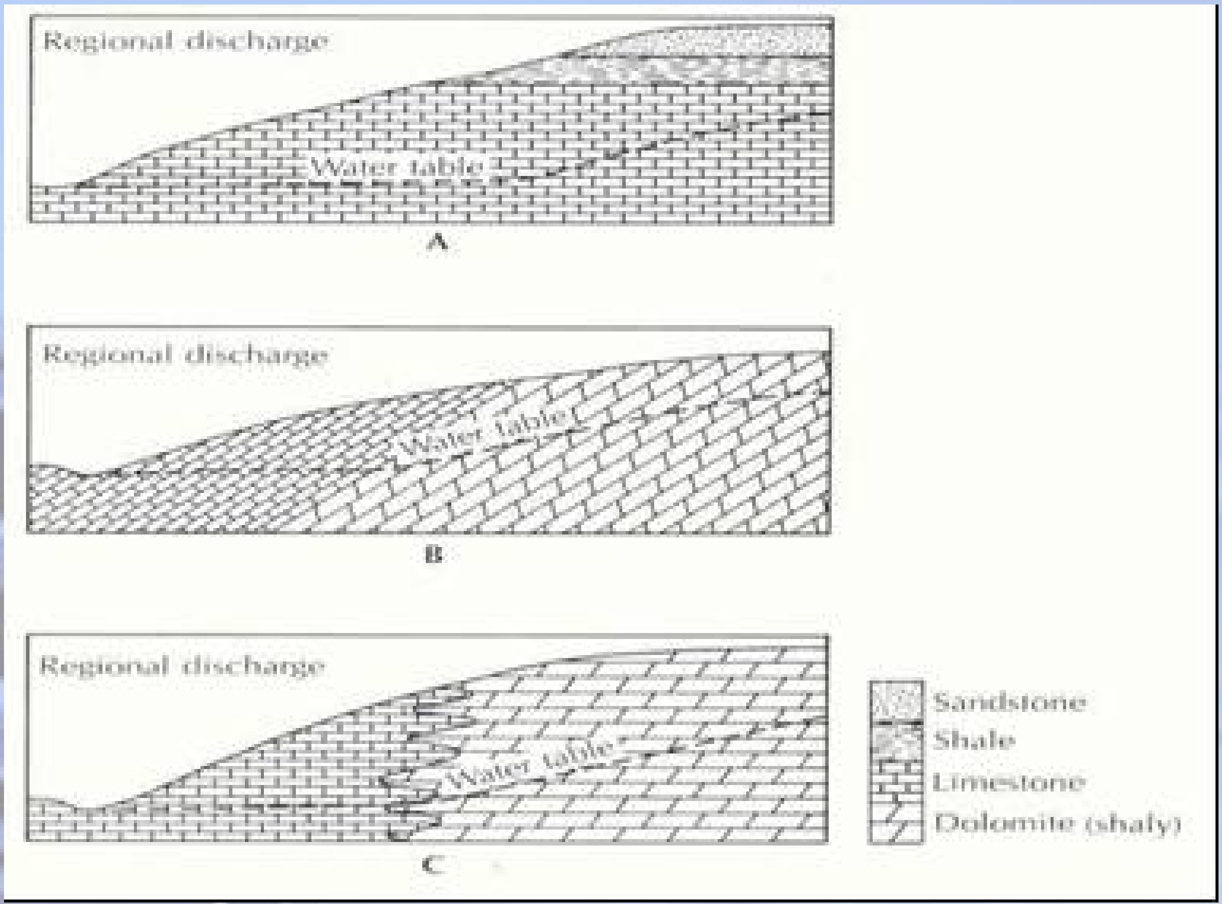


Figure 3.15

Geologic conditions resulting in a difference in hydraulic conductivity and, hence, a difference in the water-table gradient.

Choosing a Well Site

- **Where Shall We Drill a Well?**
  - ✓ Water will not flow uphill;
  - ✓ Water will not flow through clay or dense rock!!!;
  - ✓ Water flows freely through the fissures and between stones;
  - ✓ On a single fracture trace or intersection of two or more fracture traces;
  - ✓ Wells drilled in anticlines are better producers than wells drilled in synclines;
  - ✓ Wells in beds dipping at less than 15° had higher yields than wells in steeper beds;

Choosing a Well Site

- **What other considerations should be taken in sitting a well.**

Your choice of well site will affect the safety and performance of your well. As you examine various sites, remember to consider any future development plans for your farm or acreage such as barns, storage sheds and bulk fuel tanks. You must also consider provincial regulations that dictate well location.

Most contaminants enter the well either through the top or around the outside of the casing. Sewage or other contaminants may percolate down through the upper layers of the ground surface to the aquifer. The following criteria are intended to prevent possible contamination of your well and the aquifer. It is both your and the driller's responsibility to ensure that:

Choosing a Well Site

- The well is accessible for cleaning, testing, monitoring, maintenance and repair;
- The ground surrounding the well is sloped away from the well to prevent any surface run off from collecting or ponding;
- The well is up-slope and as far as possible from potential contamination sources such as septic systems, barnyards or surface water bodies;
- The well is not housed in any building other than a bona fide pumphouse. The pumphouse must be properly vented to the outside to prevent any buildup of dangerous naturally occurring gases
- The well is not located in a well pit.

Choosing a Well Site

- **Minimum distance requirements.**

Provincial regulations outline minimum distance requirements as follows. Equivalent imperial distances in feet are rounded up to nearest foot. The well must be:

- ✓ 10 m (33 ft.) from a watertight septic tank;
- ✓ 15 m (50 ft.) from a sub-surface weeping tile effluent disposal field or evaporation mound;
- ✓ 50 m (165 ft.) from sewage effluent discharge to the ground;
- ✓ 100 m (329 ft.) from a sewage lagoon;
- ✓ 50 m (165 ft.) from above-ground fuel storage tanks;
- ✓ 3.25 m (11 ft.) from existing buildings;

Choosing a Well Site

- **Minimum distance requirements.**

  - ✓ 2 m (7 ft.) from overhead power lines if: the line conductors are insulated or weatherproofed and the line is operated at 750 volts or less;
  - ✓ 6 m (20 ft.) from overhead power lines if the well: does not have a pipe and sucker rod pumping system has a PVC or non-conducting pipe pumping system has well casing sections no greater than 7 m (23 ft.) in length;
  - ✓ 12 m (40 ft.) from overhead power lines for all other well constructions;
  - ✓ 500 m (1,641 ft.) from a sanitary landfill, modified sanitary landfill or dry waste site.

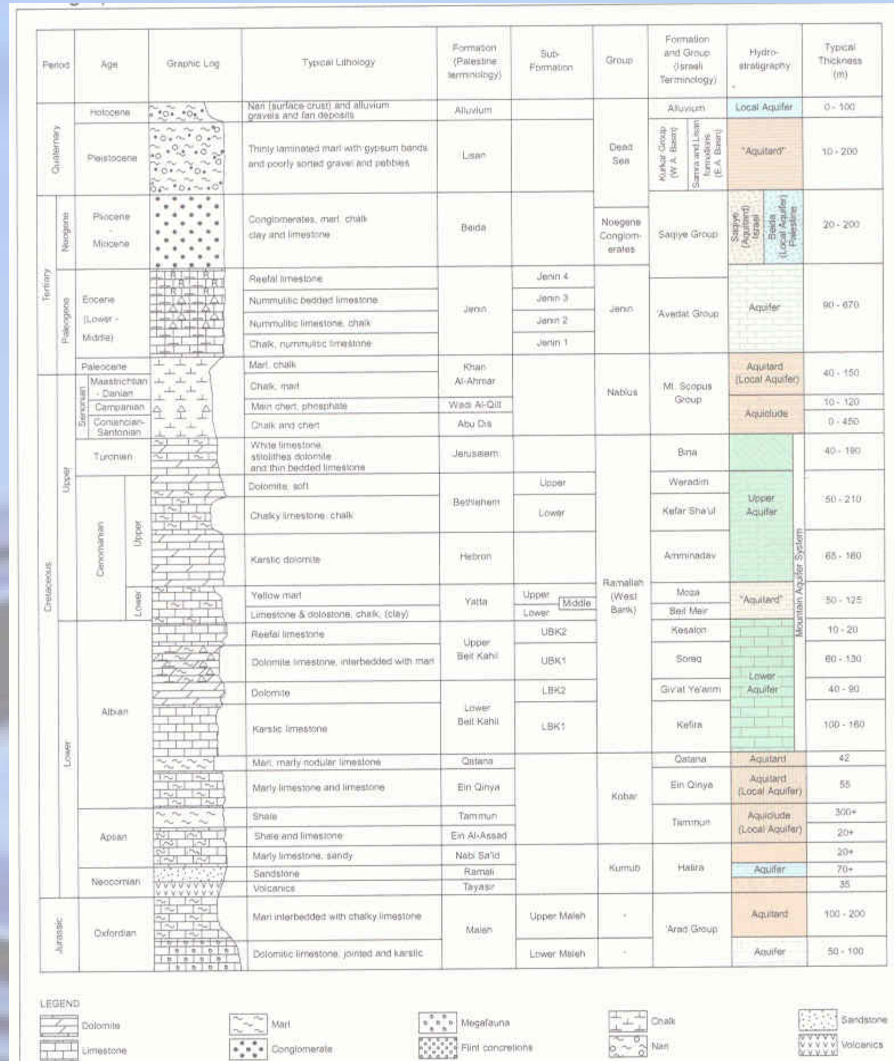
3 Desk Studies and Preliminary Field Reconnaissance

3.6 Hydrogeological Mapping and Well inventories

- Hydrogeological mapping is the study of rock types and drainage conditions in the field with emphasis on hydrogeological aspects (see **Figure 3.16**);

3 Desk Studies and Preliminary Field Reconnaissance

Stratigraphic section of the West Bank



Period	Age	Graphic Log	Typical Lithology	Formation (Palestine terminology)	Sub-Formation	Group	Formation and Group (Israeli Terminology)	Hydro-stratigraphy	Typical Thickness (m)
Quaternary	Holocene		Marl (surface crust) and alluvium gravels and fan deposits	Alluvium		Dead Sea	Alluvium	Local Aquifer	0 - 100
	Pleistocene		Thinly laminated marl with gypsum bands and poorly sorted gravel and pebbles	Lisan			Kurkar Group (W.A. Basin) / Samra and Lisan formations (E.A. Basin)	"Aquitard"	10 - 200
Tertiary – Neogene	Pliocene - Miocene		Conglomerates, marl, chalk clay and limestone	Beida		Noegene Conglom-erates	Saqiye Group	Saqiye (Aquitard) Israel / Beida (Local Aquifer) Palestine	20 - 200
Paleogene	Eocene (Lower - Middle)		Reefal limestone	Jenin	Jenin 4	Jenin	'Avedat Group	Aquifer	90 - 670
			Nummulitic bedded limestone		Jenin 3				
			Nummulitic limestone, chalk		Jenin 2				
			Chalk, nummulitic limestone		Jenin 1				
	Paleocene		Marl, chalk	Khan Al-Ahmar		Nablus	Mt. Scopus Group	Aquitard (Local Aquifer)	40 - 150
Cretaceous – Upper – Senonian	Maastrichtian - Danian		Chalk, marl						
	Campanian		Marl chert, phosphate	Wadi Al-Qilt				Aquiclude	10 - 120
	Coniancian-Santonian		Chalk and chert	Abu Dis					0 - 450
	Turonian		White limestone, stilolithes dolomite and thin bedded limestone	Jerusalem		Ramallah (West Bank)	Bina	Upper Aquifer (Mountain Aquifer System)	40 - 190
	Cenomanian – Upper		Dolomite, soft	Bethlehem	Upper		Weradim		50 - 210
			Chalky limestone, chalk		Lower		Kefar Sha'ul		
			Karstic dolomite	Hebron			Amminadav		65 - 160
	Cenomanian – Lower		Yellow marl	Yatta	Upper / Middle		Moza	"Aquitard"	50 - 125
			Limestone & dolostone, chalk, (clay)		Lower		Beit Meir		
Lower	Albian		Reefal limestone	Upper Beit Kahil	UBK2		Kesalon	Lower Aquifer	10 - 20
			Dolomite limestone, interbedded with marl		UBK1		Soreq		60 - 130
			Dolomite	Lower Beit Kahil	LBK2		Giv'at Ye'arim		40 - 90
			Karstic limestone		LBK1		Kefira		100 - 160
			Marl, marly nodular limestone	Qatana		Kobar	Qatana	Aquitard	42
			Marly limestone and limestone	Ein Qinya			Ein Qinya	Aquitard (Local Aquifer)	55
	Aptian		Shale	Tammun			Tammun	Aquiclude (Local Aquifer)	300+
			Shale and limestone	Ein Al-Assad					20+
			Marly limestone, sandy	Nabi Sa'id		Kurnub	Hatira		20+
	Neocomian		Sandstone	Ramali				Aquifer	70+
			Volcanics	Tayasir					35
Jurassic	Oxfordian		Marl interbedded with chalky limestone	Maleh	Upper Maleh	-	'Arad Group	Aquitard	100 - 200
			Dolomitic limestone, jointed and karstic		Lower Maleh	-		Aquifer	50 - 100

3 Desk Studies and Preliminary Field Reconnaissance

Northern West Bank cross section

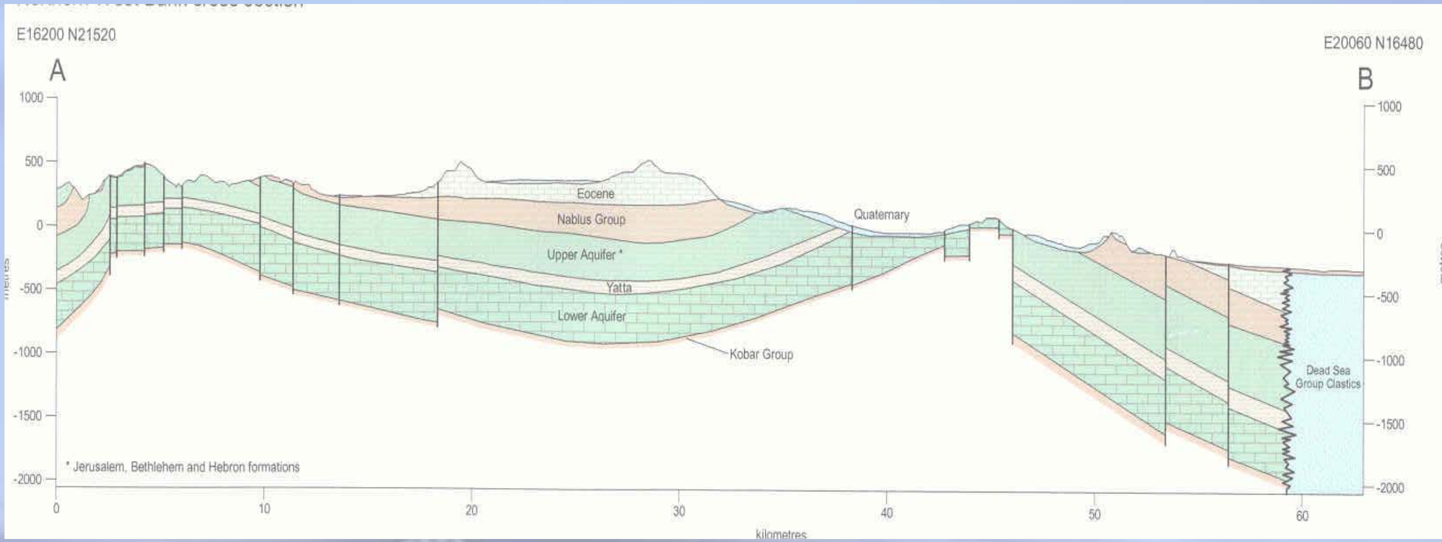
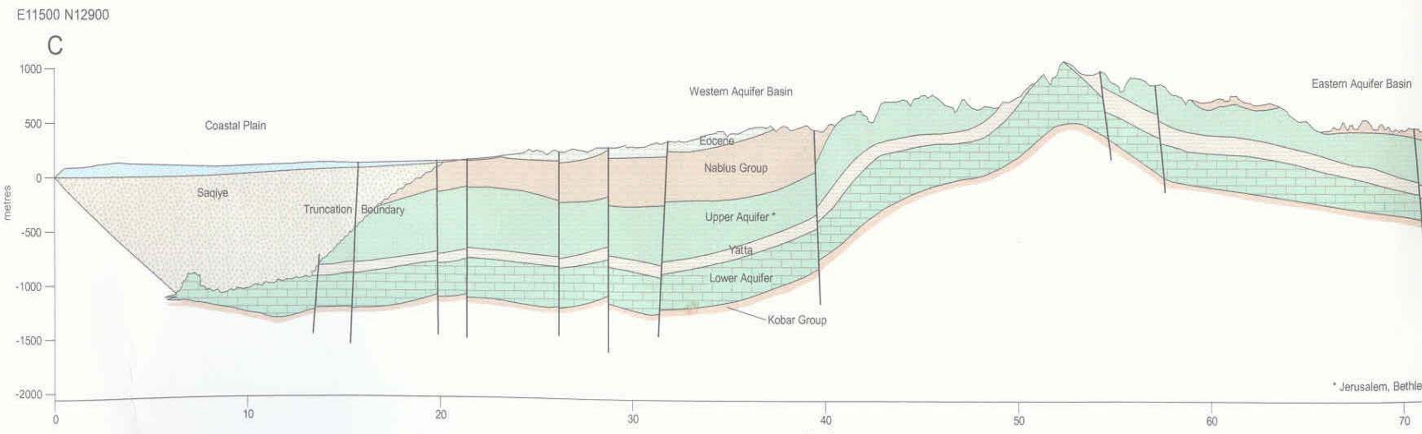


Figure 3.16 Hydrogeological Map of the West Bank

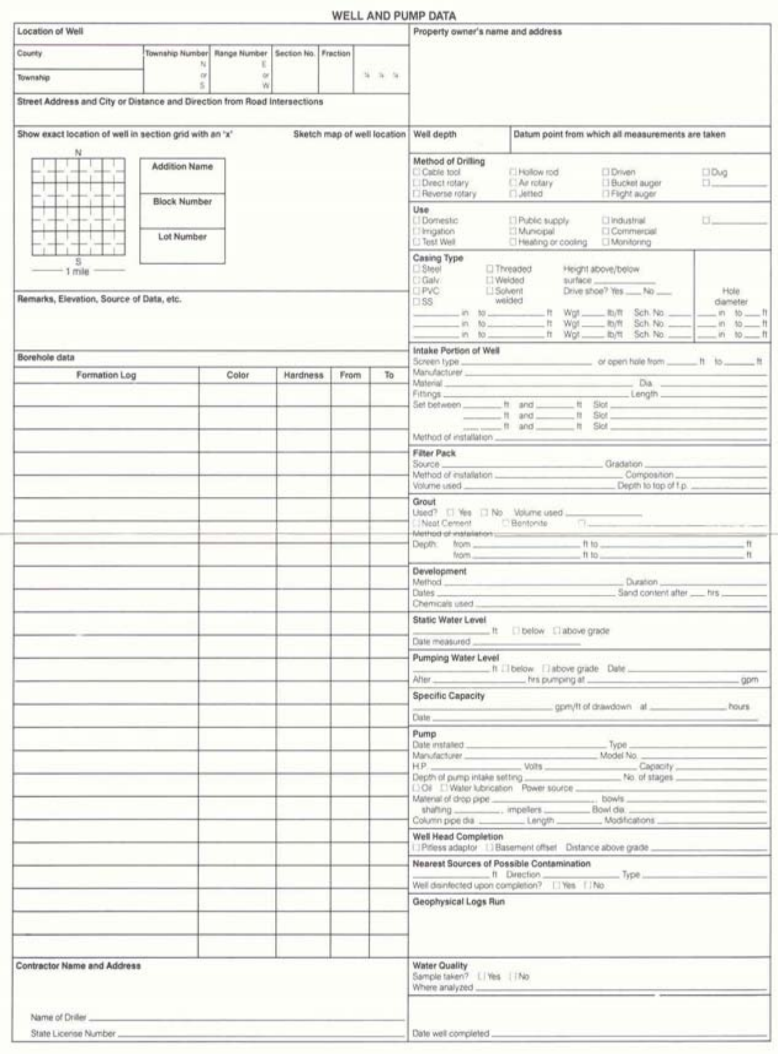
Southern West Bank cross section



3 Desk Studies and Preliminary Field Reconnaissance

- Well inventories is the preparation of inventories of well existing in an area while aiming to analyze the local hydrogeological conditions (see Table 3.1);

Table 3.1 Well and Pump Data



WELL AND PUMP DATA

Location of Well

County | Township Number N or S | Range Number E or W | Section No. | Fraction | ¼ ¼ ¼

Township

Street Address and City or Distance and Direction from Road Intersections

Show exact location of well in section grid with an 'x' — N — S — 1 mile

Addition Name

Block Number

Lot Number

Sketch map of well location

Remarks, Elevation, Source of Data, etc.

Borehole data

Formation Log	Color	Hardness	From	To

Contractor Name and Address

Name of Driller

State License Number

Property owner's name and address

Well depth

Datum point from which all measurements are taken

Method of Drilling
☐ Cable tool ☐ Hollow rod ☐ Driven ☐ Dug
☐ Direct rotary ☐ Air rotary ☐ Bucket auger ☐
☐ Reverse rotary ☐ Jetted ☐ Flight auger

Use
☐ Domestic ☐ Public supply ☐ Industrial ☐
☐ Irrigation ☐ Municipal ☐ Commercial
☐ Test Well ☐ Heating or cooling ☐ Monitoring

Casing Type
☐ Steel ☐ Threaded Height above/below
☐ Galv ☐ Welded surface
☐ PVC ☐ Solvent welded Drive shoe? Yes No
☐ SS
in to ft Wgt lb/ft Sch. No
in to ft Wgt lb/ft Sch. No
in to ft Wgt lb/ft Sch. No
Hole diameter
in to ft
in to ft
in to ft

Intake Portion of Well
Screen type or open hole from ft to ft
Manufacturer
Material Dia
Fittings Length
Set between ft and ft Slot
ft and ft Slot
ft and ft Slot
Method of installation

Filter Pack
Source Gradation
Method of installation Composition
Volume used Depth to top of f.p.

Grout
Used? ☐ Yes ☐ No Volume used
☐ Neat Cement ☐ Bentonite ☐
Method of installation
Depth: from ft to ft
from ft to ft

Development
Method Duration
Dates Sand content after hrs
Chemicals used

Static Water Level
ft ☐ below ☐ above grade
Date measured

Pumping Water Level
ft ☐ below ☐ above grade Date
After hrs pumping at gpm

Specific Capacity
gpm/ft of drawdown at hours
Date

Pump
Date installed Type
Manufacturer Model No.
H.P. Volts Capacity
Depth of pump intake setting No. of stages
☐ Oil ☐ Water lubrication Power source
Material of drop pipe , bowls
shafting , impellers Bowl dia.
Column pipe dia Length Modifications

Well Head Completion
☐ Pitless adaptor ☐ Basement offset Distance above grade

Nearest Sources of Possible Contamination
ft Direction Type
Well disinfected upon completion? ☐ Yes ☐ No

Geophysical Logs Run

Water Quality
Sample taken? ☐ Yes ☐ No
Where analyzed

Date well completed

3 Desk Studies and Preliminary Field Reconnaissance

- Mapping and inventory activities may lead to full hydrogeological analyses by itself and to determine planning of any exploration program;
- At sites the following features are of interest:
  - Mineral content of rock type;
  - Colours;
  - Layering of rocks and bed thicknesses;
  - Dip of beds;
  - Presence, types and dimensions of faults and joints;
  - Fossil content;
  - Evaluated rock types;
  - Porosity of the rocks;
  - Degree of cementation;
  - Degree of weathering.

3 Desk Studies and Preliminary Field Reconnaissance

- Well inventories cover all type of wells, production, monitoring, abandoned, exploration, … etc.
- Table 3.2 shows the index for Model Map

Table 3.2 Index for the Model Map →

3 Desk Studies and Preliminary Field Reconnaissance

Table 3.2 Index for the Model Map

C. GEOLOGY GEOLOGIE GEOLOGIA ГЕОЛОГИЯ

1a	Contact between different units, lines broken where approximate Contact entre des unités différentes, en traits interrompus si hypothétique Contacto entre unidades distintas, en trazos discontinuos si es hipotética Контакт между различными единицами, если гипотетический пунктиром
2	Depth of top of the limestone Profondeur du toit de la calcaire Profundidad del techo de la caliza Абсолютная отметка кровли известняка
	Depth of top of the sandstone Profondeur du tout du grès Profundidad del techo de la arenisca Абсолютная отметка кровли песчаника
5	Strike and dip Direction et pendage Dirección y buzamiento Простирание и падение
6	Axis of anticline, with direction of axial plunge Axe anticlinal, avec direction de plongement axial Eje anticlinal, indicando su dirección de buzamiento Ось антиклинали и направление ее погружения
7	Axis of syncline, with direction of axial plunge Axe synclinal, avec direction de plongement axial Eje sinclinal, indicando su dirección de buzamiento Ось синклинали и направление ее погружения
10	Fault, with direction of downthrow side, line broken where uncertain Faille, avec direction du côté affaissé, en traits interrompus si hypothétique Falla con dirección del labio hundido, en trazos discontinuos, si es supuesta Сброс с указанием опущенного крыла пунктиром сброса, если гипотетический

D. LITHOLOGY LITHOLOGIE LITOLOGIA ЛИТОЛОГИЯ

3	Sands and gravels Sables et graviers Arenas y gravas Пески, галечники и гравий.
6	Sandstones with conglomerates Grès avec conglomérats Areniscas con comglomerados Песчаники с конгломератами
7	Limestones Calcaires Calizas Известняки
13	Extrusive rocks, fissured Roches extrusives, fracturées Rocas efusivas, fisuradas Экструзивные породы, трещиноватые

E. HYDROGRAPHY HYDROGRAPHIE HIDROGRAFIA ГИДРОГРАФИЯ

1	Perennial stream with direction of flow Cours d'eau pérenne, avec sens d'écoulement Curso de agua perenne con dirección de la circulación Постоянный водоток с направлением течения
4	Seasonal stream with direction of flow Cours d'eau saisonnier avec sens d'écoulement Curso de agua estacional con dirección de la circulación Сезонный водоток с направлением течения
E.6	Disappearance point of stream Point de disparition d'un cours d'eau Punta de desparición de un curso de agua Пункт исчезновения водотока
9	Marsh Marais Marisma Болото
10	Area inundated during floods Terrain inondé pendant les crues Terreno inundado en las crecidas Участок, затопленный паводковыми водами
11	Surface-water divide Ligne de partage des eaux superficielles Línea divisoria de las aguas superficiales Водораздел поверхностных вод
12	Spring Source Fuente Источник
13	Group of springs Groupe de sources Grupo de fuentes Группа источников
14	Thermal or thermomineral spring (see G.4. and G.6.) Source thermale ou thermominérale (voir G.4. et G.6.) Fuente termal o termomineral (ver G.4. y G.6.) Термальный или термоминеральный источник (см.G 4 и G6)
15	Natural pond or waterhole with no outlet Etang ou point d'eau naturel sans écoulement Laguna o punto de agua natural sin escorrentia Бессточный естественный водоем или водохранилище (пруд)
16	Lake Lac Lago Озеро

F. GROUNDWATER HYDROLOGY HYDROLOGIE DES EAUX SOUTERRAINS HYDROLOGIA DE LAS AGUAS SUBTERRANEAS ДИНАМИКА ПОДЗЕМНЫХ ВОД

1	Groundwater contours (piezometric surface on the section) for the limestone Courbes isopièzes (niveau piézométrique de la coupe) pour la calcaire Curvas isopiezas (nivel piezométrico en la sección) por la caliza Изогипсы — (пьезометрическая поверхность разреза) для известняка
	Groundwater contours (piezometric surface on the section) for the sandstone Courbes isopièzes (niveau piézométrique de la coupe) pour le grès Curvas isopiezas (nivel piezométrico en la sección) por la arenisca Изогипсы (пьезометрическая поверхность разреза) для песчаника
2	Direction of groundwater flow with velocity in m per day Sens d'écoulement de la nappe, avec la vitesse en m par jour Dirección de la escorrentia de la capa acuífera, con la velocidad en m por día Направление движений подземных вод с скоростью в м/сут
3	Groundwater divide Ligne de partage des eaux souterraines Línea divisoria de las aguas subterráneas Граница бассейна подземных вод
5	Boundary of area of artesian flow, with date Limite d'extension de la zone d'artésianisme, avec date Línea de la superficie de la zona artesiana, con la fecha Граница артезианского бассейна с датой
F.11	Lines of equal thickness of saturated zone for the limestone Courbes dégale puissance de la couche saturée pour la calcaire Líneas de igual potencia de la capa saturada por la caliza Линии равной мощности известняка
18	Natural replenishment of the groundwater in mm per year Alimentation naturelle de la nappe, en mm par an Alimentación natural del acuífero, en mm por año Естественное питание водоносного горизонта в мм/год

G. HYDROCHEMISTRY HYDROCHIMIE HIDROQUIMICA ГИДРОХИМИЯ

2	Depth of interface between fresh and saline groundwater Profondeur de la surface de séparation entre l'eau douce et l'eau salée Profundidad de la superficie de separación entre el agua dulce y la salada Глубина залегания поверхности раздела пресных и соленых вод.
5	Water temperature in degrees Celsius Température de l'eau en degrés Celsius Temperatura del agua en grados Celsius Температура воды по Цельсию.
4 and 6	Dug well with sodium chloride water, not fit for use Puits creusé avec eaux chlorurées sodiques, non utilisables Pozo excavado con aguas cloruradas sódicas, no utilizables Копаный колодец с хлоридной натриевой водою, неиспользуемой.
	Dug well with sodium chloride water, 2 - 4 g/l Puits creusé avec eaux chlorurées sodiques, 2 - 4 g/l Pozo excavado con aguas cloruradas sódicas, 2 - 4 g/l Копаный колодец с хлоридной натриевой водою 2—4 г/л
	Dug well with sodium chloride water, 4 - 8 g/l Puits creusé avec eaux chlorurées sodiques, 4 - 8 g/l Pozo excavado con aguas cloruradas sódicas, 4 - 8 g/l Копаный колодец с хлоридной натриевой водою 4—8 г/л
	Dug well with sodium chloride water > 8 g/l Puits creusé avec eaux chlorurées sodiques, > 8 g/l Pozo excavado con aguas cloruradas sódicas, > 8 g/l Копаный колодец с хлоридной натриевой водою > 8 г/л.
	Group of springs with magnesium sulphate water, > 8 g/l Groupe de sources avec eaux sulfatées magnésiennes, > 8 g/l Grupo de fuentes con aguas sulfatadas magnesianas, > 8 g/l Группа источников с сульфатной магниевой водою > 8 г/л.
	Group of springs with sodium chloride water, 4 - 8 g/l Groupe de sources avec eaux chlorurées sodiques, 4 - 8 g/l Grupo de fuentes con aguas cloruradas sódicas, 4 - 8 g/l Группа источников с хлоридной натриевой водою 4—8 г/л
8	Highly polluted stream (organic pollution) Cours d'eau fortement pollué (pollution organique) Curso de agua muy polucionada (polución orgánica) Сильно загрязненный водоток (органическое загрязнение).
9	Stream with high salinity Cours d'eau salé Curso de agua salada Соленый водоток
10	Salt lake Lac salé Lago salado Соленое озеро

H. BOREHOLES, WELLS AND OTHER WORKS FORAGES, PUITS ET AUTRES OUVRAGES SONDEOS, POZOS Y OTRAS OBRAS СКВАЖИНЫ, КОЛОДЦЫ И ДРУГИЕ ВЫРАБОТКИ

H.3	Dug well, non-artesian Puits creusé, dans une nappe libre Pozo excavado, en una capa acuífera libre Копаный колодец в безнапорном водоносном горизонте
	Dug well, artesian, not overflowing Puits creusé, dans une nappe captive, mais non-jaillissant Pozo excavado, artesiano no surgente Копаный колодец в напорных водоносных горизонта, но не самоизливающийся
	Dug well, artesian, overflowing Puits creusé artésien (jaillissant) Pozo excavado, artesiano (surgente) Копаный колодец артезианский (самоизливающийся)
	Recharge well Puits creusé, d'injection Pozo excavado de recarga Поглощающий колодец
	Dry well Puits creusé, sec Pozo excavado, seco Сухой колодец
4	Drilled well (see also H.3.) Puits foré (voir aussi H.3.) Pozo perforado (ver también H.3.) Буровой колодец (см. также H.3)
8	Spring used for supply Captage de source Captación en una fuente Каптированный источник
9	Drainage gallery Galerie drainante Galería de drenaje Дренажная галлерея
10	Groundwater pumping station Captage d'eau souterraine Estación de bombeo de agua subterranea Насосная станция из подземых вод
11	Groundwater observation station, with recorder Station de jaugeage de l'eau souterraine, avec enregistreur Estación de aforo de aguas subterráneas, con registrador Наблюдательная станция за режимом подземных вод
	Decade station Station de la Décennie hydrologique Estación del Decenio hidrológico Станция гидрологического десятилетия
12	Stream gauging station, with yearly average flow and area of catchment Station de jaugeage d'un cours d'eau, avec débit moyen annuel et surface du bassin de drainage Estación de aforo de un curso de agua indicando el caudal medio anual y la superficie de la cuenca de drenaje Наблюдательная станция на водотоке, указывается среднегодовой расход и площадь дренируемого бассейна
17	Dam (with capacity of reservoir in million m^3) Barrage de retenue ou de dérivation (avec capacité de réservoir en millions de m^3) Presa de embalse o derivación (con capacidad en milliones de m^3) Плотина водохранилища с емкостью в млн. $м^3$
19	Canal, irrigation canal (perennial waters) Canal, canal d'irrigation (eau pérenne) Canal, canal de irrigación (agua perenne) Канал, ирригационный канал (постоянный водоток)
20	Canal, flood waters Canal, eaux de crue Canal, (aguas de crecida) Канал, (паводковые воды)
21	Drainage canal Canal de drainage Canal de drenaje Дренажный канал

SESSION 9

GROUNDWATER EXPLORATION II

Dr Amjad Aliewi

House of Water and Environment

Email: amjad.aliewi@hwe.org.ps , Website: www.hwe.org.ps

4 Surface Geophysical Techniques

The objectives of surface geophysical techniques are:

1. To determine indirectly the extent and the nature of the geological materials beneath the surface
   - ✓ Thickness of formations;
   - ✓ Depth of water table;
   - ✓ Location of subsurface faults;
   - ✓ Depth of the basement rocks;

4 Surface Geophysical Techniques

2. To minimize the extent and thickness of fresh groundwater lenses in saline aquifer (water quality) or clay lenses in aquifers (lithology).

The correlation of geophysical data with well logs or test-boring data is generally more reliable than either type of information used by itself. The interpretation of physical parameters into rock type requires information from remote sensing surveys, mapping and, in particular, data from exploration drilling activities.

4 Surface Geophysical Techniques

In geophysical techniques, rock parameters are measured as a response to energy fluxes injected into the earth. The most common geophysical techniques are:

- ✓ Geo-electrical;
- ✓ Electromagnetic;
- ✓ Seismic;

4 Surface Geophysical Techniques

4.1 Surface Geo-electrical Techniques (Electrical Resistivity)

4.1.1 Working Principle

- These techniques are based on the injection of an electrical current of very low frequency into the earth by means of two current electrodes (**Figure 4.1**);
- The potential differences which are created between these electrodes are measured at another pair of intermediate electrodes, the measuring or potential electrodes;
- Readings of current strength at the current electrodes, and potential differences at the measuring electrodes, and potential differences at the measuring electrodes enable us to determine rock resistivities;
- These resistivities can be related to subsurface rock types, rock water contents and groundwater quality (pore water resistivity). This information can be used to identify permeable rocks.

4 Surface Geophysical Techniques

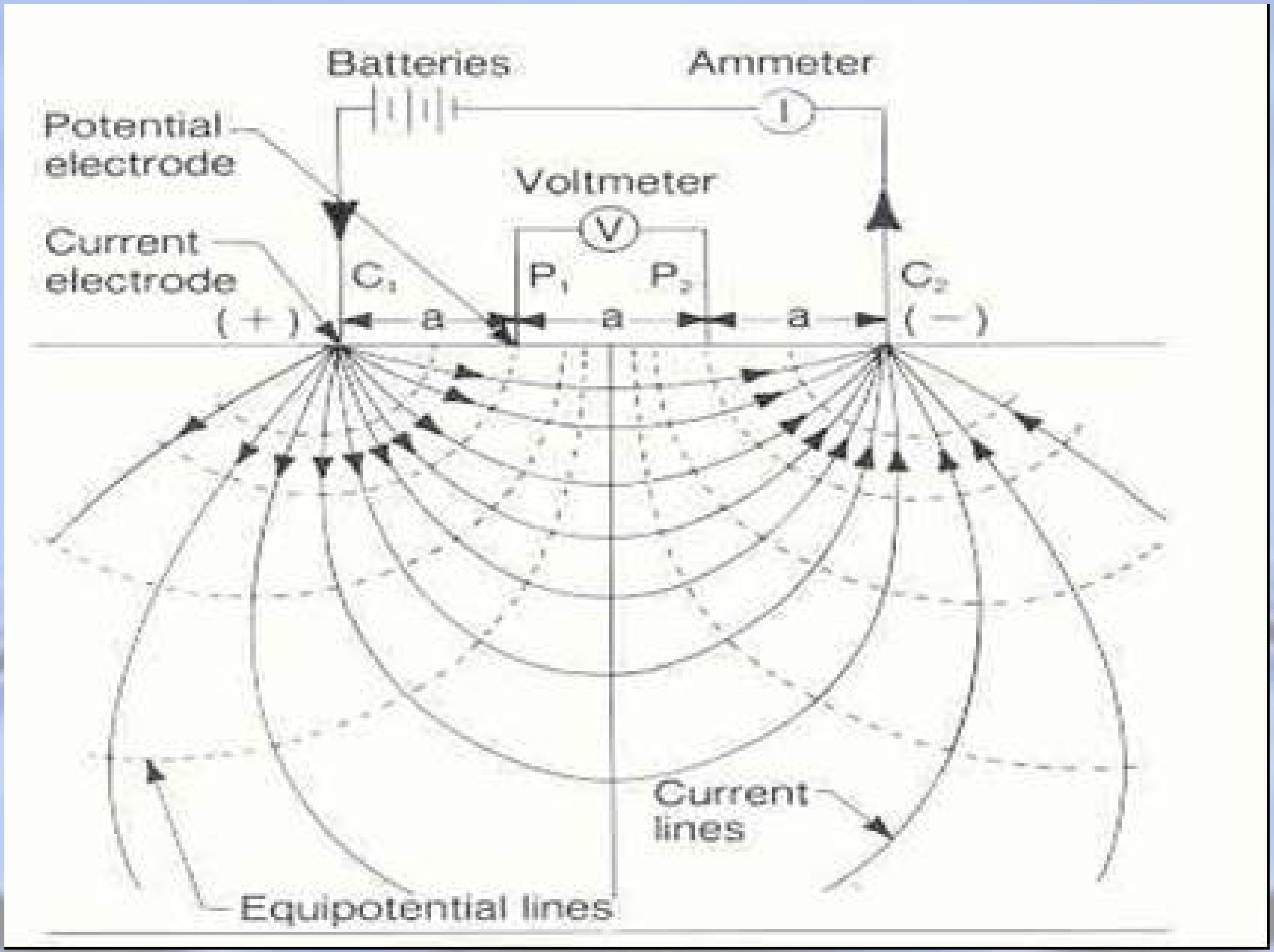


Figure 4.1 Set up for a geo-electrical measurement

4 Surface Geophysical Techniques

4.1.2 The Concept of Apparent Resistivity

- When carrying out a geo-electrical measurement we do not measure the resistivities of the individual layers, but we are able to compute a so-called apparent resistivity. The apparent resistivity is in fact a combination of the resistivities of the individual layers (see **Figure 4.2**);

4 Surface Geophysical Techniques

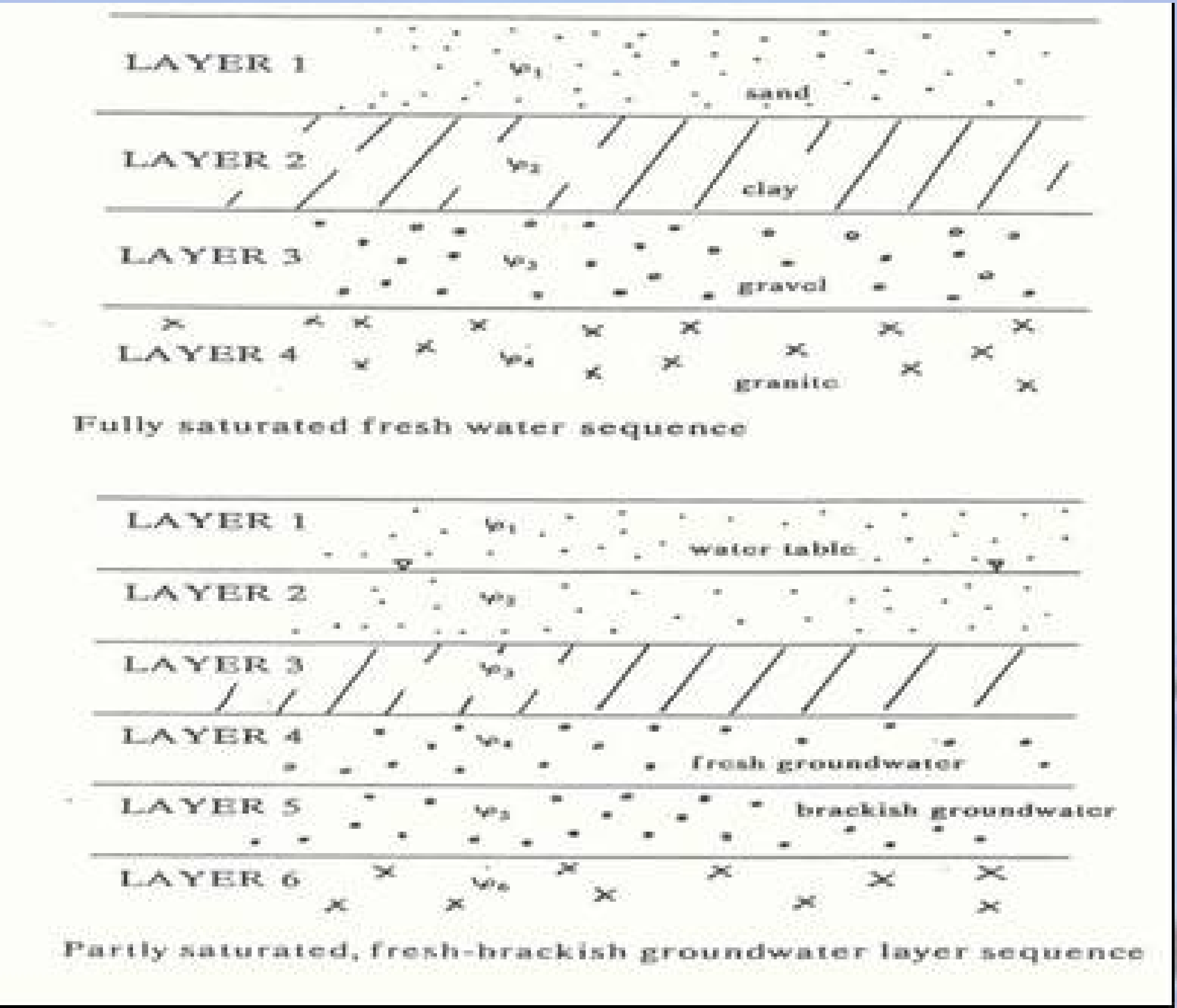


Figure 4.2 Examples of layer sequences

4 Surface Geophysical Techniques

- The general formulation of Ohm's law is as follows:

$$-dV = I \times R \qquad (1)$$

Where,

dV	potential drop	(volt/m)
I	current length	(Ampere)
R	resistance	(ohm)

- Imagine a single current source at land surface. Assume that the resistivities of the individual rock layers can be combined in apparent resistivities. The current (I) injected at the current sources expands itself as a semi sphere into the earth, with the atmosphere acting as a complete insulator. Figure 4.3 shows that around the source semi-spherical shells can be considered through which the current is passing at right angles.

4 Surface Geophysical Techniques

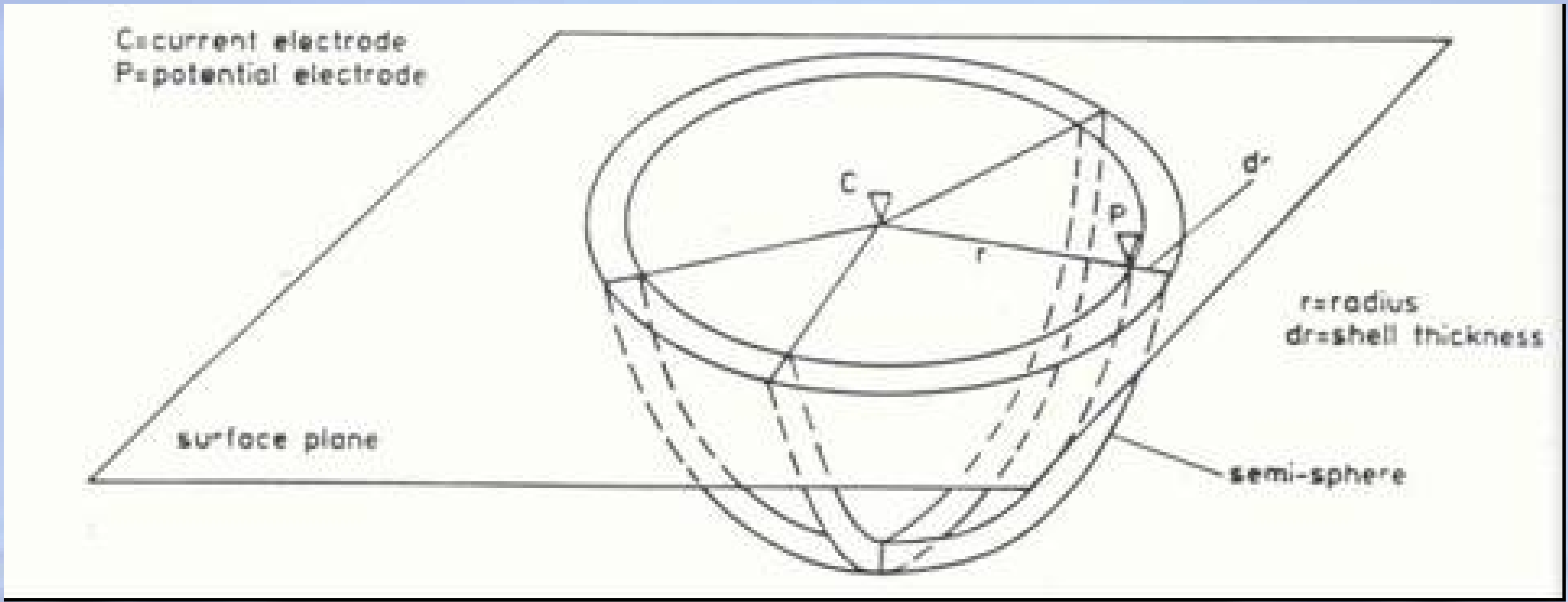


Figure 4.3 Semi-sphere around current electrode

4 Surface Geophysical Techniques

- Consider such a semi-spherical shell located at a given distance from the current source. If we consider equation 1 for the shell then the resistance (R) is proportional to the width of this shell and it is inversely proportional to the cross sectional area. The resistance is also proportional to the apparent resistivity of the medium. Thus, we can write:

$$R = \varphi_a \; x \frac{dr}{2\pi r^2} \qquad (2)$$

Where,

φ_a	apparent resistivity	(Ω-m)
dr	width of shell	(m)
r	distance from shell to current source	(m)

4 Surface Geophysical Techniques

- Equations (1) and (2) can be combined. This resulting expression can be written as follows:

$$dV = -I \, x \, \varphi_a \, x \frac{dr}{2\pi r^2} \qquad (3)$$

- Integration of equation (3) yields for the potential at a distance (r) from the current source:

$$V(r) = \frac{I \, x \, \varphi_a}{2\pi r} \qquad (4)$$

- In the set up for the geo-electrical field measurement, we have two current electrodes acting as current sources. Simultaneously we apply a current strength **+I** at one current electrode and a current strength **–I** at the other electrode. This means that we have to consider the potential at a measuring electrode as generated by both current sources; the positive source and the negative source. Using equation (4) the potentials can be determined for a generalized electrode configuration (see **Figure 4.4**)

4 Surface Geophysical Techniques

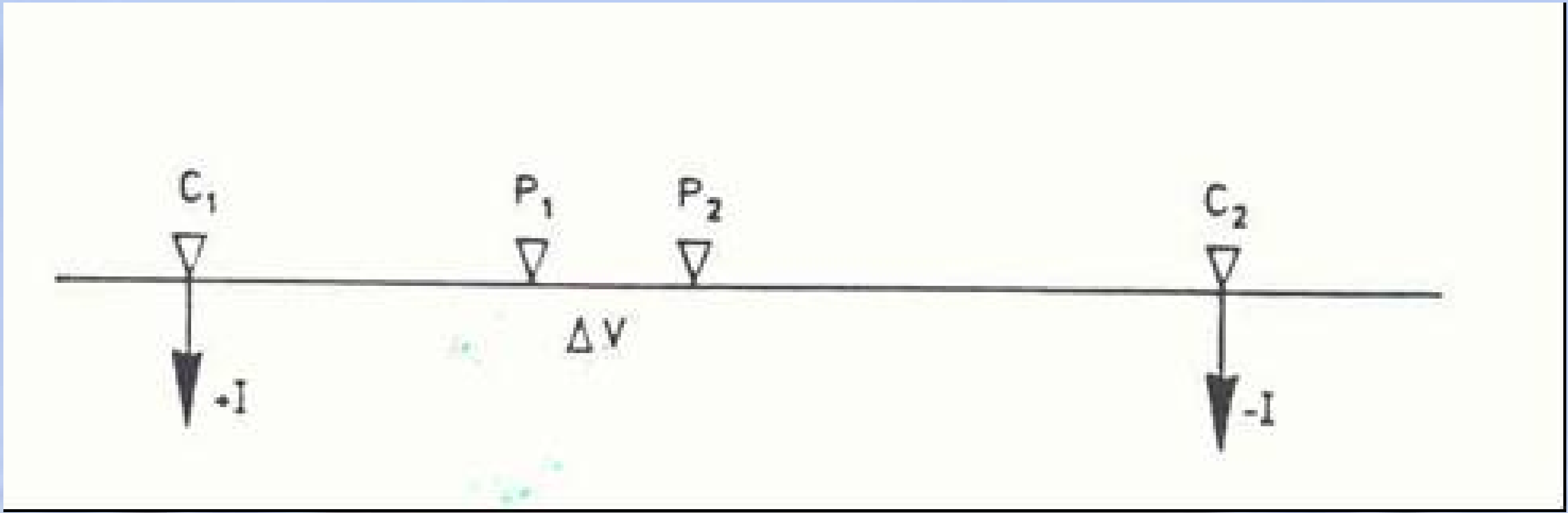


Figure 4.4 Generalized layout for a measurement

4 Surface Geophysical Techniques

- Let us denote the current electrodes by C_1 and C_2, the measuring electrodes by P_1 and P_2 and the distances between the electrodes by C_1P_1, C_2P_1, C_1P_2, and C_2P_2. The potential at P_1 is then:

$$V(P_1) = \frac{I\,x\varphi_a}{2\pi(C_1P_1)} + \frac{-I\,x\varphi_a}{2\pi(C_2P_1)} \qquad \textbf{(5)}$$

- and the potential at P_2 is:

$$V(P_2) = \frac{I\,x\varphi_a}{2\pi(C_1P_2)} + \frac{-I\,x\varphi_a}{2\pi(C_2P_2)} \qquad \textbf{(6)}$$

4 Surface Geophysical Techniques

- In a geo-electrical field measurement we measure the potential difference **(ΔV)** between the two measuring electrodes: **$V(P_1) - V(P_2)$**. Thus the above equations are subtracted from each other:

$$\Delta V = -I\,\frac{\varphi_a}{2\pi}\,x\left[\frac{1}{C_1P_1}-\frac{1}{C_2P_1}-\frac{1}{C_1P_2}+\frac{1}{C_2P_2}\right] \qquad \textbf{(7)}$$

- Re-arranging the terms in the above equation yields the apparent resistivity:

$$\varphi_a = \frac{\Delta V}{I}\,x\,\frac{2\pi}{\left[\frac{1}{C_1P_1}-\frac{1}{C_1P_2}-\frac{1}{C_2P_1}+\frac{1}{C_2P_2}\right]} \qquad \textbf{(8)}$$

4 Surface Geophysical Techniques

- The most commonly used electrode layouts are the '**Wenner**' (see **Figure 4.5**) and '**Schlumberger**' configurations (see **Figure 4.6**). Wenner configuration is symmetrical with the four electrodes always at equal distances from each other. The Schlumberger configuration is also symmetrical, but the distance between the measuring electrodes differs from the spacing between the measuring and current electrodes.

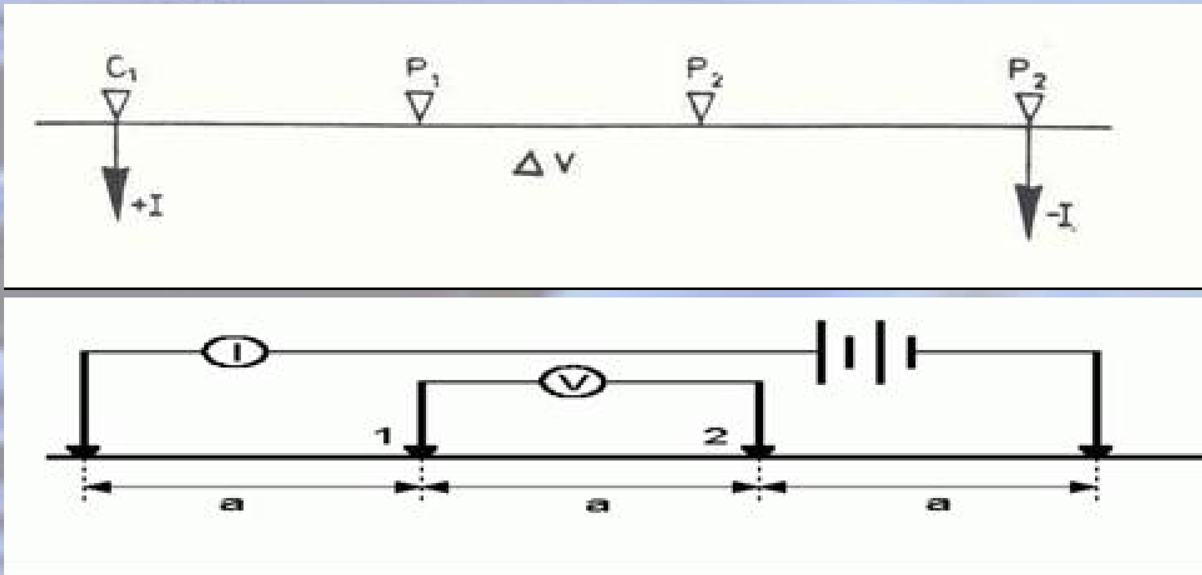


Figure 4.5

Wenner layout

4 Surface Geophysical Techniques

- **For the Wenner spacings** (see **Figure 4.5)**

$$C_1P_1 = P_1P_2 = \frac{1}{2} x\, C_1P_2 = \frac{1}{2} x\, C_2P_1 \qquad \textbf{(9)}$$

- When writing the electrode spacing in **equation 8** in terms of the spacing between the measuring electrodes, **P_1P_2**, then the resulting **apparent resistivity** (ohm-meter) for the **Wenner** layout can be written as follows:

$$\varphi_a = \frac{\Delta V}{I} x\, 2\pi\, x\, P_1P_2 \qquad \textbf{(10)}$$

- For the **Schlumberger** spacings (see **Figure 4.6**):

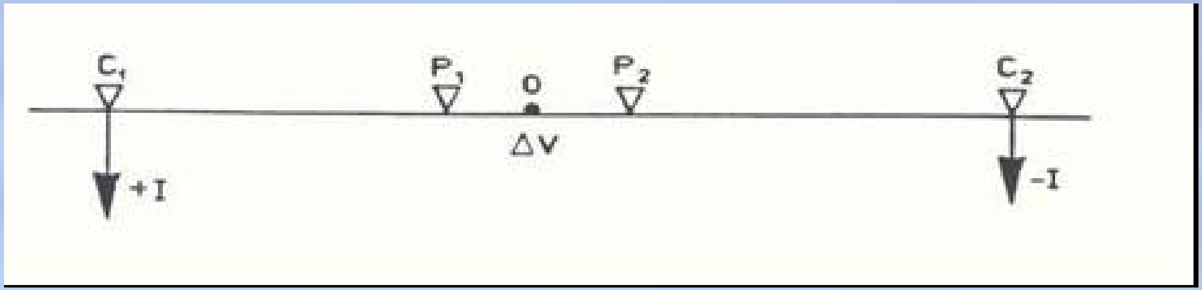
$$C_1P_1 = C_2P_2 = \frac{(C_1C_2 - P_1P_2)}{2}$$

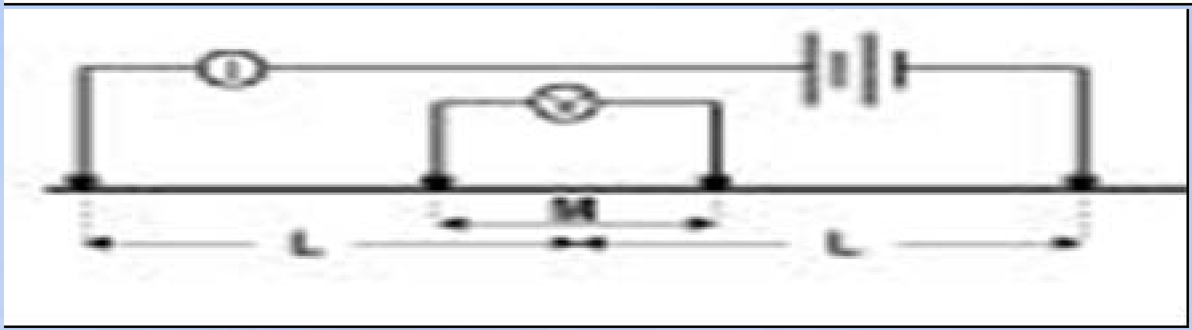
$$\textit{and} \quad C_1P_2 = C_2P_1 = \frac{(C_1C_2 + P_1P_2)}{2} \qquad \textbf{(11)}$$

4 Surface Geophysical Techniques

Figure 4.6

Schlumberger layout





- This expression can also be combined with **equation 8**. Expression the spacings in (8) in terms of the spacings between measuring electrodes and the current electrodes, **C_1C_2**, results in the following equation for the **apparent resistivity** (Ohm-meter) for the **Schlumberger** arrangement:

$$\varphi_a = \frac{\Delta V}{I} x \pi x \frac{\left[(C_1C_2)^2 - (P_1P_2)^2\right]}{4P_1P_2} \qquad \textbf{(12)}$$

4 Surface Geophysical Techniques

4.1.3 The Variable Electrode Distance Technique

- During measurement, the distances between the current and measuring electrodes are gradually increased, while the center of the layout remains at a fixed point. Various current strength and potential difference readings are taken at one location.

- Apparent resistivities computed from current strength and potential difference readings can be translated into resistivities and thicknesses of individual subsurface layers.

4 Surface Geophysical Techniques

4.1.4 Field Guidelines

- Select the area for geoelectrical surveying using the variable electrode distance technique on the basis of all existing data available (remote sensing; hydrogeological mapping and well inventories).
- Geo-electrical techniques are used in areas of varying geologic nature. The technique is also engaged in areas of varying geological nature. The technique is also engaged in areas with consolidated sedimentary rock and in the weathered parts of metamorphic and igneous rocks. The method works best when we have:
  - ✓ Simple stratigraphical and tectonic conditions;
  - ✓ Moderate or no dip of the rock layers;
  - ✓ Large resistivity contrasts between subsurface layers

4 Surface Geophysical Techniques

- Plot the measurements on section lines which are perpendicular to the main strike direction of the subsurface rock layers. The distance between section lines, and between the individual measurements depends on the required amount of detail. Distances between measurements are 50-1000 m.

4 Surface Geophysical Techniques

- Extend the electrode spacing along a straight line perpendicular to the selected section lines. I and ΔV are measured from each electrode spacing, while the center of the measurement line (the axes through the electrodes) remains at a fixed position. At small electrode spacing the depth penetration of the electrical current is small and the potential difference readings relate to the resistivity of the first rock layer. When we proceed, the readings at larger spacings relate to the deeper layers. We will continue until the maximum electrode spacing is reached (as a “rule of thumb” we can take that the maximum spacing between current electrodes is equal to (3-4) times the required investigation depth). However, the final decision on the completion of the measurements should be taken in the field itself and depends on the shape of the (apparent) resistivity curve and on the smoothness of this curve (only smooth curves lend themselves to interpretation).

4 Surface Geophysical Techniques

- Selection of layout: In the **Wenner** set-up the electrode spacing C_1P_1, P_1P_2, and P_2C_2 remain constant, but this also implies that after each reading all four electrodes have to be brought to new, larger spaced positions. In the **Schlumberger** arrangement the electrode spacings C_1P_1, C_2P_2 are identical but differ from P_1P_2. During the measurement the P_1P_2 is kept constant during a series of readings for increasing current electrode spacing. Then the P_1P_2 is increased and again kept constant while the next set of readings for increasing current electrode distances C_1C_2 is taken. On the field curve we can distinguish the various sets of readings for typical P_1P_2 values as "branches" which partly overlap each other.

4 Surface Geophysical Techniques

- In Wenner surveys ΔV can usually be measured somewhat more accurate than in Schlumberger surveys where P_1P_2 is relatively small as compared to the current electrode spacing. The Schlumberger set up has as its main advantage that lateral changes in the subsurface geology can better be detected from shifts in the various field curve branches. The interpretation of Schlumberger field curves with curve matching techniques is also more accurate. Wenner surveys may be somewhat faster than the Schlumberger surveys, but the Wenner survey usually requires one or more laborer to replace the electrodes.

4 Surface Geophysical Techniques

- Taking the measurements: select the electrode spacings in such a way that half the current electrode spacing, $C_1C_2/2$, plot more or less equidistantly on double-logarithmic paper. Measuring tapes may be rolled out to mark the sites for the electrodes or marks may be made on the cables. During the measurement, determine the apparent resistivity for each electrode spacing from the recorded **I** and **ΔV** (or their ratio). Multiply ΔV/I with a **geometrical factor G** (equal to that part of equation 10 or 12 describing the electrode spacings) will give us the value for the apparent resistivity.

4 Surface Geophysical Techniques

- Plot the φ_a values for the production of a field curve straightaway on log-log paper. φ_a values are usually plotted along the y-axes and the corresponding $C_1C_2/2$ along the x-axes. Direct plotting helps identifying errors become in the field, and not later in the office. An example of a typical Schlumberger configuration is presented in **Table 4.1**

4 Surface Geophysical Techniques

Table 4.1 Example of a typical Schlumberger configuration

$P_1P_2/2$	$C_1C_2/2$	G	$P_1P_2/2$	$C_1C_2/2$	G
0.5	1.5	6.28	10	25	82.8
0.5	2.5	18.8	10	30	126
0.5	4	49.5	10	40	235
0.5	6	112	10	50	377
0.5	8	200	10	60	549
0.5	10	313	10	75	867
0.5	12	451	10	100	1554
0.5	15	706	25	75	314
4	12	55.7	25	100	589
4	15	82	25	125	942
4	20	151	25	150	1374
4	25	239	25	200	2473
4	30	347	25	250	3886
			25	300	5616

4 Surface Geophysical Techniques

4.1.5 Principles of Resistivity Interpretation

- In the field we measure **I** and **ΔV** for various electrode spacings. Then apparent resistivity values are computed using **equations 11 and 12**. We end up with a whole series of apparent resistivities for a range of electrode spacings. The next step is to translate the values of apparent resistivity into layer resistivities φ_1, φ_2, φ_3 etc. and into layer thicknesses h_1, h_2, h_3 etc.

- This interpretation is done by means of curve matching techniques which are valid for horizontally stratified earth layers. Field curves showing apparent resistivities against current electrode spacings are matched with master curves which are computed from mathematical expressions. In case field and master curves fit, the layer resistivities thickness at a measurement location are similar to those used for the computation of the master curves.

4 Surface Geophysical Techniques

- Traditionally sets of master curves which were determined from the mathematical expressions were drawn on paper, and curve matching with field curves was done manually. Nowadays the computation and presentation of 'master' curves, and the storage and presentation of the field curves is largely done on the personal computer.
- **Mathematical Expressions**: for the case of two layers the final result of the derivation for the mathematical expression will be presented. The equation relates apparent resistivities to resistivities of the first and second layer, the thickness of the first layer, and to current electrode spacings. The deepest layer, which in case is the second layer, is always assumed to be of infinite thickness (see **Figure 4.7**). Also, note that an electrode configuration following the Schlumberger arrangement has been assumed. The expression with a written on the left hand side in equation 13.

4 Surface Geophysical Techniques

$$\frac{\varphi_a}{\varphi_1} = 1 + 2x\sum \frac{\left(\frac{C_1 C_2}{2h_1}\right)^3 x\, {K_{12}}^n}{\left[\left(\frac{C_1 C_2}{2h_1}\right)^2 + 4n^2\right]^{1.5}} \qquad (13)$$

Where,

K_{12}	$(\varphi_2-\varphi_1)/(\varphi_2+\varphi_1)$
h_1	thickness of first layer (m)
n	n-times of mirroring

4 Surface Geophysical Techniques

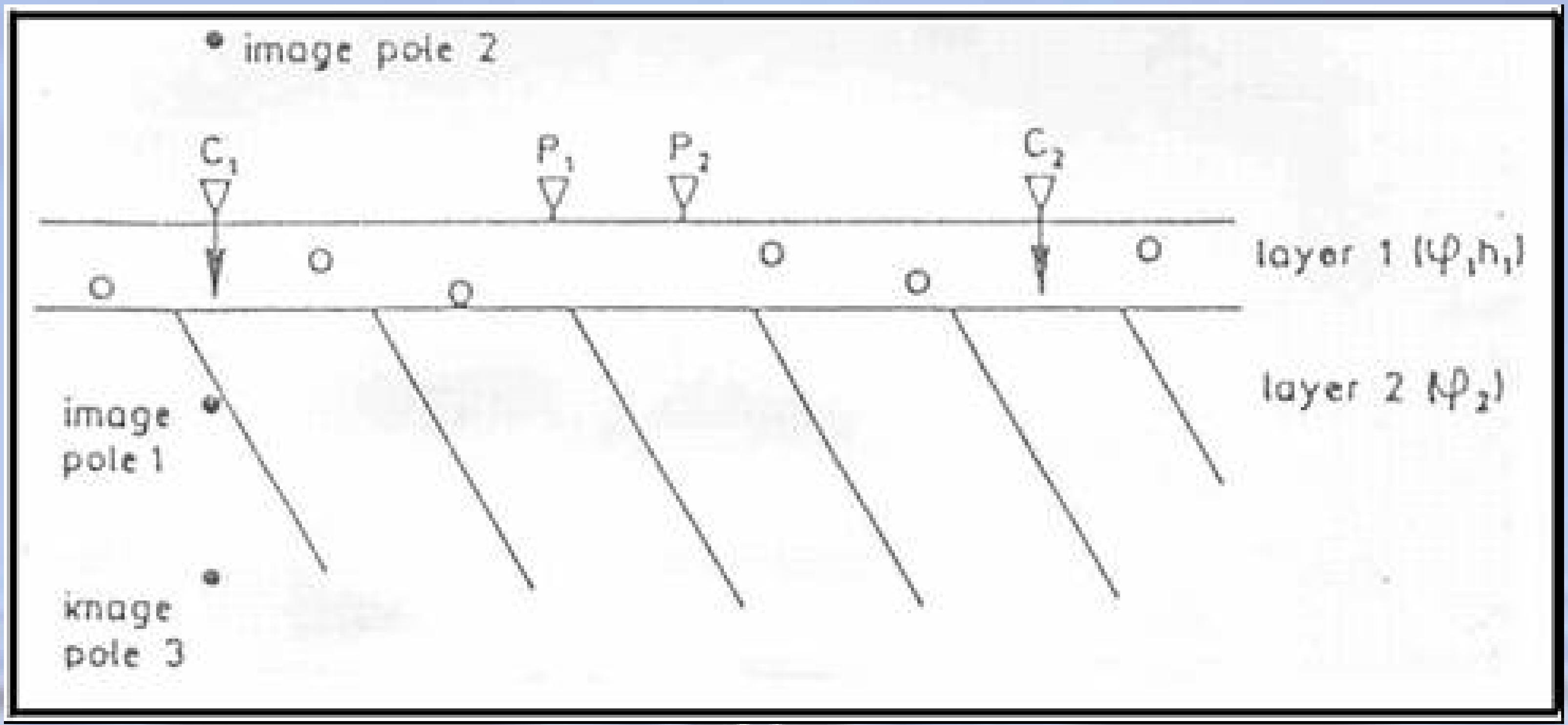


Figure 4.7: Image poles in a two-layer case

4 Surface Geophysical Techniques

- For small current electrode spacings, the apparent resistivity approaches the resistivity of the first layer. On the other hand, for very large electrode spacings, the apparent resistivity will then be equivalent to the resistivity of the second layer.
- Two layer master curves: equ.13 shows that hundreds of master curves could be drawn up for as many combinations of selected values for the layer resistivities φ_1 and φ_2, and the thickness of the first layer h_1. By plotting on double logarithmic paper the ratios of the apparent resistivity values and the resistivity of the first layer, and the ratio of half the current electrode distance and the thickness of the first layer ($C_1C_2/2h_1$), the master curves can be reduced to a set that fits on one sheet of paper. Figure 4.8 presents schematically the set of two-layer master curves. Note that the first layer and the second layer are reflected respectively by the asymptotic end at the left hand side and the right end side of the curve.

4 Surface Geophysical Techniques

- Figure 4.8 shows that the two-layer master curves have been drawn up for various ratios of φ_2/φ_1. Field curves are also plotted on double logarithmic paper, but on the Y-axes the unit is φ_a and on the X- axes we assume a unit of $C_1C_2/2$. Thus, in case a field curve fits to a two-layer master curve, constant shift between X axes and the Y-axes of both curves can be observed: in the Y direction, the shift is φ_1 and in the X direction, the shift is h_1. By reading off the shifts in the Y and X direction between fittings field and master curves, the two-layer master curves can be used for the determination of the resistivity φ_1 and the thickness h_1 of the first layer. The resistivity of the second layer can be computed from the ration φ_2/φ_1.

4 Surface Geophysical Techniques

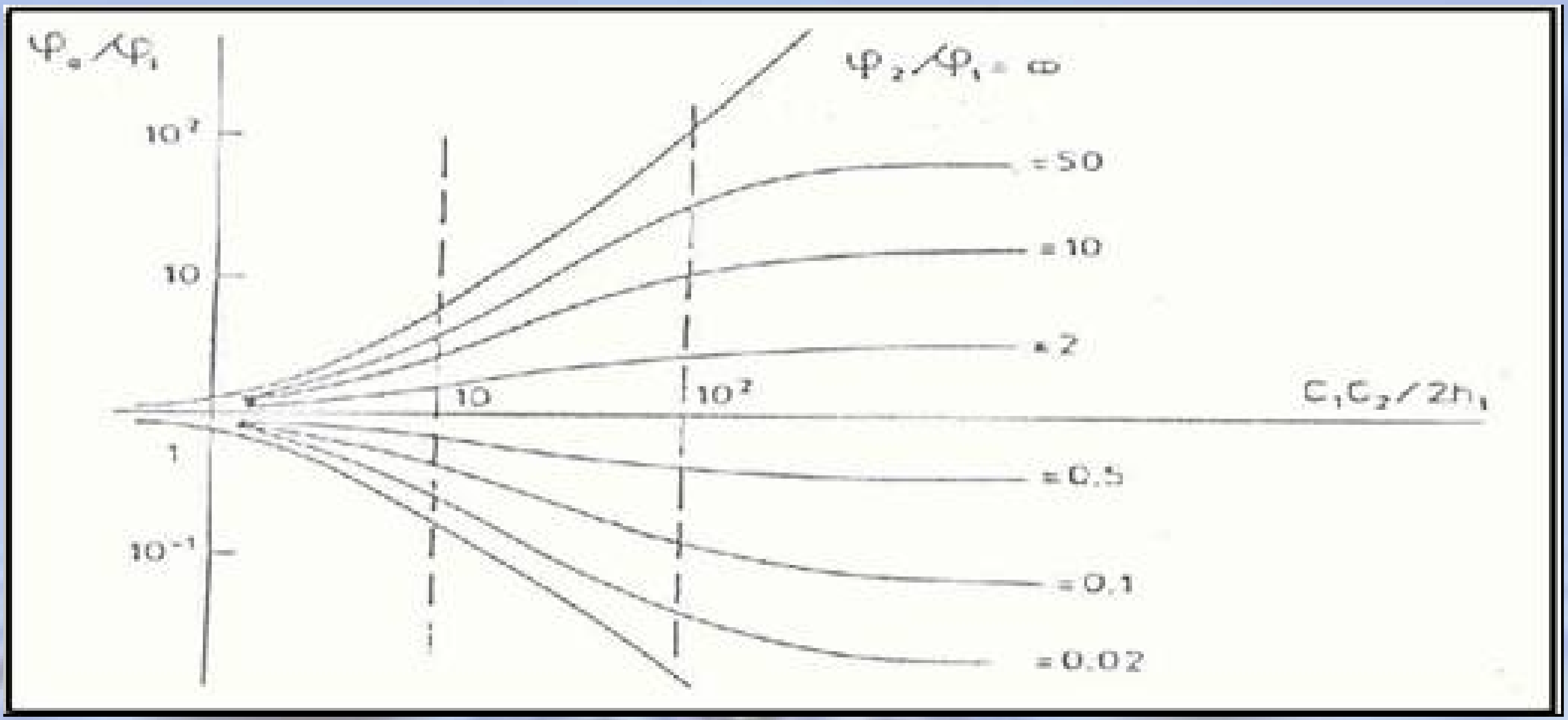


Figure 4.8: Two layer Master Curves

4 Surface Geophysical Techniques

- **Three layers master curves**: master curves for the three-layer case cannot be presented in a single diagram. Sets of three-layer master curves can be classified according to their shape. **Figure 4.9** presents examples of each of the four types of three-layer master curves. In these curves the first layer is reflected in the left hand side of the curve; the middle layer is reflected in a maximum, minimum or a distinctive change in slope in the ascending and descending segment somewhere in the middle of the curve, and the third layer corresponds to the right hand side of the curve.

4 Surface Geophysical Techniques

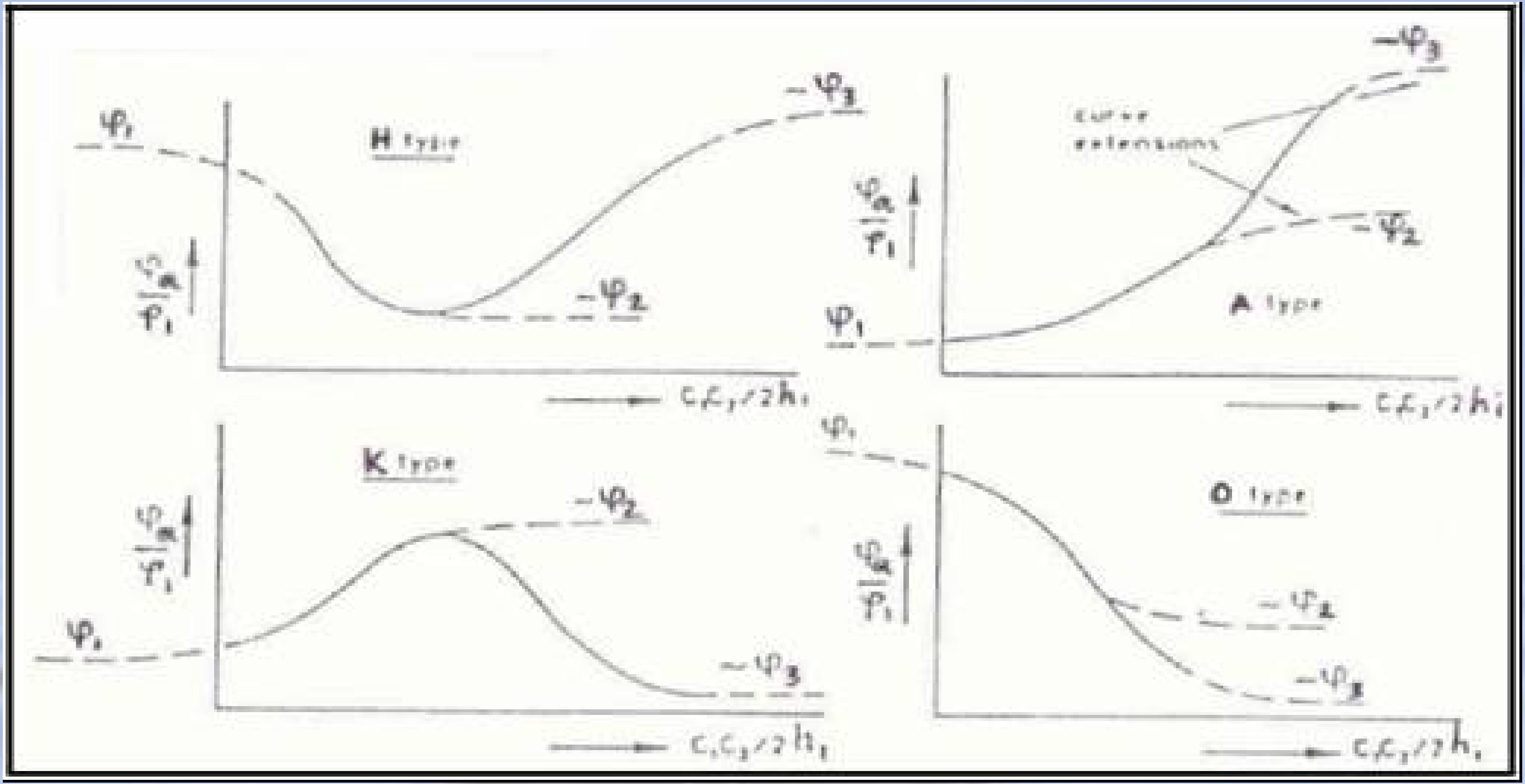


Figure 4.9: Types of three Layer Master Curves

4 Surface Geophysical Techniques

4.1.6 Porewater Resistivity

- The resistivity of a subsurface layer (formation resistivity) depends on:

- ✓ Porewater resistivity;
- ✓ Rock type pore space (porosity);
- ✓ Water content of the rock.

4 Surface Geophysical Techniques

- The porewater resistivity is determined by the properties of the groundwater in pores, joints, fractures and solution holes contained in rock. Properties include the concentration of total solids in solution, the type of ions dissolved and water temperature. Therefore, the porewater resistivity is also a measure of the groundwater quality. The influence of the concentration of total dissolved solids is most influential. The higher the concentration of total dissolved solids, the higher is the water conductivity, and the lower is the porewater resistivity. This relationship is shown in **Figure 4.10,** where the concentration of two of the most common solids dissolved in groundwater (sodium chloride $NaCl$, and sodium bicarbonate $NaHCO_3$), are set out against the water conductivity and the water resistivity of the solution.

4 Surface Geophysical Techniques

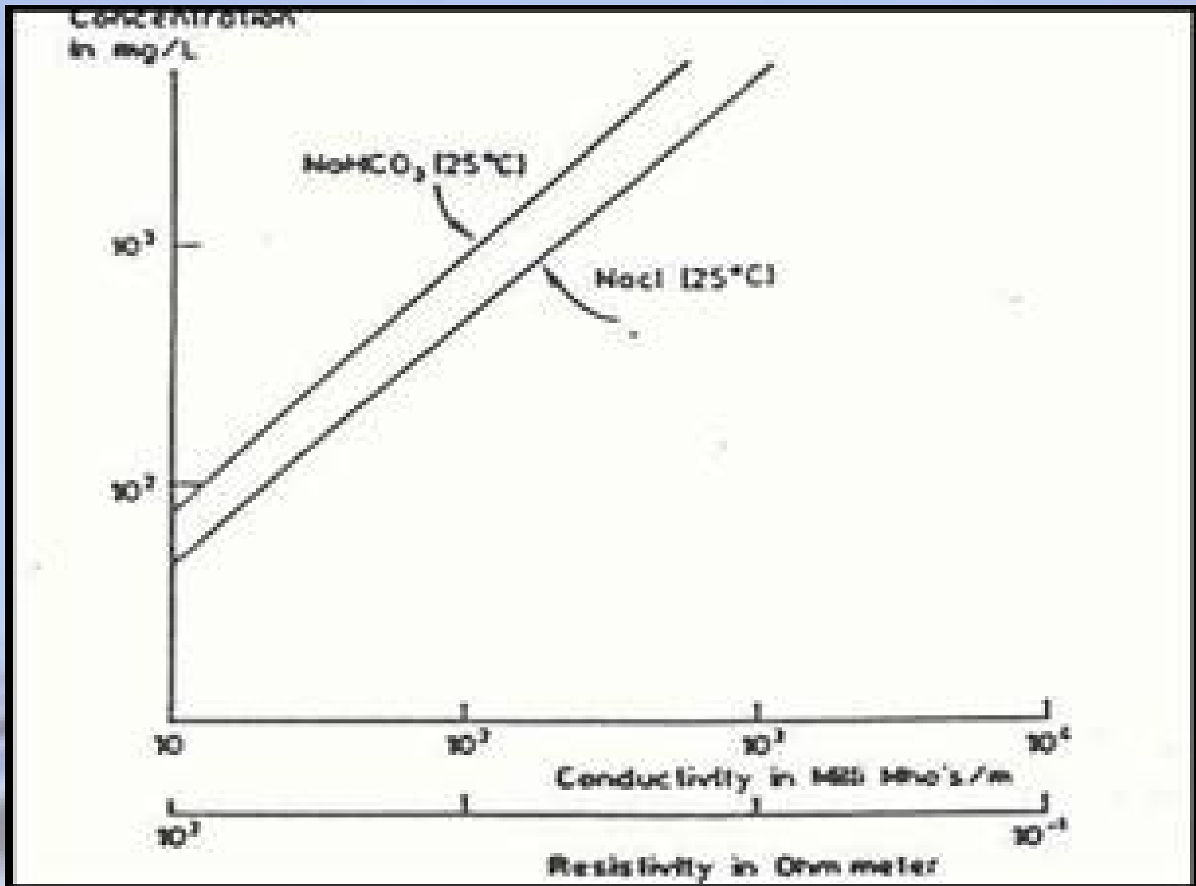


Figure 4.10: Relation between concentration and resistivity

4.1.7 Formation Factor

- For saturated conditions, the formation resistivity is made up of the resistivity of the porous rock and the porewater resistivity. The resistivity of the rock is usually much larger than the resistivity of the porewater. Thus, the formation resistivity is generally larger than the porewater resistivity. The formation factor F is defined by:

$$F = \frac{\varphi}{\varphi_w} \quad \textbf{(14)}$$

Where,

φ	formation resistivity	(Ω-m)
φ_w	porewater resistivity	(Ω-m)

4 Surface Geophysical Techniques

- The formation factor can be related to rock type characteristics and rock porosity. The expression which is only valid for sedimentary rocks is as follows:

$$F = C\,x\,\theta^{-m} \qquad \textbf{(15)}$$

Where,

θ porosity of the rock

C tortuosity depending on the mineralogy of the rock and the angularity of the grains; for rounded grains C~1.

m Cementation factor which ranges from 1.3 for loose sediment to 1.95 for well cemented formations.

4 Surface Geophysical Techniques

- The formation factor for unconsolidated sediments ranges from about 1 to 6 (e.g. for clays F is in the 1-2 range, while for coarser sands, F values in the order of 5-6 are common). **Table 4.2** gives a summary of formation factors common for unconsolidated sediments. In the more consolidated sediments the porosities are usually lower and formation factors for these rocks tend to be higher.

4 Surface Geophysical Techniques

Table 4.2: formation factors for some unconsolidated sediments

Lithology	F
Gravel	7.5
Coarse sand and gravel	6
Coarse san	5
Medium sand	4.2
Fine sand	3.5
Clayey sand	<2.5

4 Surface Geophysical Techniques

4.1.8 Hydrogeological Interpretation Procedures

- The interpretation means in the first place that we will have to associate the formation resistivities (rock layer resistivities) determined at geo-electrical measurement sites with rock types, rock water contents and porewater resistivities. Follow the **resistivity allocation and correlation** procedure:

- ✓ Allocation is the assignment of rock type and formation factor, rock water content, and porewater resistivity or conductivity value interpreted at an individual geo-electrical measurement site. The formation which is compiled on the so-called calibration tables should be used to complete these activities. Preferably, calibration tables are prepared on the basis of data collected during an exploration drilling programme.

4 Surface Geophysical Techniques

- Correlation is the activity whereby the interpreted formation resistivities at the various individual measurement sites are compared with each other. Correlation may first be carried out on the basis of resistivity values alone and then be finalized after rock characteristics have been assigned (see above). This can best be carried out by setting up cross sections along the lines of geo-electrical measurement sites and any exploration wells on these lines. Subsurface layers with similar characteristics on these sections may be connected with each other, presenting an excellent view of the (hydro)geological conditions within an investigated area.
- See Table 4.3 as an example for calibration of porewater resistivity

4 Surface Geophysical Techniques

Table 4.3: Example of a calibration table (the Rada Area in Yamen)

Formation φ (Ω-m)	Rock Type	Water Content	Porewater φ (Ω-m)
< 10	Alluvial sand	Saturated	< 3.3 (brackish)
30 - 70	Alluvial sand	Saturated	10 – 25 (fresh)
30 - 100	Weathered basement	Saturated	10 – 25 (fresh)
80 - 200	Sandstone	Saturated	10 – 25 (fresh)
> 1000	Alluvial sand	Unsaturated	
> 1000	Basement gneiss	Dense rock	

4 Surface Geophysical Techniques

4.1.9 Interpretation Hazards

- The use of allocation and correlation techniques for geoelectrical interpretation may be complicated or tricky for a number of reasons. First, the formation resistivities at the measurement sites may be considerably higher or lower than the range of values offered by the calibration table.
- Secondly, it is normally assumed that in case the formation resistivity values at the measurements sites and at the exploration, drilling sites are similar, the φ_w and F values are also similar. This is not always correct. Formation resistivities in an investigation area would not show any spatial variation as long as the product [Fx φ_w] is constant. The case may present itself that at a geo electrical measurement site this product is indeed the same as at exploration drilling sites, but that nevertheless, the F and the φ_w are quite different. We are then inclined to make an interpretation error. Only when we have a good perception of the area interpretation errors like these can be avoided.

4.1.10 Data Interpretation for Constant Electrode Distance

- For the Wenner arrangement (constant electrode distance survey), the apparent resistivity values for the successive measurement positions can be calculated from Eq. 11. For reconnaissance, surveying the apparent resistivities can be plotted on a topographical or geological map. Contour lines (iso-resistivity lines) may be drawn on these maps and sub-areas with typical apparent resistivity values can be delineated. For "discontinuity" surveying a plot may be made showing distances to the measuring points from the start of the section line (on x axis) against the corresponding apparent resistivity values (on y axes).

SESSION 10

GROUNDWATER EXPLORATION III

Dr Amjad Aliewi

House of Water and Environment

Email: amjad.aliewi@hwe.org.ps , Website: www.hwe.org.ps

4 Surface Geophysical Techniques

- The hydrological interpretation based on measurements following the constant electrode distance technique is a rather qualitative interpretation. For the case of reconnaissance surveying the rock type, the rock water content or the porewater resistivity can also be estimated for a selected investigation depth. Only estimates are possible.

- **Figure 4.11** shows an apparent resistivity map for the North of Surinam gives details. The coastal groundwater basin underlying the area consists of unconsolidated sediments up to several hundreds of meters of unconsolidated sediments up to several hundreds of meters below ground surface. The resistivity values and iso-resistivity lines which are shown on the map correspond with an investigation depth of 150 to 200 m below ground surface. The interpretation is as follows:

4 Surface Geophysical Techniques

✓The sub-area near to the coastline with relatively low formation resistivities in the order of **2.5 to 5 Ω-m** point to low porewater resistivities. This correlates with the occurrence of brackish to saline groundwater at the elected investigation depth.

✓For similar depths ranges, the higher resistivities in the order of **6 to 8 Ω-m** for the sub-areas farther inland represent fresh to brackish groundwater.

4 Surface Geophysical Techniques

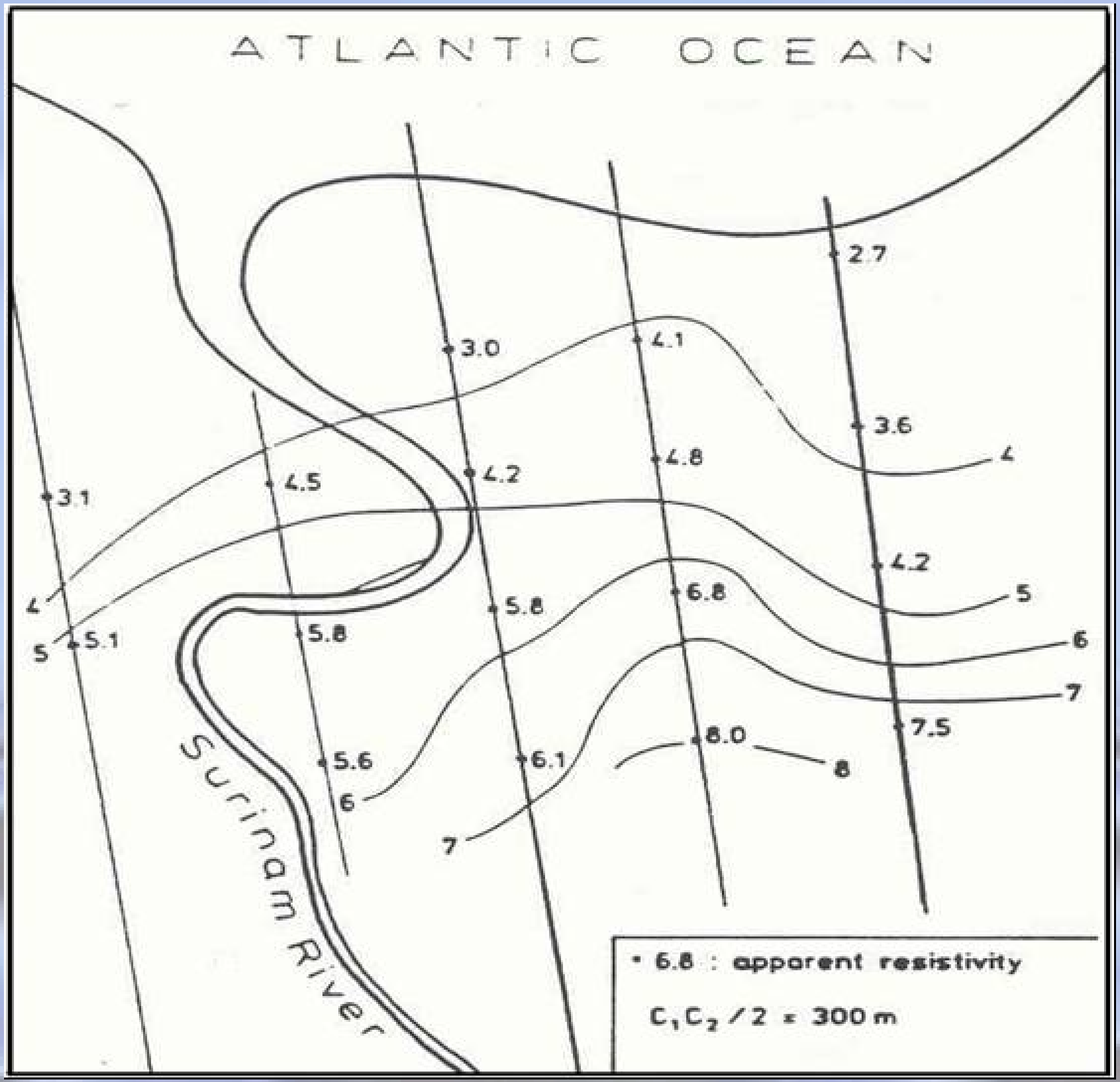


Figure 4.11: Map with resistivities: North of Surinam

4 Surface Geophysical Techniques

- When surveying for "discontinuities" the hydrogeological interpretation is also largely qualitative. For example, fault zones usually have higher water contents than the surrounding rock. This is reflected in a low apparent resistivity. Thus, a fault can be detected by low apparent resistivity values in a measurement series. Let us consider another example of a "discontinuity": a dolerite dike. Dikes may be associated with a low formation factor due to the presence of conductive iron-containing minerals. This will also be reflected in low apparent resistivity values which will be indicated when surveying across the dike. We can conclude from the above that an interpretation of apparent resistivity data cannot stand alone: they have to be considered in combination with data from other sources.

4 Surface Geophysical Techniques

4.1.11 CASE STUDY (Driscoll, pp 179-181)

- A consultant was retained by a developer to locate suitable groundwater supply for a proposed mobile home park.

- A test well drilled on the northwest potion of the property to a depth of 250 ft, encountered about 50 to 60 ft of fine sand. The yield was about 100 gpm, much less than the developer required. The consultant recommended that a surface resistivity survey be conducted over the entire parcel to define the most promising area for another well.

4 Surface Geophysical Techniques

- A resistivity survey consisting of 44 stations was laid out on a grid shown in **Figure 4.12**. Earth resistivity was taken with a Wenner array using 10, 20, 40, 60, 80, 120 and 160 ft a-spacing readings. These data enabled the consultant to construct an apparent resistivity/depth profile at each location. Cross sections of corrected resistivity were plotted in **Figure 4.13**. The profiles were contoured and then studied to determine whether any particular depth intervals displayed high values of resistivity which would indicate the presence of saturated sand and gravel lenses.

4 Surface Geophysical Techniques

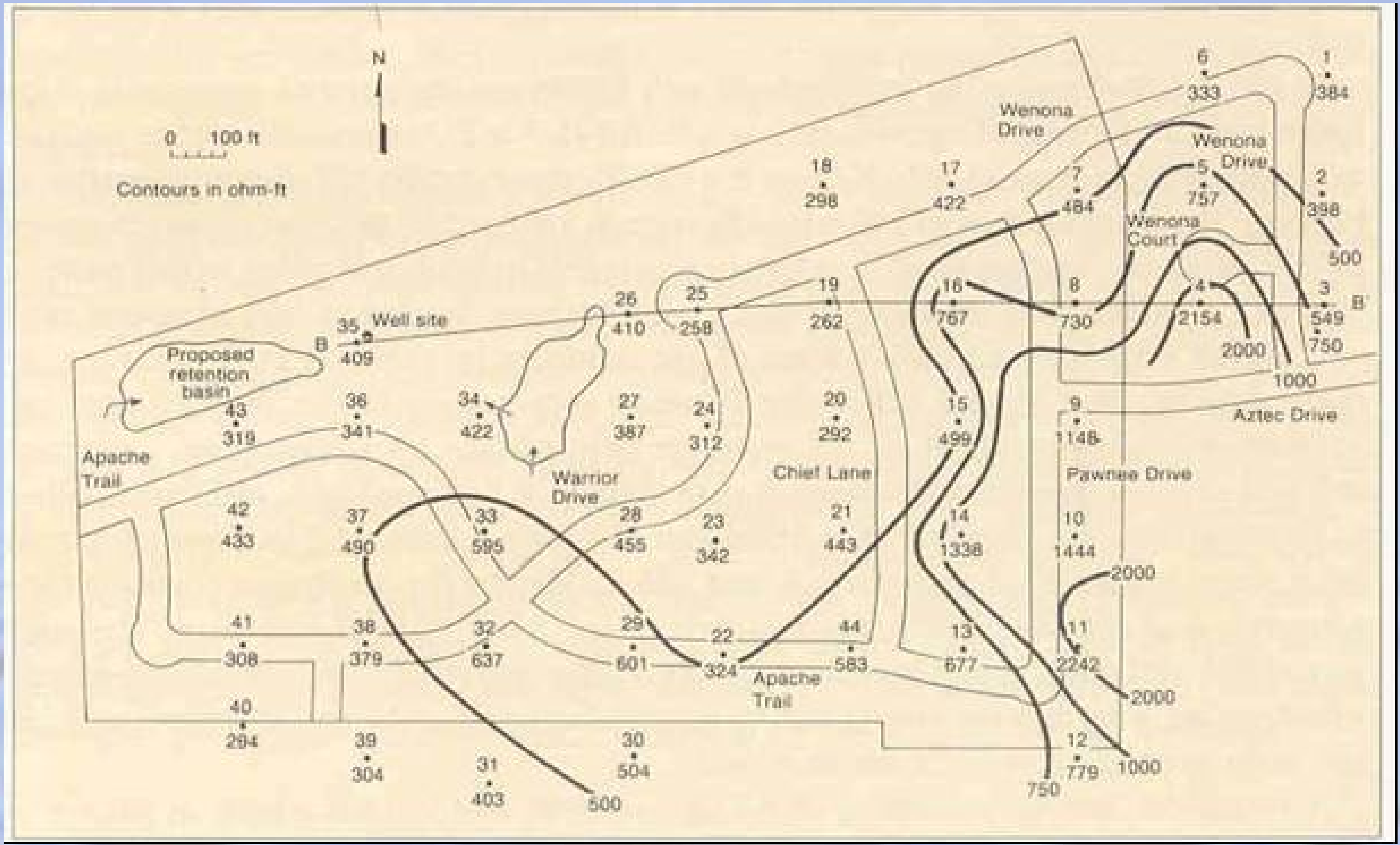


Figure 4.12: Resistivity layout for the proposed mobile home park. Values for the 40, 60, and 80 ft readings have been averaged

4 Surface Geophysical Techniques

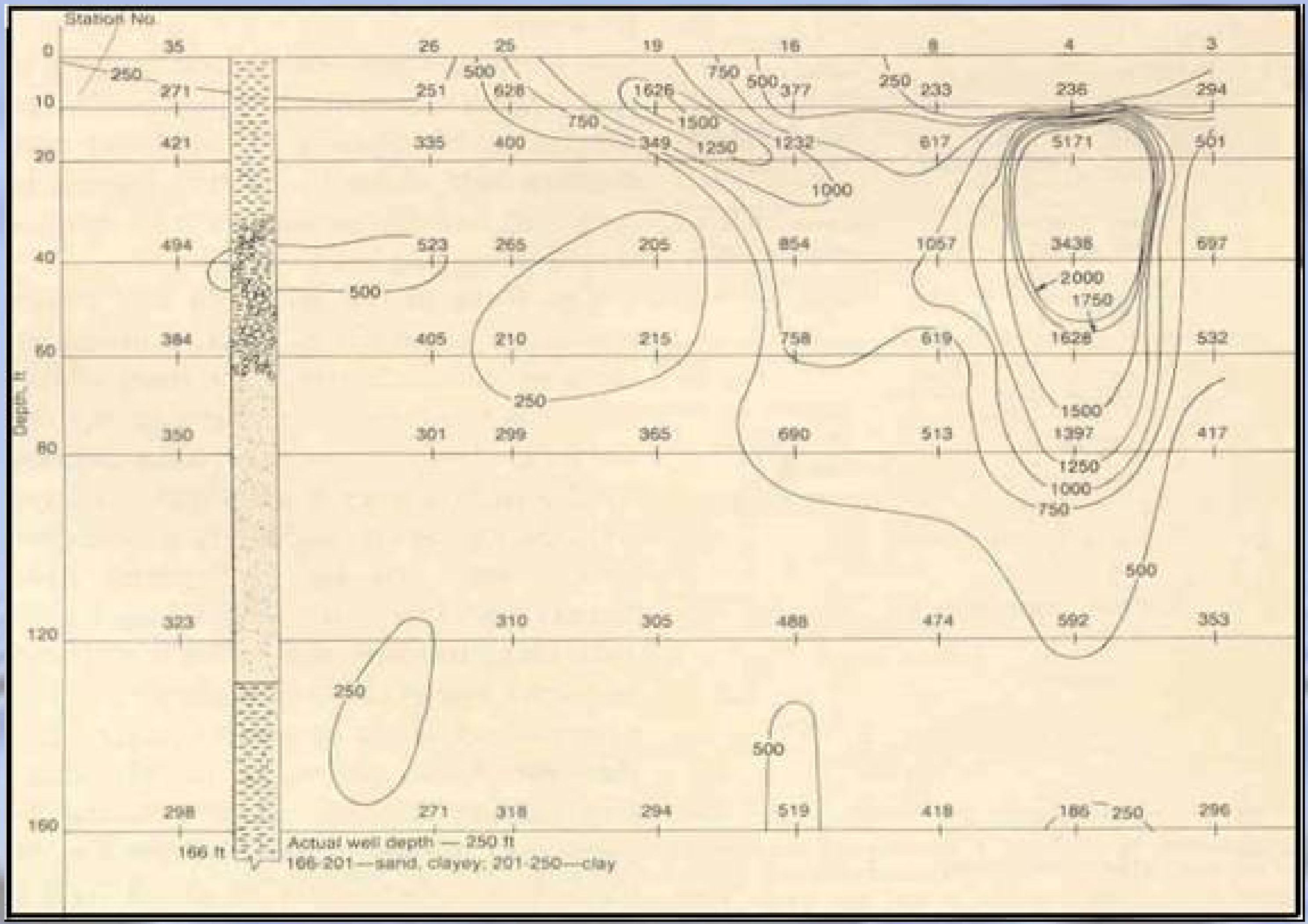


Figure 4.13: Profiles, or cross sections, of corrected resistivity. The readings indicate a thick sequence of saturated sand and gravel near the eastern border of the site.

4 Surface Geophysical Techniques

- Interpretation of resistivity values obtained from the survey indicate that aquifer conditions would be much more promising toward the eastern end of the property. Test drilling was recommended along the line of stations 8, 9, and 10. Ideally, drilling should have occurred along the line of stations 4, 5 and 6 but this area had already been developed with homes (see **Figure 4.14**).

4 Surface Geophysical Techniques

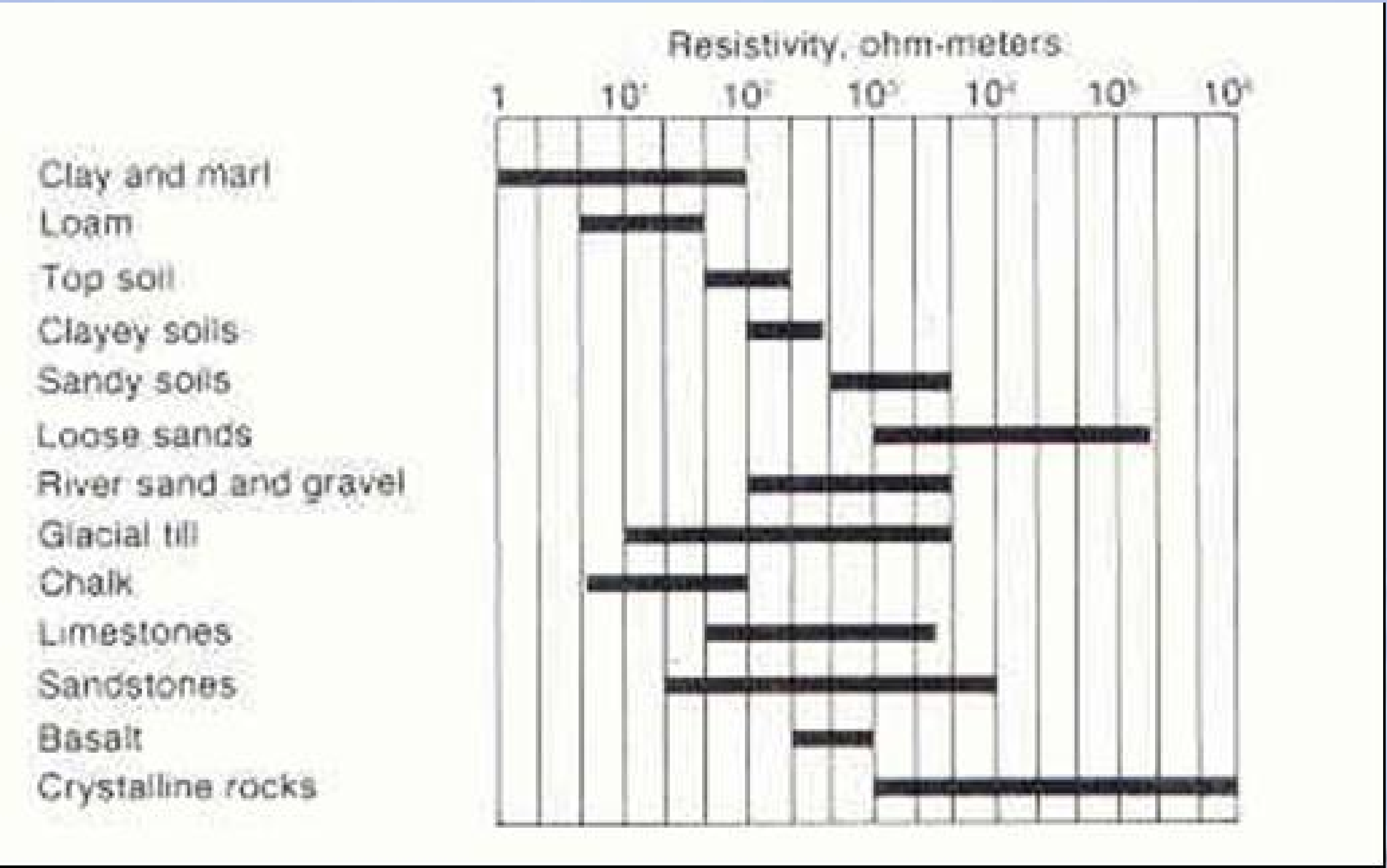


Figure 4.14: Ranges of resistivity values for various earth materials

4 Surface Geophysical Techniques

- Subsequently, a 12-in well was installed to a depth of 90 ft at the selected location. The boring encountered sand and gravel from a depth of about 5 ft to the bottom of the boring at 19 ft. during a 24 hour aquifer test, the well was pumped at 1,250 gpm, the specific capacity was 70 gpm for 100 days of continuous pumping which far exceeded the short term 100 gpm yield of the original test well a few hundred feet to the West.

4 Surface Geophysical Techniques

4.2 Surface Electro-Magnetic Techniques

4.2.1 Working Principle

- Primary electro-magnetic fields are generated by a transmitter at land surface. They induce currents at subsurface conductors which include rock types of a low resistivity. The induced currents produce a secondary electro-magnetic field that differs in magnitude and orientation, and in phase from the primary field. A recover measures the resulting total field. The principle is illustrated in **Figure 4.15**.

4 Surface Geophysical Techniques

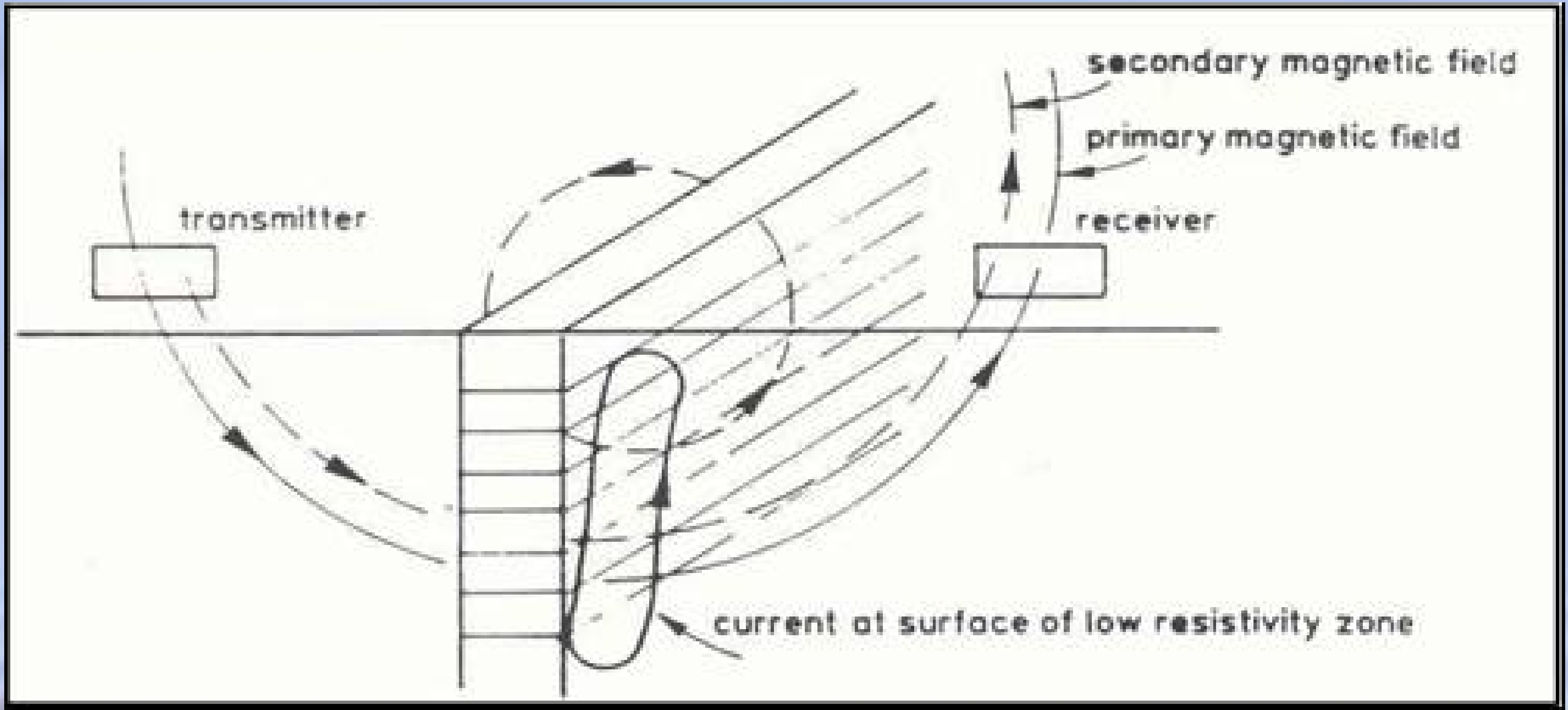


Figure 4.15: Principles of electro-magnetic techniques

4 Surface Geophysical Techniques

- The receiver measures the phase or the resulting primary plus secondary field (total field). The phases of the individual primary and secondary fields can be determined from these measurements. We will find that the phase of the secondary field generated by the subsurface conductor differs from the phase of the primary field. The better the conductor the more lags the phase of the secondary field behind the phase of the primary magnetic field. For very good conductors the phase of the secondary field may even lag 180 degrees behind the phase of the primary field. For poor conductors the phase difference between primary and secondary magnetic fields is usually in the order of 90 degrees (see **Figure 4.16**).

4 Surface Geophysical Techniques

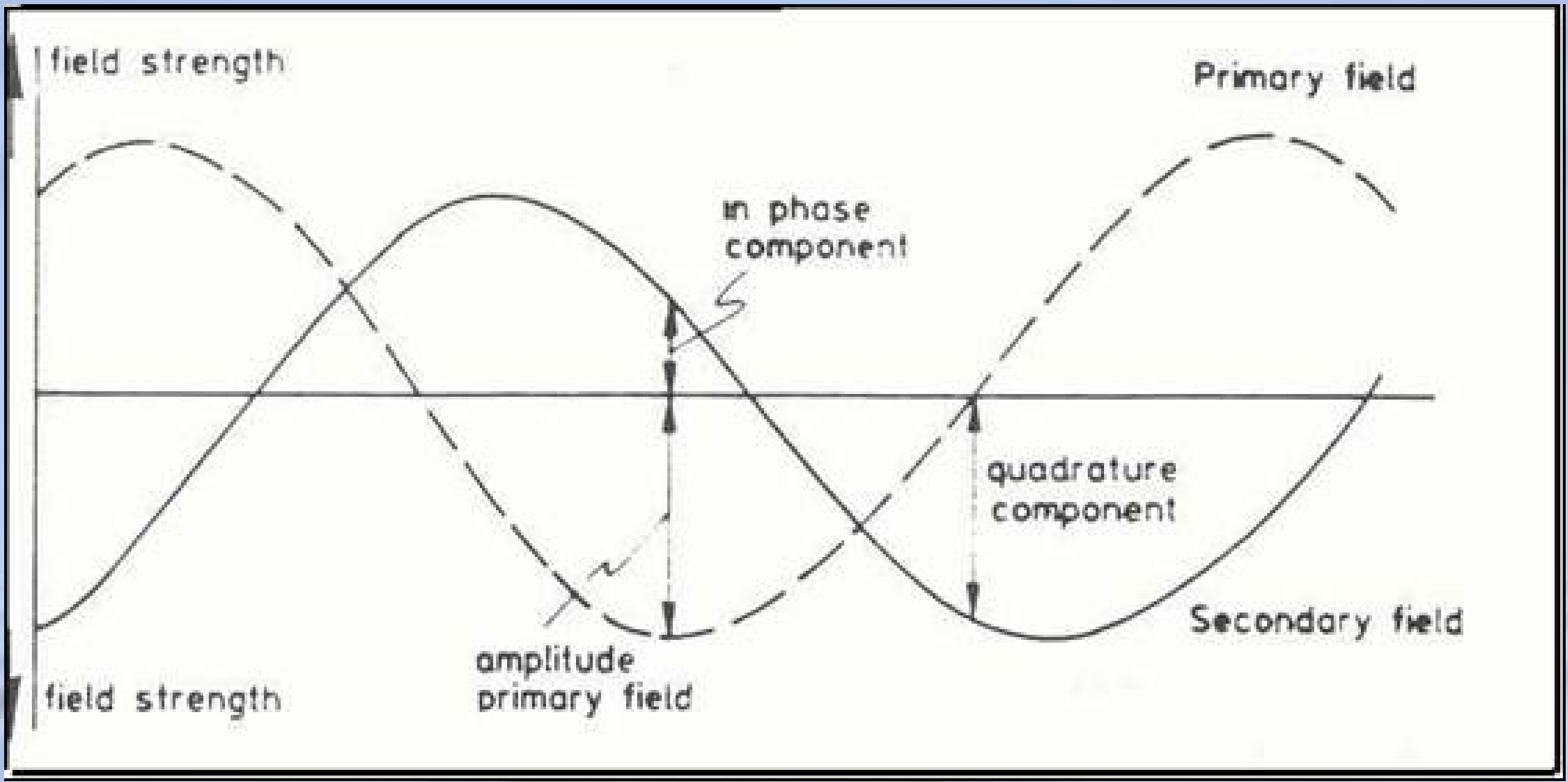


Figure 4.16: primary and secondary magnetic fields

4 Surface Geophysical Techniques

- Field strengths for the secondary field can be computed from the measurements recorded by the receiver. These field strengths can be used to find implicit values for the resistivities of subsurface conductive rock layers.

4 Surface Geophysical Techniques

4.2.2 Variable Electrode Distance Geo-electrical Technique

ADVANTAGES

- It can be used for the exploration of underground in a large variety of areas with diverse geological conditions.
- It is still the superior surveying techniques when information on the individual subsurface rock layers is required.
- The time needed for surveying and interpretation can be shortened.

4 Surface Geophysical Techniques

DISADVANTAGES

- A large entry resistance at the current electrodes (very dry conditions) may jeopardize the measurements. Mineralized water is usually added to improve conditions.

- In areas with very low layer resistivities (brackish to saline groundwater), the potential differences to be measured may be too small and cannot be accurately measured. Working with larger currents may help.

- The method is still time consuming and expensive. In comparison with other geophysical techniques survey time may be 3 to 4 times as long.

4 Surface Geophysical Techniques

4.2.3 Electro-Magnetic Techniques

- These are often considered compatible with Geo-electrical techniques. In particular electro-magnetic surveys are thought to be in the same league as the Geo-electrical surveys following the constant electrode distance arrangement. Engaged in reconnaissance surveying, both techniques can be used to obtain a quick impression of the resistivities of the subsurface layers in an area. Also, both techniques are well suited for tracking down vertical or steeply dipping "discontinuities" such as fault zones or intrusive dykes and sills in hard rock areas.

4 Surface Geophysical Techniques

ADVANTAGES

- Electro-magnetic surveying is faster than Geo-electrical surveying following the constant electrode distance technique.
- Electro-magnetic surveying is relatively inexpensive. Capital investment for some of the instrument is similar to the acquisition cost of Geo-electrical equipment. The cost gain is in time and in labor. For electro-magnetic surveying one or two men are usually required, while in Geo-electrical surveying at least three men will have to be employed (see **Figure 4.17**).

4 Surface Geophysical Techniques

Figure 4.17: Hand-carried terrain conductivity devices use electromagnetic waves to measure the conductivity of earth materials. Direct contact with the ground is not required during data gathering. Thus, subsurface information can be obtained quickly in both highly urbanized and rural environments.

4 Surface Geophysical Techniques

- In case surface layers with a sufficiently high resistively are present then the electro-magnetic method is ideally suited to unravel conductive rock layers, or bodies etc at larger depths. This is done for relatively small transmitter-receiver spacings. If we employ Geo-electrical techniques following the constant electrode distance method large electrode spacings are needed and more geological details may be lost. Such detail could have been detected if an electro-magnetic survey would have been set up.
- Electro-magnetic surveying may work better in case we deal with resistive surface layers. The magnetic fields that we use in electro-magnetic surveying are by no means hampered by such layers. On the other hand, electric currents which we use in Geo-electrical surveying may be obstructed due to large entry resistance.

4 Surface Geophysical Techniques

DISADVANTAGES

- Electro-magnetic surveying is severely hindered by the presence of man-made conductors, e.g. power lines, buried pipes, cables and wire fences.

- In case surface layers have a low resistivity then the electro-magnetic response tends to be primarily generated by these layers. There will be an inadequate response of any deeper rock layers, or these layers may not even be detected.

- Interpretation may be carried out in a qualitative way. There is no direct information on rock properties such as apparent rock resistivities.

4 Surface Geophysical Techniques

4.3 Seismic Refraction Method

4.3.1 Working Principle

- The seismic refraction method is based on the fact that elastic waves travel through different earth materials at different earth velocities. The denser the material, the higher the wave velocity.

- The waves are called elastic because as the waves pass a point in the rock, the particles are momentarily displaced or distorted but immediately return to their original position or shape after wave passes;

4 Surface Geophysical Techniques

- Three types of waves can be created: Compressional waves (P), Shear waves (V), and surface waves. Compressional waves are the first to arrive at the geophones and therefore are the most useful in seismic surveys;

- In general, the higher the density and elasticity of the rock unit, the faster the P wave will be transmitted. The velocity is much less and the energy is dissipated more quickly if the material is unconsolidated or poorly consolidated.

- Three distinct paths are taken by compressional waves in the ground: direct, refracted and reflected (see **Figure 4.18**). A single seismic impulse can be recorded as three separate arrivals at the geophone. In practice, however, only the first arrival can be readily recognized.

4 Surface Geophysical Techniques

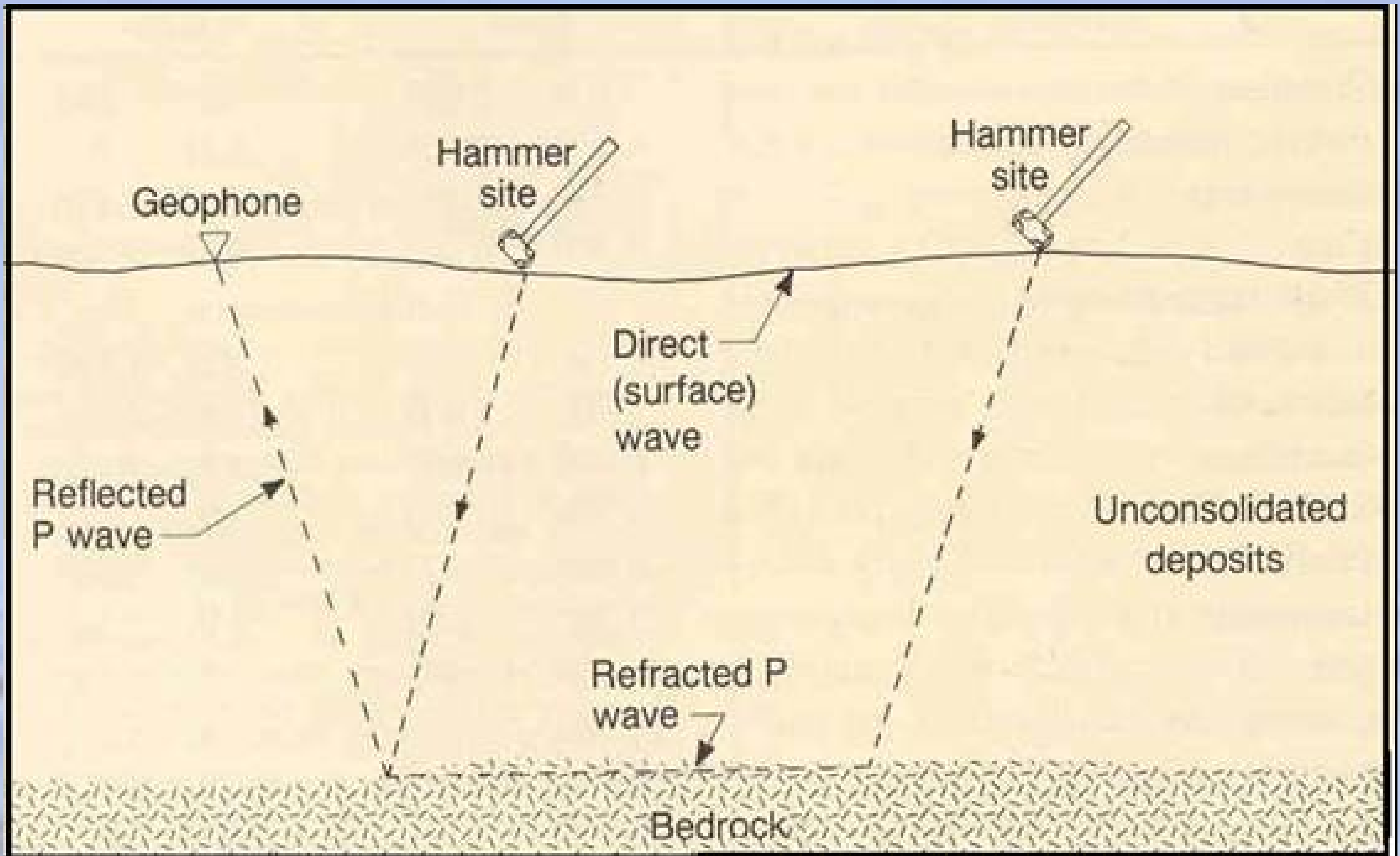


Figure 4.18: Waves from a seismic disturbance can travel as surface, reflected, and refracted waves. In water well exploration, analyses of refracted and reflected waves can determine the depth to bedrock at a potential drilling site

4 Surface Geophysical Techniques

- When elastic waves cross a geological boundary between two formations with different elastic properties, the velocity of wave propagation changes and the wave paths are refracted.

- Seismic methods use artificially seismic waves traveling through the ground. By studying the arrival times of seismic waves at various distances from energy source, the depth to bedrock can be determined.

- These methods are useful in determining depth to bedrock, depth to water table and in some cases general lithology.

4 Surface Geophysical Techniques

- Seismic refraction method is used to determine the thickness of unconsolidated materials overlying bedrock. The loose material transmits seismic waves more slowly than consolidated bedrock. By studying the arrival times of seismic waves at various distances from energy source, the depth to bedrock can be determined.
- The energy source can be a small explosive charge set in a shallow drill hole. One or two sticks of dynamite are sufficient for depths to bedrock in excess of 30 to 50 m.
- The seismic wave is detected by geophones placed in the earth in a line extending away from the energy source. Waves initiated at the surface and refracted at the critical angle by a high-velocity layer at depth will reach the more distant geophones more quickly than waves that travel directly through the low-velocity surface layer.

4 Surface Geophysical Techniques

4.3.2 Interpretation

- Each geological formation has a characteristic seismic velocity that affects arrival time. Some representative seismic velocities are given in **Table 4.4**
- A seismograph records the travel time for the wave to go from energy source (short point) to geophone. This time should be plot against distance from shot point to geophone;
- The most difficult problem with the reflection method is that the reflected wave is never the first to appear on the seismic record. Therefore, on an ordinary receiving device its arrival is almost impossible to recognize among the multitude of other wave arrivals. This problem can be overcome by using signal enhancement, which permits the operator to separate the primary reflected wave from others.

4 Surface Geophysical Techniques

Table 4.4: Approximate range of velocities of compressional waves (P) for representative materials found in the Earth's crust

Material	Velocity*	
	Ft/sec	m/sec
Weathered surface material	1,000 - 2,000	305 – 610
Gravel, rubber, or san (dry)	1,500 – 3,000	457 - 915
Sand (wet)	2,000 – 6,000	610 – 1,830
Clay	3,000 – 9,000	915 – 2,740
Water (depending on temperature and salt	4,700 – 5,500	1,430 – 1,680
content	4,800 – 5,000	1,460 – 1,520
Sea water	6,000 – 13,000	1,830 – 3,960
Sandstone	9,000 – 14,000	2,740 – 4,270
Shale	6,000 – 13,000	1,830 – 3,960
Chalk	7,000 – 20,000	2,130 – 6,100
Limestone	14,000 – 17,000	4,270 -5,180
Salt	15,000 – 19,000	4,570 -5,790
Granite	10,000 – 23,000	3,050 – 7,010
Metamorphic rocks	12,050	3,670
Ice		

* The higher values in a given range are usually obtained at depth.

4 Surface Geophysical Techniques

- **Figure 4.19** illustrates the travel paths of compressive seismic waves traveling through a two-layer earth. The seismic velocity in the lower layer is greater than that in the upper layer. As the energy travels faster in the lower layer, the way passing through it gets ahead of the wave in the upper layer. At the boundary between the two layers, part of the energy is refracted back upward from the lower-layer boundary to the surface;

4 Surface Geophysical Techniques

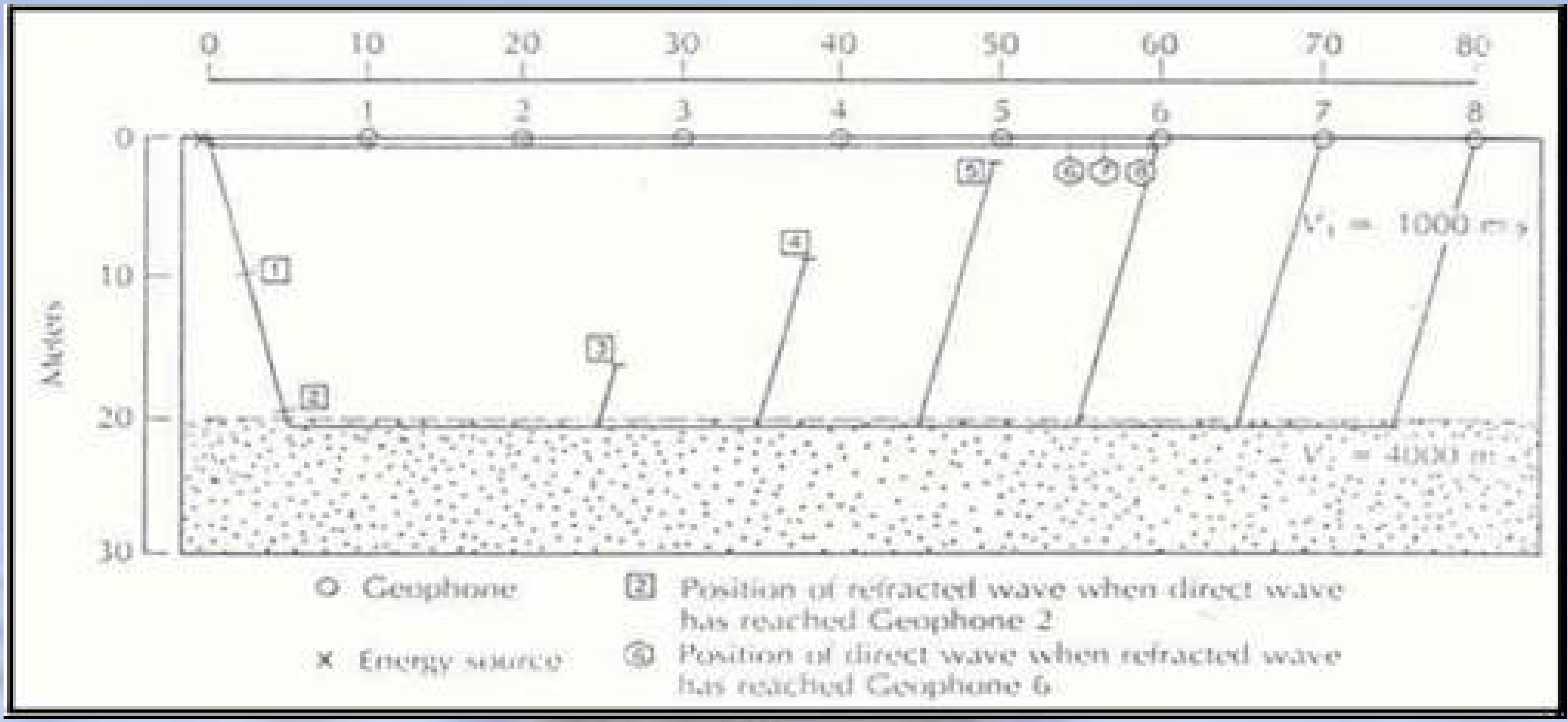


Figure 4.19: Travel paths of a refracted seismic wave and a direct wave. The direct wave will reach the first five geophones first, but for the more distance geophones the first travel is from a refracted wave. Numbers inside symbols refer to distances traveled by wave paths going toward the indicated geophone.

4 Surface Geophysical Techniques

- The angle of refraction of each wave front is called the critical angle i_c, and is equal to the arc sin of the ration of the velocities of the two layers:

$$i_c = \sin^{-1}\frac{V_1}{V_2} \tag{16}$$

- **Figure 4.20** illustrates a wave front and the path of the refracted energy that travels along the lower-layer boundary. A direct wave in the upper layer is also shown.

- If $V_2 < V_1$ then the wave will be refracted downward and no energy will be directed upward. Thus the refraction method will show higher-velocity layers but no lower-velocity layers that are overlain by a high-velocity layer.

4 Surface Geophysical Techniques

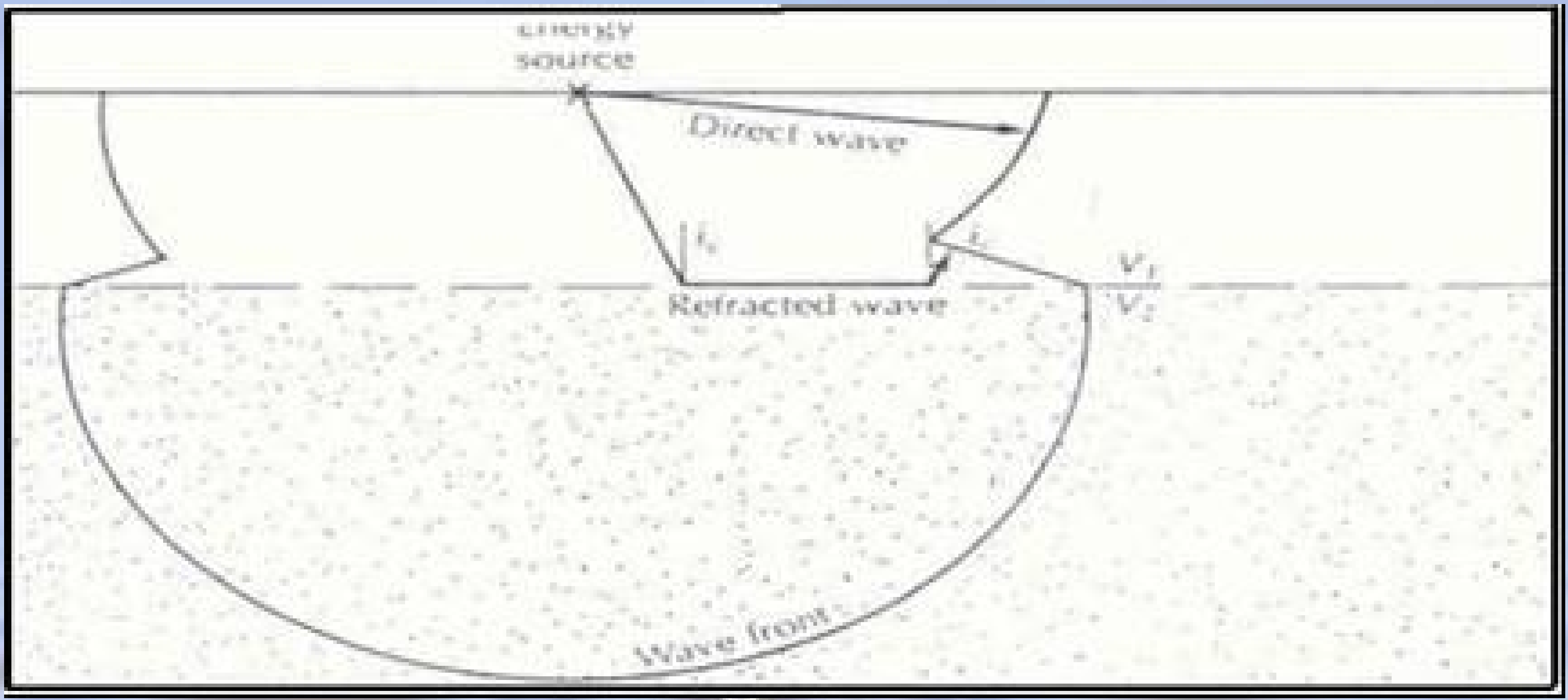


Figure 4.20: A seismic wave front at a given time after a charge is detonated

4 Surface Geophysical Techniques

- Energy travels directly through the upper layer from the source to the geophone. This is the shortest distance, but the waves do not travel as fast as those traveling along the top of the lower layer. The latter go farther, but with a higher velocity. **Figure 4.19** shows the positions of waves traveling to each geophone. Geophones 1 through 5 first receive waves that have traveled through only the upper layer. The sixth and succeeding geophones measure arrival times of refracted waves that have gone through the high-velocity layer as well. The figure shows the position of the trailing wave front at each time the leading front reaches each geophone;

4 Surface Geophysical Techniques

- A graph is made of the arrival time of the first wave to reach geophone versus the distance from the energy source to the geophone (travel-time or time-distance curve). **Figure 4.21** shows the time-distance curve for the shot in **Figure 4.19**. The reciprocal of the slope of each straight-line segment is the apparent velocity in the layer through which the first arriving wave passed. The slope of the first segment is 10 milliseconds per 10 m so that the reciprocal is 10 m per 10 ms or 1000 m/s.

4 Surface Geophysical Techniques

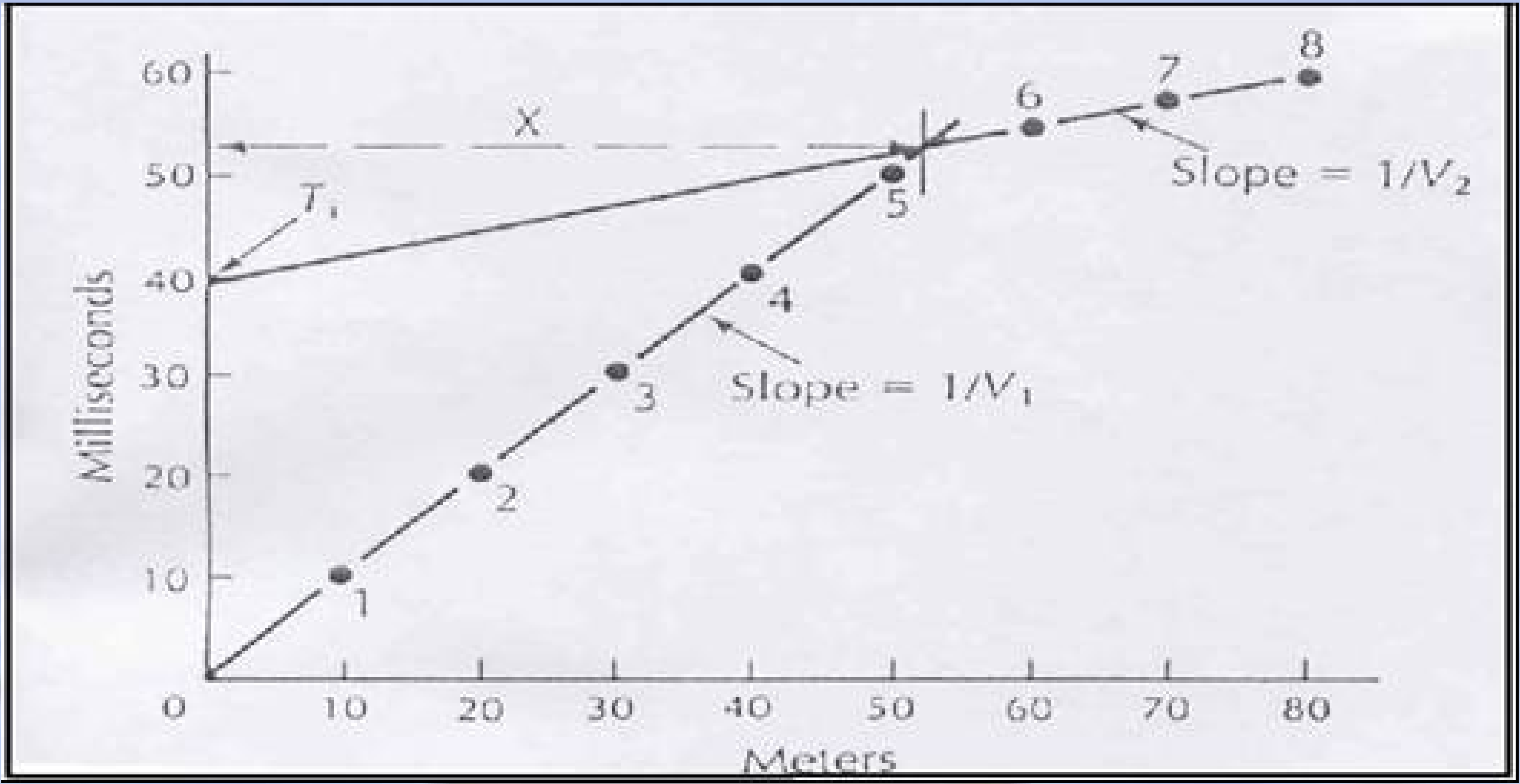


Figure 4.21: Arrival time-distance diagram for a two-layered seismic problem. Numbers refer to geophones in Figure 4.19.

4 Surface Geophysical Techniques

- The projection of the second line segment backward to the time-axis (X=0) yields a value known as the intercept time, T_i. As shown in **Figure 4.21**, T_i is 39 ms and X=52 m.

- The depth to the lower layer Z, is found from:

$$Z = \frac{T_i}{2} \frac{V_1 V_2}{\sqrt{V_2^{\,2} - V_1^{\,2}}} \qquad \textbf{(17)}$$

4 Surface Geophysical Techniques

- The depth to the lower layer can be also found from the equation:

$$Z = \frac{X}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \quad \textbf{(18)}$$

where X is the distance from the shot to the point at which the direct wave and the refracted wave arrive simultaneously. This is shown in Figure 4.21 as the x-axis distance where the two line segments cross.

- A more typical case in the hydrogeology is a three-layer earth, the top layer being unsaturated, unconsolidated material. In the next layer below the water table, the unsaturated deposits are saturated, which yield a higher seismic velocity. The third layer is then bedrock. Under such conditions the seismic method can be used to find the water table.

4 Surface Geophysical Techniques

➢The three-layer seismic case with $V_1<V_2<V_3$ is shown in **Figure 4.22**. The first arriving waves show three line segments. The reciprocal of the slope of each line is the seismic velocity of the respective layers. The intercept time for each of the two deeper layers is the projection of the line segment back to the time-axis. Indicated on the Figure is the distance X_1, from the shot to the point at which waves from layers 1 and 2 arrive simultaneously and the distance X_2, to the point at which waves from layers 2 and 3 arrive simultaneously. The thickness Z_1 of layer 1 is found from the values of V_1 and V_2 and either T_{i1} or X_1 using **equation 17 or 18**. the thickness of the second layer Z_2 is found from:

$$Z = \frac{1}{2}\left[T_{i2} - 2Z_1\sqrt{\frac{V_3^{\,2} - V_1^{\,2}}{V_3 V_1}}\right] x \left[\frac{V_2 V_3}{\sqrt{V_3^{\,2} - V_2^{\,2}}}\right] \quad \textbf{(19)}$$

4 Surface Geophysical Techniques

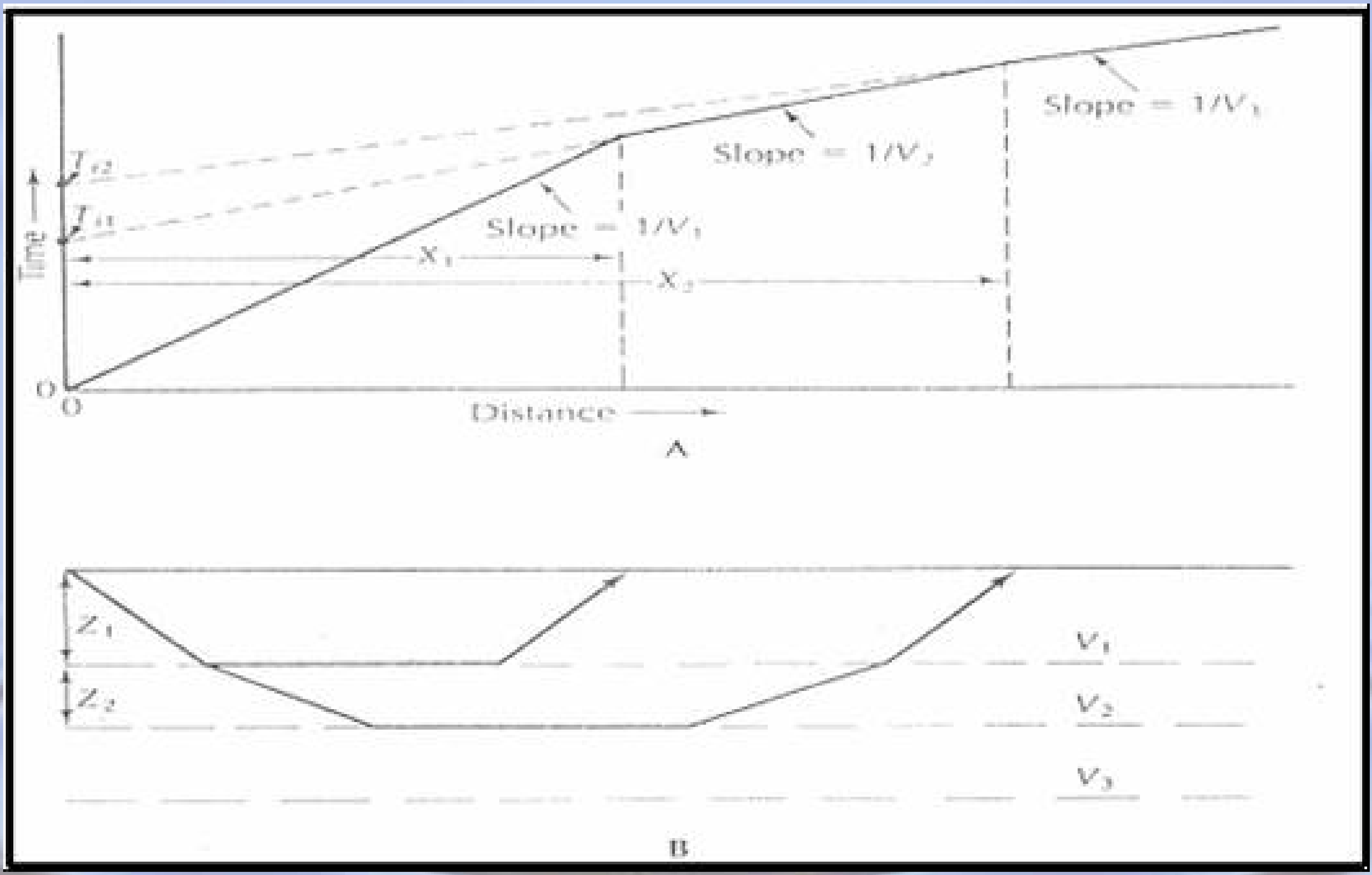


Figure 4.22: **A.** Diagram of arrival time versus distance for a three-layered seismic problem. **B.** Wave path for a three-layered seismic problem

4 Surface Geophysical Techniques

- The velocities computed from the reciprocals of the slope are called apparent velocities. If the lower layer is horizontal, they represent the actual velocity.
- If the lower layer is sloping, the arrival time for a shot measured down slope will be different from one measured upslope. Seismic lines are routinely run with a shot at either end, so that dipping beds can be determined.
- Time-distance curves for a dipping stratum are shown in **Figure 4.23**, with travel times measured from shots at either end of the line. The upper layer is unaffected by the dip of the lower bed, so that the reciprocal of the slope of the first line segment is V_1. in order to find the values of V_2 and the depth to the bedrock at the undip end of the line Z_d, as well as at the downdip end Z_u, a complex series of computations must be made.

4 Surface Geophysical Techniques

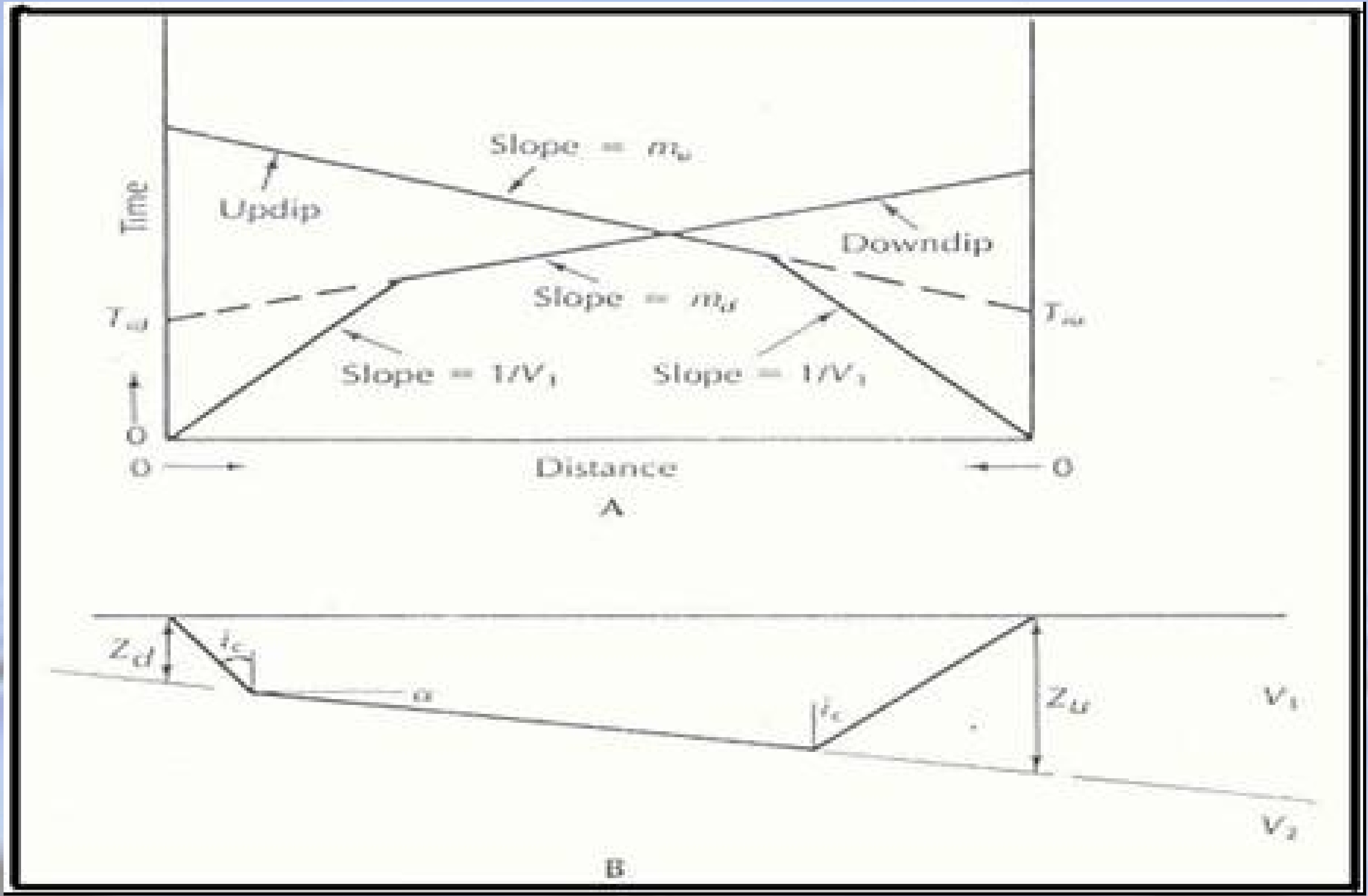


Figure 4.23: **A.** Diagram of arrival time versus distance for two-layered seismic problem with a sloping lower layer. **B.** Wave path for the preceding problem **4/4**

4 Surface Geophysical Techniques

- The slope of the second line segment of the downdip line m_d, and the slope of the second line segment of the updip line is m_u. The value of the angle refraction i_c, is found from:

$$i_c = \frac{1}{2}\left[\sin^{-1} V_1 m_d + \sin^{-1} V_1 m_u\right] \qquad \textbf{(20)}$$

- The value of V_2 is given by:

$$V_2 = \frac{V_1}{\sin i_c} \qquad \textbf{(21)}$$

- The angle of slope of the dipping layer is found from:

$$\alpha = \frac{1}{2}\left[\sin^{-1} V_1 m_d - \sin^{-1} V_1 m_u\right] \qquad \textbf{(22)}$$

4 Surface Geophysical Techniques

- The depths to the lower layer at either end of the shot line are found from:

$$Z_u = \frac{V_1 T_{iu}}{(\cos \alpha)(2 \cos i_c)} \quad \textbf{(23)}$$

$$Z_d = \frac{V_1 T_{id}}{(\cos \alpha)(2 \cos i_c)} \quad \textbf{(24)}$$