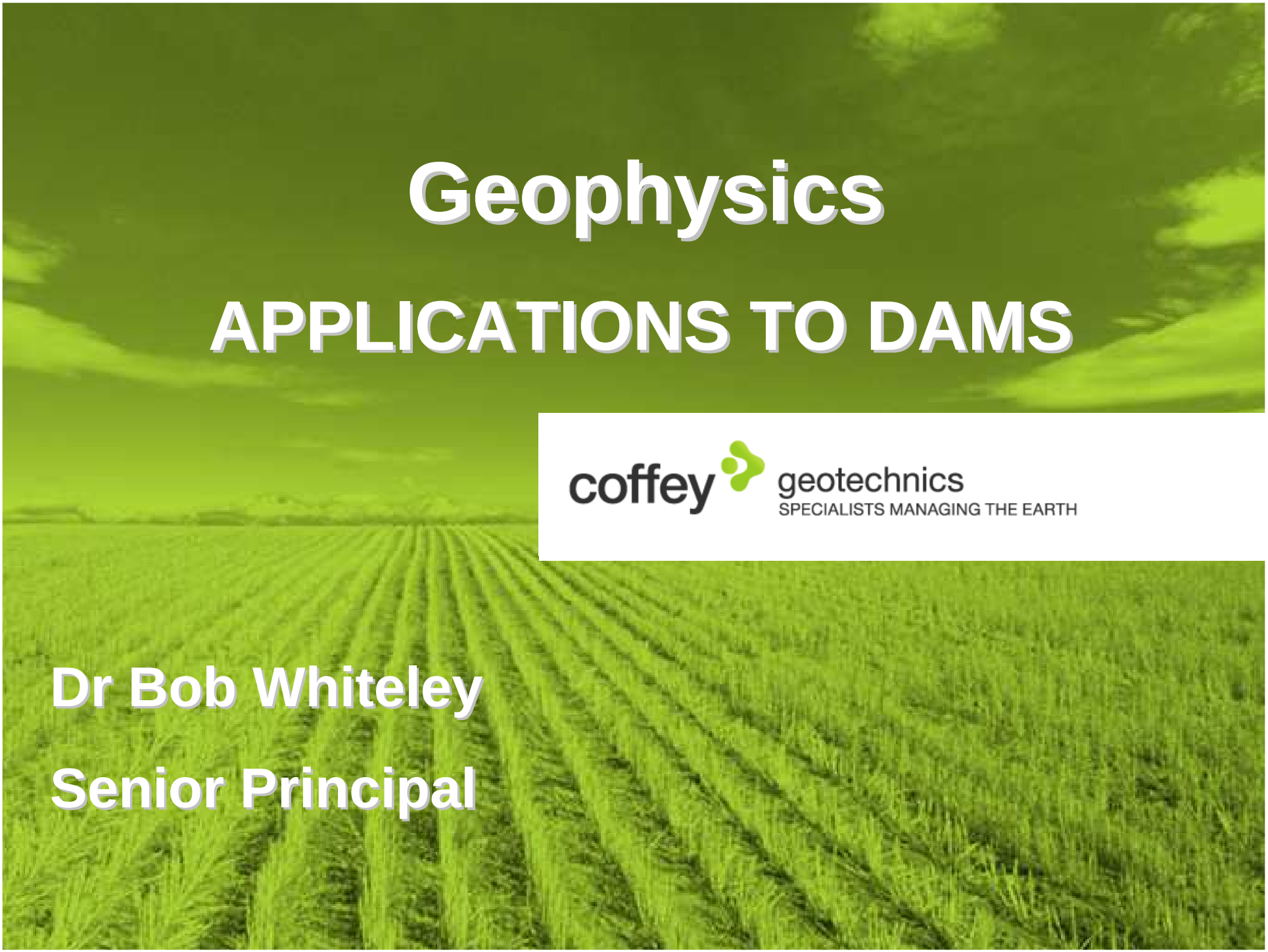
Geophysics

APPLICATIONS TO DAMS



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SPECIALISTS MANAGING THE EARTH

Dr Bob Whiteley

Senior Principal

Outline

- ***Geophysics*: Where to use it**
- ***Geophysics*: What is it?**
- ***Geophysics*: Methods & Examples**

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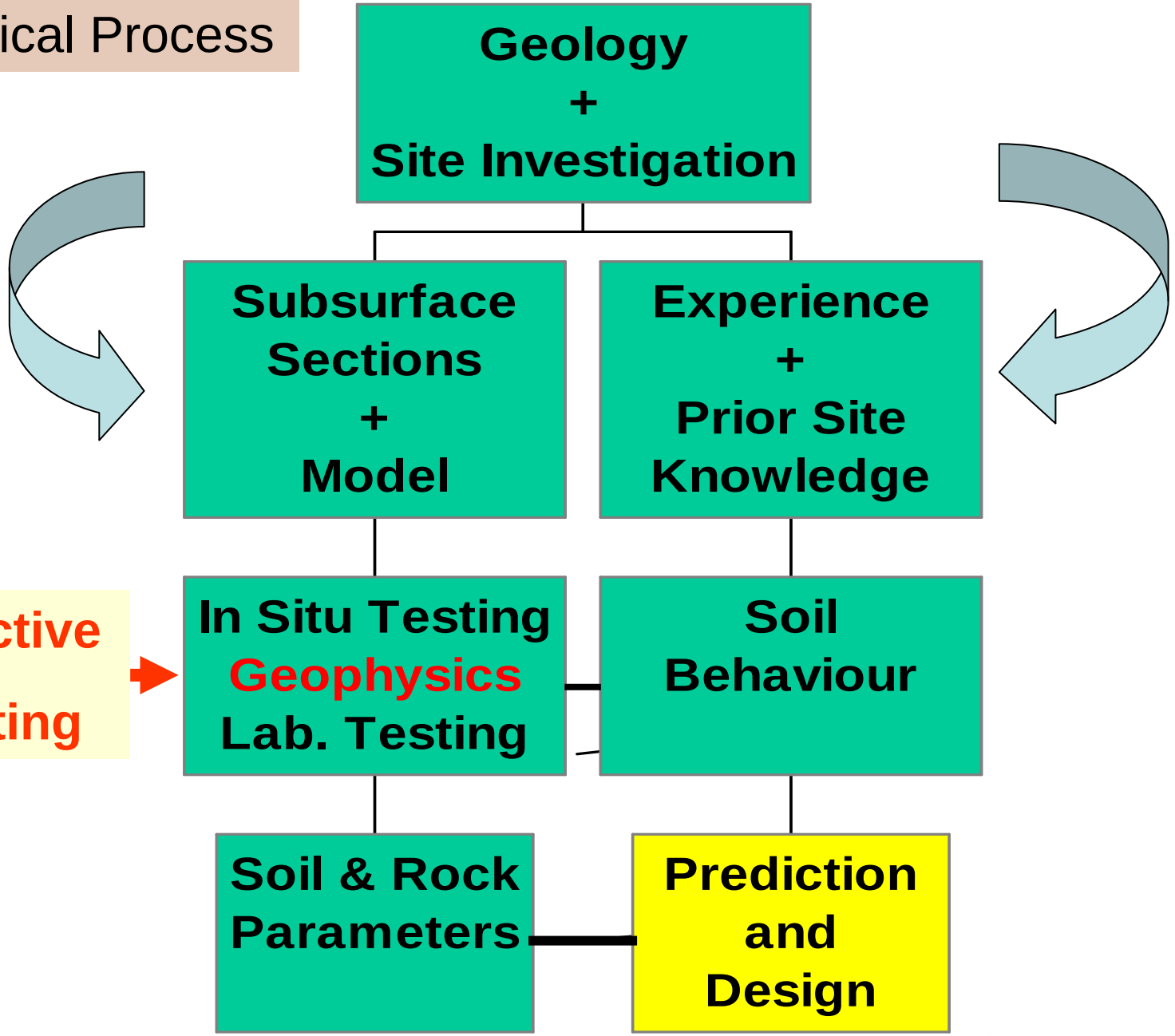
Dam Geophysics: where to use it

- Site selection & feasibility
- Geotechnical characterisation
- Materials location & mapping
- Problems & Safety
  - leakage/contamination
  - unstable slopes
  - integrity

The Geotechnical Process



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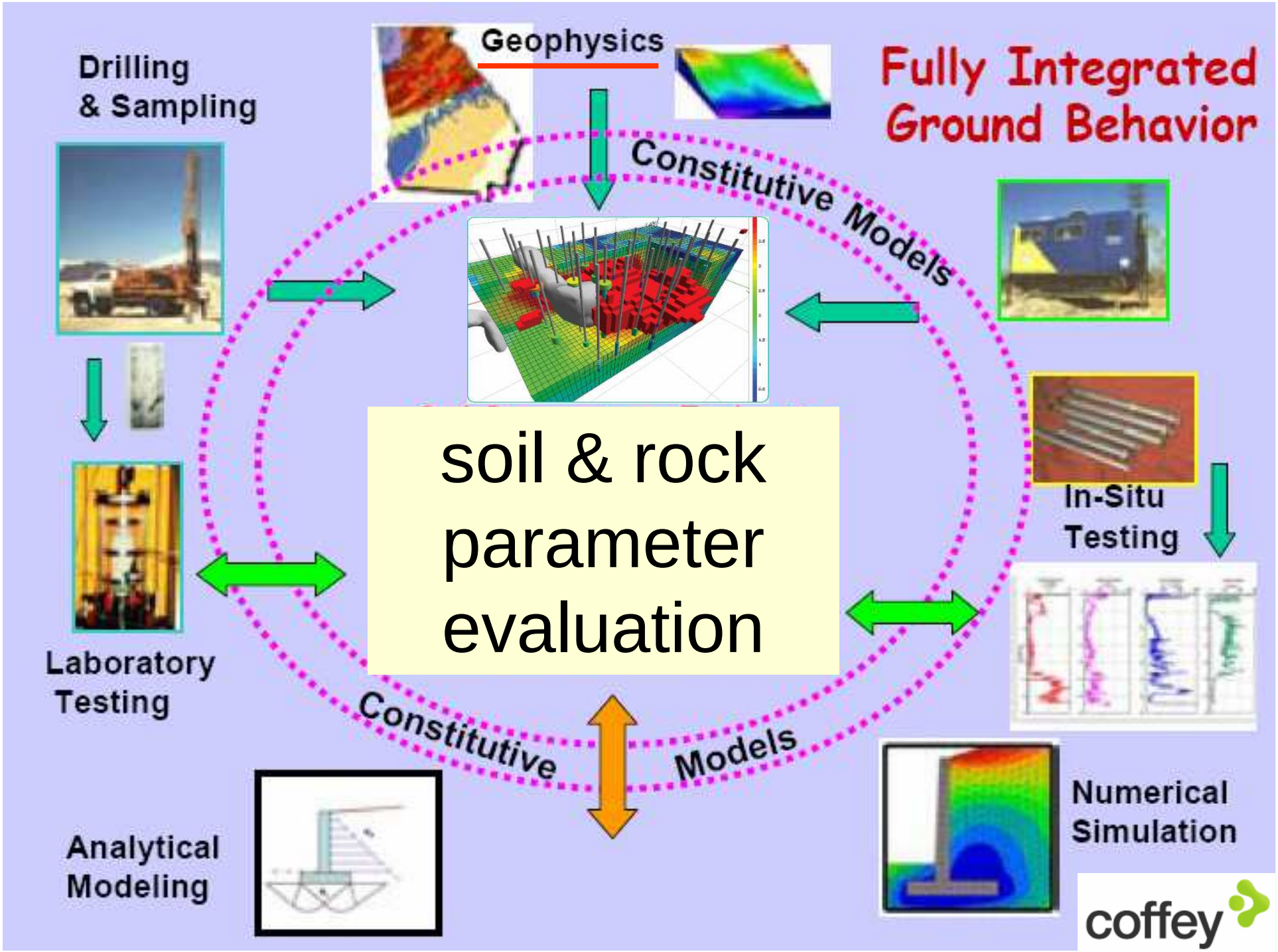
Fully Integrated
Ground Behavior
Drilling
& Sampling
Geophysics
Constitutive Models
soil & rock
parameter
evaluation
In-Situ
Testing
Laboratory
Testing
Constitutive
Models
Analytical
Modeling
Numerical
Simulation
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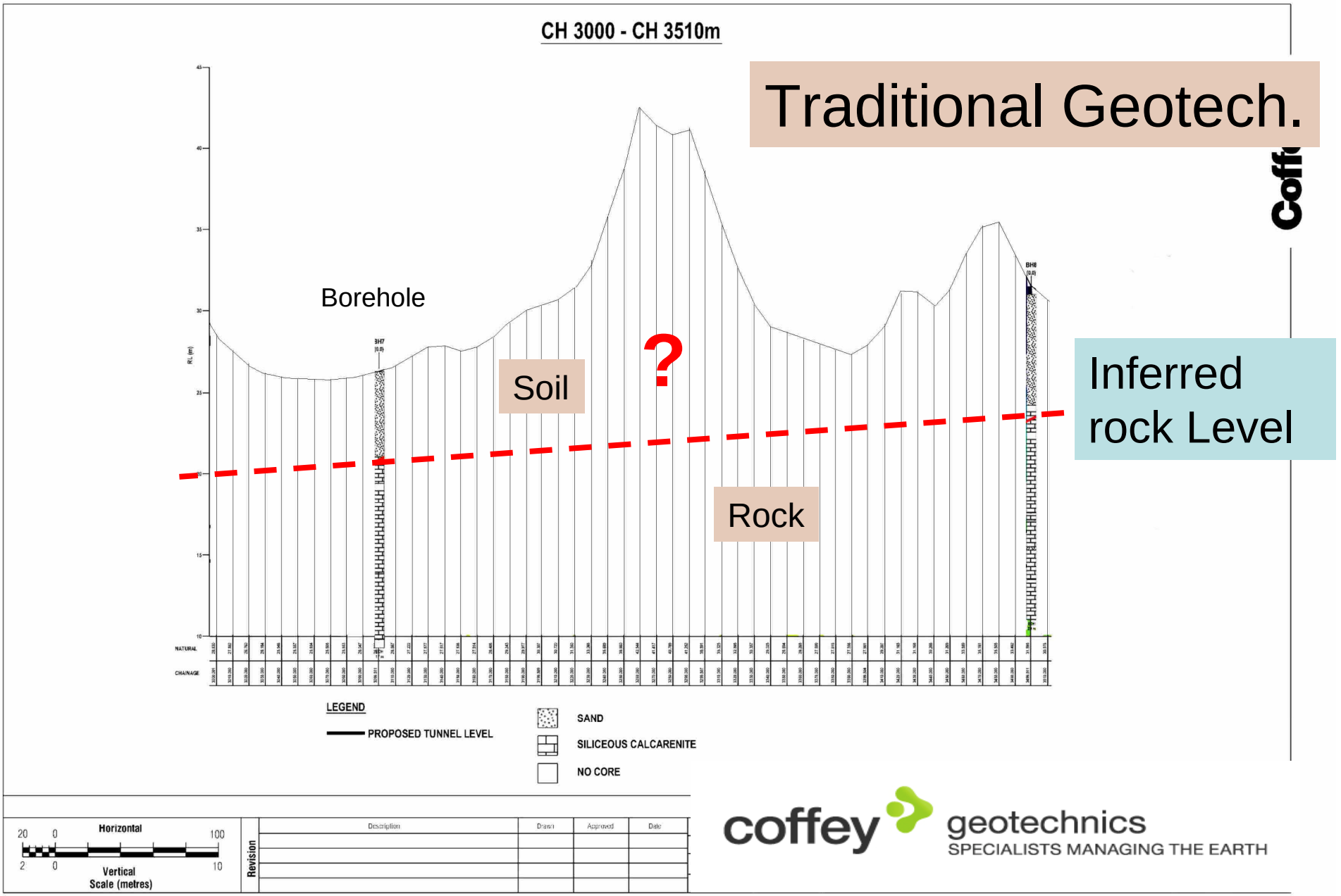
CH 3000 - CH 3510m
Traditional Geotech.
Borehole
Soil
?
Rock
Inferred rock Level
LEGEND
PROPOSED TUNNEL LEVEL
SAND
SILICEOUS CALCARENITE
NO CORE
Horizontal
Vertical
Scale (metres)
Revision
Description
Drawn
Approved
Date
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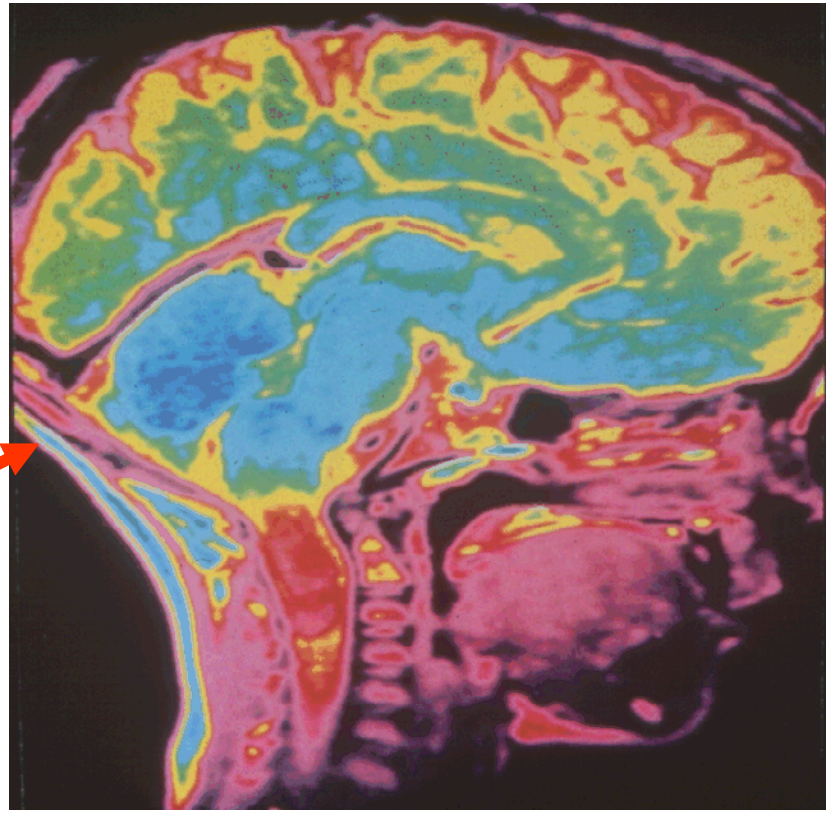
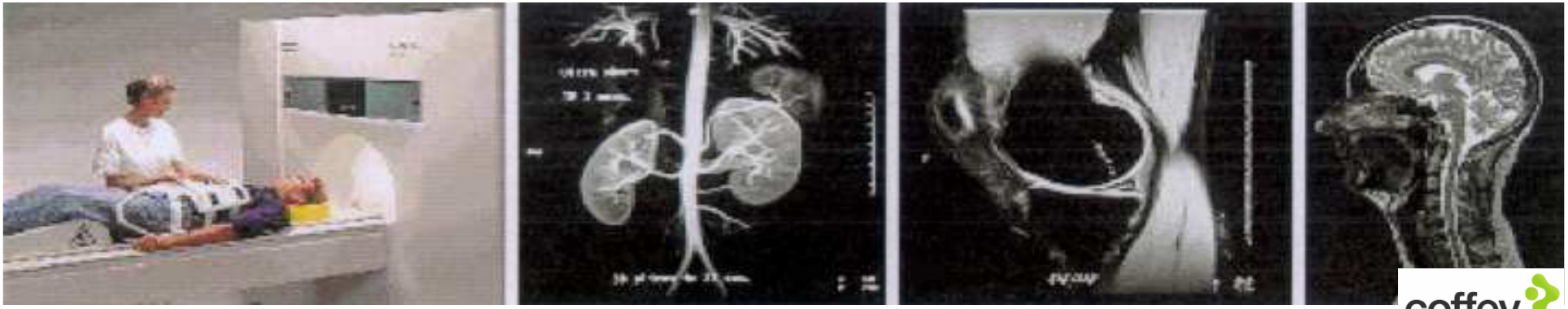
TRADITIONAL ?

NEW ?



Advances in geophysical imaging parallel advances in medical imaging



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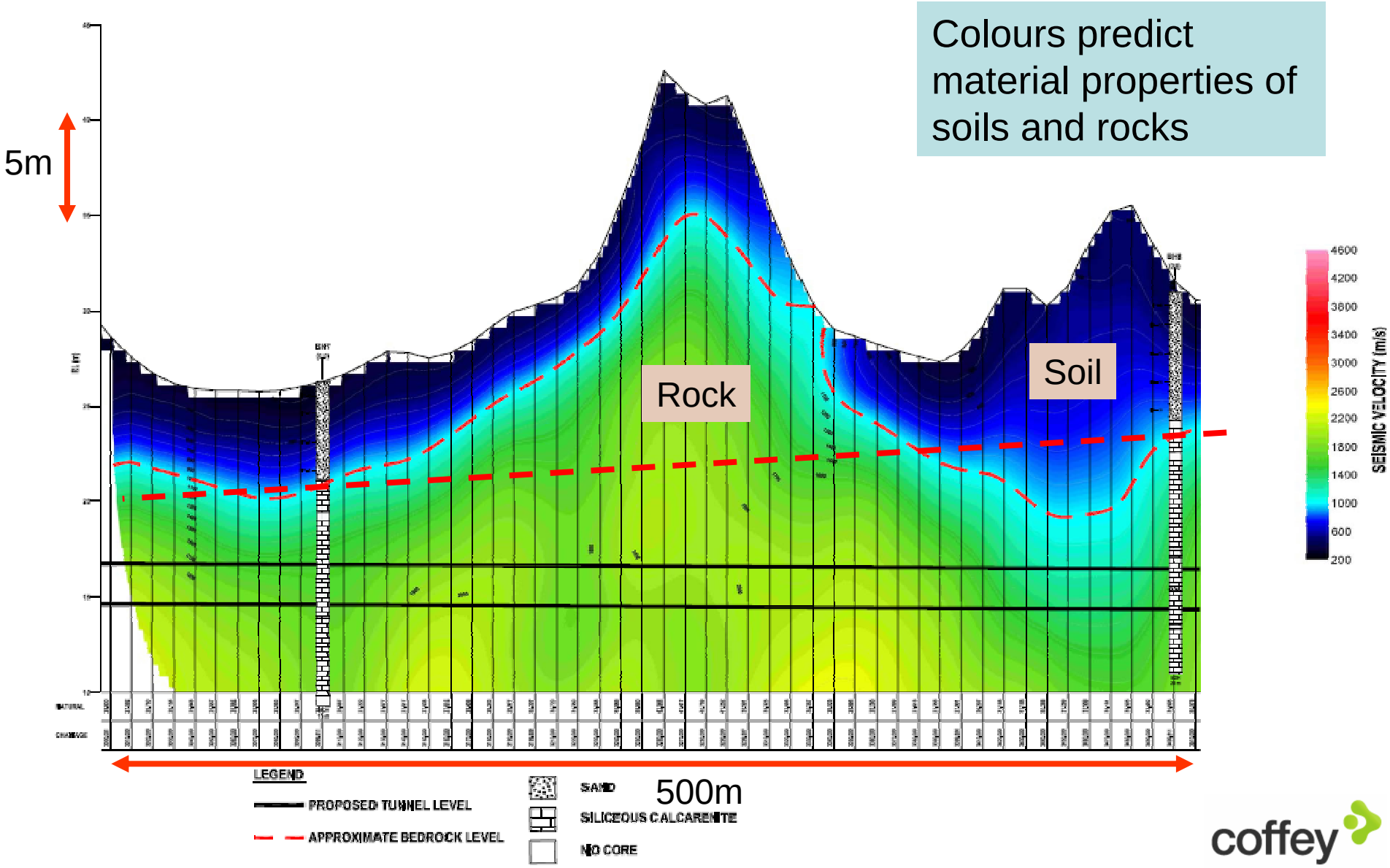
Geophysics + Geotech.

Colours predict material properties of soils and rocks



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Investigation Method	***Scale of Sample***	***Sample size/ Site size***
Traditional drill & sample	**mm to m**	**1: 1,000,000**
+ geophysics	**m**	**1 : 10,000**

Geophysics supplements traditional methods & enhances ground knowledge

Geophysical Methods	Derived Parameters	General Relationships with other properties
Gravity	Mass excess/deficiency	Density
Magnetics	Magnetisation	Magnetic iron content
Electromagnetics	Electrical conductivity	Salinity, saturation,clay content, porosity
Radar	Dielectric constant	Fluid content
Resistivity	Electrical resistivity (=1/conductivity)	Salinity, saturation,clay content, porosity
Self Potential	Groundwater flow	Permeability
Seismic	Seismic velocity	Saturation, strength, density, stability
Nuclear	Radioactivity	Density, porosity, saturation
Thermal	Temperature	Groundwater/contaminant flow

Soils & Rocks

Geophysical Response = physical property contrast

x

active volume

x

x

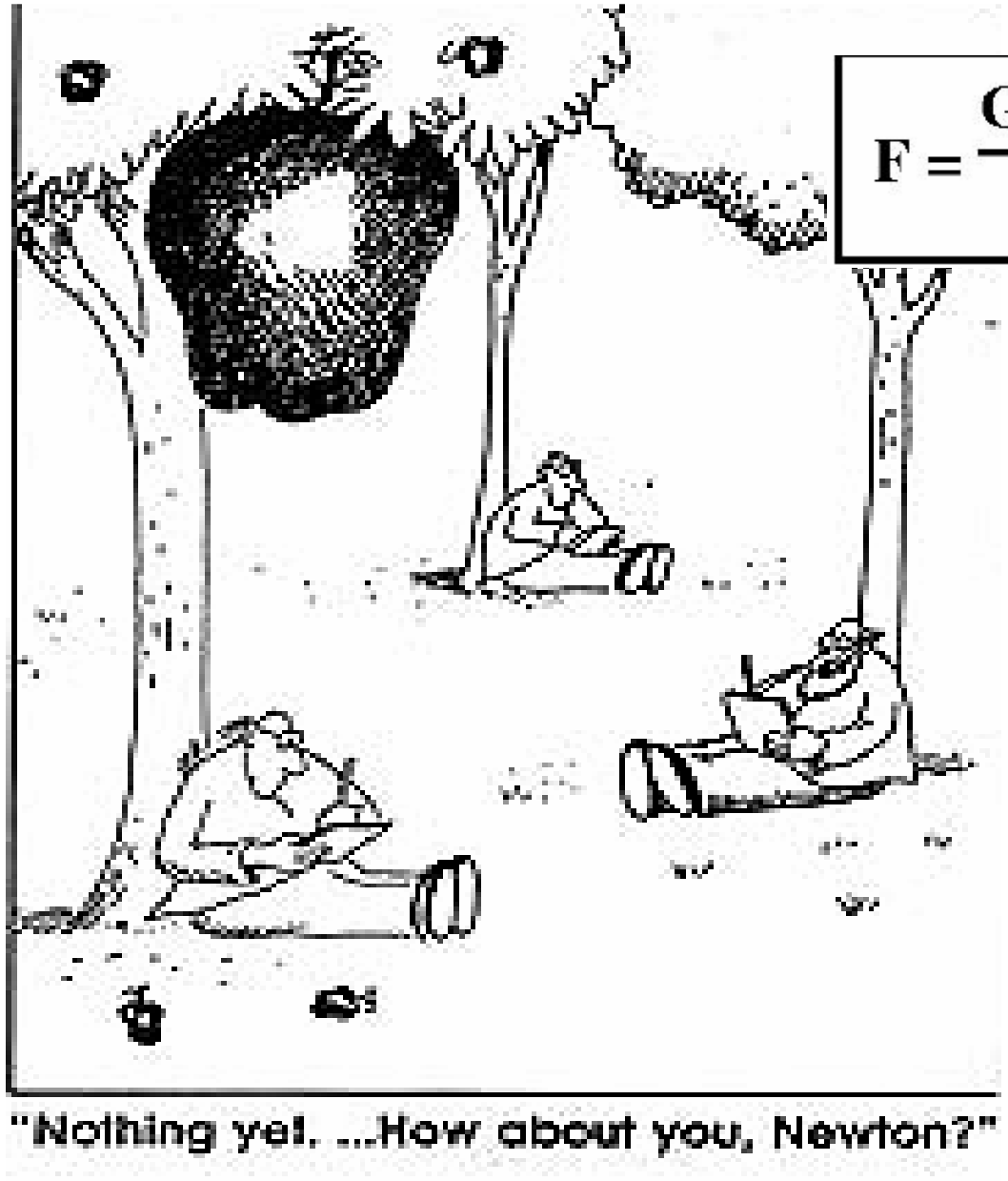
n = 2 to 5 1/distance (or depth) ^{n}

x

primary field

Type	Material Property	Order of Magnitude Variation
Geotechnical	Stiffness/strength	6
	Permeability	13
	Density	<1
Geophysical	Electrical conductivity	6
	Seismic velocity	1
	Seismic wave attenuation	4
Structural	Made to specification (e.g. steel)	<<1

Geophysical Method	Examples of Applications to Dams
Gravity	Buried river channels, voids in karst
Magnetics	Igneous rocks, lithologies, faults & contacts
Electromagnetics	faults/contacts, leakage, groundwater contamination
Radar	Voids in concrete structures/tunnel lining
Resistivity	Faults & contacts, slopes, leakage, groundwater contamination
Seismic	Bedrock mapping, excavation, lithologies, fault & shears, slopes, strength, voids, liquefaction
Borehole Logging	Stratigraphy, fractures/voids, groundwater



$$F = \frac{G m_1 m_2}{r^2}$$

$$g = \frac{G m_1}{r^2}$$

Gravity

Application of *Gravity* to Dams

- Site Characterisation
  - Bedrock mapping in valley
  - Sediment volume/stored water estimations
  - Void & cavities in karst

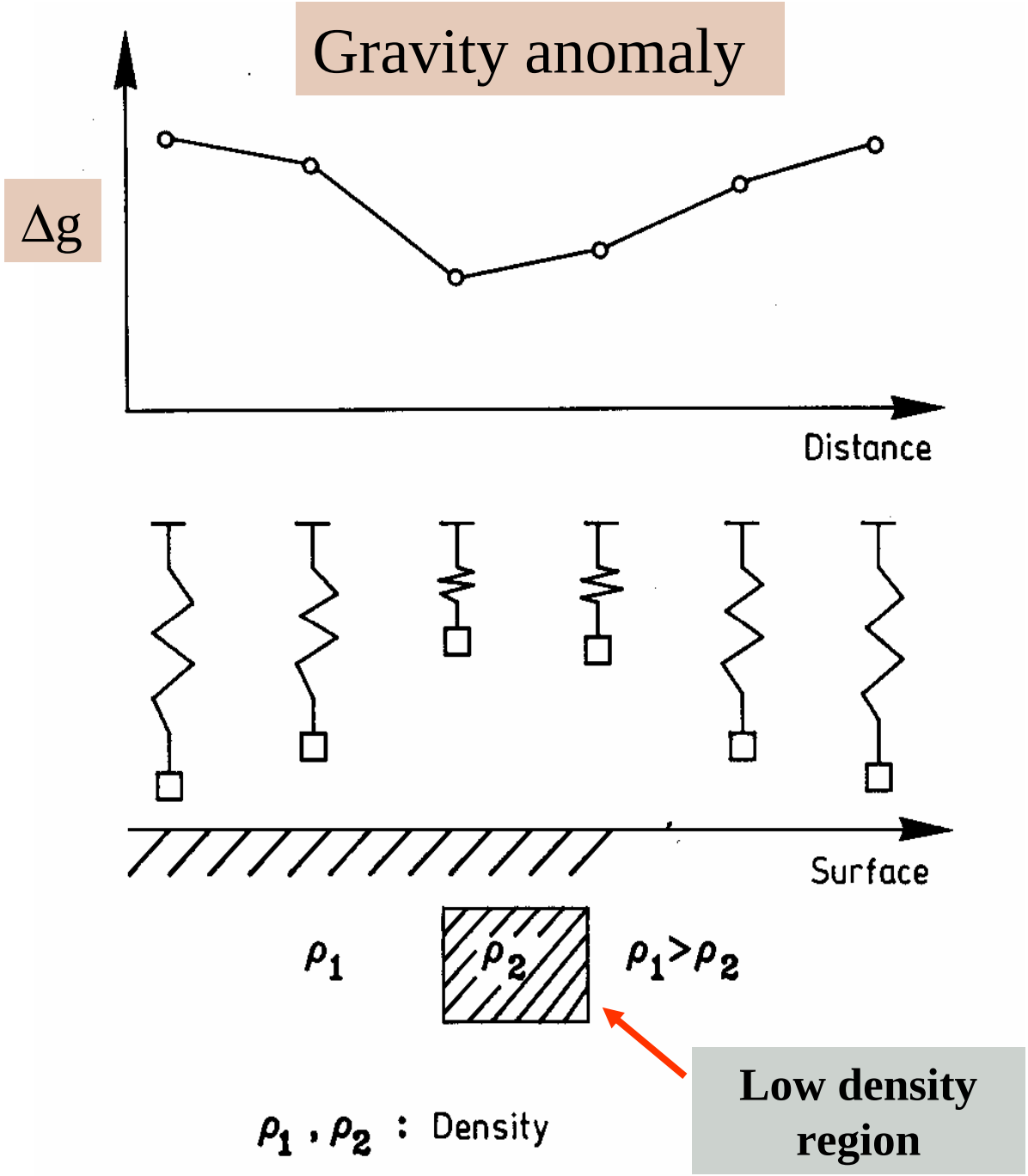
Density of Natural Materials

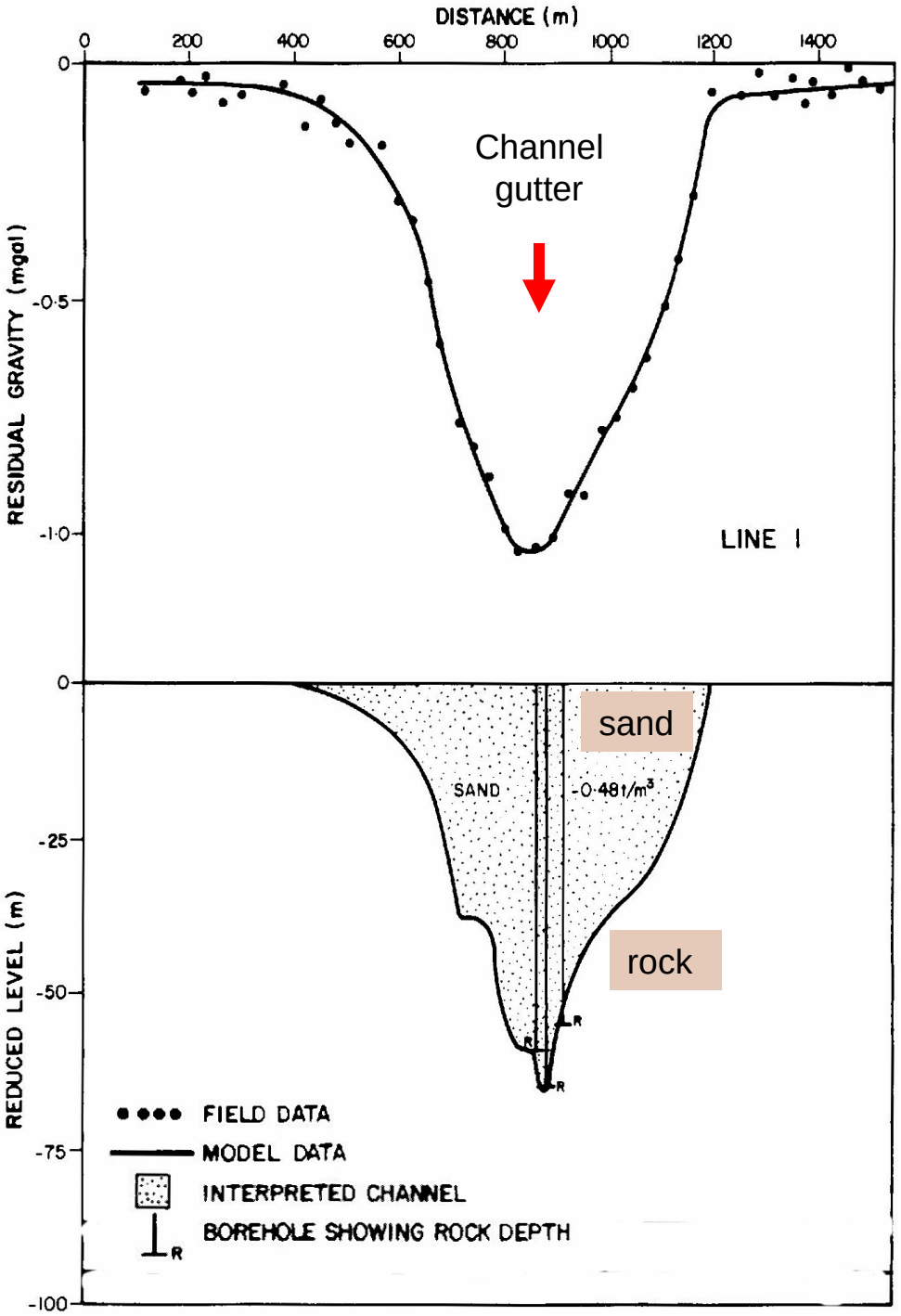
Material	Density (gm/cm^3)
Air	~0
Water	1
Sediments	1.7-2.3
Sandstone	2.0-2.6
Shale	2.0-2.7
Limestone	2.5-2.8
Granite	2.5-2.8
Basalts	2.7-3.1
Metamorphic Rocks	2.6-3.0

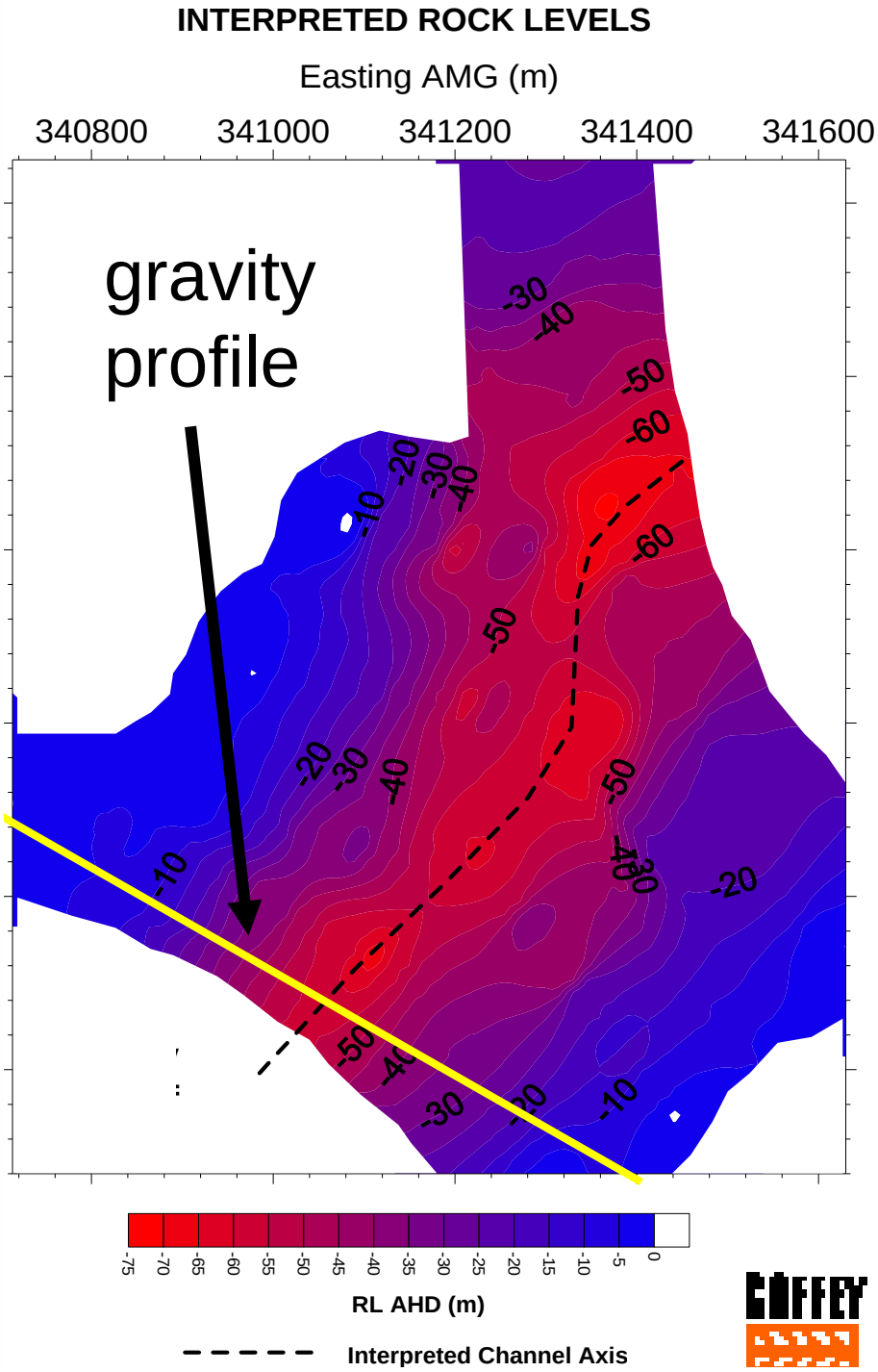
GRAVITY

$$g = \frac{G m_1}{r^2}$$

Gravity anomaly



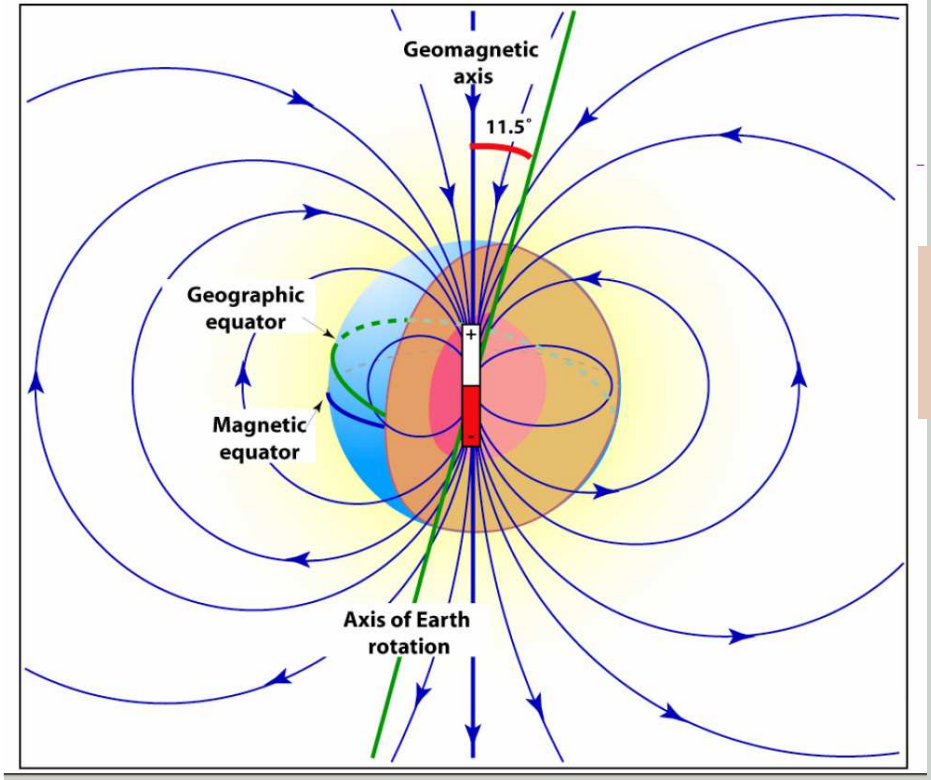

DISTANCE (m)
0
200
400
600
800
1000
1200
1400
RESIDUAL GRAVITY (mgal)
0
-0·5
-1·0
Channel
gutter
LINE 1
REDUCED LEVEL (m)
0
-25
-50
-75
-100
sand
rock
SAND
-0·48t/m³
R
FIELD DATA
MODEL DATA
INTERPRETED CHANNEL
BOREHOLE SHOWING ROCK DEPTH


INTERPRETED ROCK LEVELS
Easting AMG (m)
340800
341000
341200
341400
341600
gravity
profile
-10
-20
-30
-40
-50
-60
-75
-70
-65
-60
-55
-50
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
RL AHD (m)
Interpreted Channel Axis

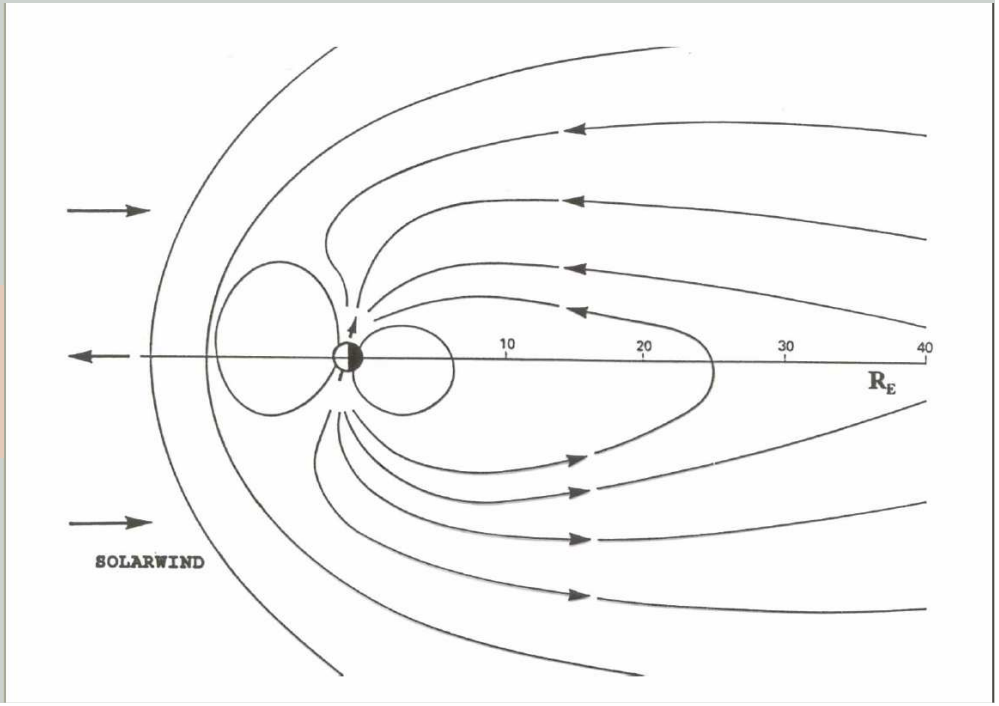
MAGNETICS

Application of *Magnetics* to Dams

- Site Characterisation
  - Identifying magnetic lithologies e.g. intrusions
  - Mapping contacts & faults
  - Locating and mapping igneous rock borrow areas



Internal component of the Earth's magnetic field

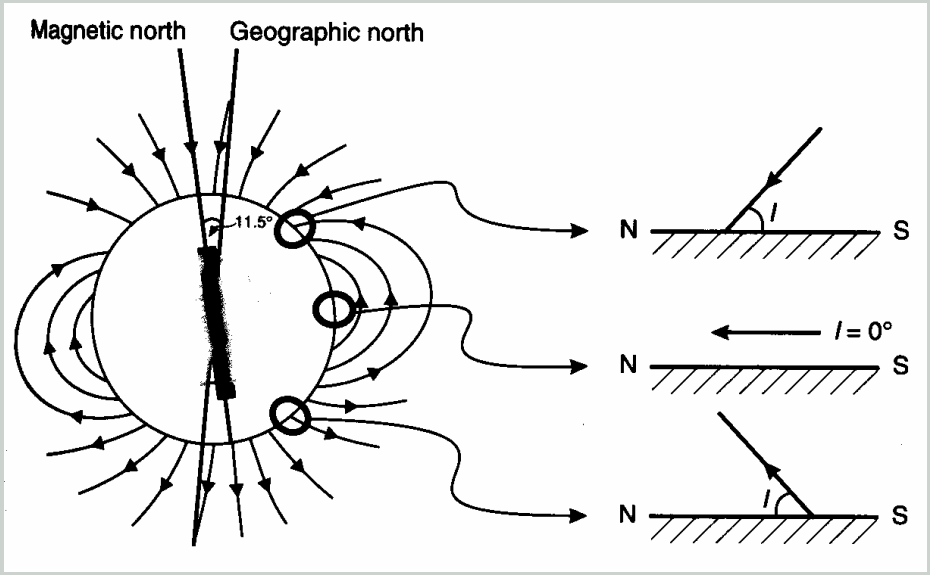


External component of the Earth's magnetic field

ROCK MAGNETISATION = *INDUCED* + REMANENT

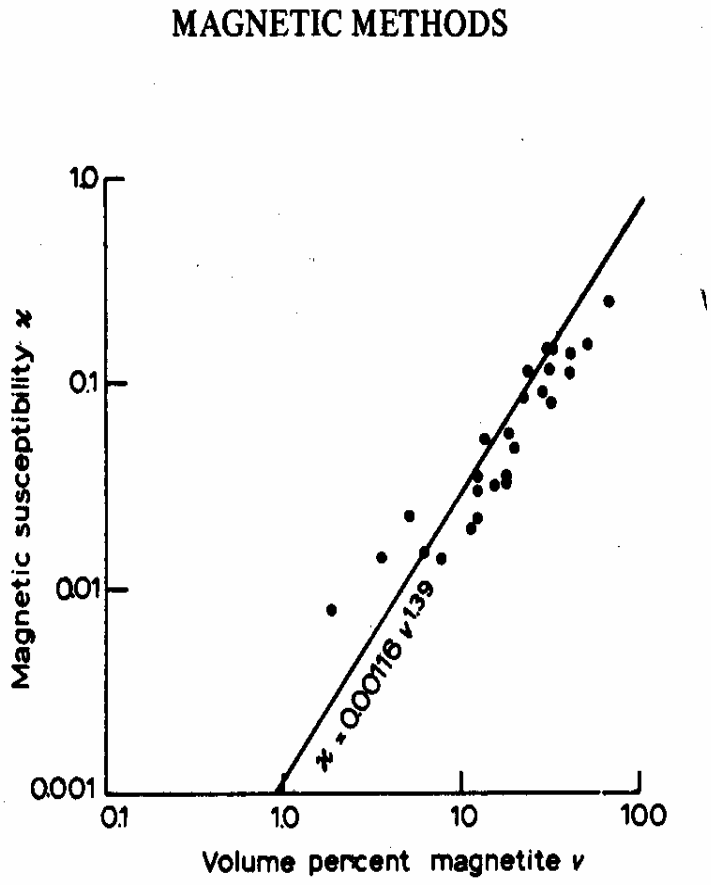
$$\underline{\mathbf{M}} = k\,\underline{\mathbf{F}}$$

F

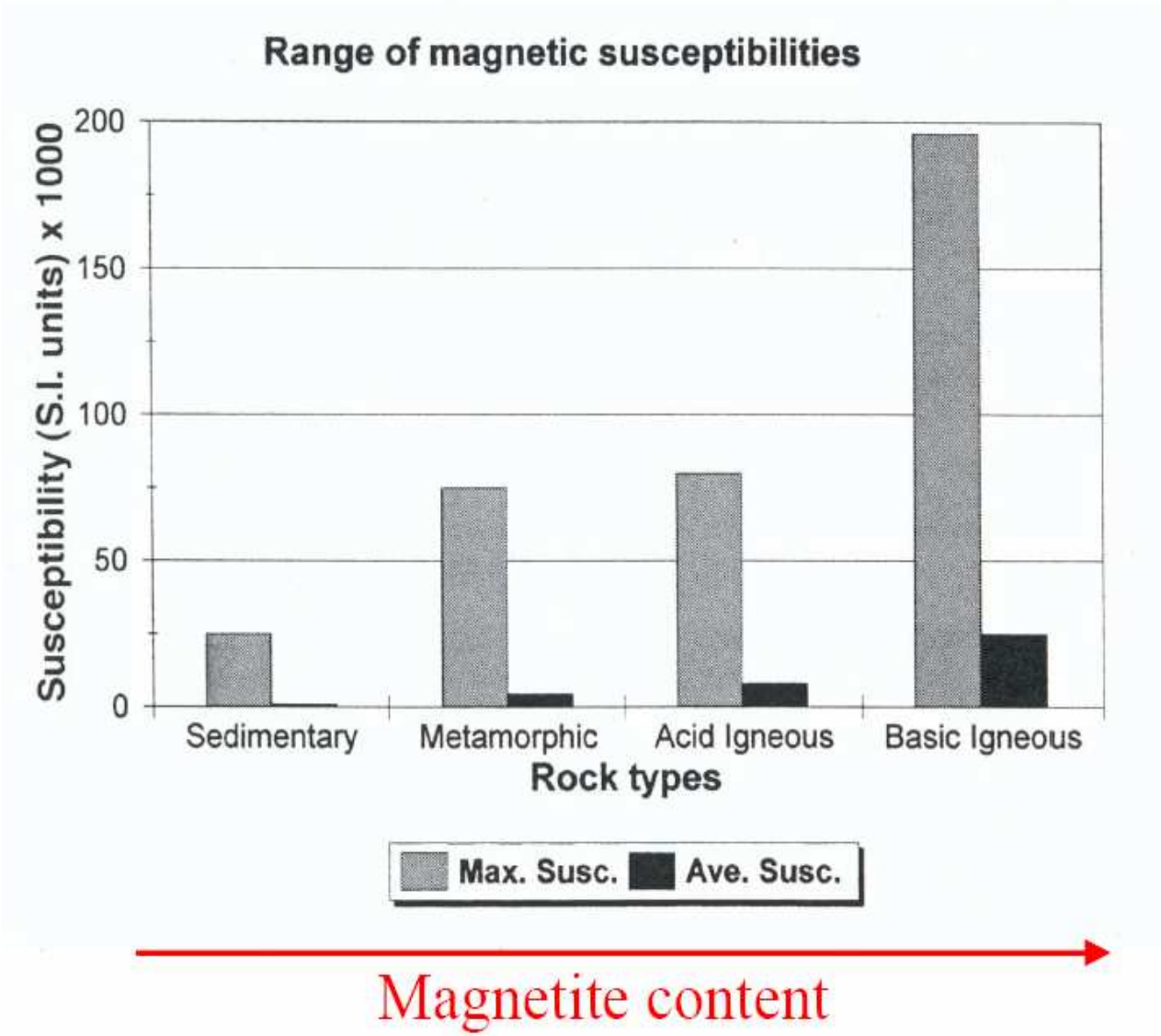


k

Magnetic Susceptibility

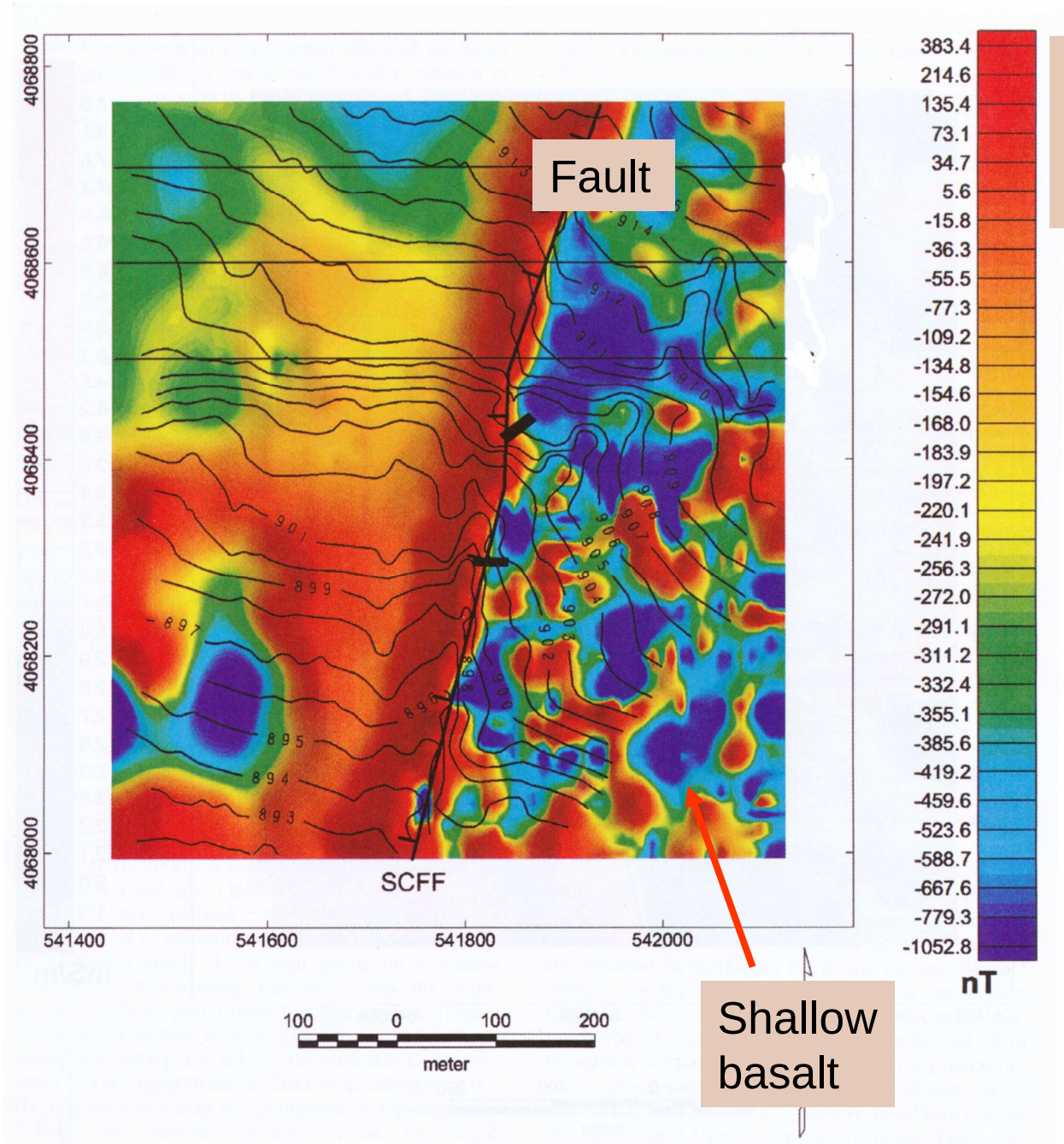


Magnetic properties of rocks



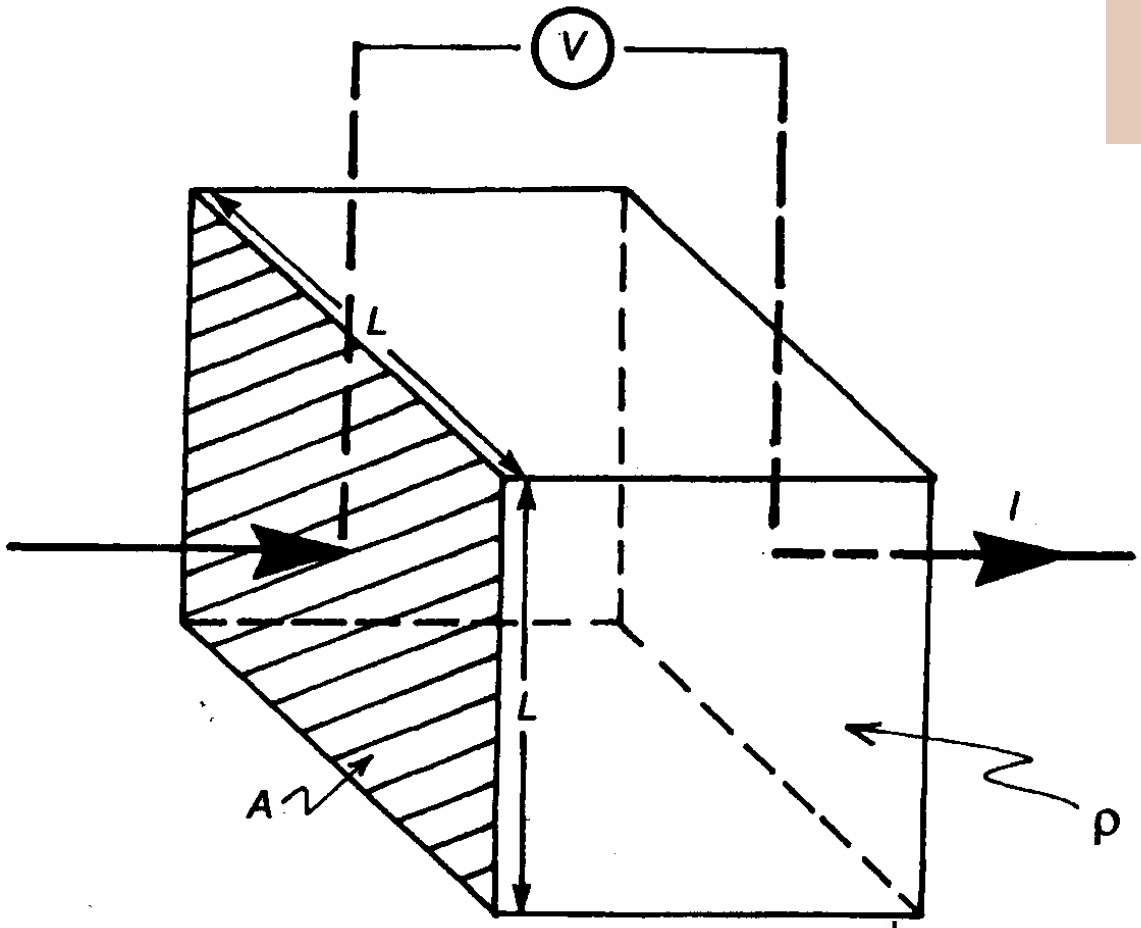
$$\vec{B} = (1+k)\,\mu_0 \vec{H}$$

Magnetic properties of rock depend mainly on the concentration size, shape and dispersion of magnetite



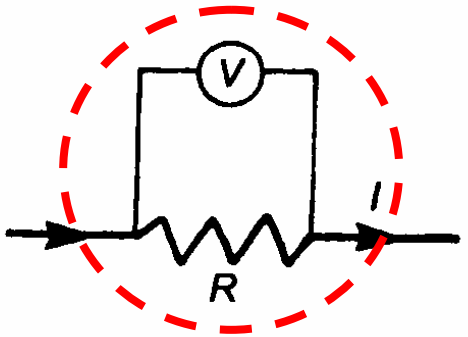
Magnetic map of faulted basalt

Resistivity



Ohms Law

R = V/I



RESISTIVITY (ρ)

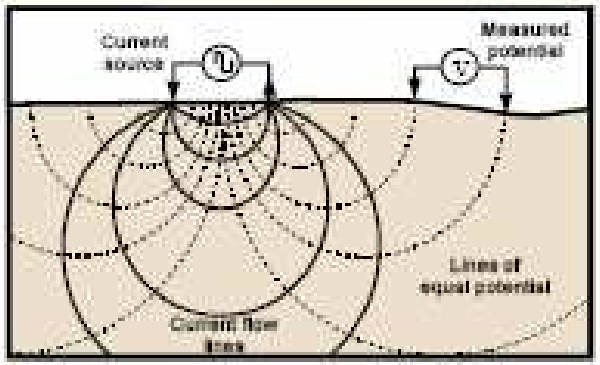
$$\rho = \frac{R\,A}{L} \text{ ohm·metres}$$

where $R = \frac{V}{I}$ ohms

CONDUCTIVITY (σ)

$$\sigma = \frac{G\,L}{A} \text{ Siemens/metre}$$

where $G = \frac{I}{V}$ Siemens

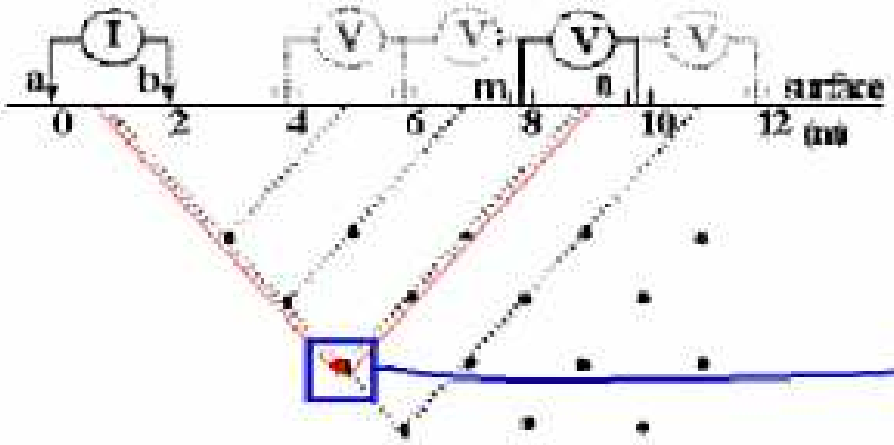


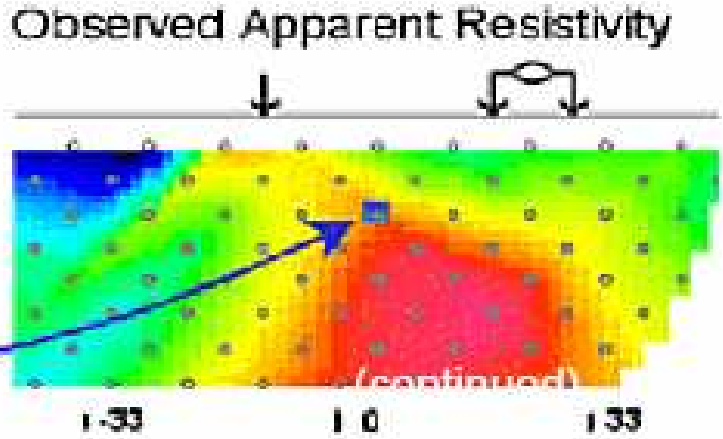
Direct Current (DC) Resistivity

Archie's Law for Porous Media w/o clay

$$\rho_e = a\,\phi^{-m}\,S^{-n}\,\rho_w$$

ρ_e = resistivity of the earth
ϕ = fractional pore volume (porosity)
S = fraction of the pores containing fluid
ρ_w = the resistivity of the fluid
n, a and m are empirical constants

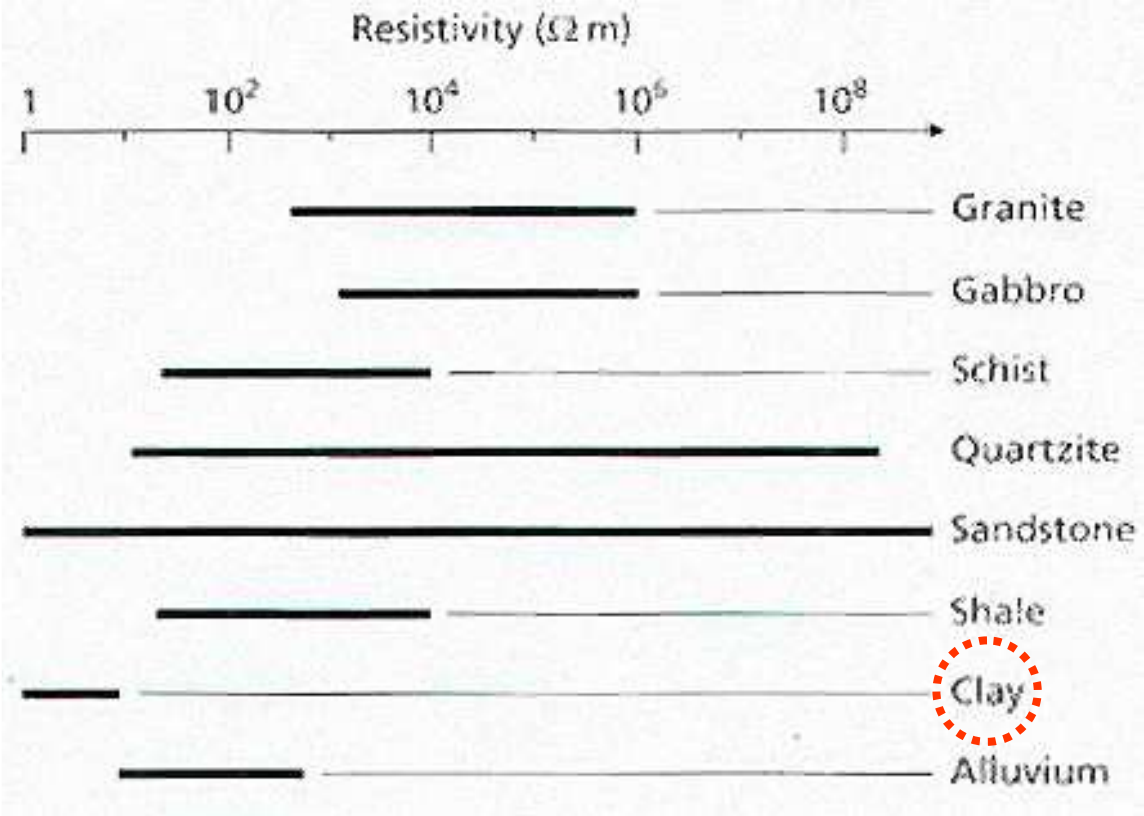




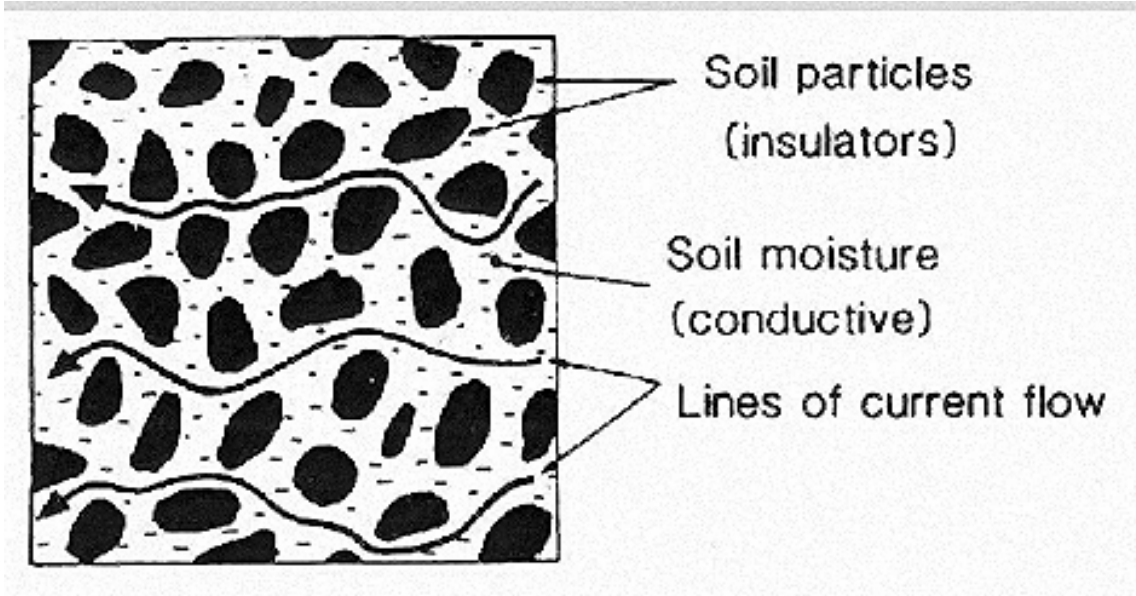
Application of *Resistivity* to Dams

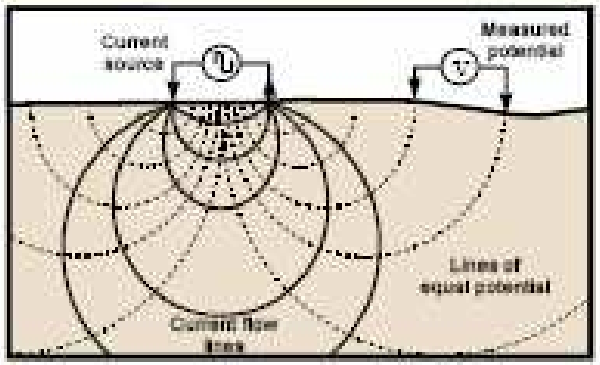
- Site Characterisation
  - Mapping of lithologies
  - Locating contact, faults, shears, voids
  - Bedrock mapping in valley floor & sediment classification
  - Locating & mapping clay borrow areas

- Problems
  - Identifying leakage and unstable zones in embankment walls & slopes
  - Locating groundwater contamination



Electrical resistivity of earth materials





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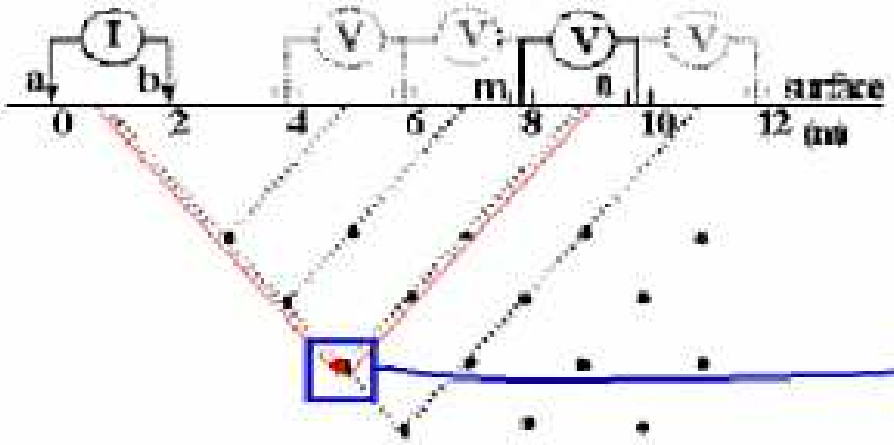
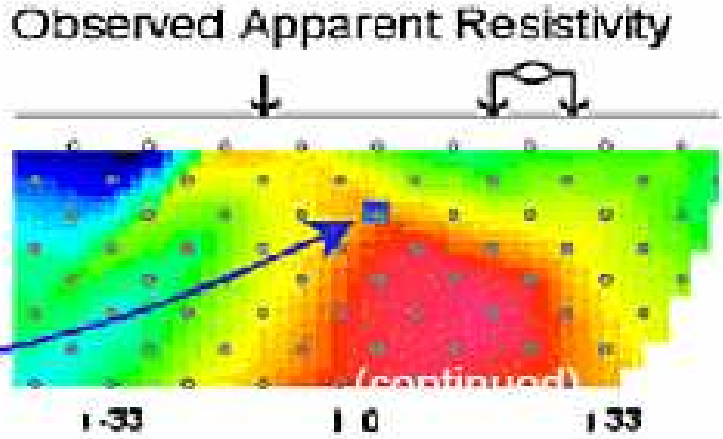
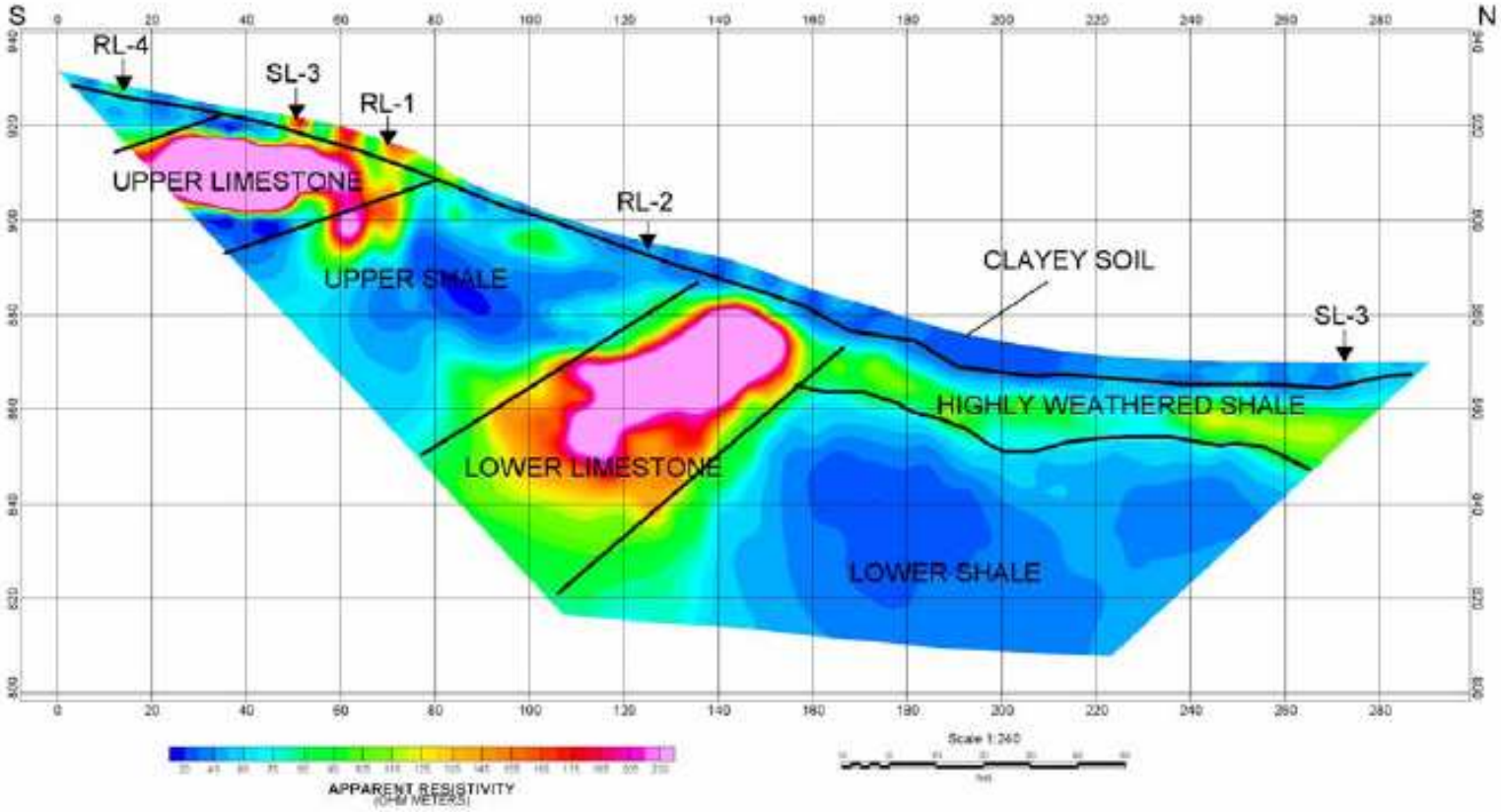
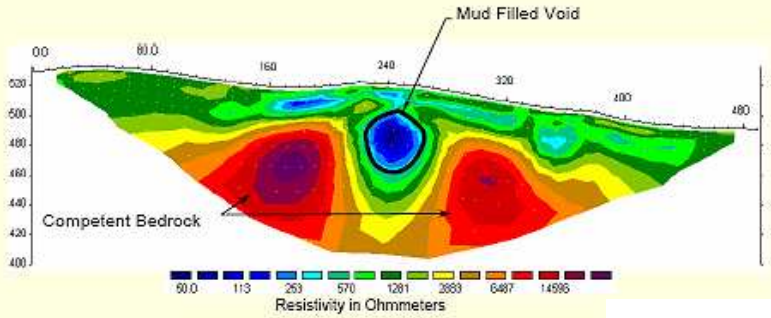






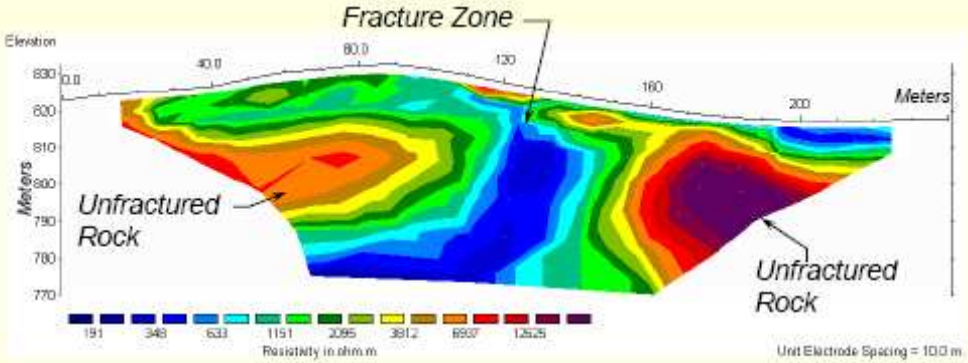
Lithological & soils mapping with Electrical Resistivity Imaging

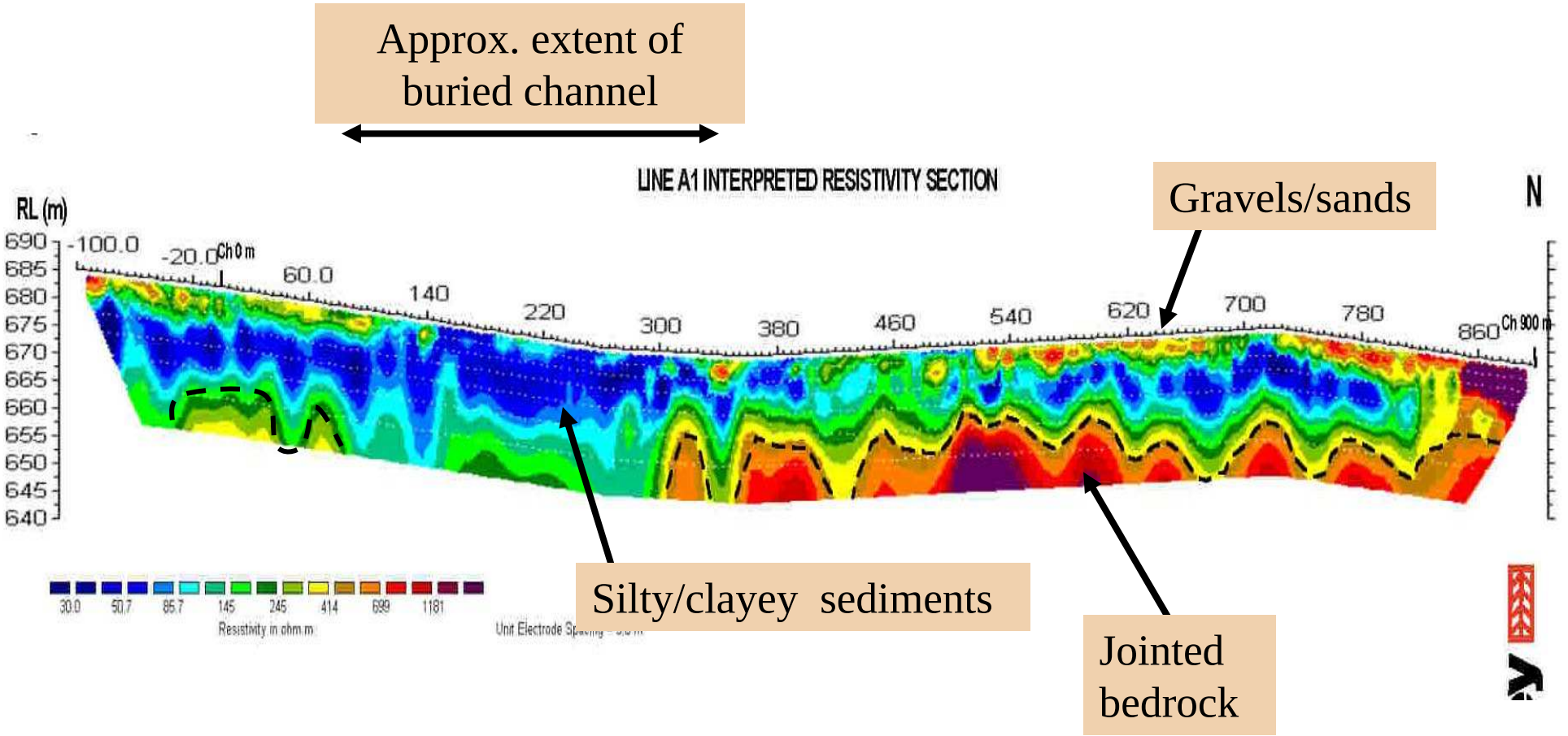
Karst Features/Voids



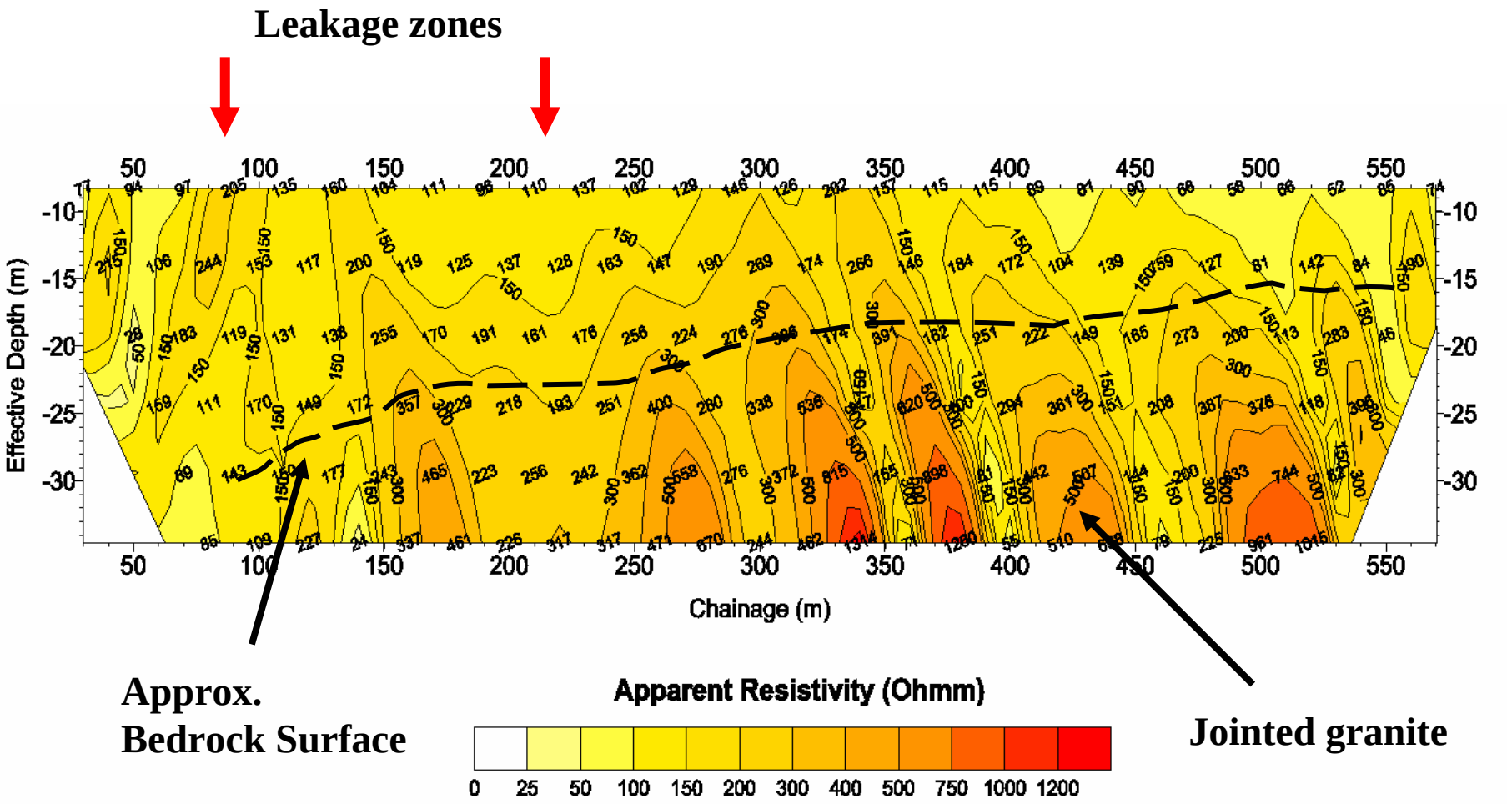
ERI in highly variable conditions

Fracture Zones




Approx. extent of buried channel
LINE A1 INTERPRETED RESISTIVITY SECTION
RL (m)
690
685
680
675
670
665
660
655
650
645
640
-100.0
-20.0
Ch 0 m
60.0
140
220
300
380
460
540
620
700
780
860
Ch 900 m
N
Gravels/sands
Silty/clayey sediments
Jointed bedrock
30.0
50.7
85.7
145
245
414
699
1181
Resistivity in ohm.m

Resistivity Imaging for Dam leakage : Granite terrain



Application of *Self Potential* to Dams

- Problems/safety
  - Identifying leakage inflow & outflow regions

Streaming Potential

caused by flow of a liquid with certain electrical properties
under a pressure gradient through a membrane, pipe, capillary,
or porous medium (with different electrical properties).

$$E_k = -\frac{1}{4\pi\eta} \cdot \zeta \cdot \Delta P \cdot k \cdot \rho$$

E_k = resulting electrokinetic potential;

$E_k > 0$ if higher potential is on the high pressure side

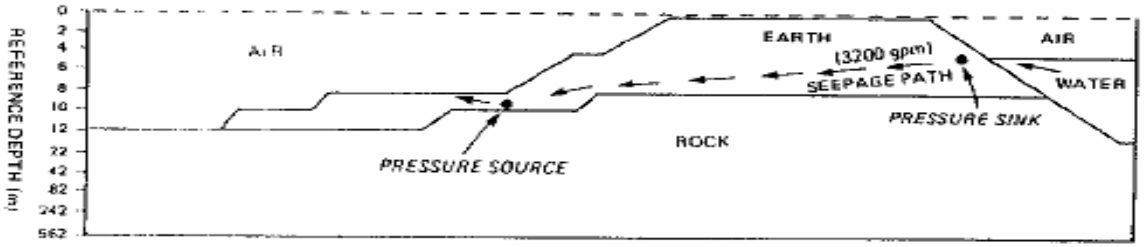
ζ = adsorption potential of double layer between solid and solution

k = solution dielectric constant (= effective permittivitiy ε)

ΔP = pressure difference (causing fluid flow through pore space)

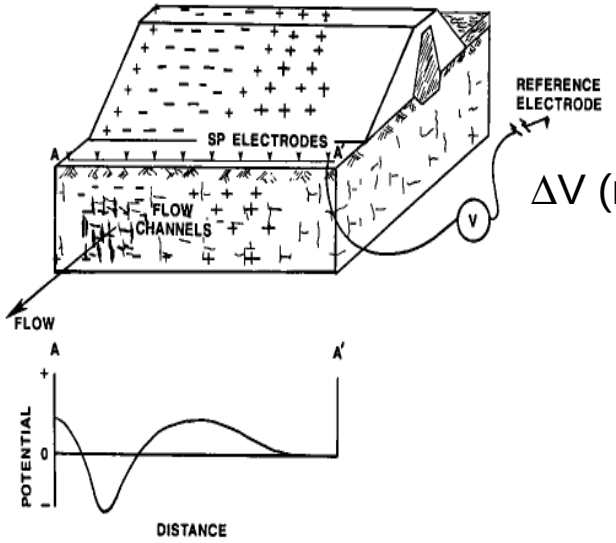
ρ = electrical resistivity

η = viscosity

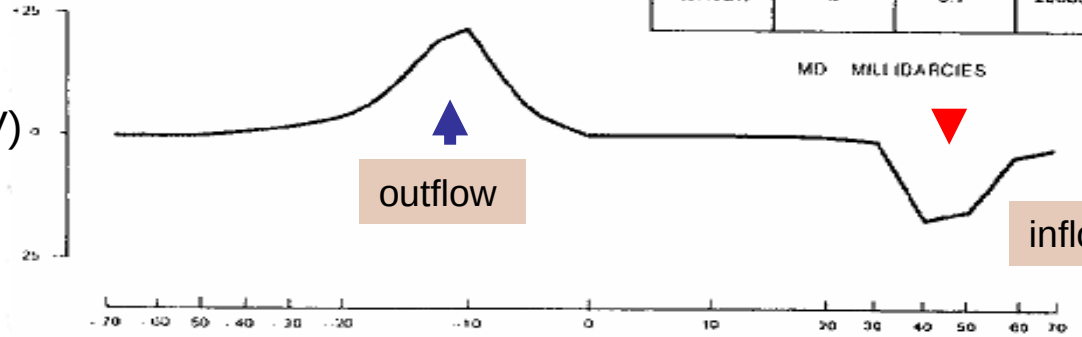


MEDIUM	PERMEABILITY (MD)	C (mV/atm)	ρ (ohm-m)
AIR	0	0.1	20000
ROCK	0.1	10	1000
EARTH	10	150	30
WATER	0	0.1	20000

SP Profile



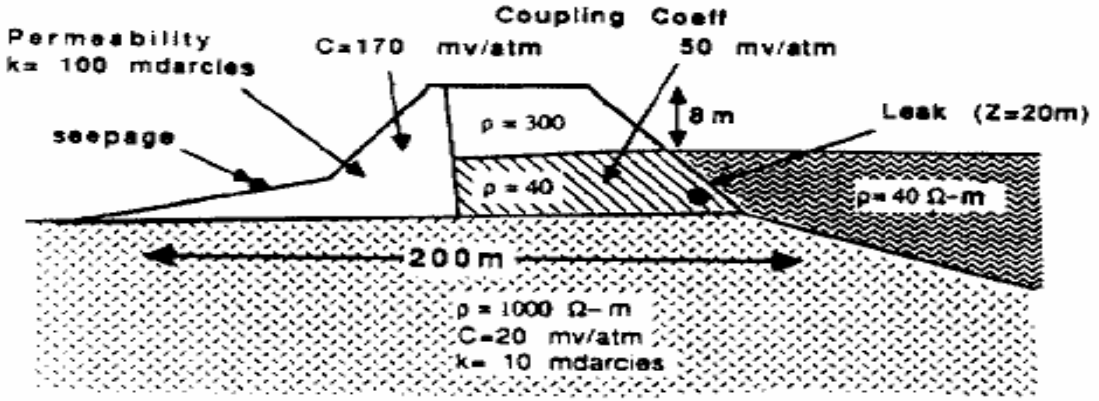
ΔV (mV)



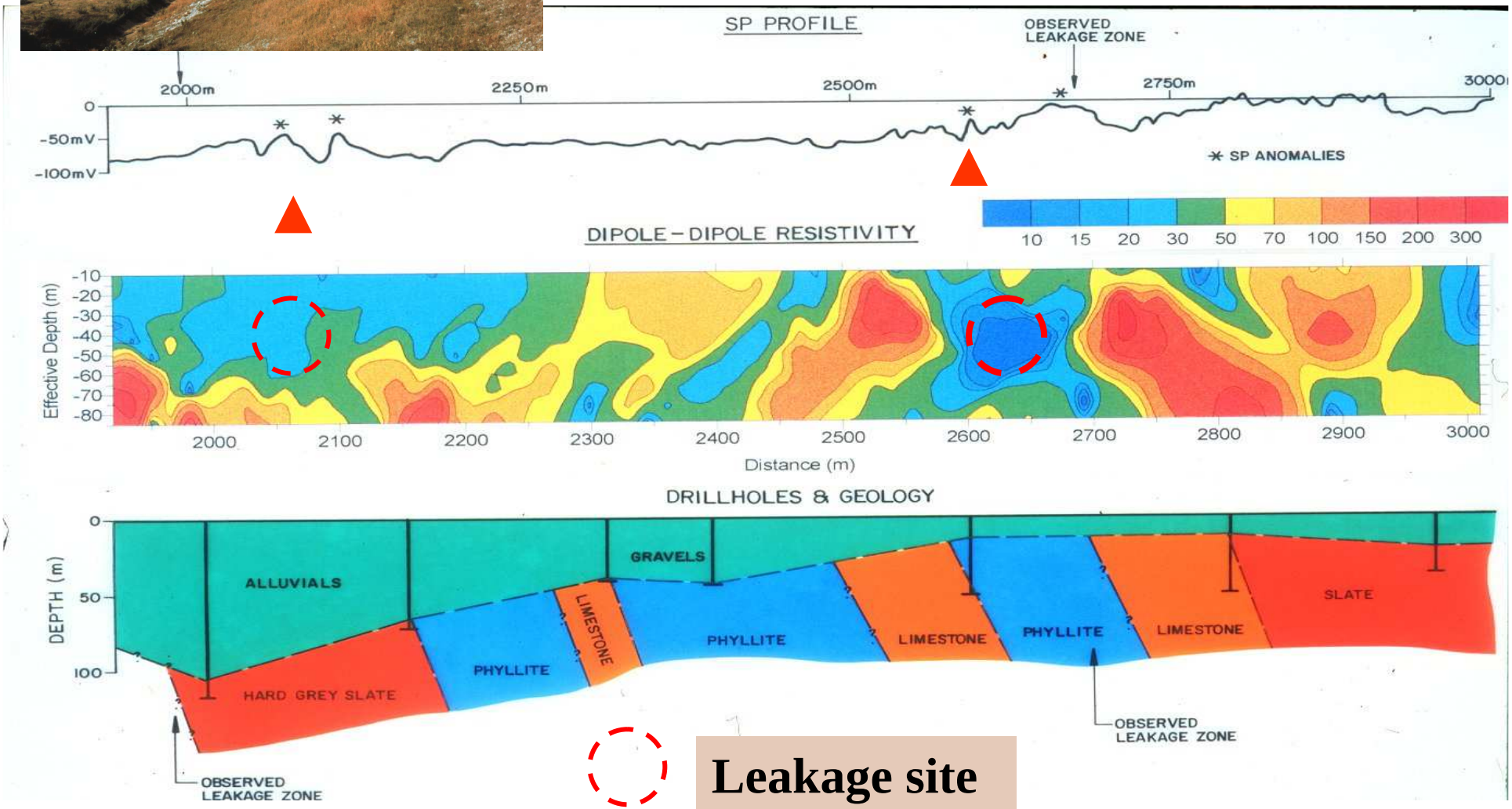
outflow

inflow

Interpreted cross-section



Self Potential & Resistivity



Leakage site

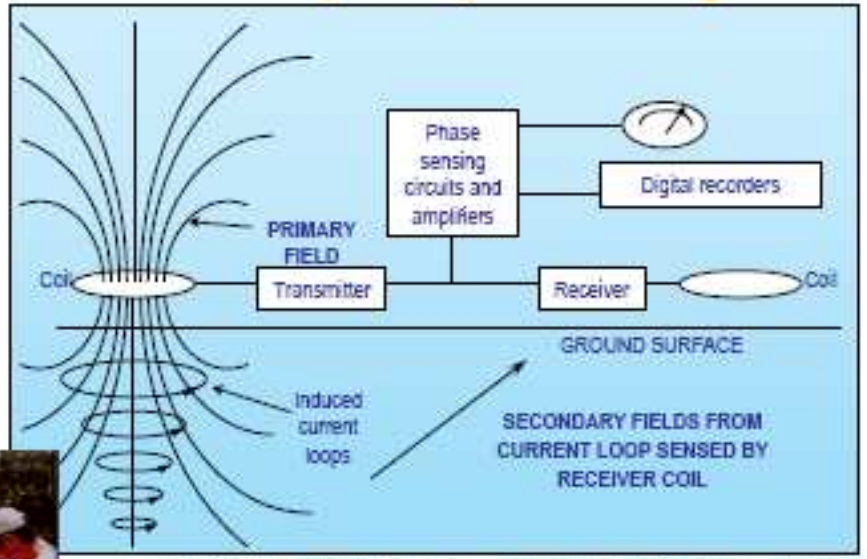
Application of *Electromagnetics* to Dams

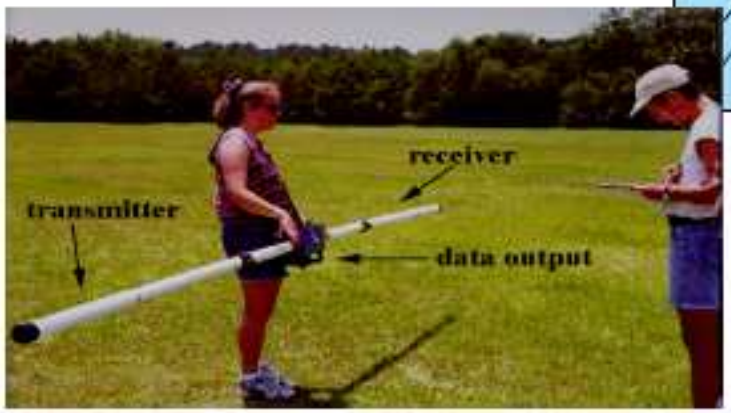
- Site Characterisation
  - Mapping of lithologies
  - Locating contact, faults, shears, voids
  - Locating & mapping clay borrow areas

- Problems & Safety
  - Identifying leakage and unstable zones in embankment walls & slopes
  - Locating groundwater contamination

Electromagnetic Induction (EMI) Surveys

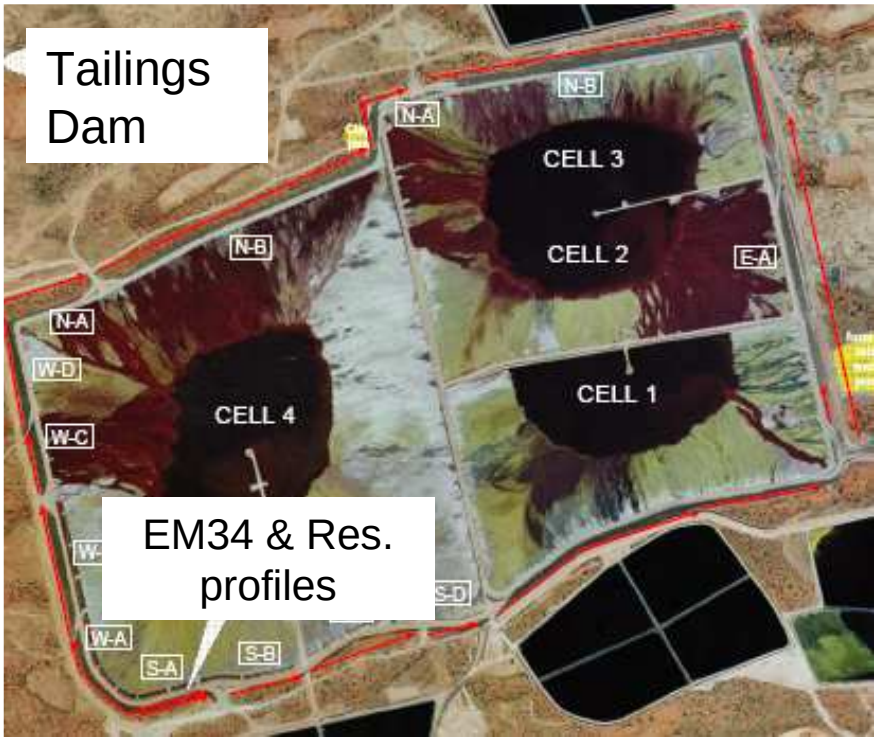
- Active electromagnetic induction techniques
- Applications
  - Profiling
  - Sounding





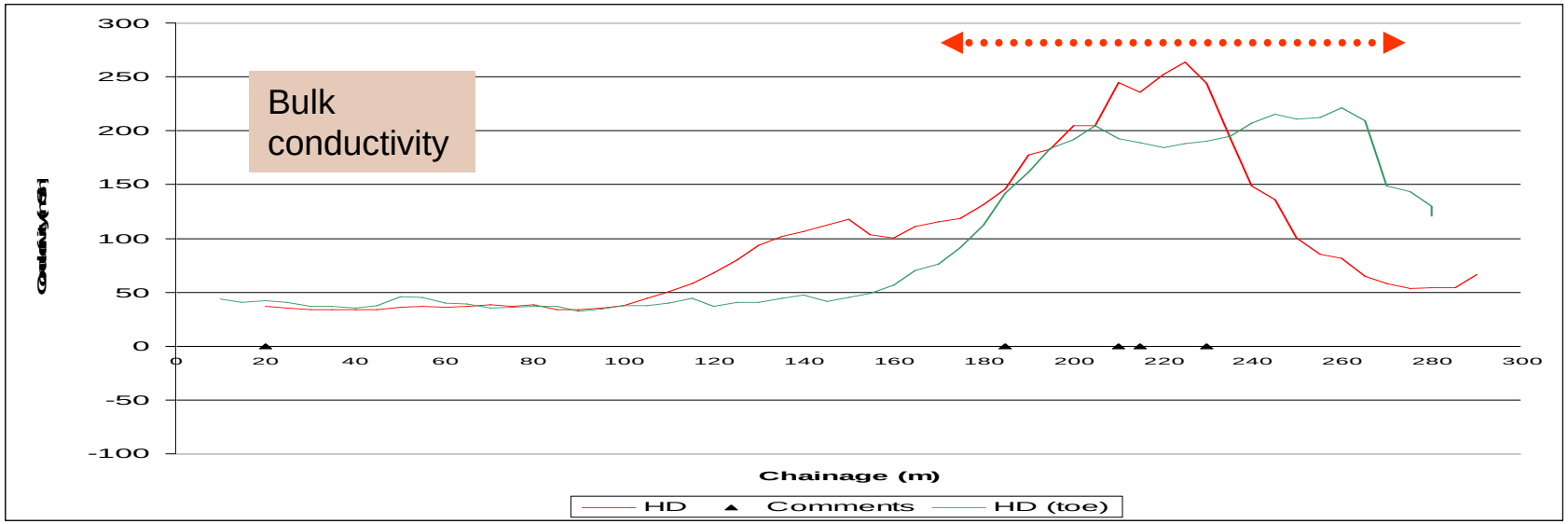
EM-31

EM-34



EM 34 profiles around margin

Possible leakage zone



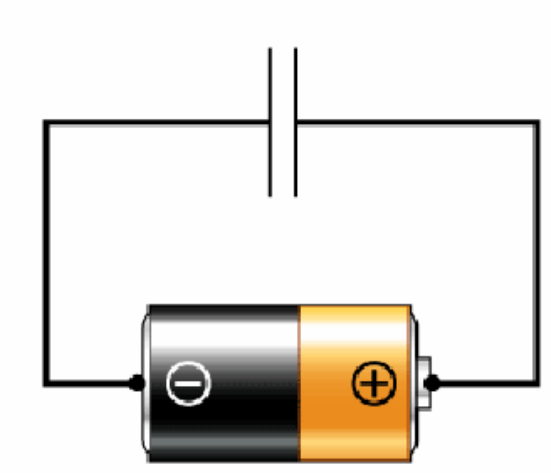
Ground Penetrating Radar (GPR)

GPR - uses reflected electromagnetic pulses to sense below ground

Application of *Radar* to Dams

- Problems/Safety
  - Voids & defects
  - Foundation conditions

capacitor



Dielectric constant (K)

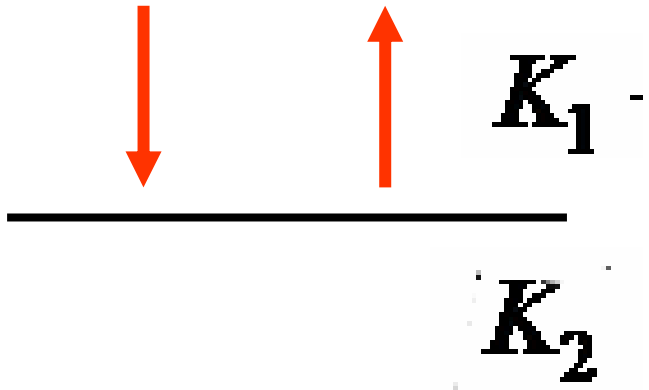
Material	K
Air	1
Distilled Water	80
Fresh Water	80
Sea Water	80
Dry Sand	3-5
Saturated Sand	20-30
Limestone	4-8
Shales	5-15
Silts	5-30
Clays	5-40
Granite	4-6

Good Concrete →

Radar reflection at interfaces

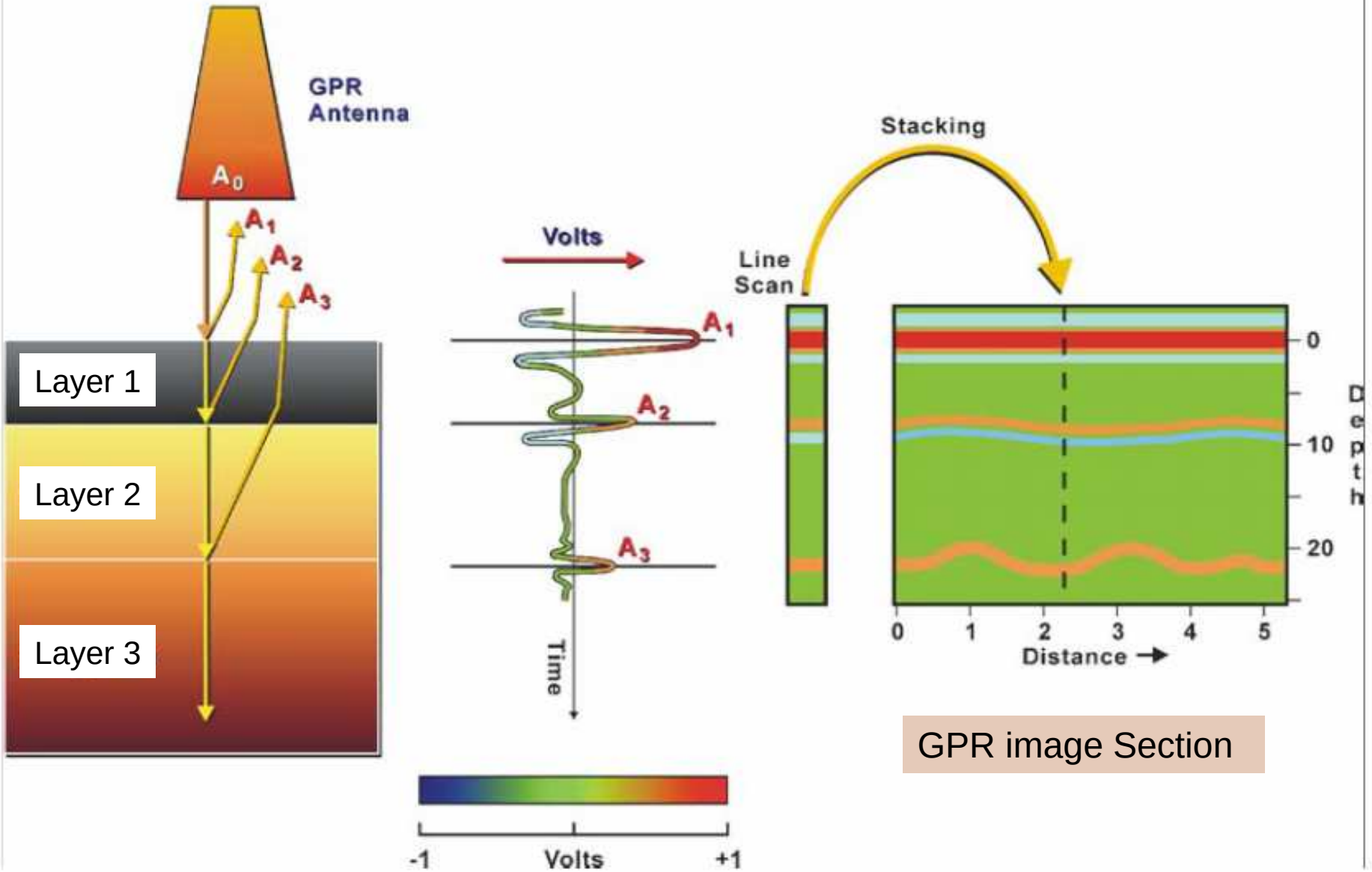
K_1 K_2 Dielectric Constants

$$R = \frac{\sqrt{K_1} - \sqrt{K_2}}{\sqrt{K_1} + \sqrt{K_2}}$$



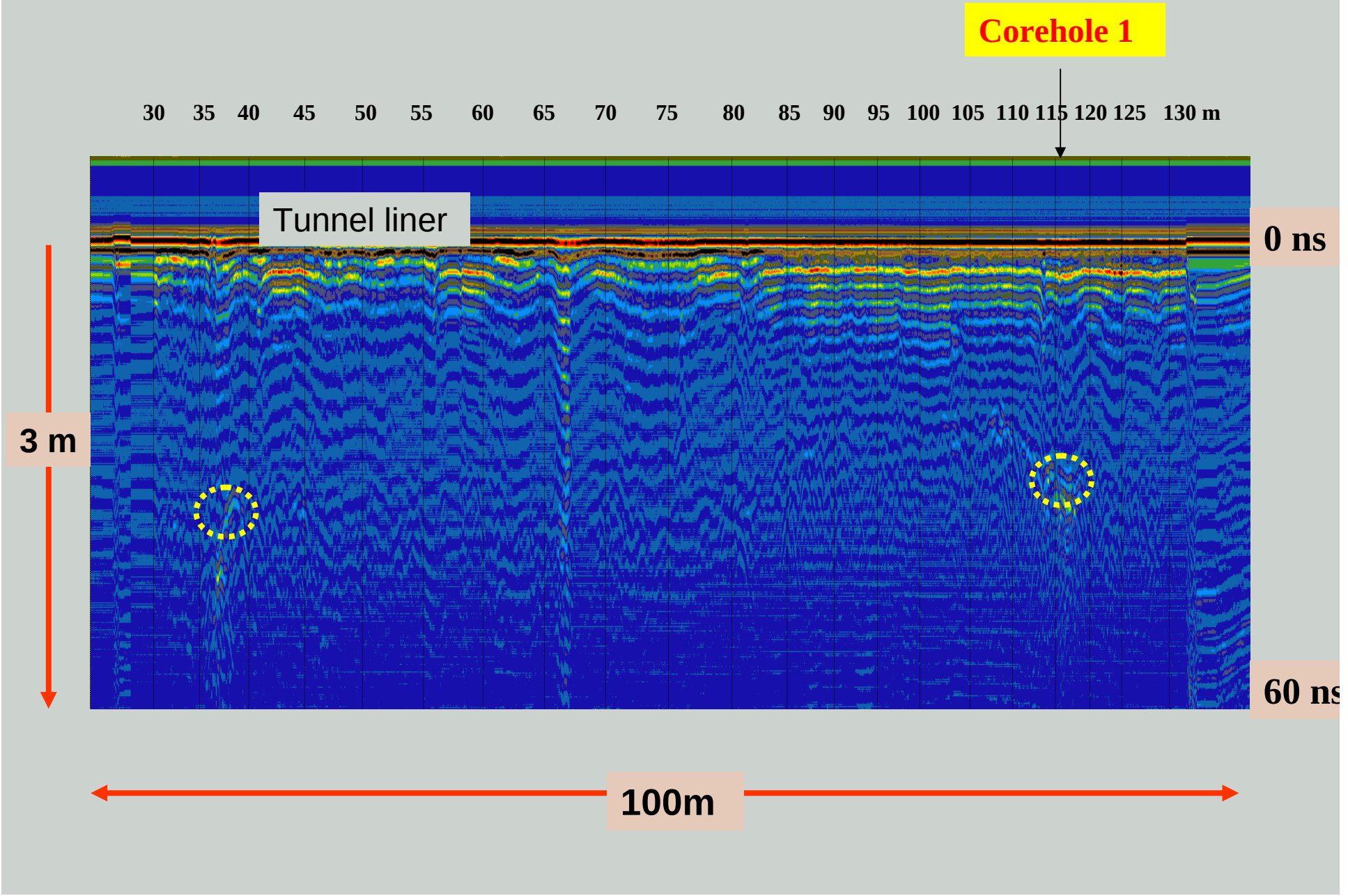
Reflected energy = R x Incident energy

Principles of Ground Penetrating Radar

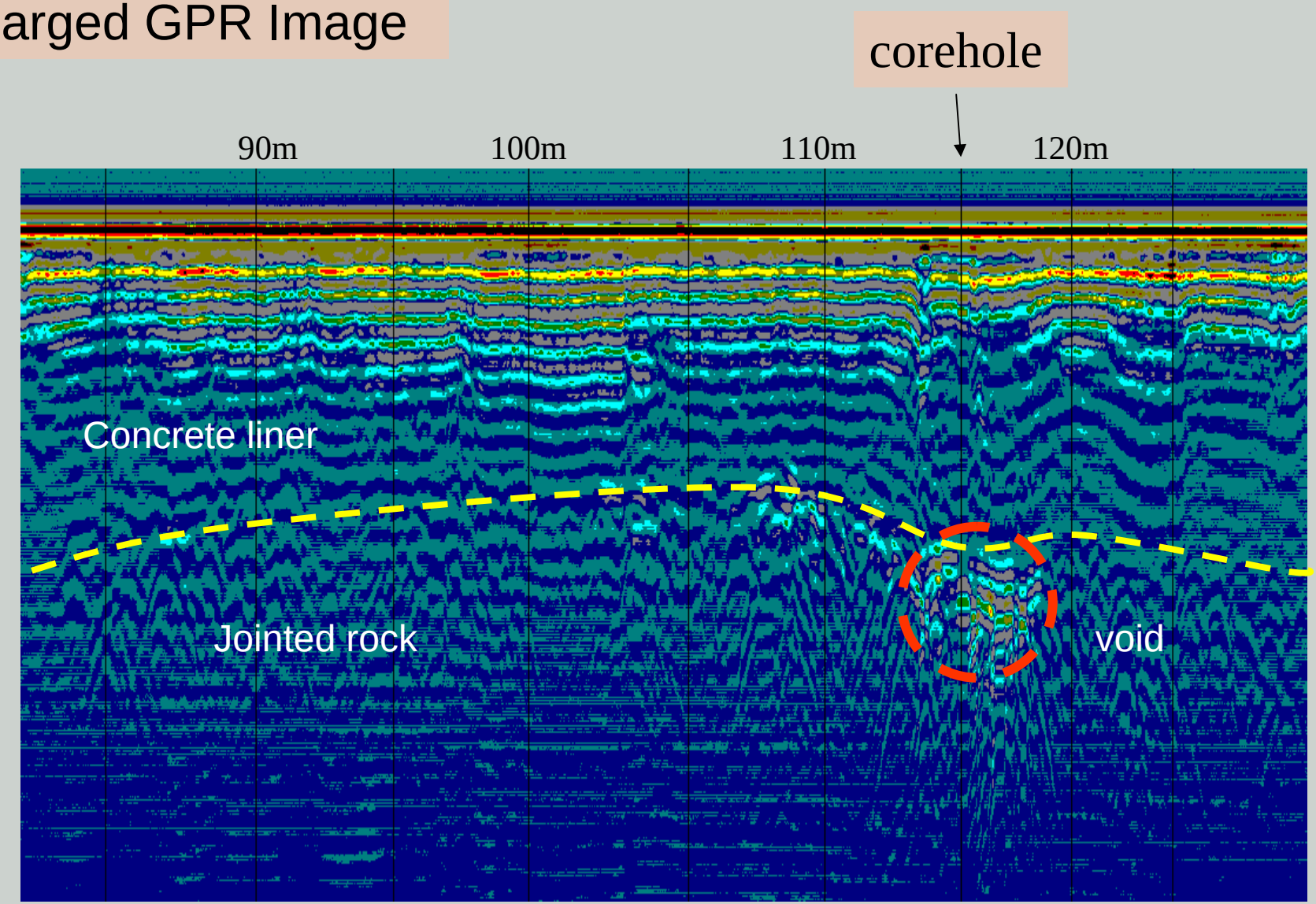


GPR image Section

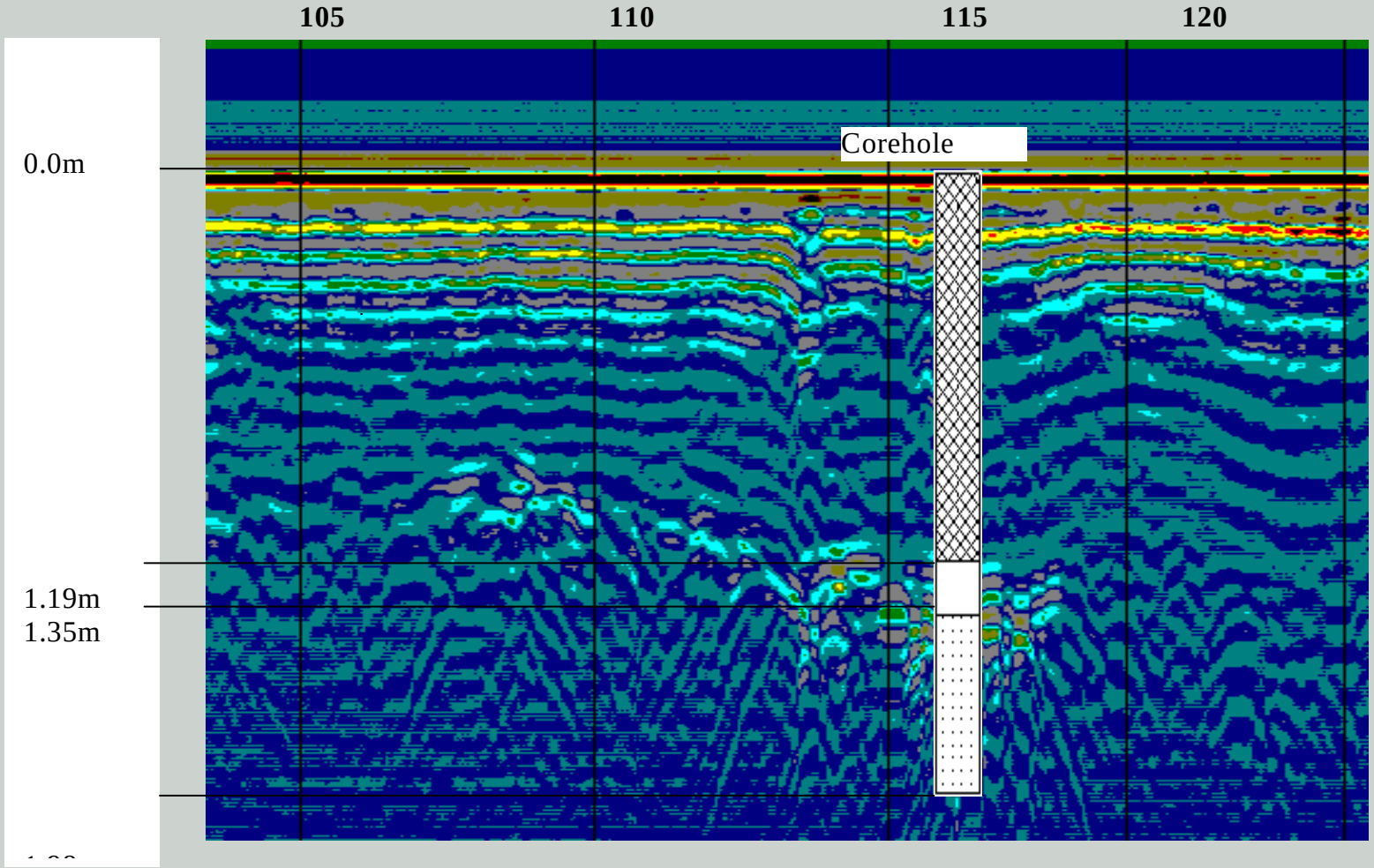
500 MHz GPR scan along tunnel liner



Enlarged GPR Image

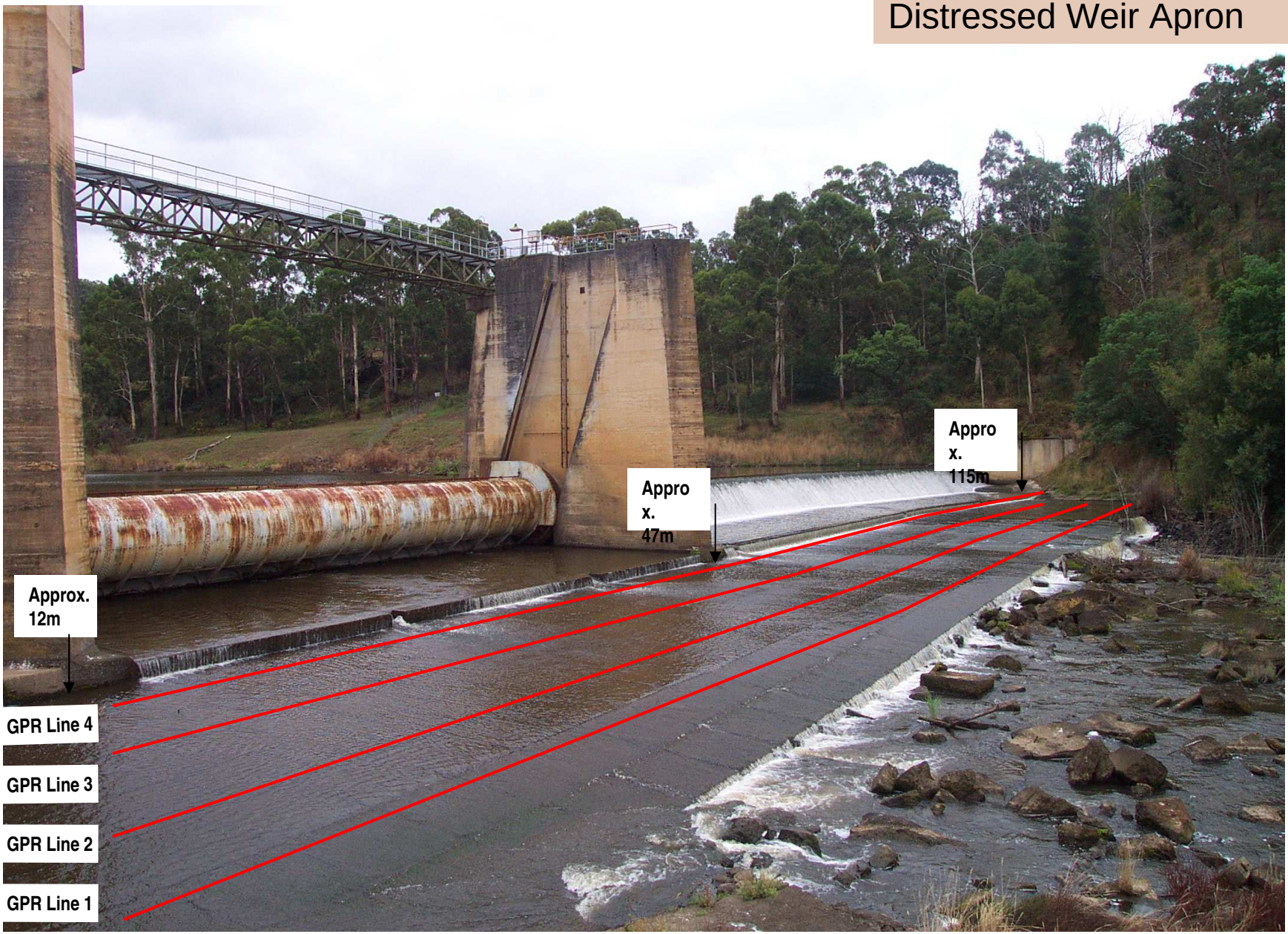


Enlarged again

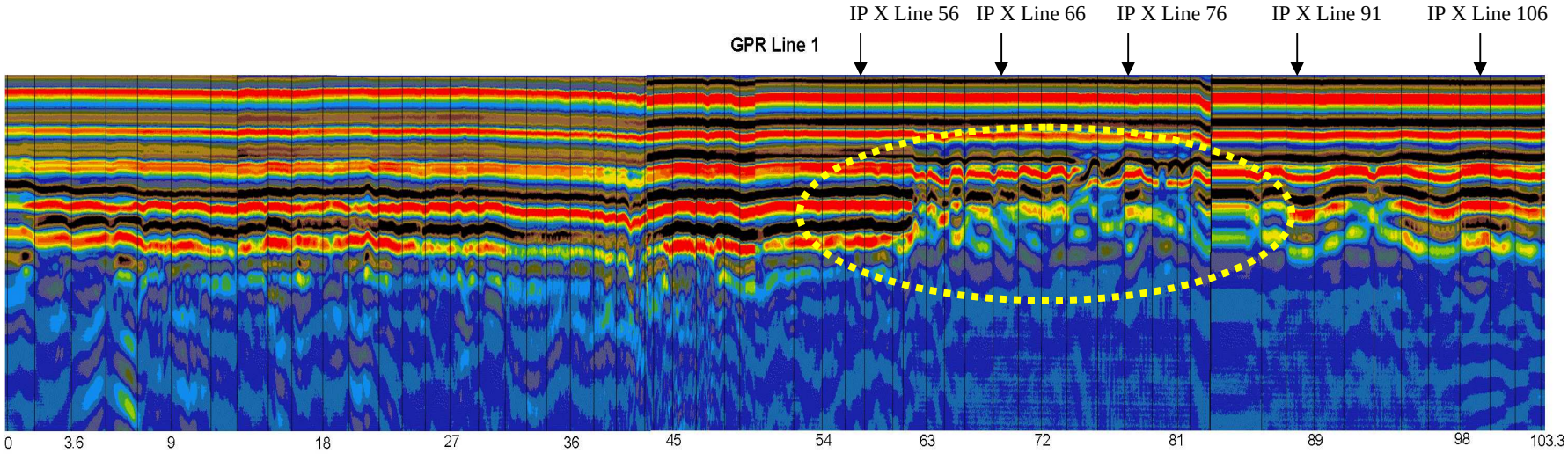


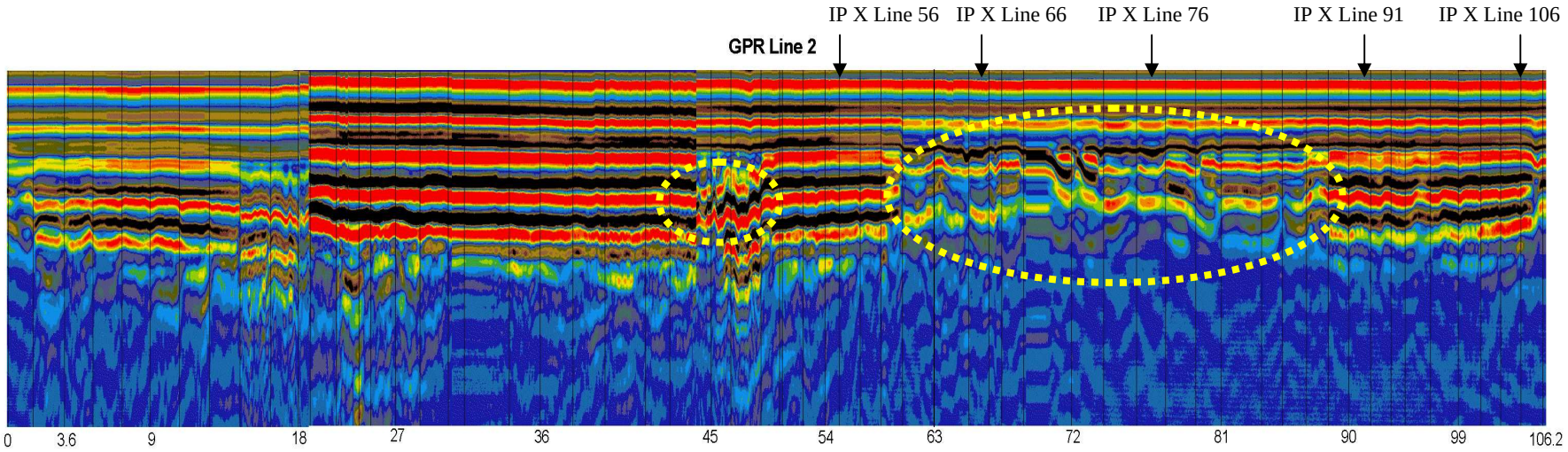
Drill depth	Recovered brick thick.	Recovered (total)	Cavity	Cavity thick.	Core loss
1.90m	1.19m	1.74m	1.19-1.35m	0.16m	0.00m

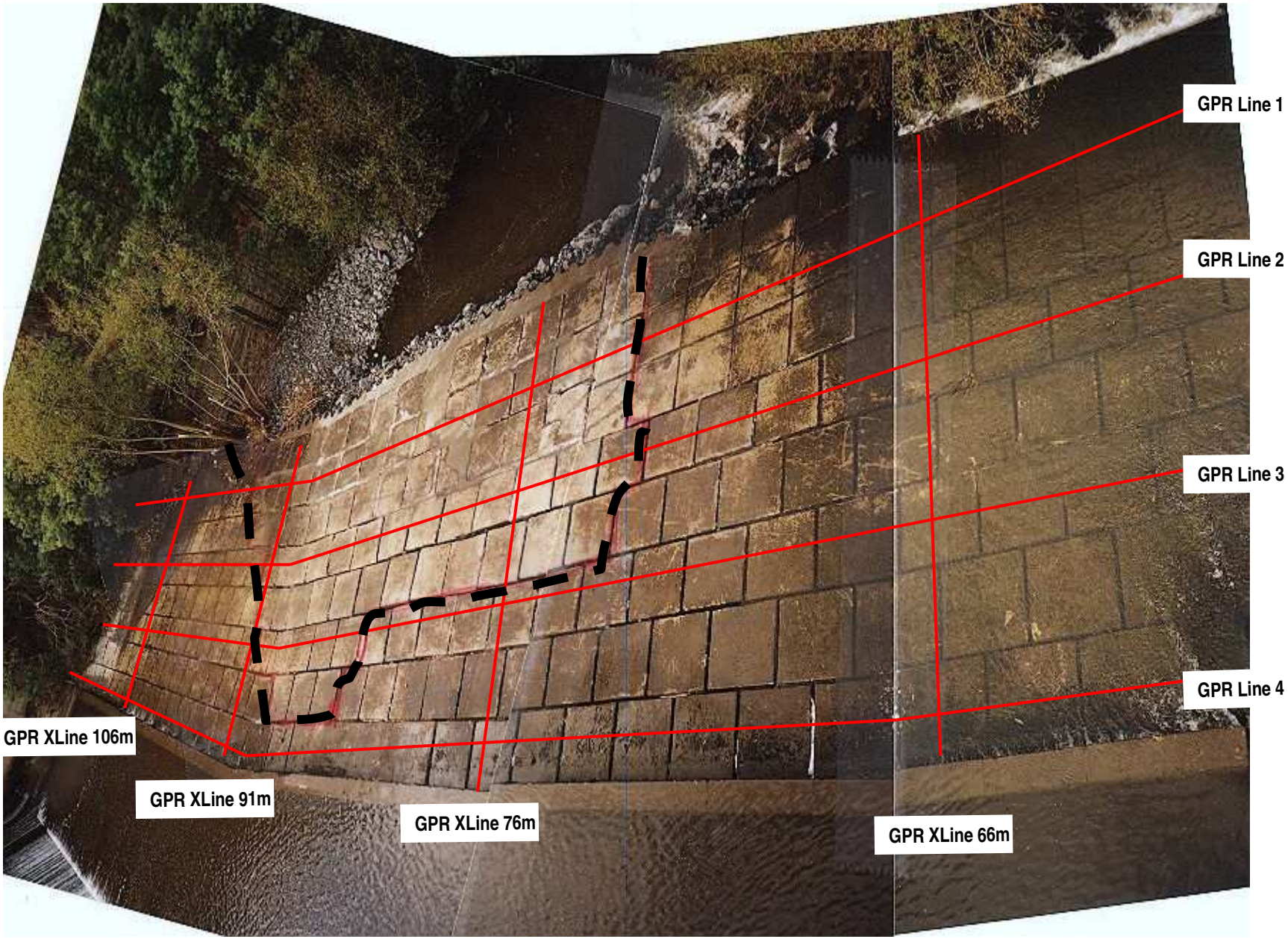
Distressed Weir Apron



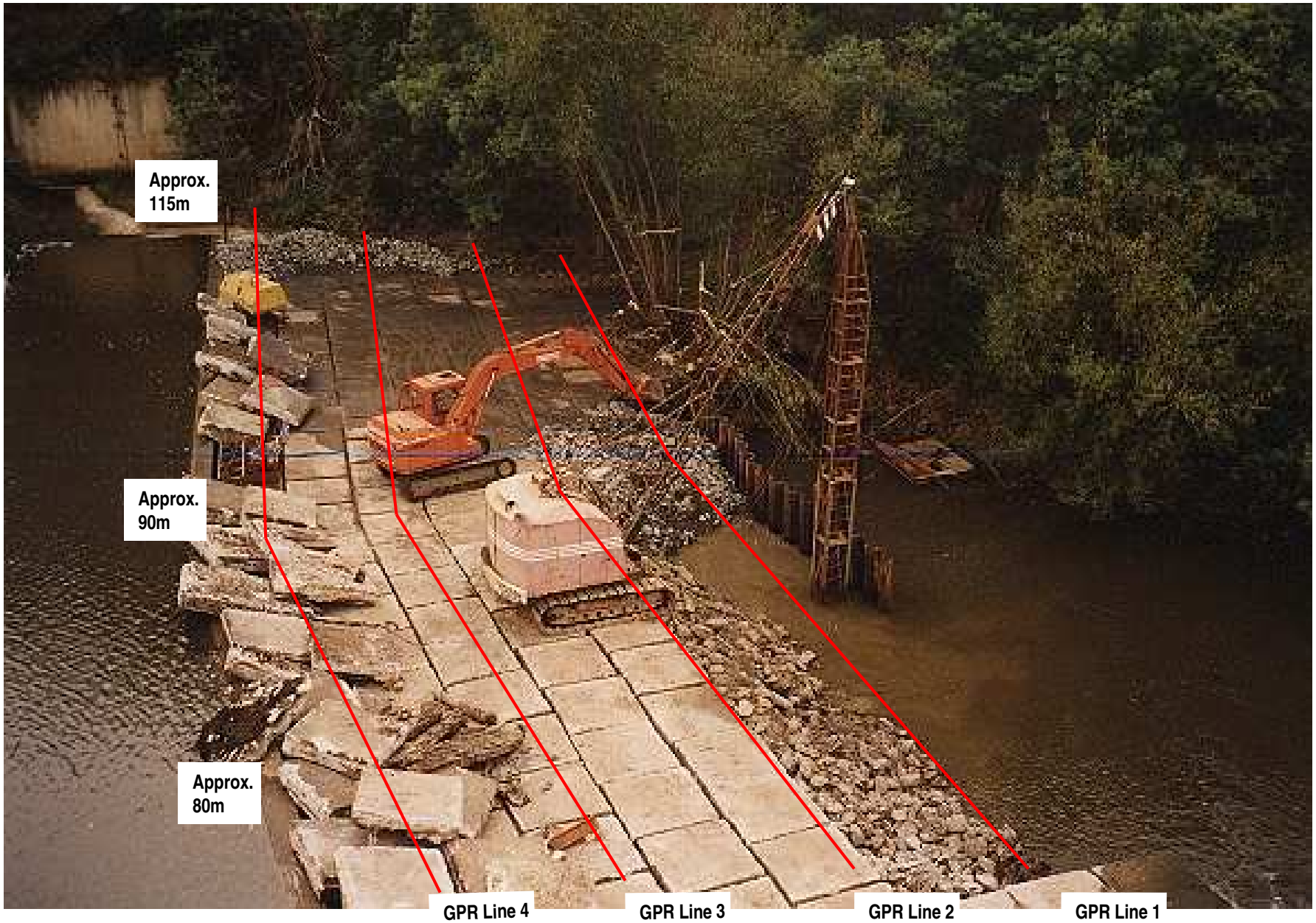
120MHz GPR Antenna





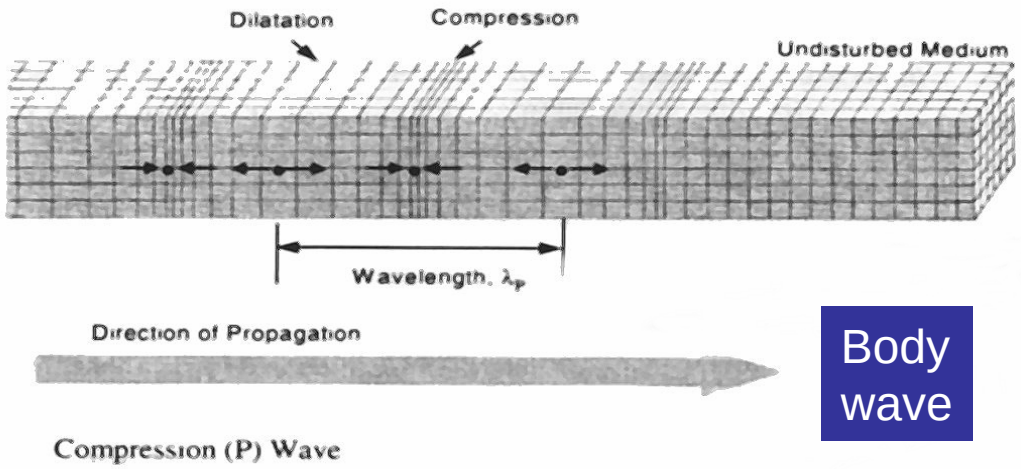


– – – Approx. extent of repair area


Approx.
115m
Approx.
90m
Approx.
80m
GPR Line 4
GPR Line 3
GPR Line 2
GPR Line 1

Seismic Technologies

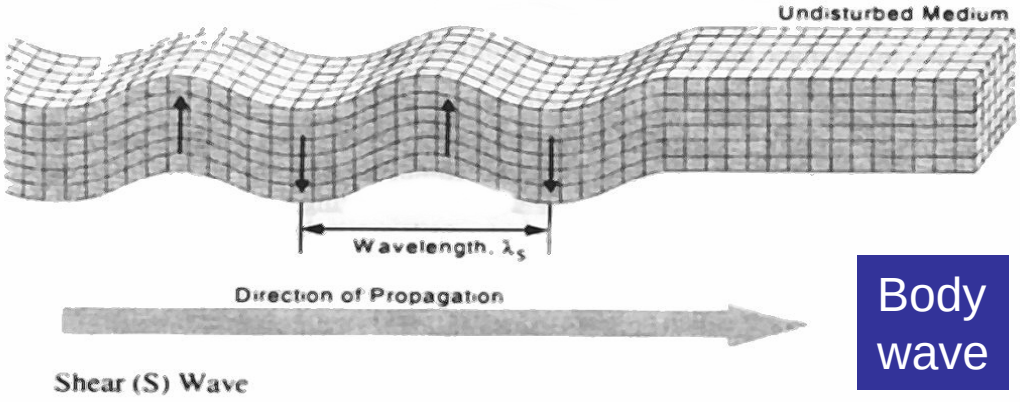
- Seismic Refraction
- Multiple Analysis of S-waves (MASW)
- Surface-to-Borehole Seismic (STBH)
- Crosshole Seismic (CH)
- Vertical Seismic S-wave Profiling (VSSP)
- Seismic Cone Penetrometer (SCPT)



Body wave

$$V_p = \sqrt{\frac{\overline{K} + \frac{4}{3}\overline{G}}{\overline{\rho}}}$$

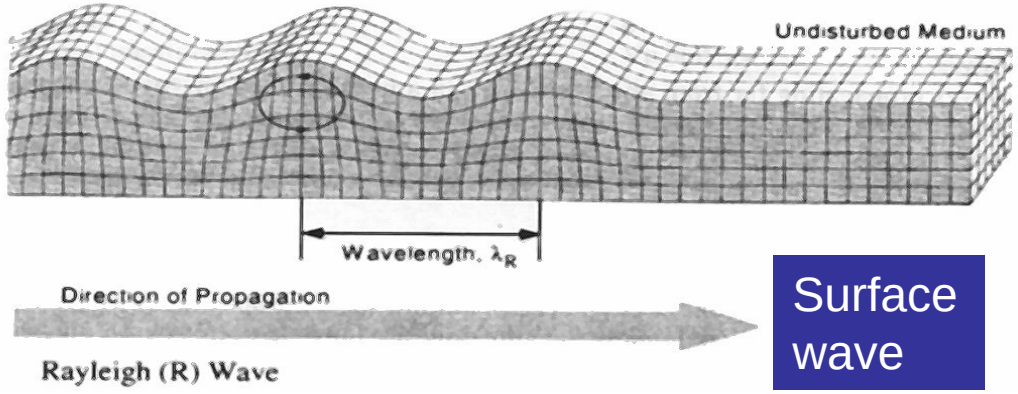
P-Wave



Body wave

$$V_s = \sqrt{\frac{\overline{G}}{\overline{\rho}}}$$

S-Wave



Surface wave

$$V_R = 0.9V_s$$

R-Wave

Poisson's Ratio and Seismic Velocities

$$\sigma = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - V_s^2\right)}$$

Youngs Modulus and Seismic Velocities

$$E = \rho V_s^2 \frac{3\left(\frac{V_p}{V_s}\right)^2 - 4}{\left(\frac{V_p}{V_s}\right)^2 - 1}$$

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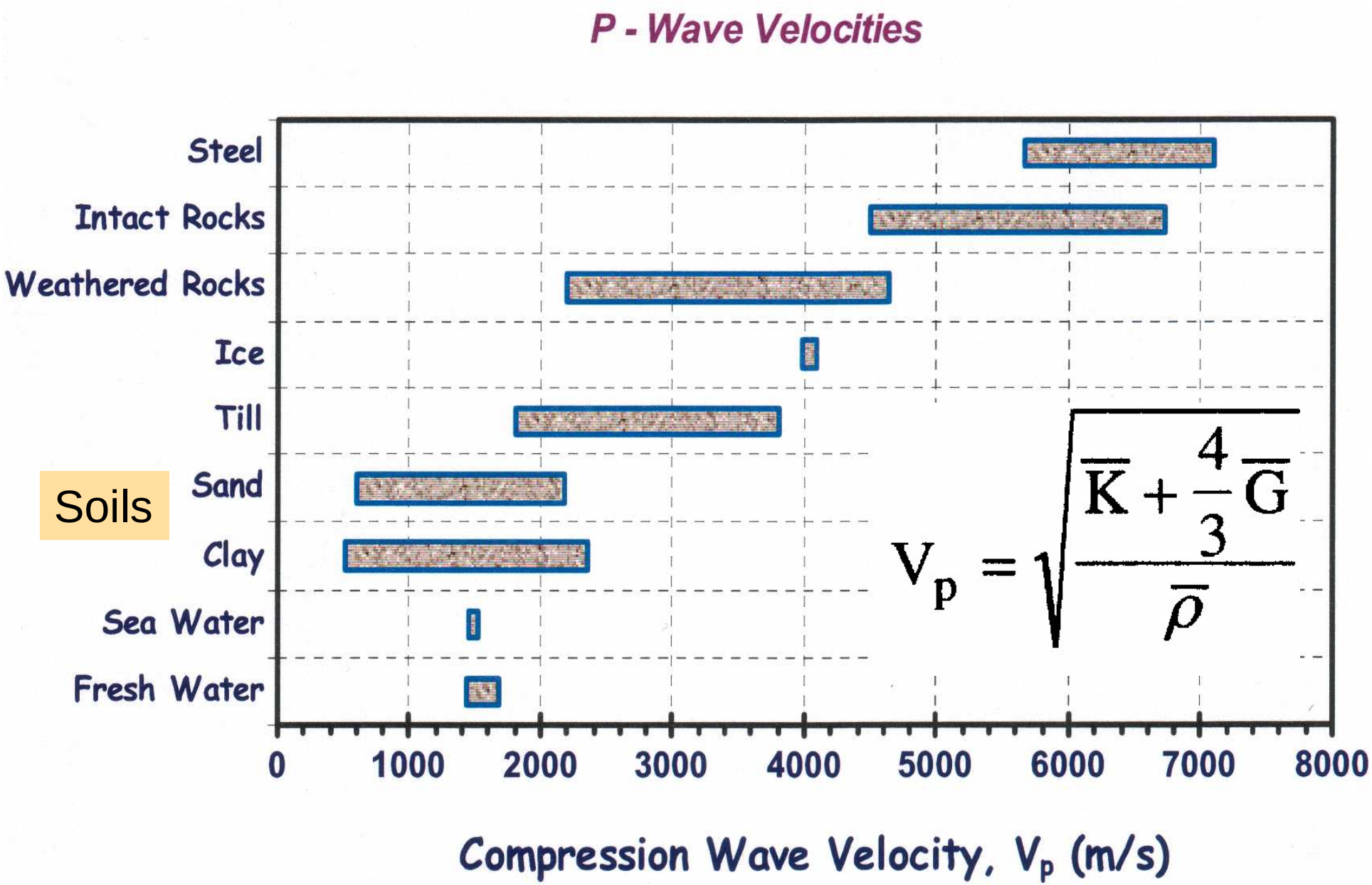
P - Wave Velocities
Steel
Intact Rocks
Weathered Rocks
Ice
Till
Sand
Clay
Sea Water
Fresh Water
Soils
$V_p = \sqrt{\frac{\overline{K} + \frac{4}{3}\overline{G}}{\overline{\rho}}}$
0
1000
2000
3000
4000
5000
6000
7000
8000
Compression Wave Velocity, V_p (m/s)

SPT N-value	Geotechnical Classification	Seismic Velocity (km/s)
0 to 4	Very loose	<0.35 to 0.43
4 to 10	Loose	0.43 to 0.52
10 to 30	Medium dense	0.52 to 0.73
30 to 50	Dense	0.73 to 1.68
>50	Very dense	>1.68

***SOILS** (in situ)*

Standard

Penetration

Test

***ROCKS** (lab.)*

Unconfined

Compressive

Strength

UCS (MPa)	Geotechnical Classification	Seismic Velocity (km/s)
< 10	Low strength rock	< 2.0
10 to 20	Medium strength rock	2.0 – 2.5
20 to 60	High strength rock; stratified, jointed	2.5 – 3.5
> 60	Very high strength rock; stressed	3.5 – 7.0

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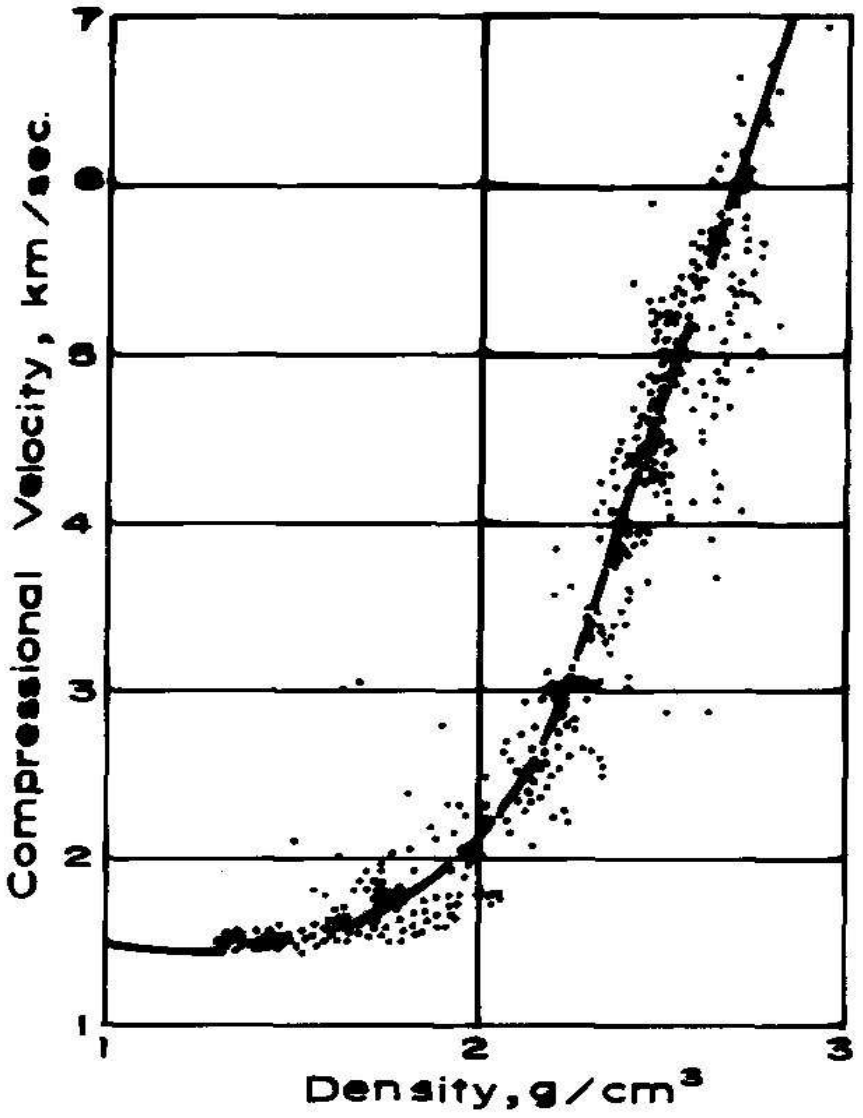
V_p

$$V_p = \sqrt{\frac{\overline{K} + \frac{4}{3}\overline{G}}{\overline{\rho}}}$$

Nafe-Drake Curve



$\overline{\rho}$

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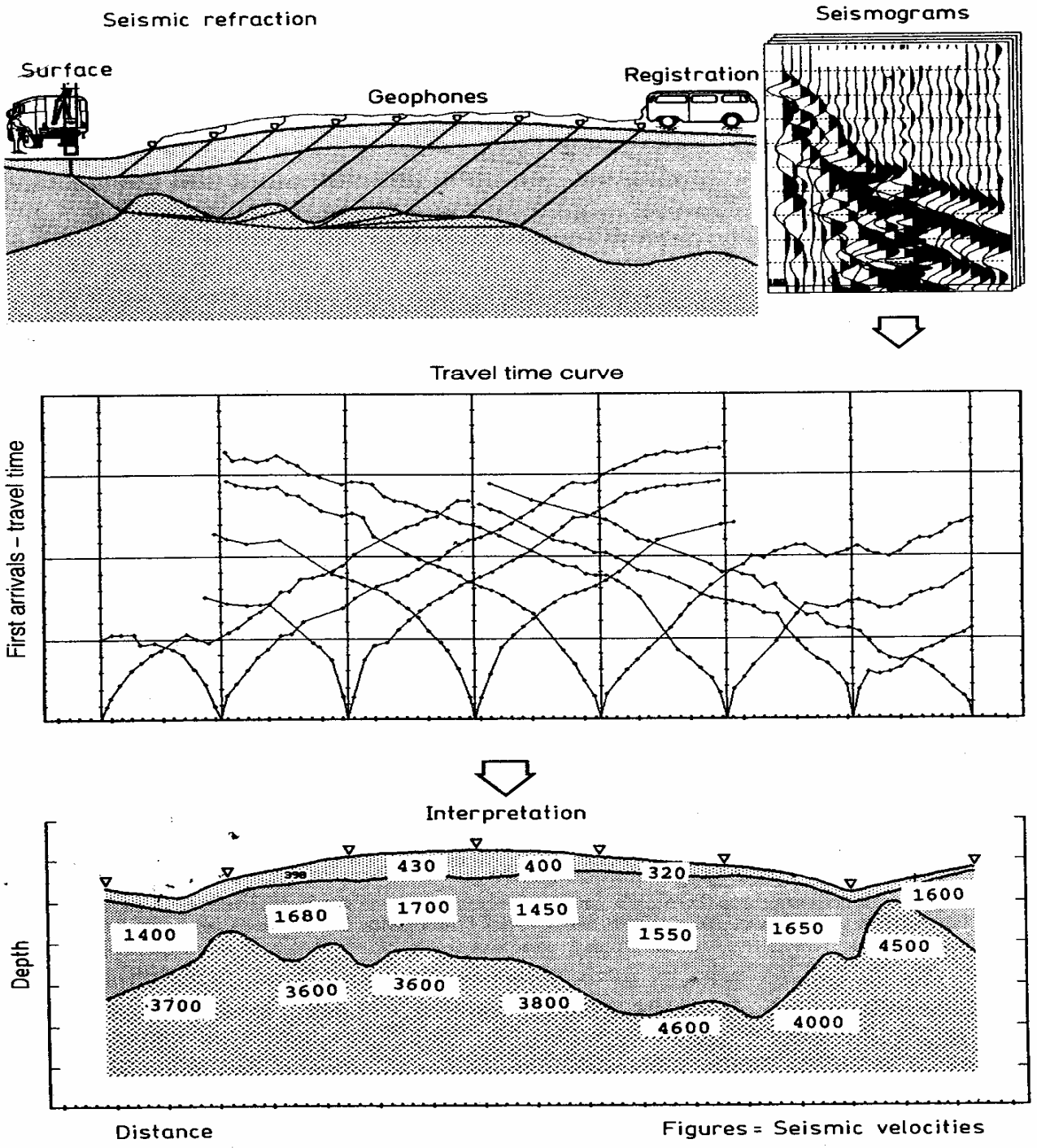
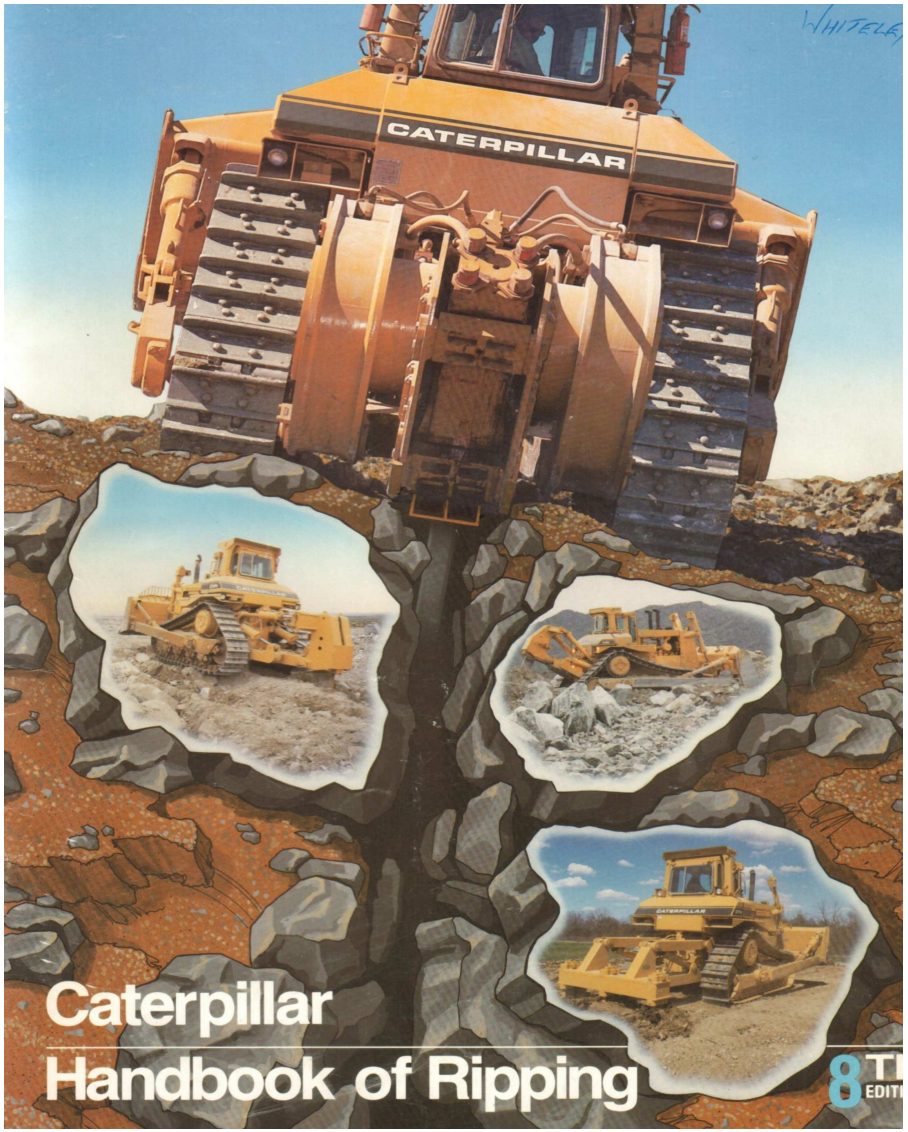
Application of *Seismic Refraction* to Dams

- Site Characterisation
  - Mapping of lithologies
  - Excavation conditions
  - Locating contact, faults, shears, voids
  - Bedrock mapping in valley floor
  - Locating & mapping hard rock borrow areas
- Problems & Safety
  - Unstable zones in embankment walls & slopes
  - Seismic & Liquefaction assessments

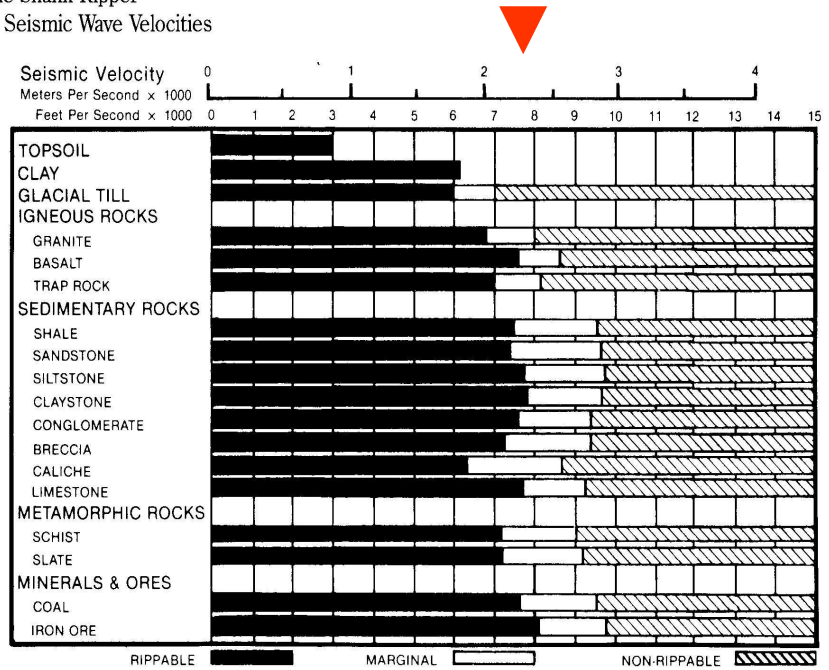
Seismic refraction uses critically refracted P-waves Waves

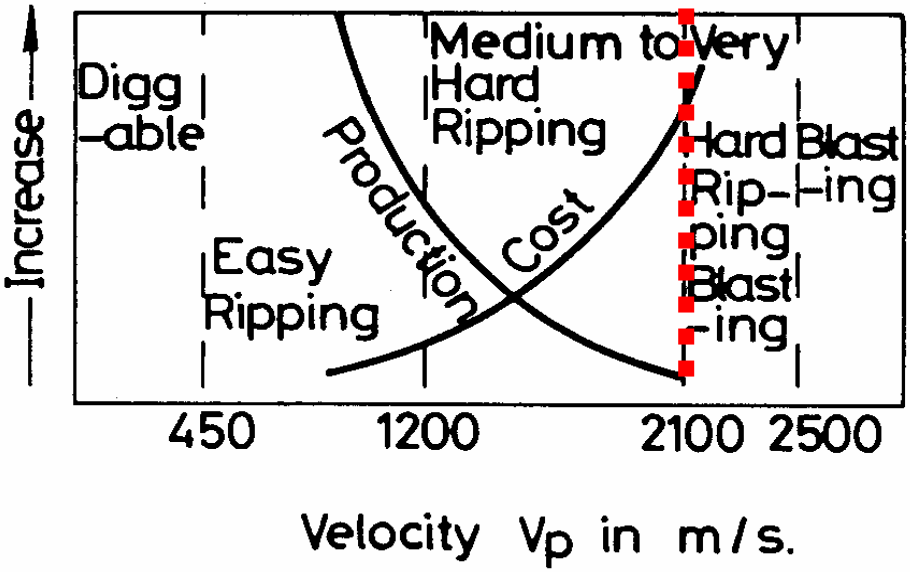




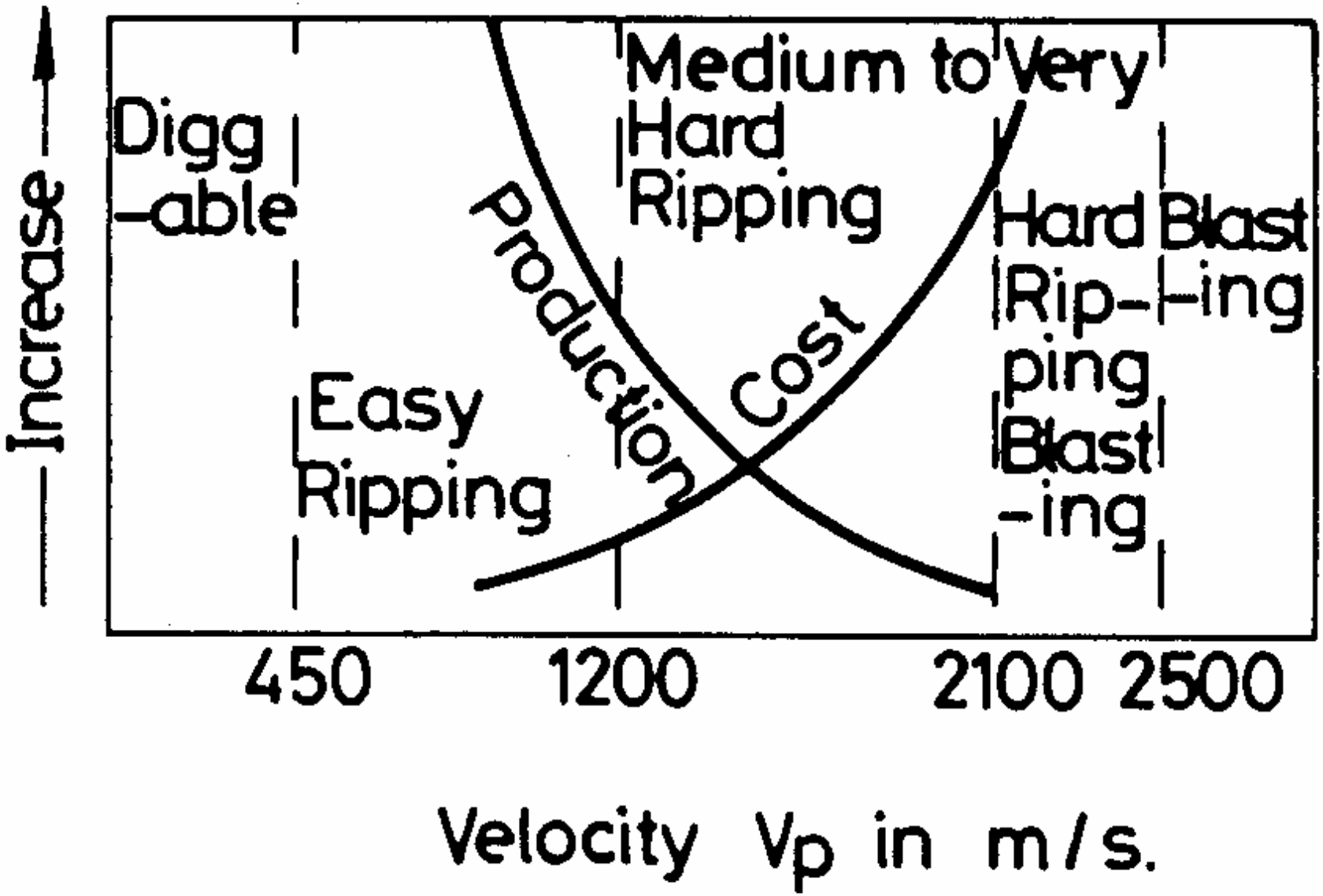
D9N Ripper Performance

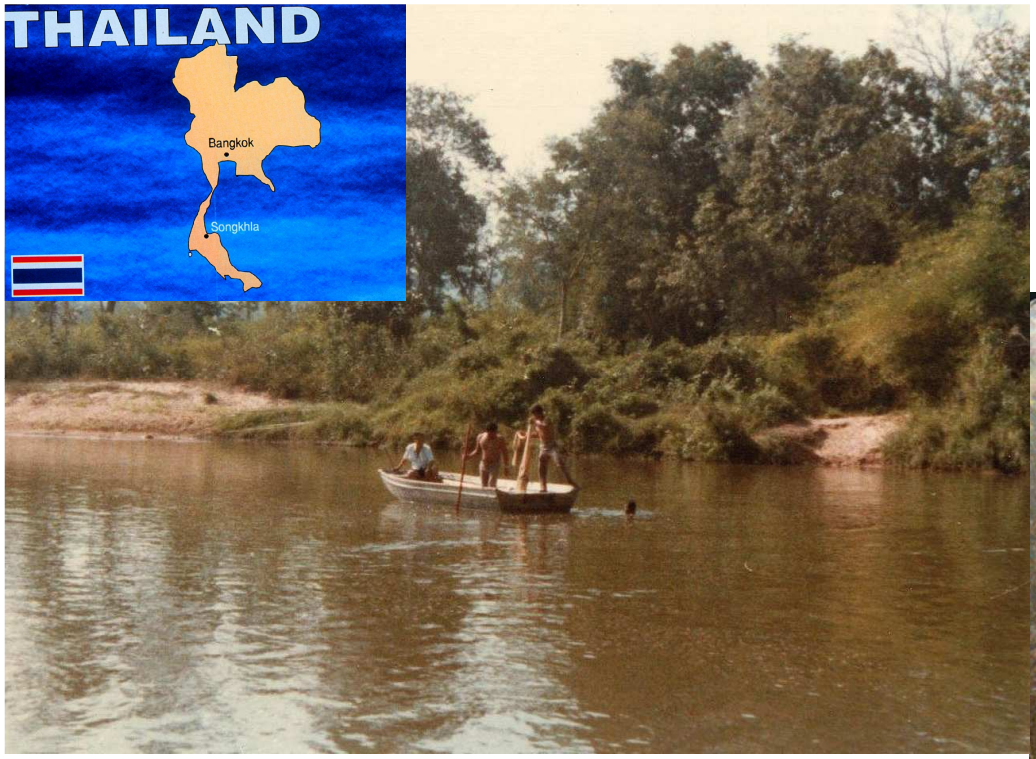
- Multi or Single Shank Ripper
- Estimated by Seismic Wave Velocities





P-wave velocity & excavation


Increase
Digg
-able
Easy
Ripping
Medium to
Hard
Ripping
Very
Hard
Rip-
ping
Blast
-ing
Blast
-ing
Production Cost
450
1200
2100
2500
Velocity Vp in m/s.

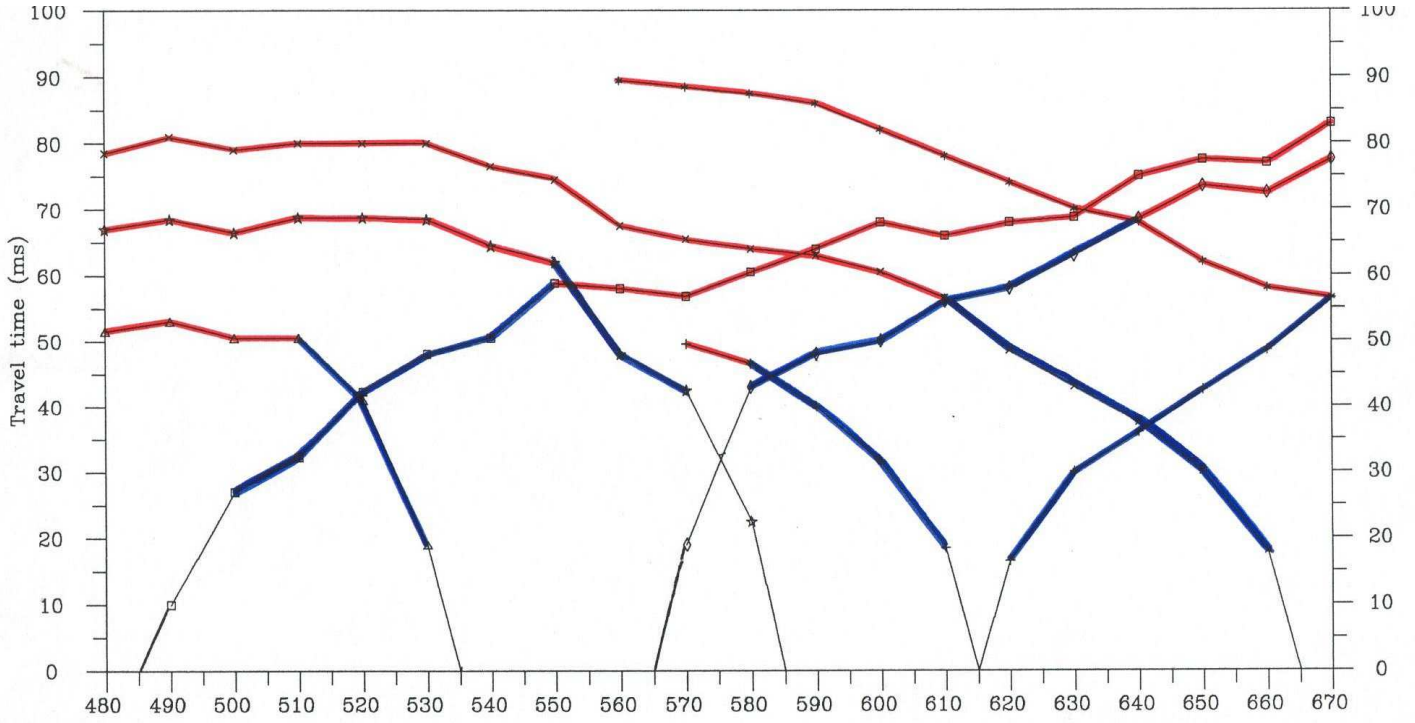


KWAE NOI RIVER

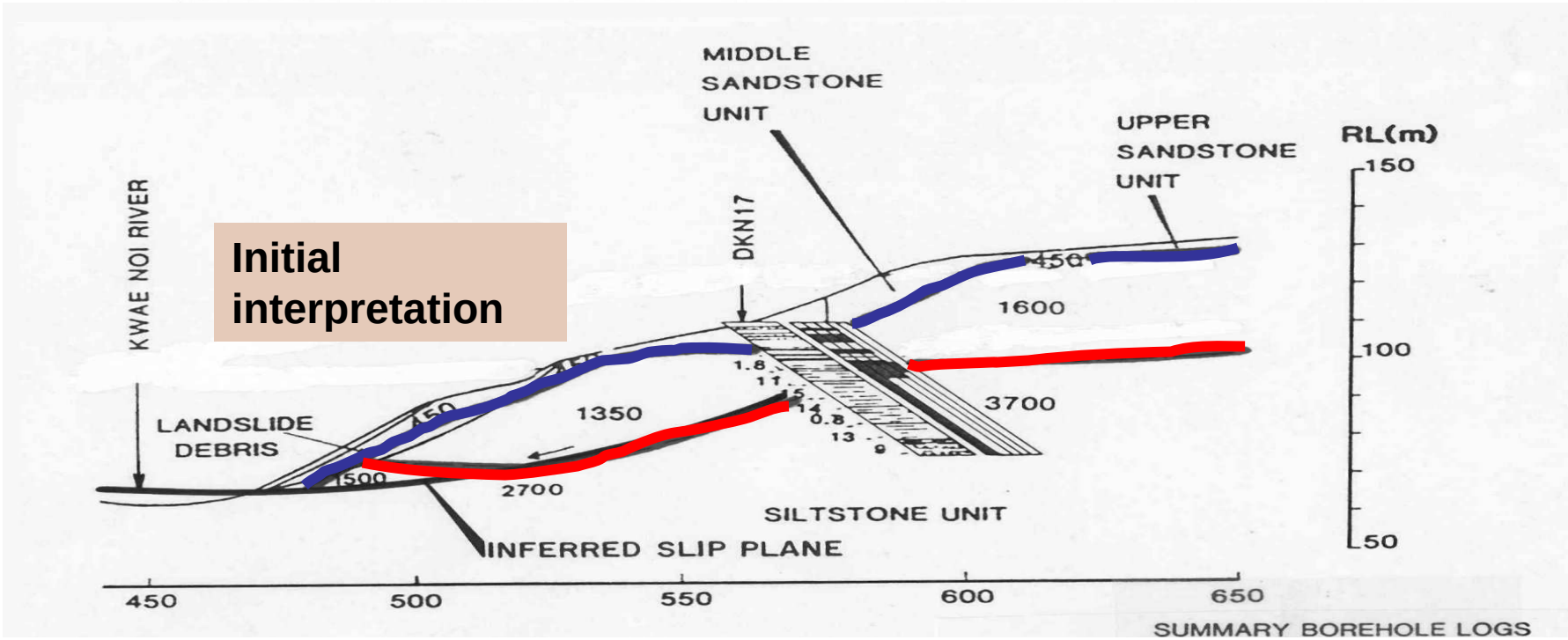
SEISMIC REFRACTION STUDY

Right abutment

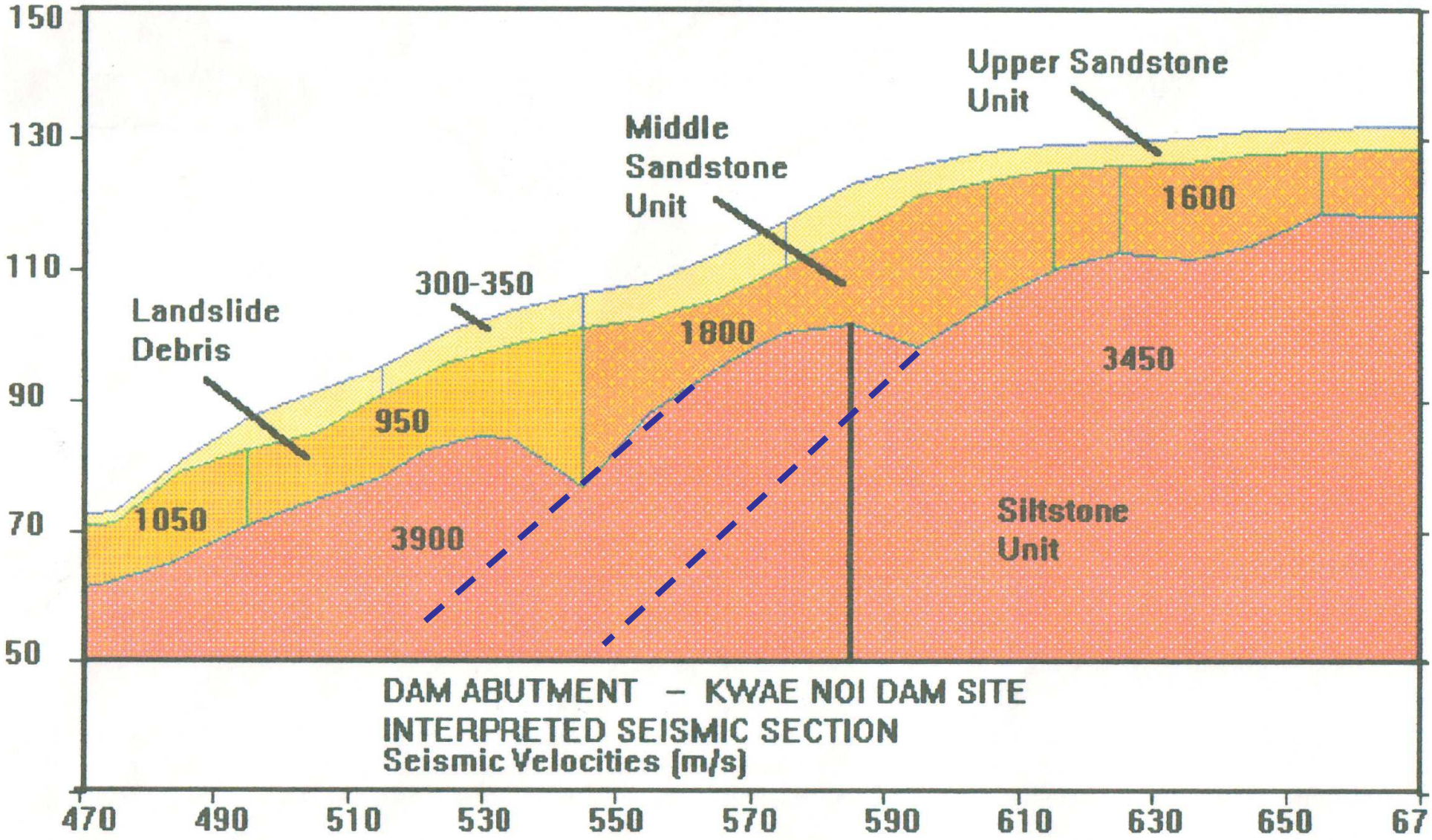
Seismic refraction data



Initial interpretation

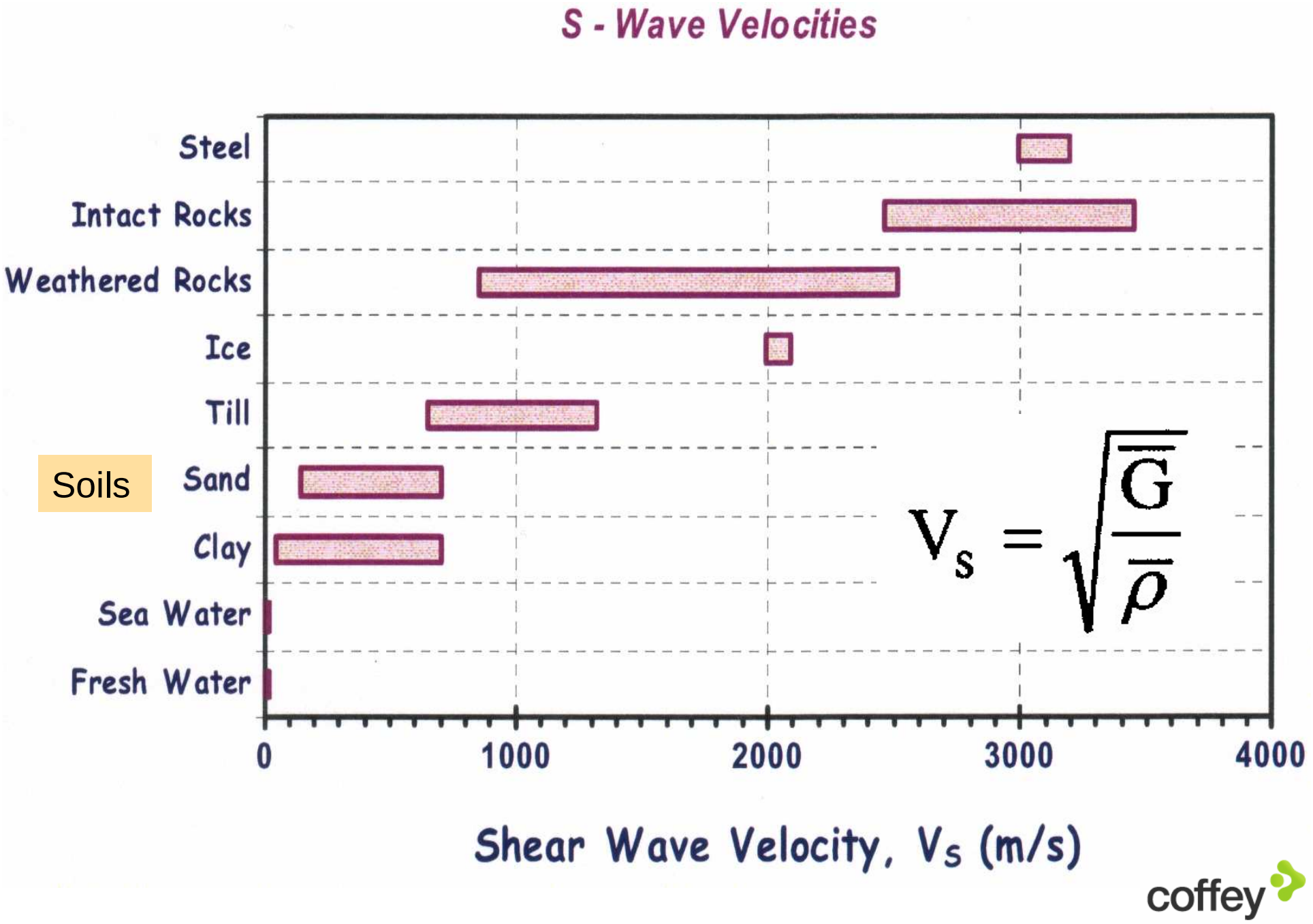


FINAL INTERPRETED SECTION

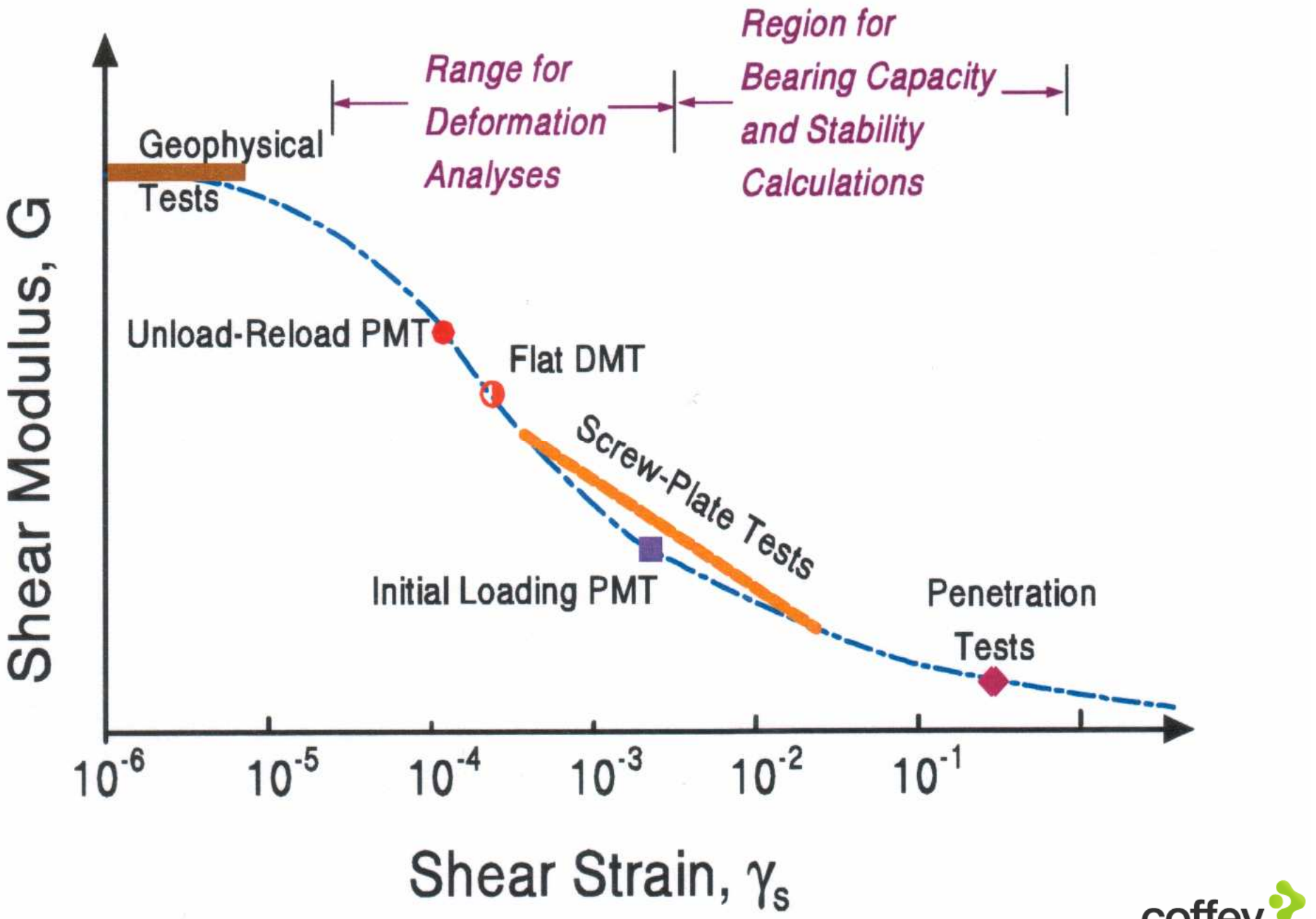


Application of *Shear Wave Methods* to Dams

- Site Characterisation
  - Conditions at buried valley margins
- Problems & Safety
  - Unstable zones in embankment walls & slopes
  - Seismic & Liquefaction assessments


S - Wave Velocities
Steel
Intact Rocks
Weathered Rocks
Ice
Till
Sand
Clay
Sea Water
Fresh Water
Soils
$V_s = \sqrt{\frac{G}{\rho}}$
0
1000
2000
3000
4000
Shear Wave Velocity, V_s (m/s)

Geotechnical Classification	S-Wave Seismic Velocity (m/s)
Very soft soils	<100
Soft soils	100 to 300
Stiff soils	200 to 500
Very Stiff soils	500 to 900
Rock	>900


Region for
Bearing Capacity
and Stability
Calculations
Range for
Deformation
Analyses
Geophysical
Tests
Unload-Reload PMT
Flat DMT
Screw-Plate Tests
Initial Loading PMT
Penetration
Tests
Shear Modulus, G
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Shear Strain, γ_s

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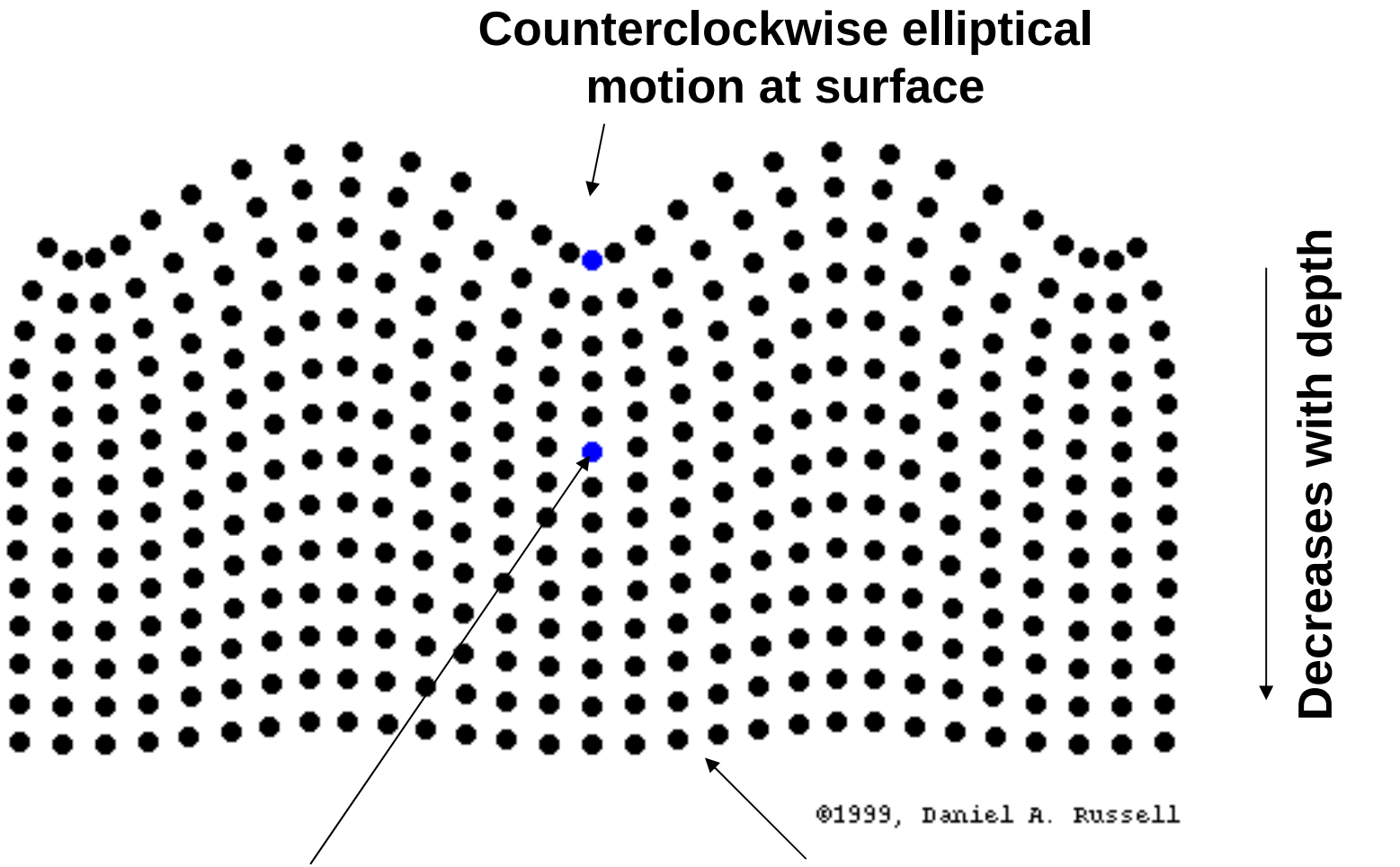
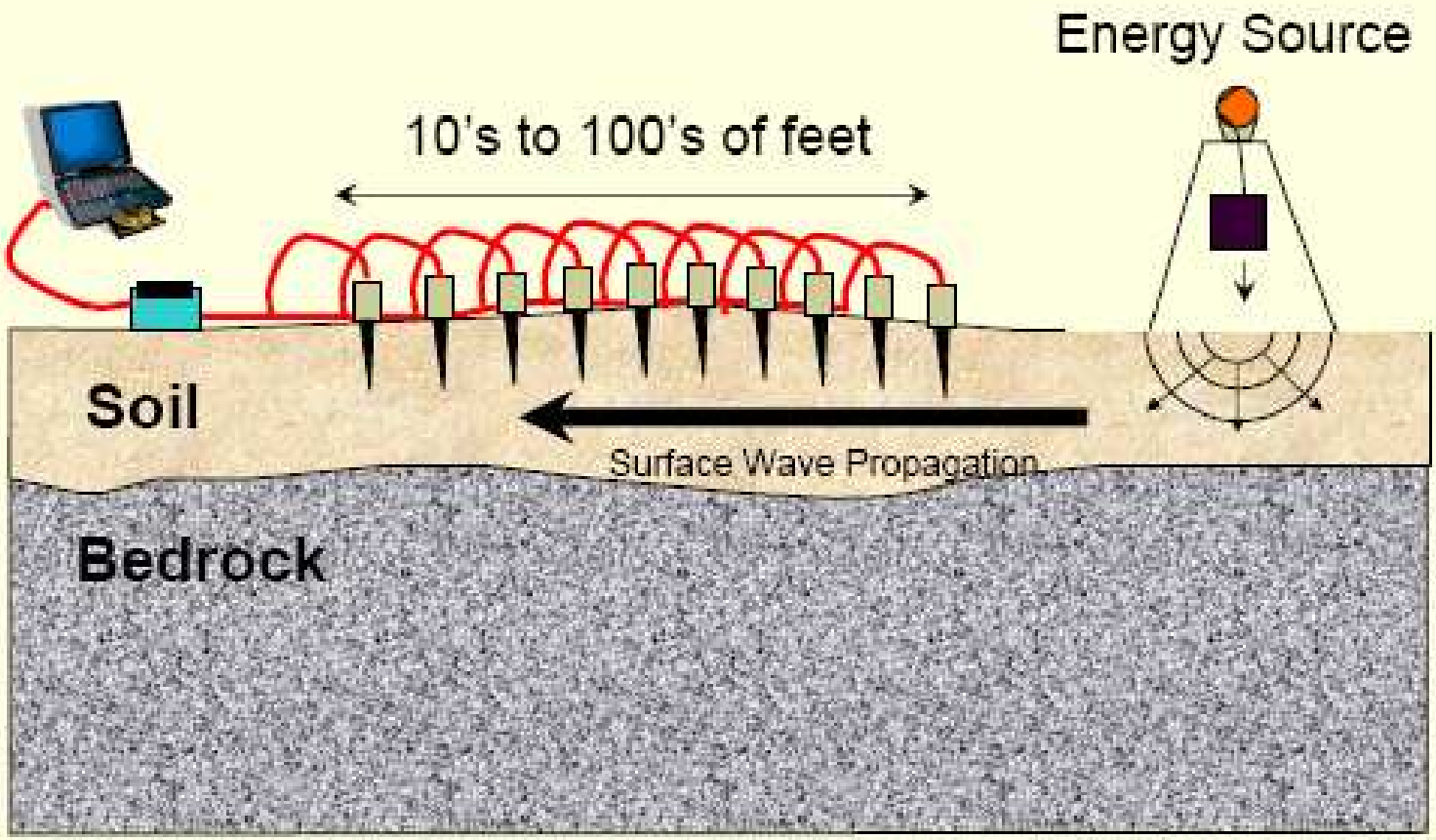
Rayleigh (R) wave motion

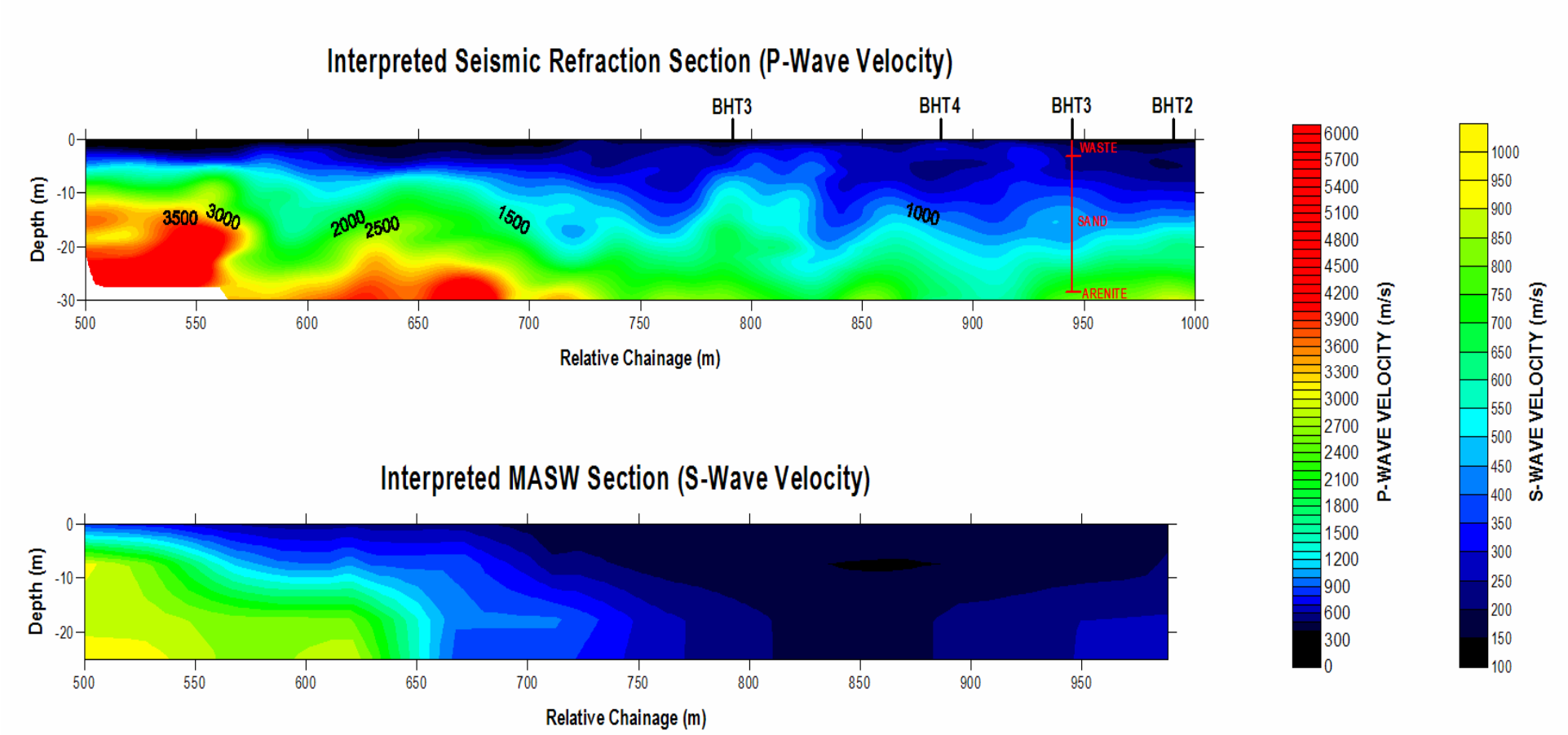


http://www.kettering.edu/~drussell/Demos/waves/wavemotion.html

MASW Field Equipment

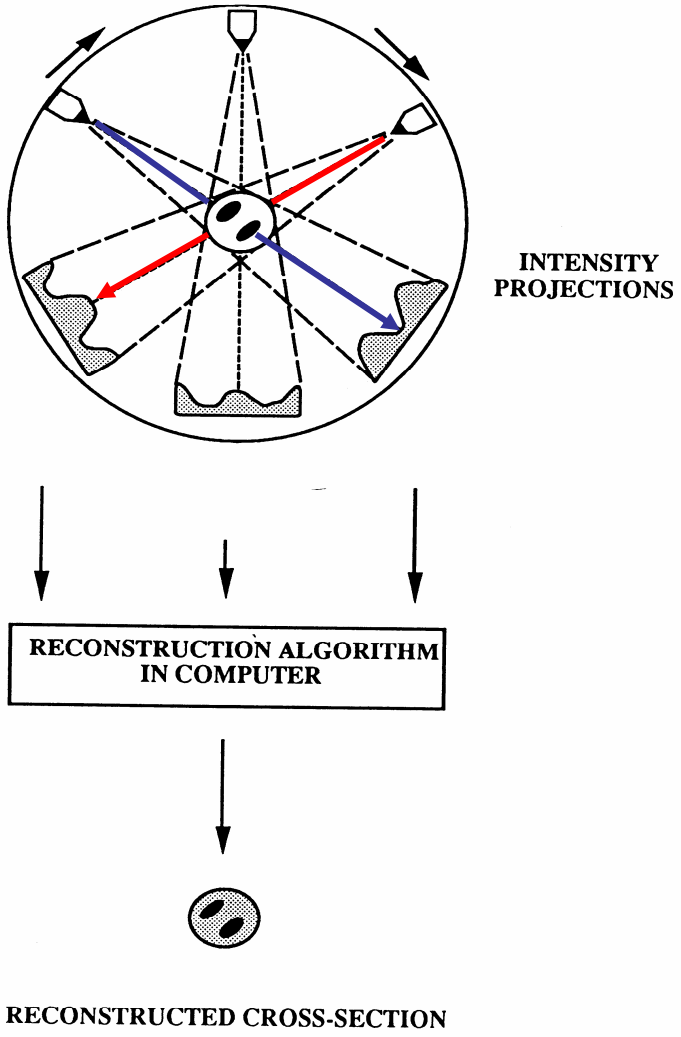


Combined P & S wave seismic sections



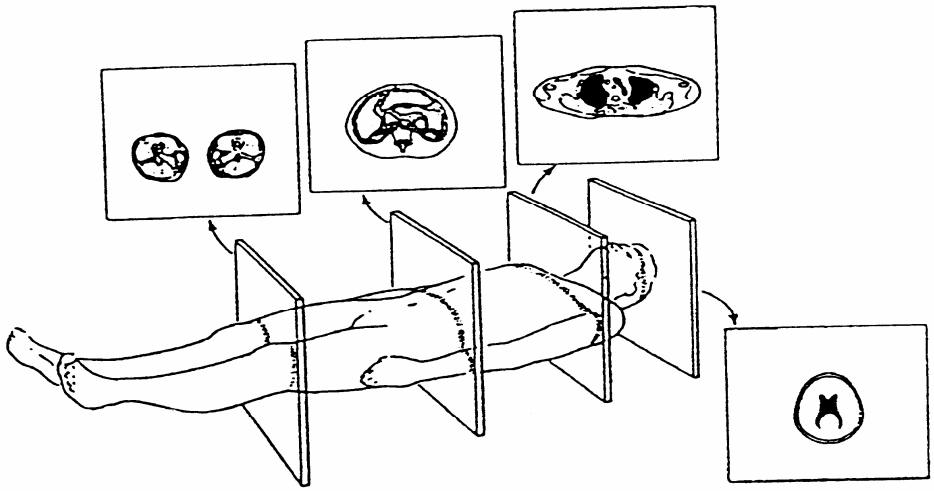
Application of *Borehole Seismic Tomography* to Dams

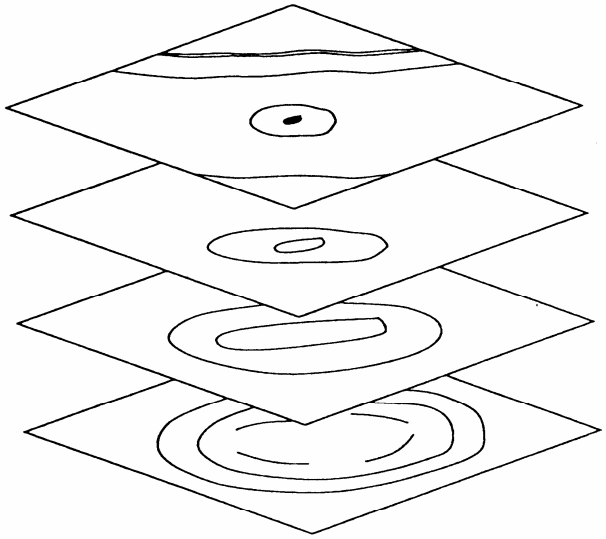
- Site Characterisation
  - Detailed mapping of weak zones
  - Grouting effectiveness
  - Bedrock mapping across river
- Problems & Safety
  - Unstable zones in embankment walls & slopes
  - Voids in concrete dams



ADVANCED PROCESSING

A 3D IMAGE IS CONSTRUCTED FROM A SERIES OF SLICES IN 2D IMAGE PLANES





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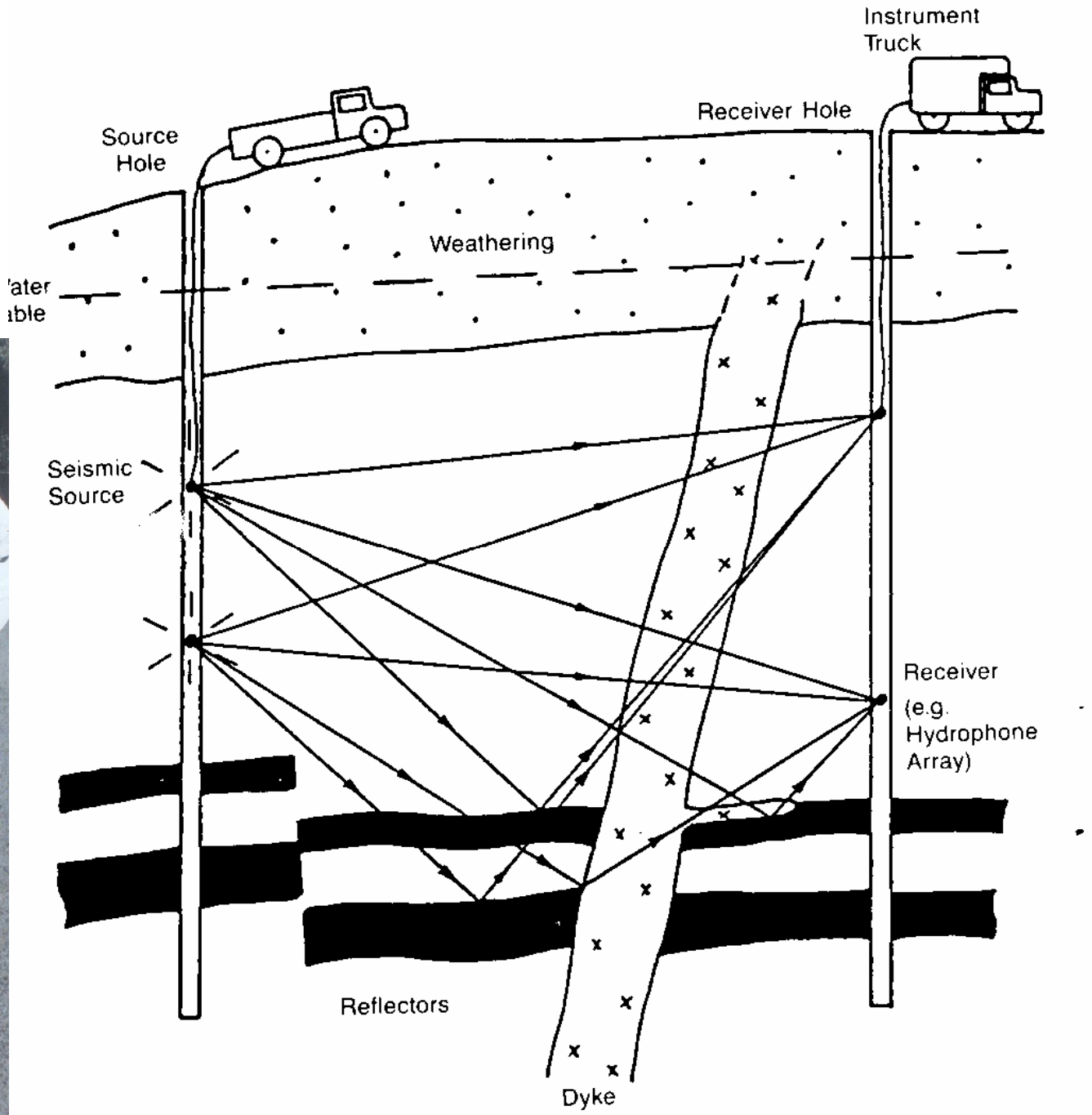
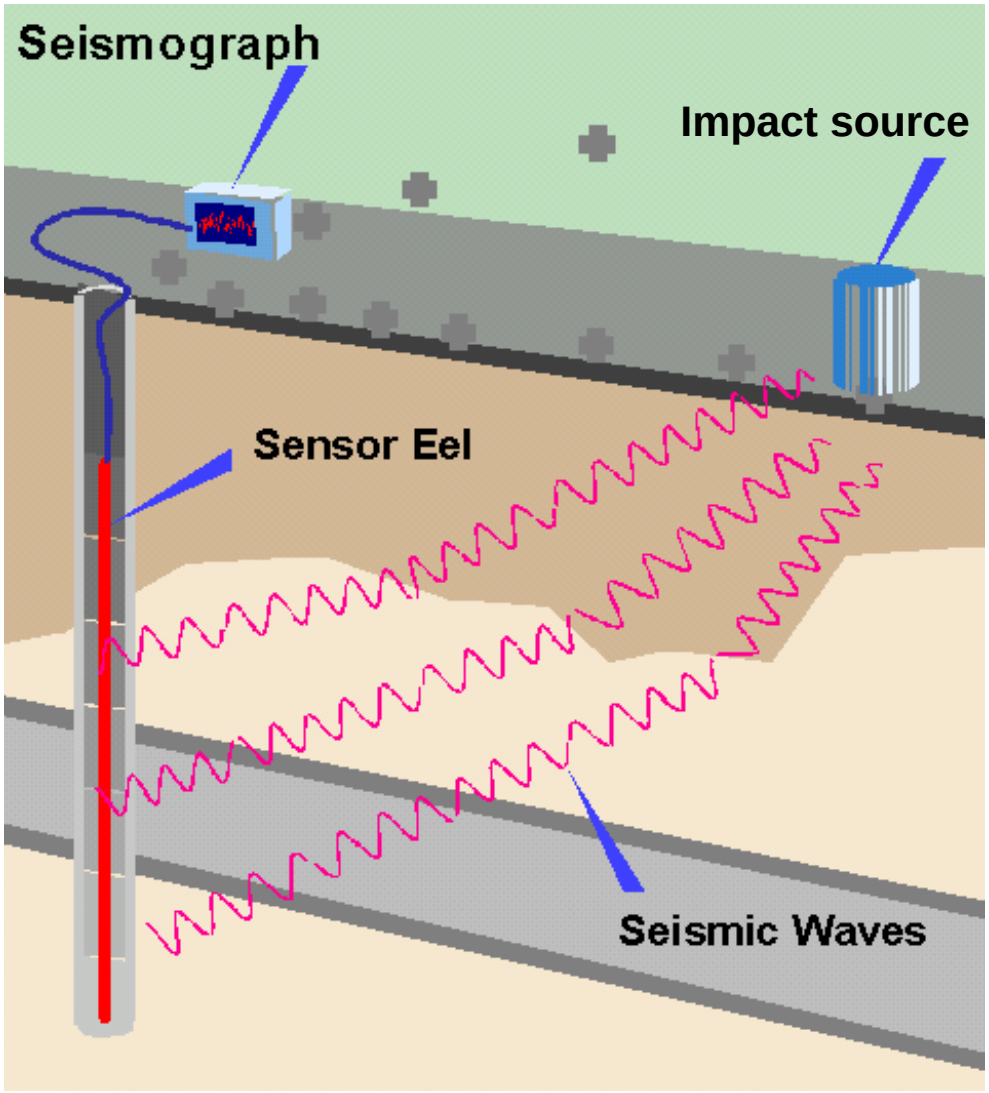
Borehole Seismic

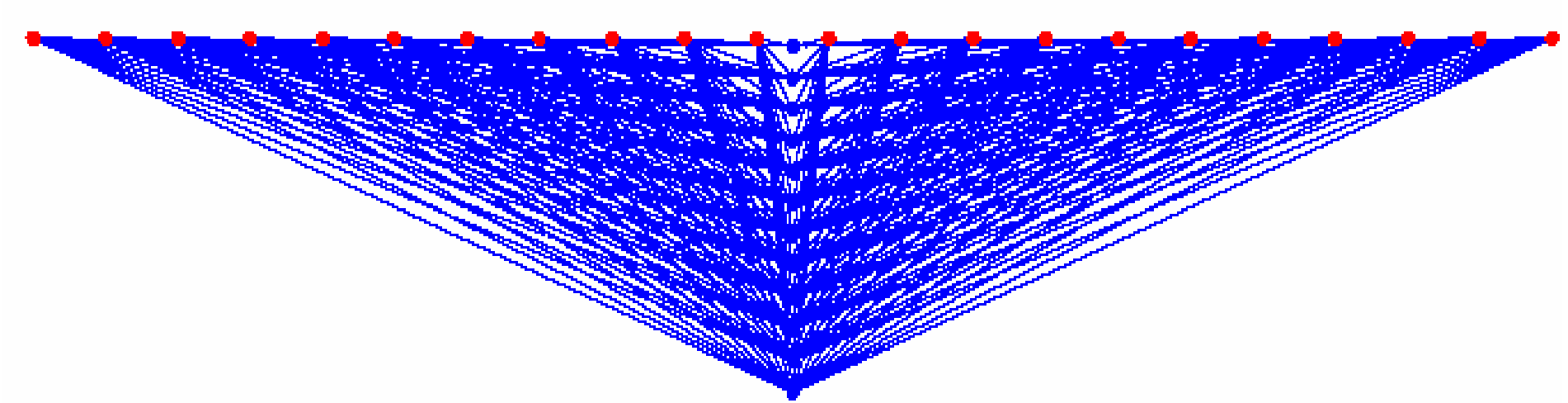


SUBS FIELD SET-UP



Single Borehole - Site Uniformity Seismic (SUBS) Test

Seismic raypath section – uniform earth



SUBS

- extends the radius of investigation of borehole

- is calibrated at the borehole with a Vertical Seismic Profile (VSP)

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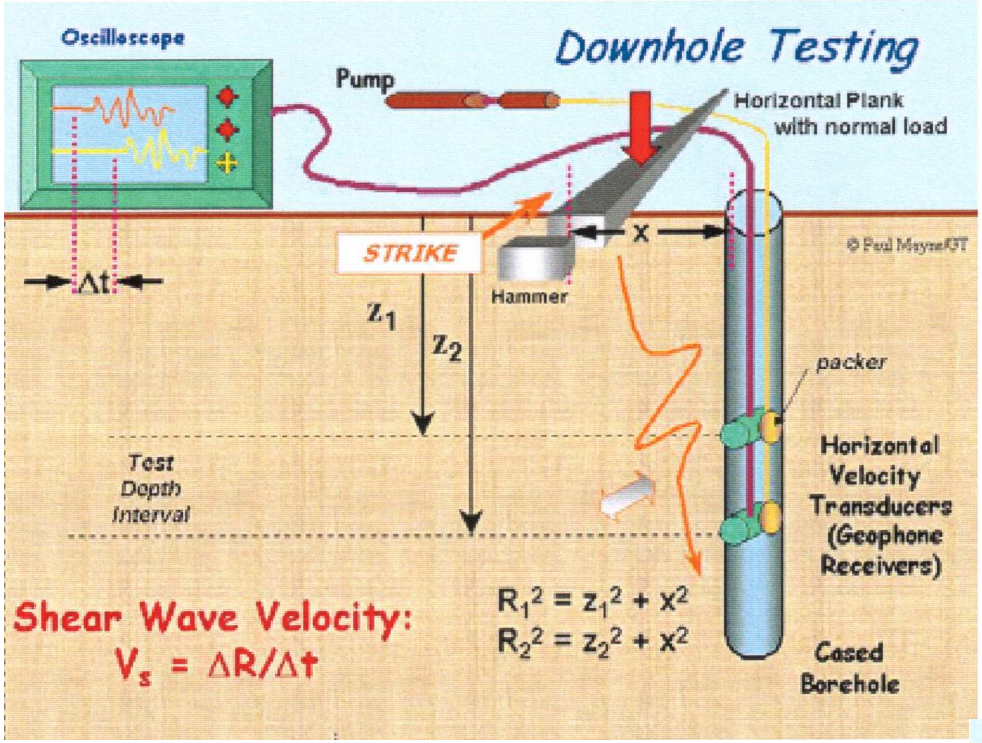
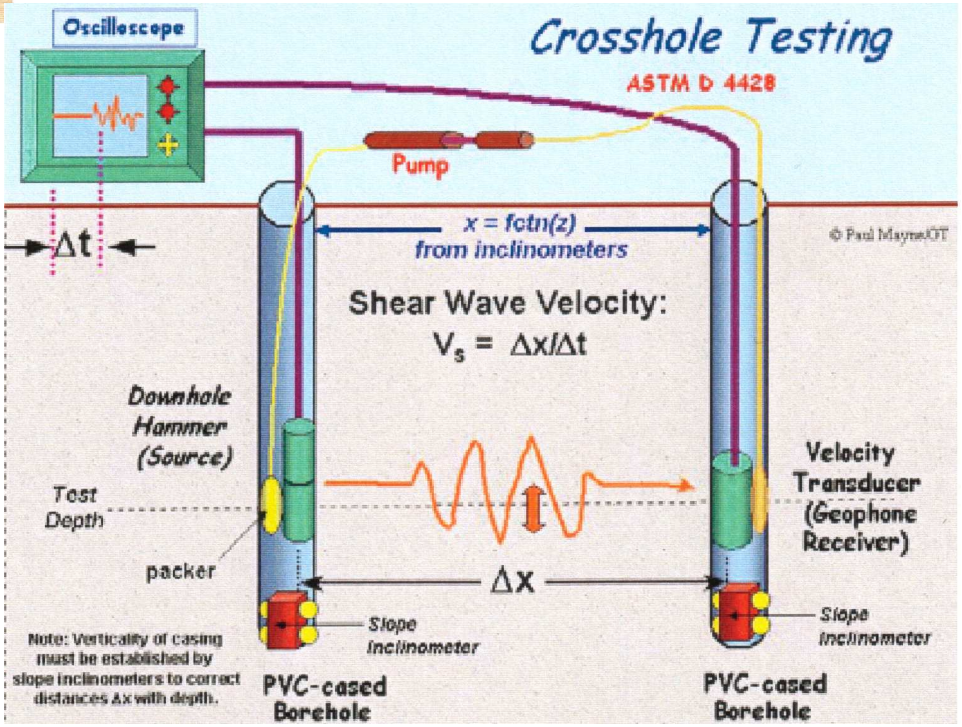


Vertical Seismic Shear Wave Profiling (VSSP)

Crosshole Shear Wave Testing (CHST)



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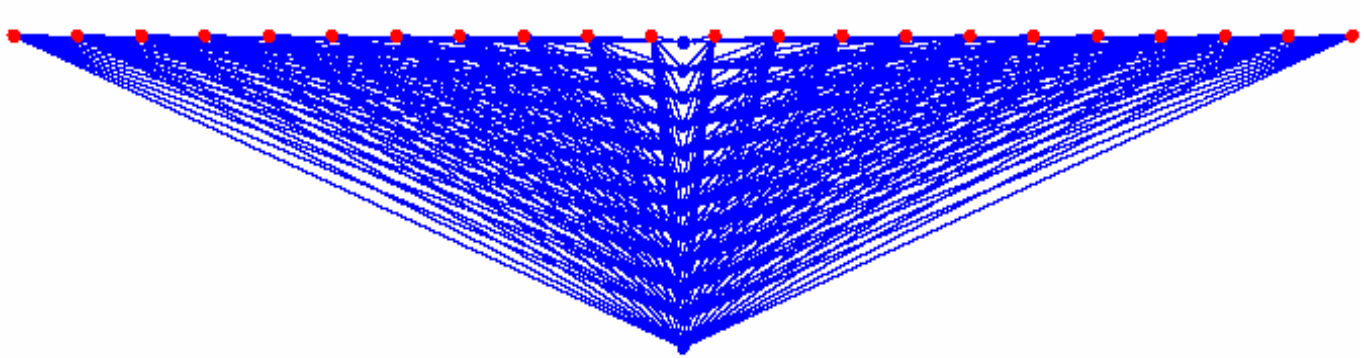
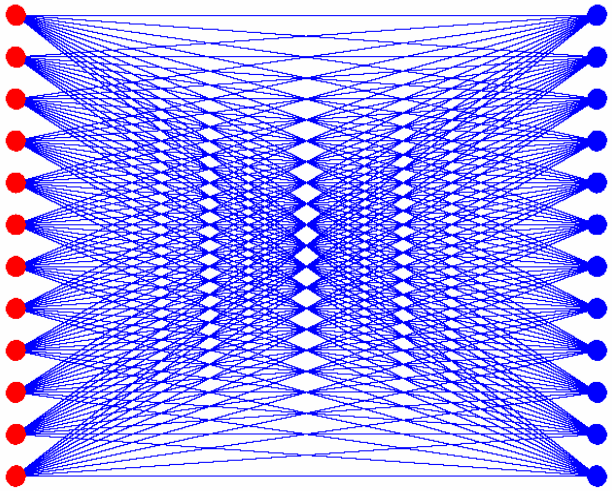
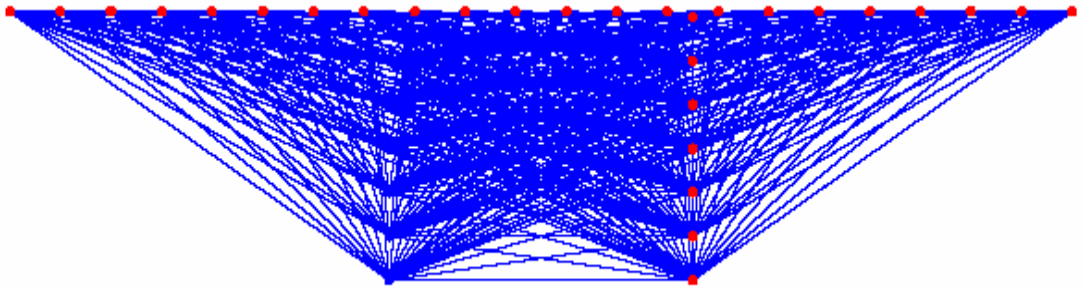
SUBS only



Crosshole only



SUBS + Crosshole



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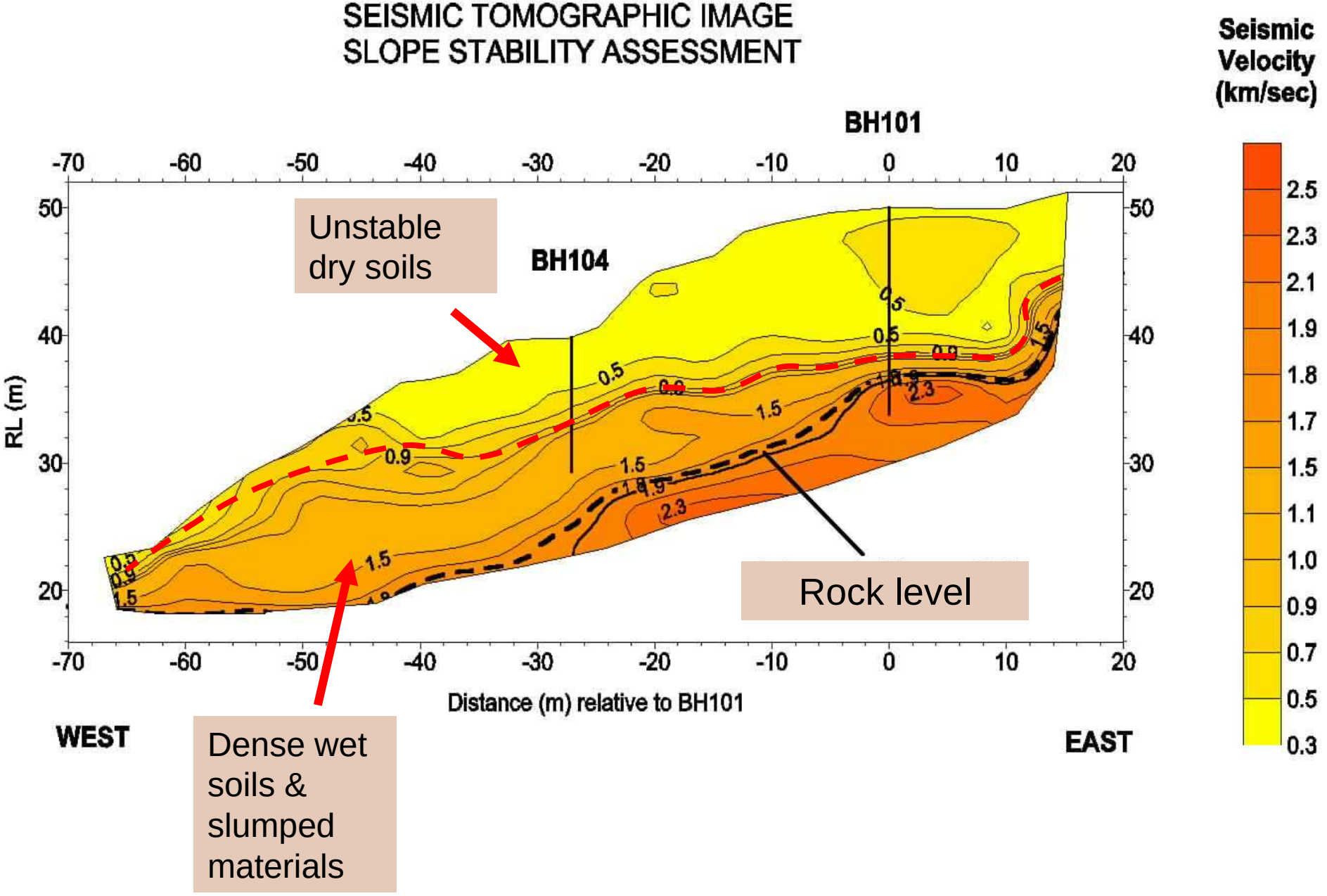
SEISMIC TOMOGRAPHIC IMAGE
SLOPE STABILITY ASSESSMENT



Coffey Partners International Pty Ltd

Consulting Engineers, Managers, and Scientists
- Environment - Geotechnics - Mining - Water Resources

A.C.N. 033 692 019

Benefits of Geophysics to Dams Projects

- Reduced “Ground Risk”
- Reduced “Ground Knowledge” cost
- Increased innovative engineering opportunity
- Faster delivery than traditional methods

coffey geotechnics
SPECIALISTS MANAGING THE EARTH