Seismic refraction surveying

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INTRODUCTION

- **Seismic refraction surveys can be undertaken at three distinct scales:**

I. *global (using earthquake waves)*
II. *crustal (using explosion seismology)*
III. *near-surface (engineering applications).*

INTRODUCTION

- The major strength of the seismic refraction method is that it can be used to resolve lateral changes in the depth to the top of a refractor and the seismic velocity within it.
- The most commonly derived geophysical parameter is the seismic velocity of the layer present.

INTRODUCTION

- From the seismic velocity values, a number of important geotechnical factors can be derived such as:

I. Assessing rock strength

II. Determining rippability

The ease with which ground can be ripped up by an excavator)

III. Potential fluid content

INTRODUCTION

- Seismic refraction is increasingly being used in hydrogeological investigations to determine saturated aquifer thickness, weathered fault zones .
- The location of faults, joints, and other such disturbed zones using seismic refraction is of major importance in the consideration of the suitability of potential sites for the safe disposal of particularly toxic hazardous wastes.

General Principles of Refraction Survey

Critical refraction

- Refraction surveys use the process of <u>critical refraction</u> to infer interface depths and layer velocities.
- When the velocity is higher in the underlying layer there is a particular angle of incidence, known as the *critical angle* θ_c, for which the angle of refraction is 90°.
- This gives rise to a critically refracted ray that travels along the interface at the higher velocity v_c .

Critical refraction

- At any angle greater of incidence there is total internal reflection of the incident energy (apart from converted S-wave rays over a further range of angles).
- The critical angle is given by

$$\sin i_c / v_1 = \sin 90^\circ / v_2 = 1/v$$

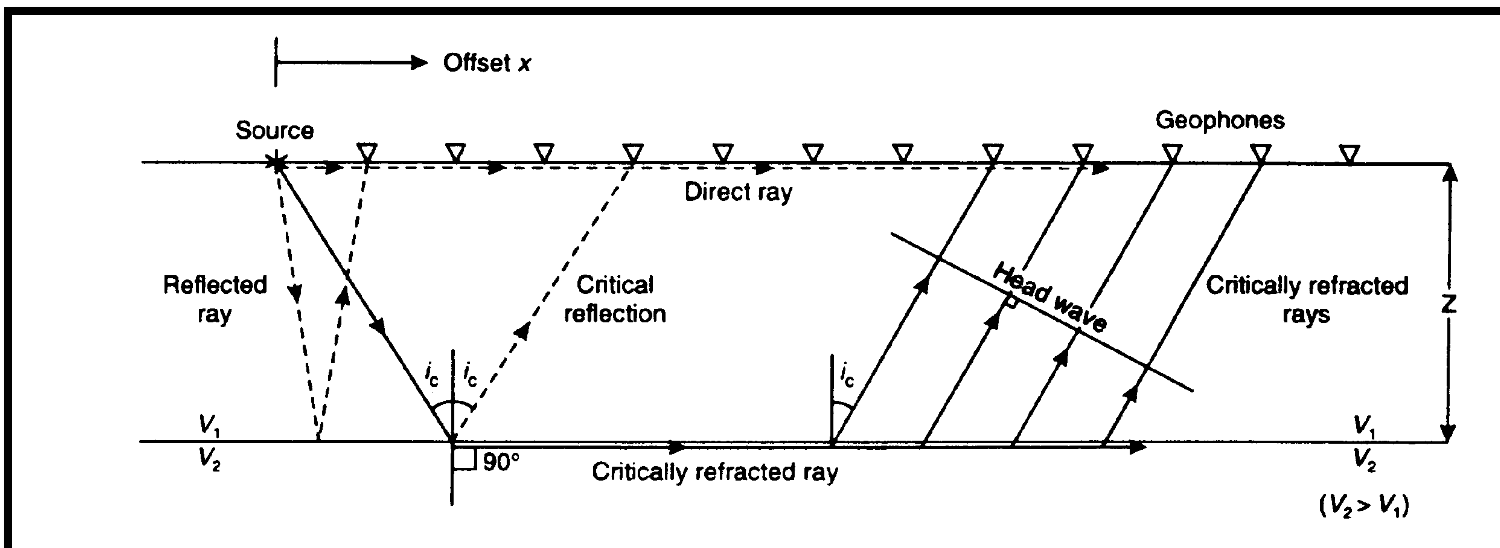
$$\sin i_c = v_1 / v_2$$

Critical refraction

- The refraction method is dependent upon there being increase in velocity with depth ($v_2 > v_1$).
- If the v_2 less than v_1 , the refracted wave will bend toward the normal.
- This gives rise to a situation known as **hidden layer.**

Critical refraction

- The basic components of a seismic refraction experiments are shown schematically below:



Critical refraction

- A source, such as sledge hammer on base plate or drop weight, is used to generate the P waves.

Critical refraction

- The waves produced travel in three principal ways, Figure 1 :

I. Directly along the top of ground surface (direct waves)
II. By reflection from the top of the refractor.
III. By critical refraction along the top of the refractor(s).

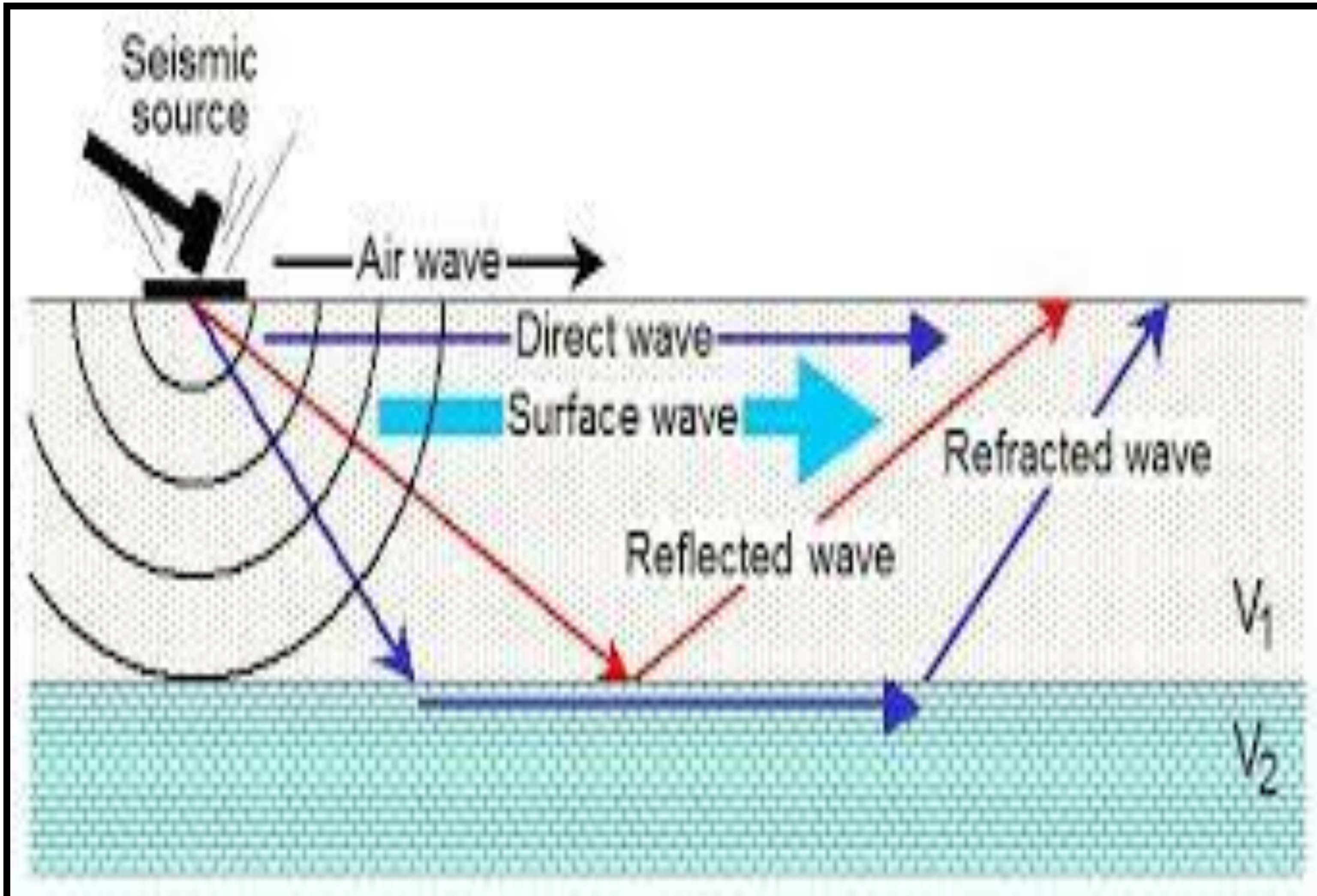

Seismic source
Air wave
Direct wave
Surface wave
Refracted wave
Reflected wave
V_1
V_2

Figure 1

Critical refraction

- The arrival of each wave is detected along a set of geophones and recorded on a seismograph, with the output of each geophone being displayed as a single trace.
- The onset of each arrival for each geophone is identified, and the associated travel time is measured and plotted on a time – distance curve (graph),Figures 2 and 3.

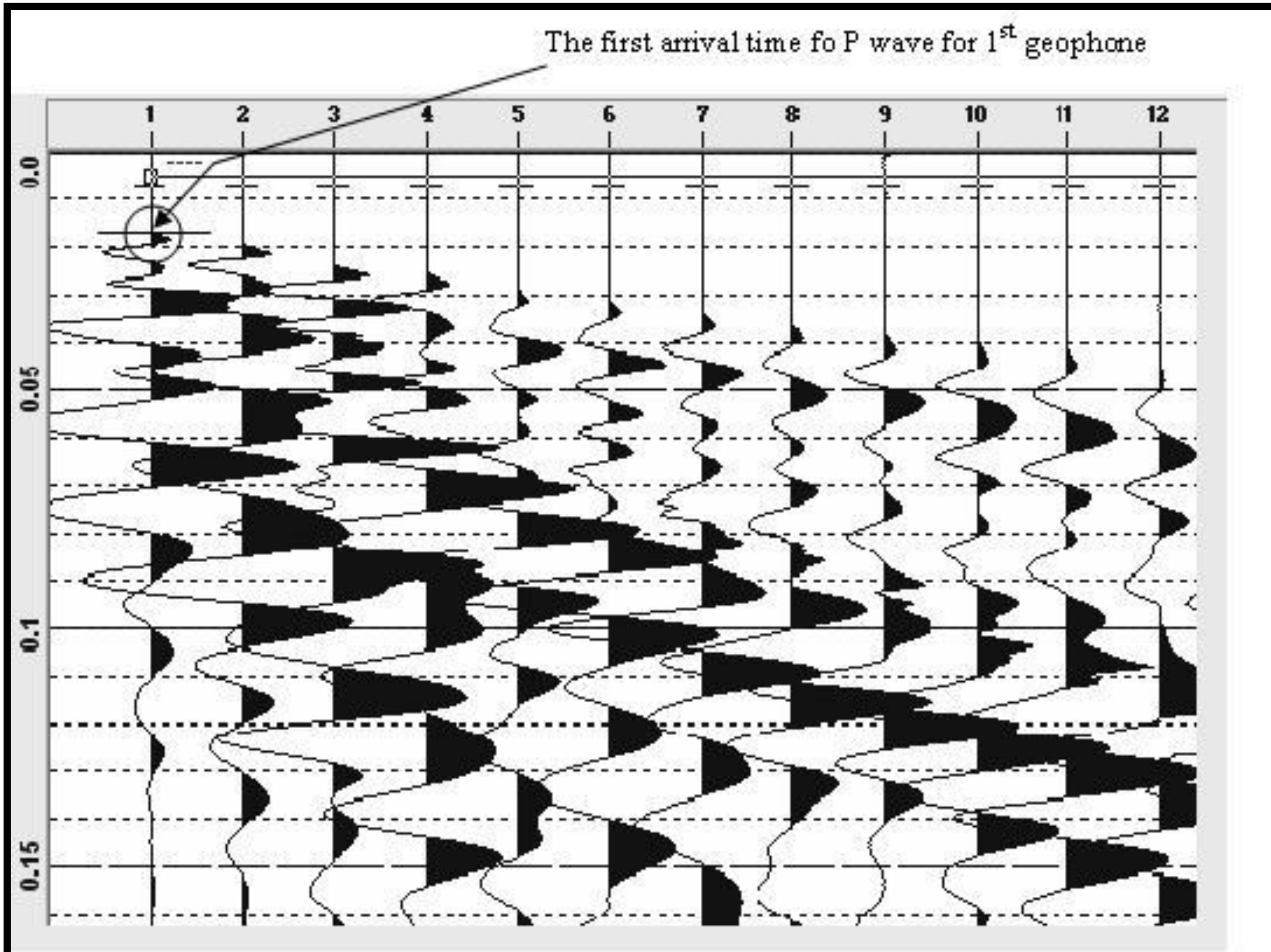


Figure 2. Seismic refraction record.

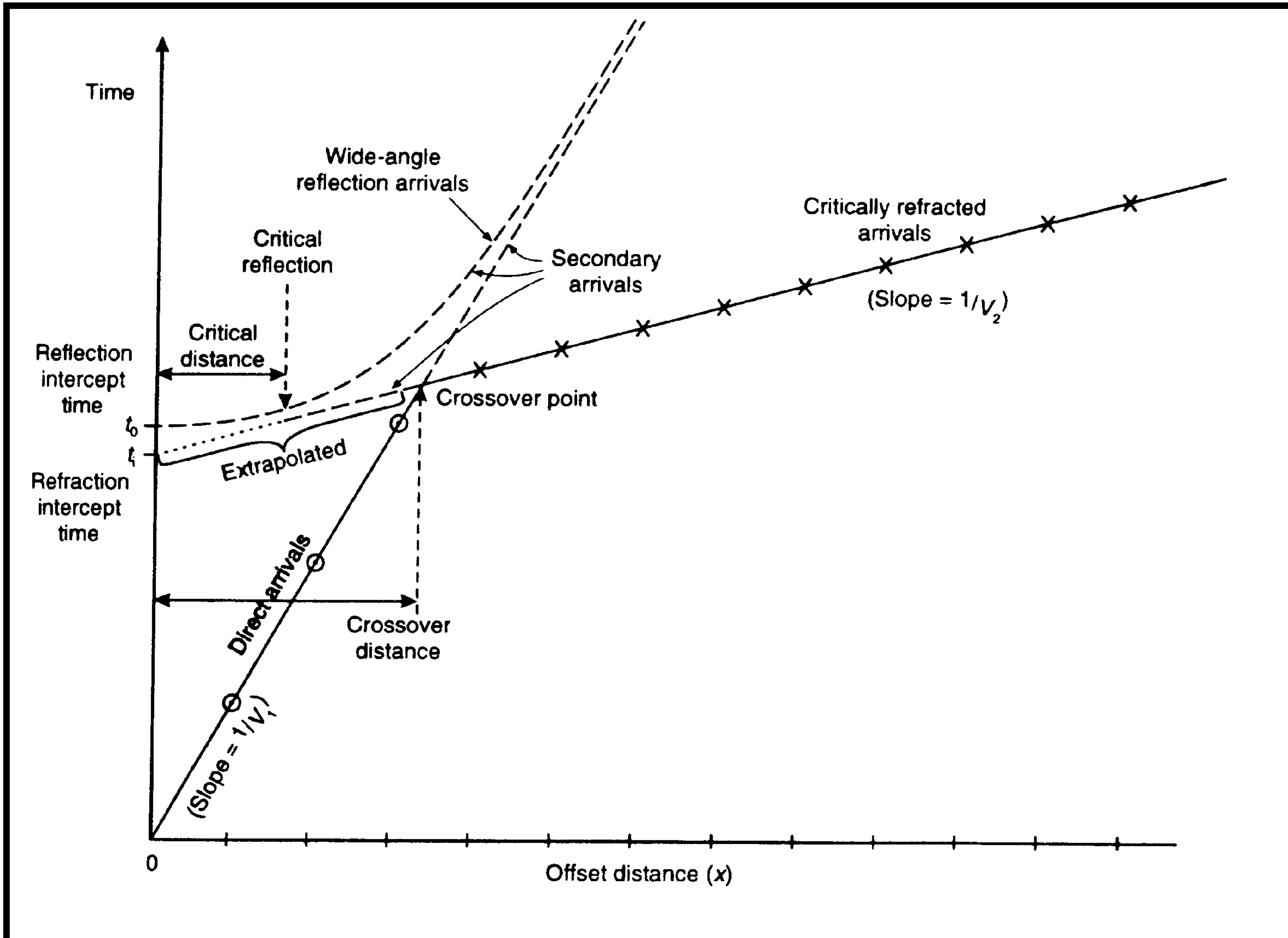


Figure 3. Time – distance curve.

Critical refraction

- At a distance called the **critical distance**, the reflected arrival is coincident with the first critically refracted arrival and the travel times of the two are identical.
- The critical distance is thus the offset at which the reflection angle equals the critical angle.
- The critical distance should not be confused with the **crossover distance.**

Critical refraction

- The crossover distance is the offset at which the critically refracted waves precede the direct waves.
- The crossover point marks the change in the gradient of the time-distance curve from the slope of the direct arrivals segment to that for the refracted signals.
- While the travel time hyperbola associated with reflected arrivals, only direct and refracted arrival times are usually considered in the refraction analysis.

Field Survey Arrangements
Land Surveys

- For a seismic refraction survey on land, the basic layout is shown in Figure 4.
- A number of geophones usually 12 or 24, are laid along a cable with a corresponding umber of takeouts along a straight line.

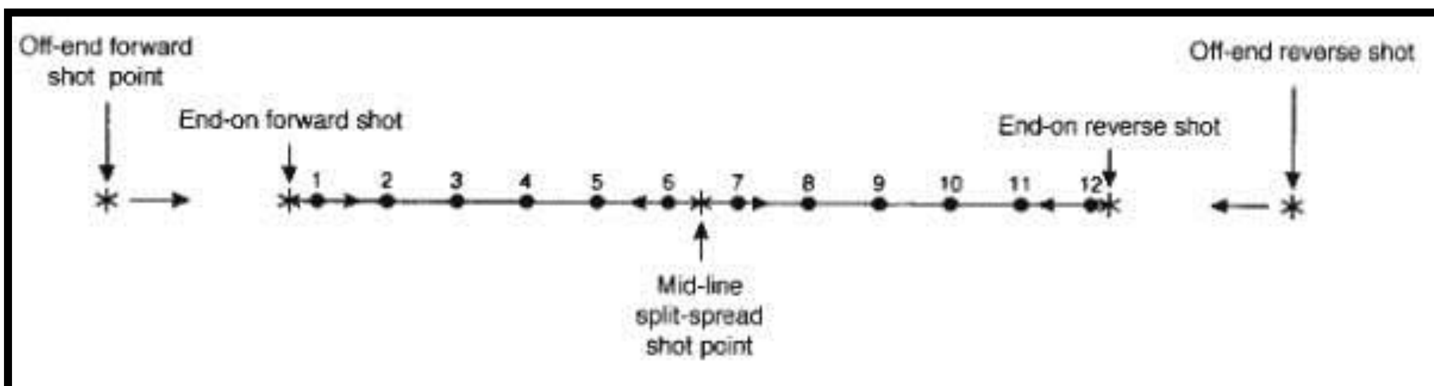


Figure 4

Land Surveys

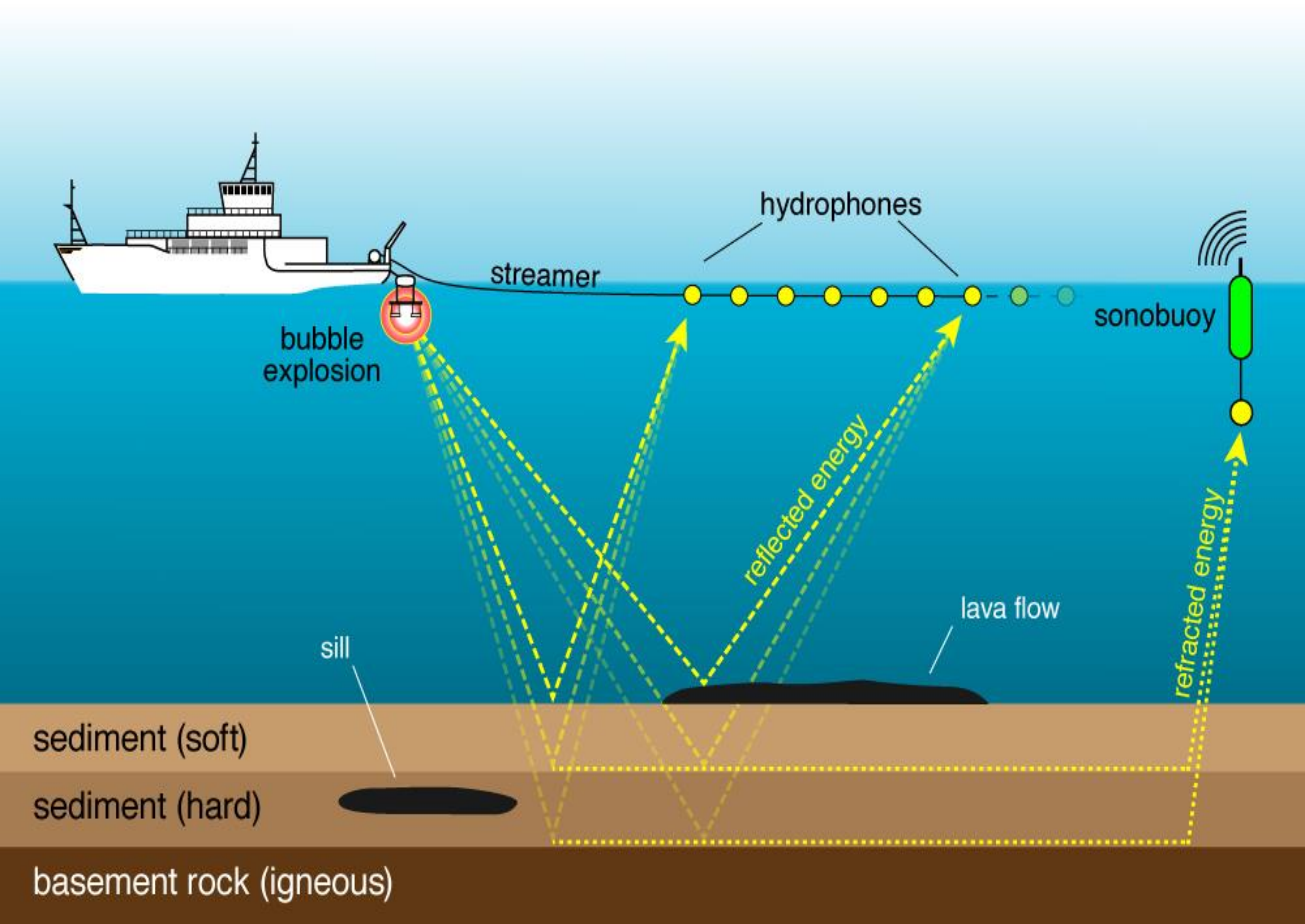
- Geophones and cable comprise a spread.
- Shot would usually be placed at one end of spread for first recording, then second recording made at other end, end -on shot.
- Off-end and split-spread shooting also possible.
- A shot located at a discrete distance off the end of the spread is known as an 'off-end shot'.

Land Surveys

- A shot positioned at a location along the spread is known as a ‘split spread’ shot; usually this is either at the mid-spread or at a quarter or three quarters along a spread.
- Shots are usually fired into a spread from each end (end-on and off-end shots).

Marine Surveys

- Seismic refraction can also be undertaken in an aquatic environment but special systems are required.
- Shot firing and seismograph recording systems are housed on a boat.
- Two options for receivers:
    I. Bottom-cable
    II. Sonobouys


hydrophones
streamer
bubble explosion
sonobuoy
reflected energy
refracted energy
lava flow
sill
sediment (soft)
sediment (hard)
basement rock (igneous)

Marine Surveys

I. Bottom-cable

Hydrophones contained in a ~55 m cable which is deployed or dragged along bottom of river or seabed.

II. Sonobouys

Hydrophone is suspended from floating buoy containing radio telemetry to transmit seismogram to boat.

- Boat steams away from sonobouy firing an airgun.

Interpretation of Refraction Travel time Data

- After completion of a refraction survey first arrival times are picked from seismograms and plotted as travel time curves.
- Interpretation objective is to infer interface depths and layer velocities.
- Data interpretation requires making assumption about layering in subsurface: look at shape and number of different first arrivals.

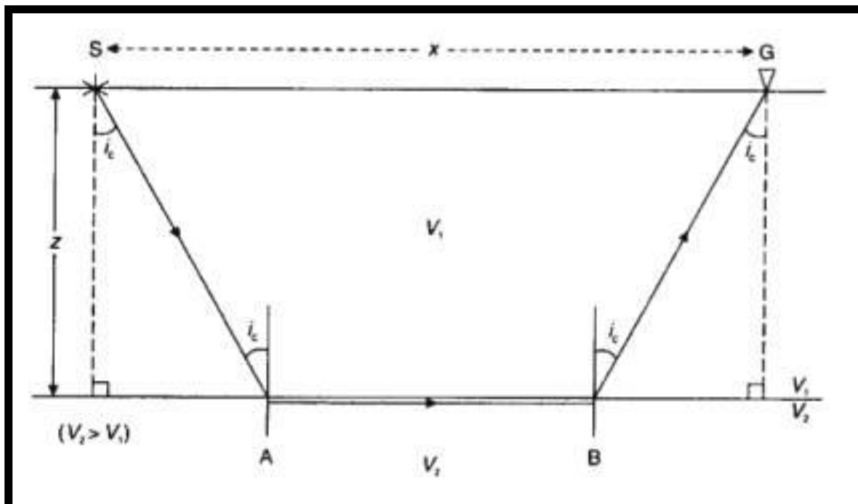
Interpretation of Refraction Travel time Data

- **Assumptions**
- Subsurface composed of stack of layers, usually separated by plane interfaces
- Seismic velocity is uniform in each layer
- Layer velocities increase in depth
- All ray paths are located in vertical plane, i.e. no 3-D effects with layers dipping out of plane of profile

Interpretation of Refraction Travel time Data

- Analysis based on considering critical refraction ray paths through subsurface.
- There are more sophisticated approaches to handle non-uniform velocity and 3-D layering.

Planar Interfaces
Two Layers



Planar Interfaces
Two Layers

- For critical refraction at top of second layer, total travel time from source S to receiver G is given by:

$$T_{SG} = T_{SA} + T_{AB} + T_{BG} \qquad (1)$$

Where

$$T_{SA} = T_{BG} = Z/(V_1 \cos i_c) \qquad (2)$$

$$T_{AB} = (x - 2z \tan i_c)/V_2 \qquad (3)$$

Planar Interfaces
Two Layers

- So, as two end triangles are the same:

$$T_{SG} = \frac{2Z}{V_1 \cos i_c} + \frac{(X - 2Z \tan i_c)}{V_2} \qquad (2)$$

$$= \frac{X}{V_2} + \frac{2Z}{V_1 \cos i_c}\left(1 - \frac{V_1}{V_2} \sin i_c\right) \qquad (3)$$

- At critical angle, Snell's law becomes:

$$\sin i_c = \frac{V_1}{V_2}$$

Planar Interfaces
Two Layers

- Substituting expression in (2) and (3) into (1), we obtain:

$$T_{SG} = z/(V_1 \cos i_c) + (x-2z \tan i_c)/V_2 + z/(V_1 \cos i_c)$$

Where simplifies to

$$T_{SG} = (1/V_2)x + 2z(\cos i_c)/V_1 \qquad (4)$$

- This has the form of the general equation of a straight line , y = mx + c, where m= slope and c = intercept on the y-axis on a time -distance curve.

Planar Interfaces
Two Layers

- So, from equation (4), the slope is $1/V_2$ and c is the refraction intercept time t_i such that

$$t_i = 2z\,(\cos i_c)/V_1$$

- Remember that $\sin i_c = V_1/V_2$ (Snell's Law), and hence

$$\cos i_c = (1 - V_1^2 / V_2^2)^{1/2} \text{ (from } \cos^2\theta + \sin^2\theta = 1)$$

Planar Interfaces
Two Layers

- An alternative form to equation (4) is:

$$T_{SG} = x(\sin i_c)/V_1 + 2z(\cos i_c)/V_1 \qquad (5)$$

Or

$$T_{SG} = x/V_1 + t_i \qquad (6)$$

Where

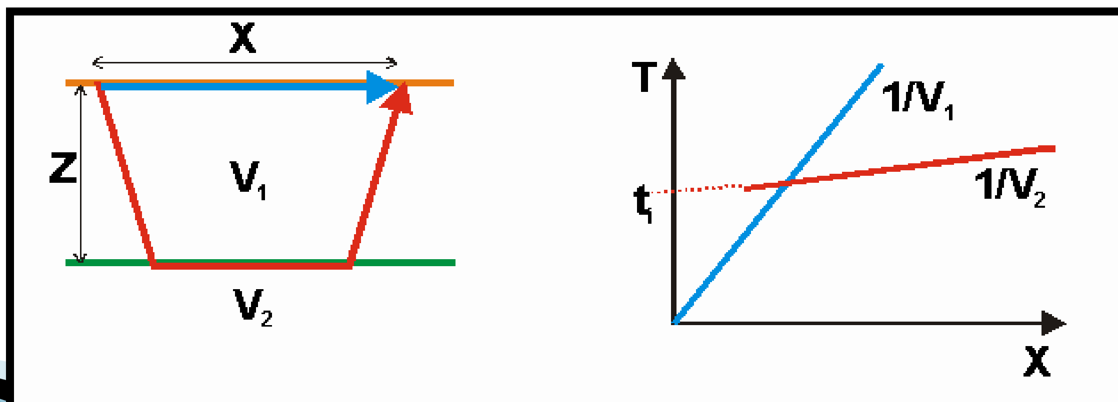
$$t_i = \frac{2Z\cos i_C}{V_1} = \frac{2Z\left(V_1^2 - V_2^2\right)^{\frac{1}{2}}}{V_1V_2} \qquad (7)$$

$$Z = \frac{t_iV_1V_2}{2\sqrt{V_2^2 - V_1^2}} \qquad (8)$$

Planar Interfaces
Two Layers

- From travel times of direct arrival and critical refraction, we can find velocities of two layers and depth to interface:

1. Velocity of layer 1 given by slope of direct arrival
2. Velocity of layer 2 given by slope of critical refraction
3. Estimate t_i from plot and solve for Z



Textbooks

-Kearey, P., Brooks, M. and Hill, I. (2002) An introduction to Geophysical Exploration. 3rd edition, Blackwell Science Ltd, UK, 261p.

-Alsadi, H.N. (1980) Seismic Exploration: Technique and Processing. Springer Basel AG, 194p.