INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS

Australian National Chapter

NSW Branch

2009 Seminar Series

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Australian Government

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Australian Nuclear Science and Technology Organisation

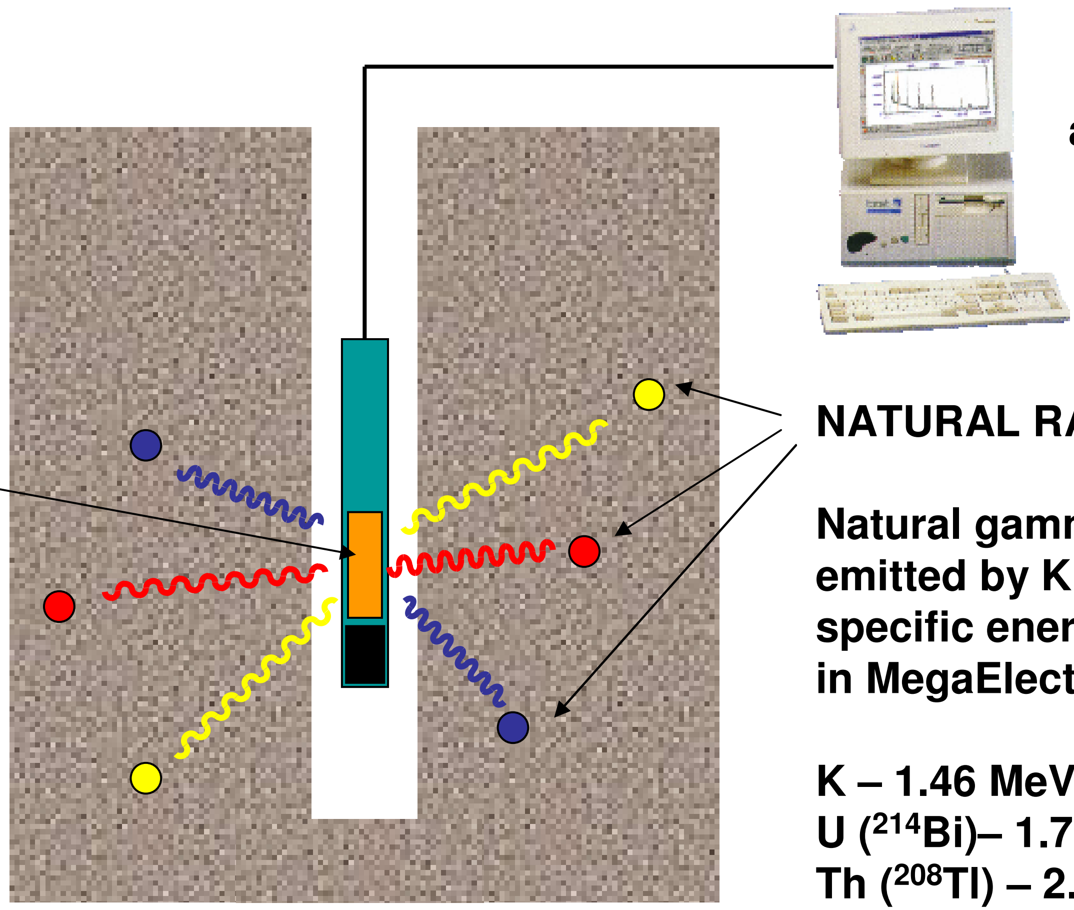
Neutron Activation Analysis applied to measuring borehole hydraulic conductivity and soil composition (+ Carbon)

Chris Waring

Overview

- borehole geophysical gamma logging
- using PGNA logging for hydraulic conductivity
- underlying nuclear physics
- advances in technology
- soil compositional analysis, + Carbon

Natural Gamma Logging (passive)
Borehole configuration and measurement



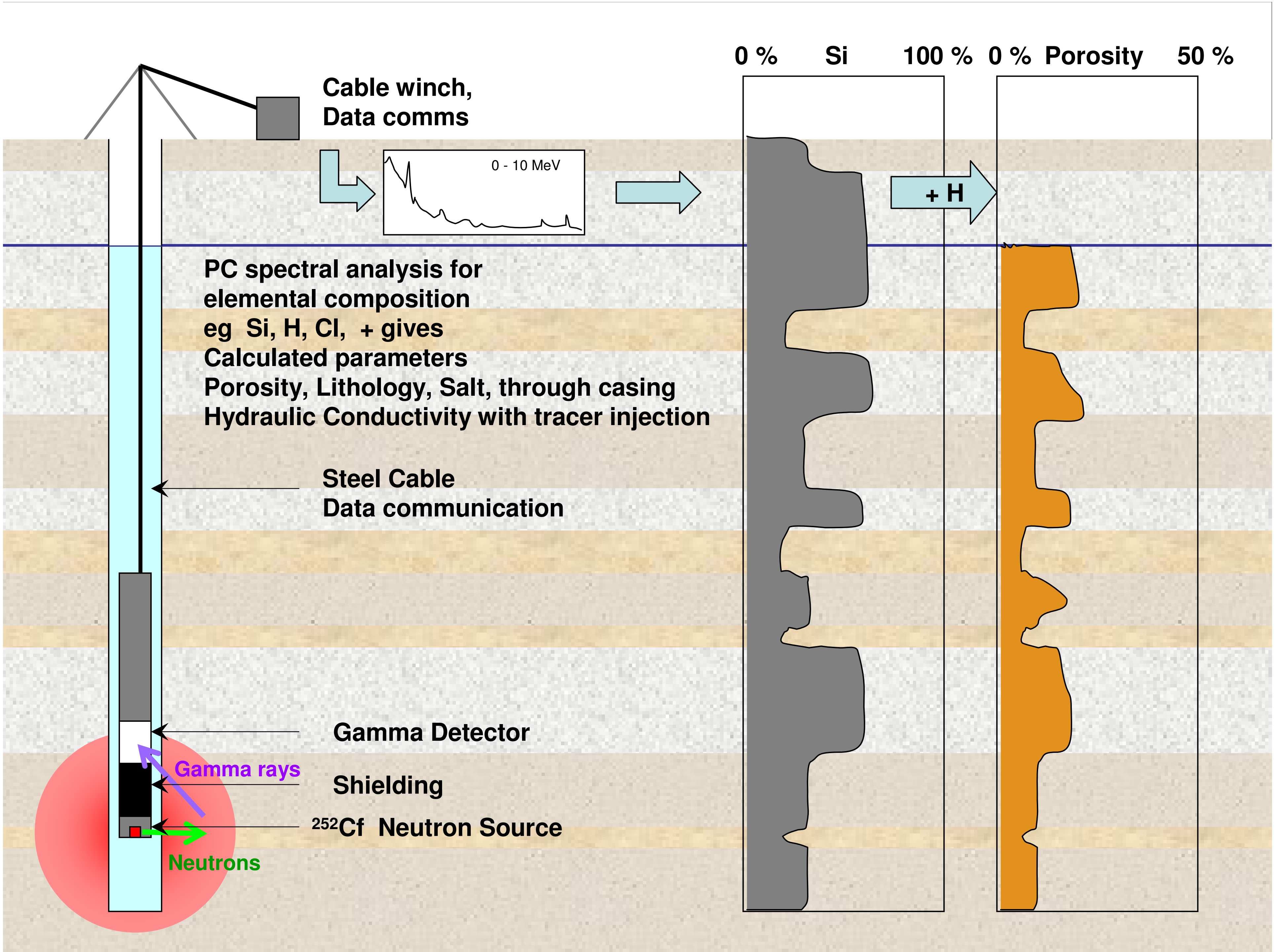
Data analysis

Borehole Probe (contains detector and electronics)

NATURAL RADIOACTIVITY

Natural gamma radiation is emitted by K, U and Th of specific energy and measured in MegaElectronvolts (MeV)

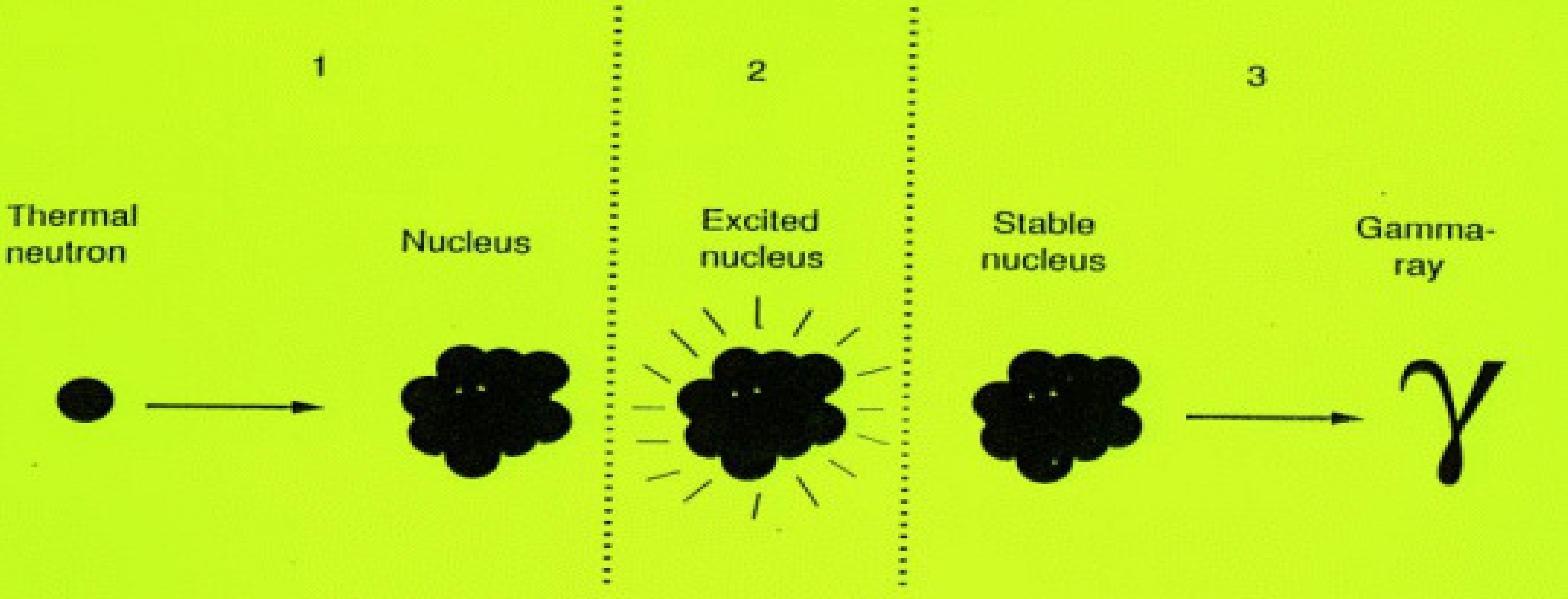
K – 1.46 MeV
U (^{214}Bi)– 1.77 MeV
Th (^{208}Tl) – 2.61 MeV


0 %
Si
100 %
0 %
Porosity
50 %
Cable winch,
Data comms
0 - 10 MeV
+ H
PC spectral analysis for
elemental composition
eg Si, H, Cl, + gives
Calculated parameters
Porosity, Lithology, Salt, through casing
Hydraulic Conductivity with tracer injection
Steel Cable
Data communication
Gamma Detector
Gamma rays
Shielding
252Cf Neutron Source
Neutrons

Prompt Gamma Neutron Activation Technique

The intensity of a given response is directly proportional to:

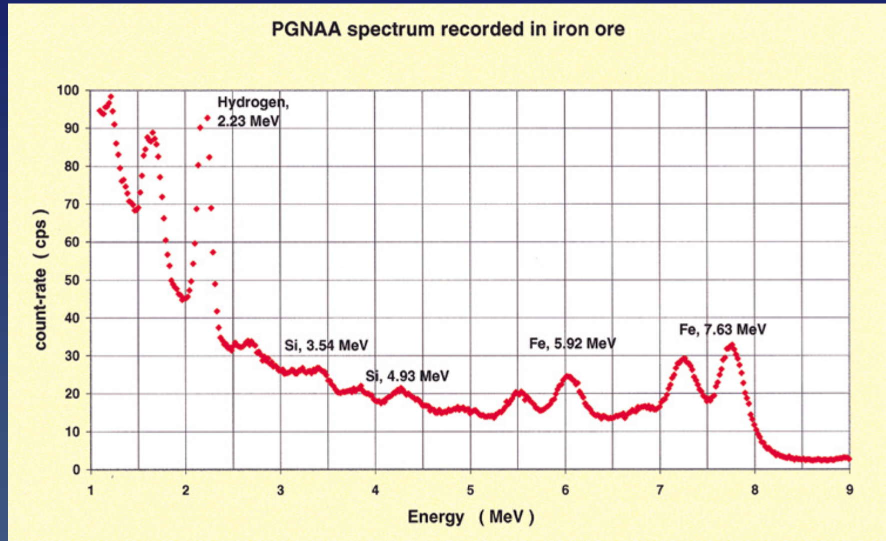
- **the abundance of that element,**
- **the thermal neutron flux,**
- **the thermal neutron capture cross section.**



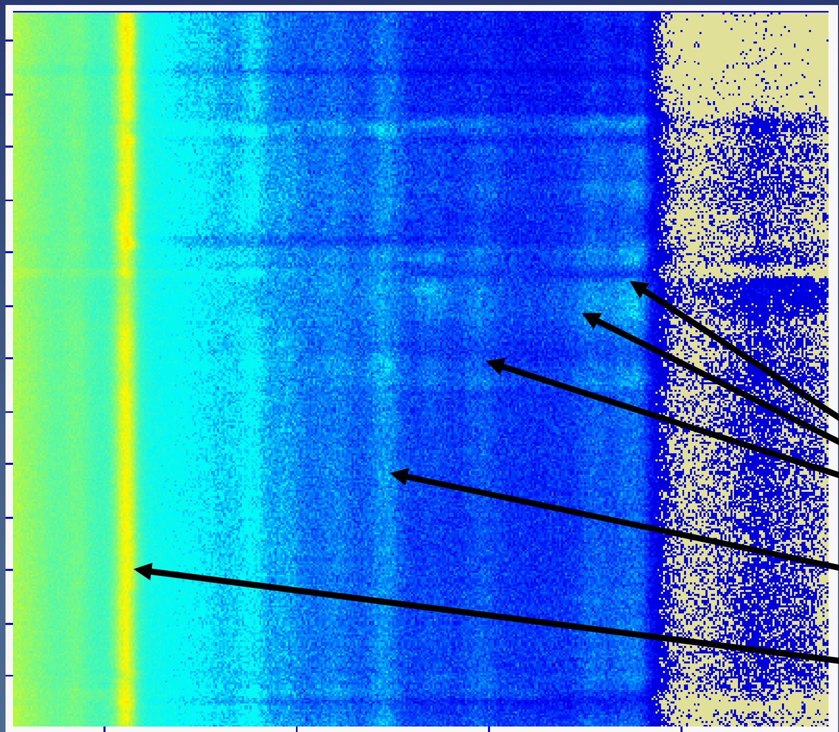
PGNAA RESPONSE FOR SELECTED ELEMENTS

Element (atomic mass)	Thermal neutron capture cross-section (barns)	Major gamma-rays (MeV)	Gamma-ray intensity (per 100 neutron radiative captures)
Hydrogen (1.0079)	0.3326	2.223	100
Carbon (12.0107)	0.00337	1.26 3.68 4.94	29.5 32.1 67.6
Iron (55.85)	2.55	5.92 6.02 7.63 7.65	9 9 24.1 28.5
Silicon (28.09)	0.16	1.16 2.09 3.54 4.93 6.38	19.9 21.5 68.0 62.7 12.4
Aluminium (26.98)	0.23	7.72	27.4
Calcium (40.08)	0.43	1.94 4.42 6.42	72.6 15.0 38.9
Sulphur (32.06)	3.32	0.84 2.38 2.93 3.22 5.42	75.6 44.5 22.3 27.1 59.1

PROMPT GAMMA NEUTRON ACTIVATION ANALYSIS (PGNAA)



Hole Depth



Channel (Energy)

- Coloured to display count rate (yellow = high, brown = low)
- Fe response
- Si response
- H response (used for stabilisation)

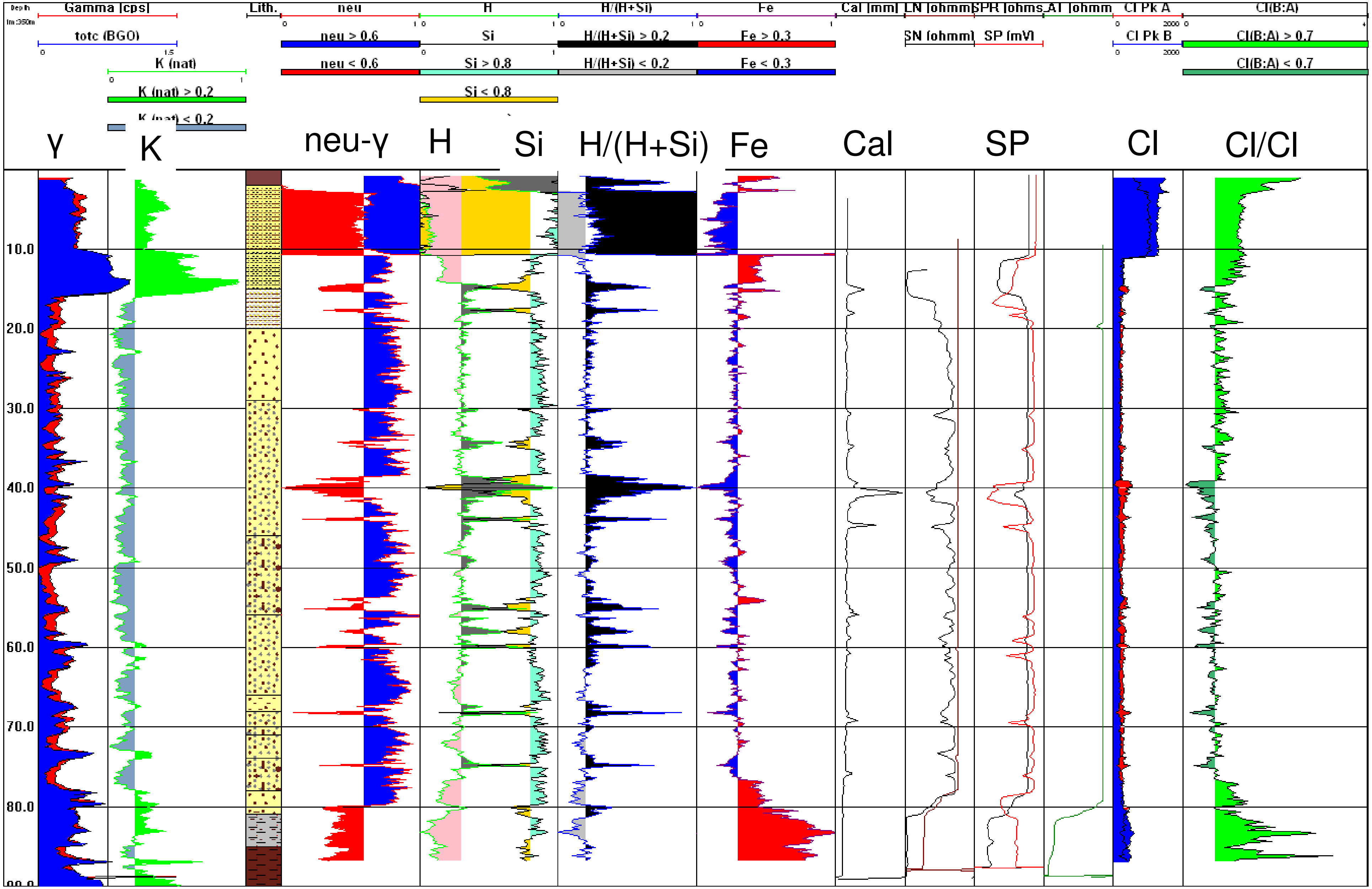
Mining Geoscience

CSIRO

Ansto
Australian Nuclear Science and Technology Organisation

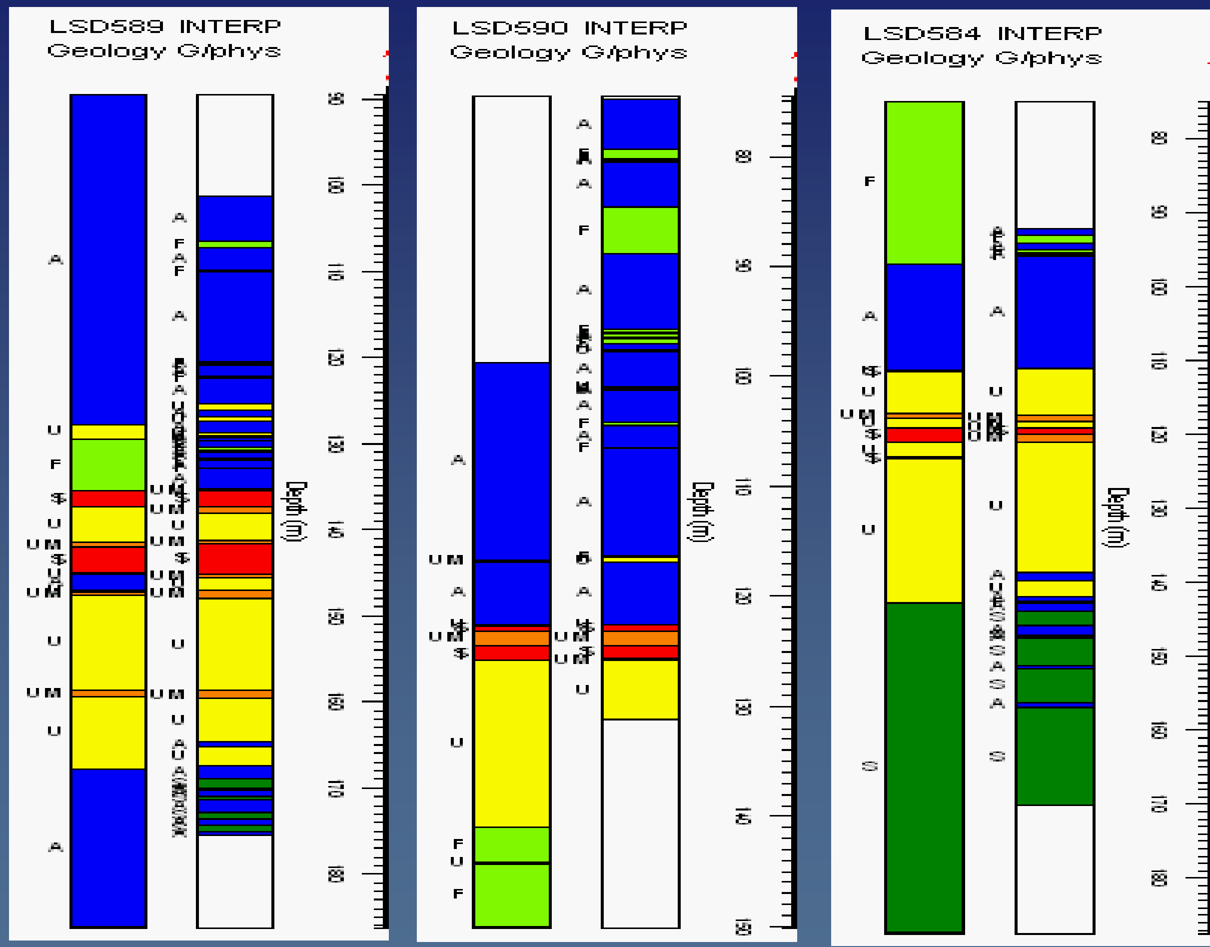
Prompt Gamma Neutron Activation Analysis
Natural Spectral Gamma: Total Counts, K-40

Bore Name: 2b
Log Date: 10/08/2005
Logged by: Chris Waring, Stuart Hankin
Tool: BGO



Automated lithology & mineralogy

Plots at right show three examples where PGNAA has been used to estimate lithology – LHS plot is logged geology and RHS plot is geology derived from geophysics.



Blue – Metavolcanics

Greens – Metasediments

Yellow – Ultramafic

Orange – Disseminated sulphide in u/mafic

Red – Massive sulphide

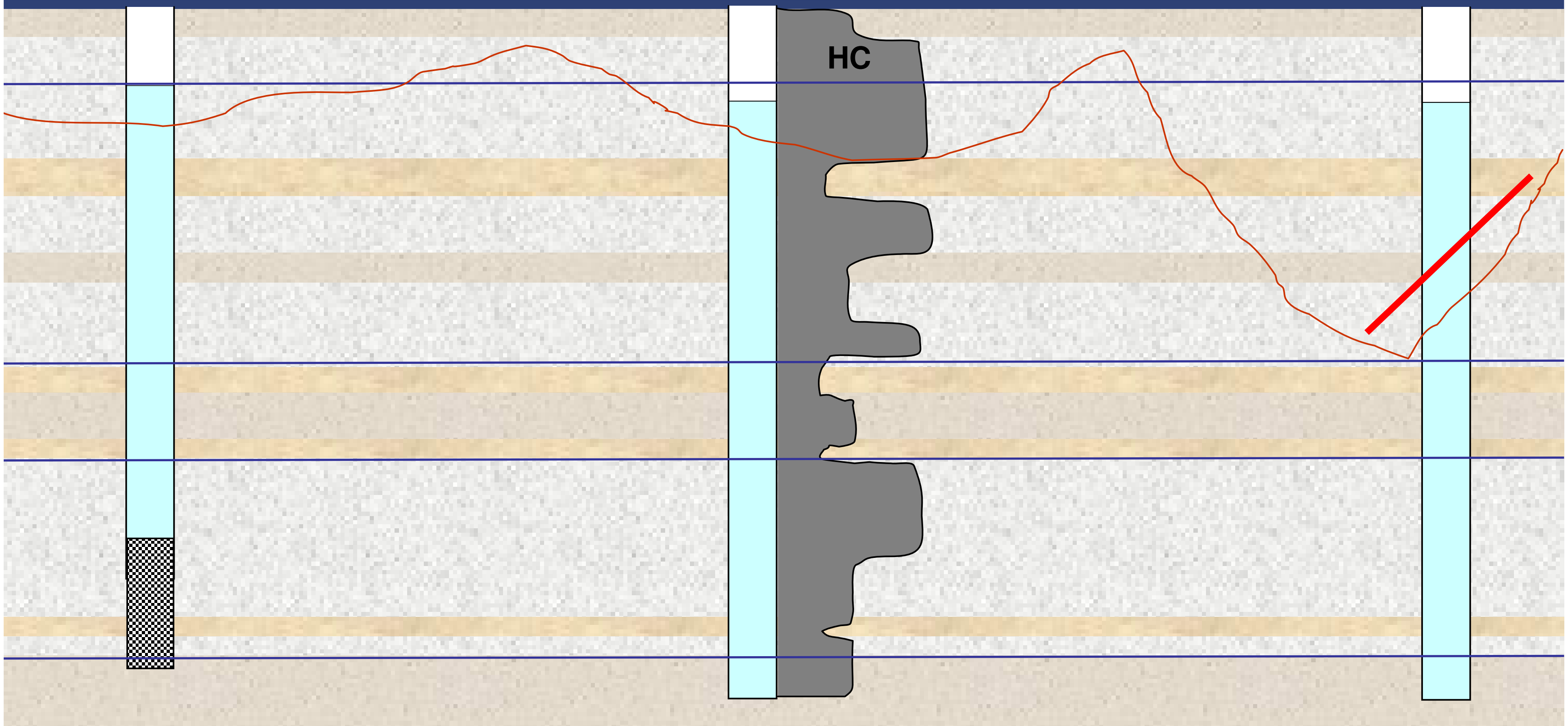
Mining Geoscience

CSIRO

Hydraulic Conductivity

Definition of full range of HC, enables stratigraphic correlation wrt HC

Better choice of groundwater flow model averaged stratigraphy based on measured HC values



Hydraulic Conductivity Calculation

•Gamma spectral analysis allows measurement of tracer at different gamma energies ie Cl at 1.95 and 6.1 MeV

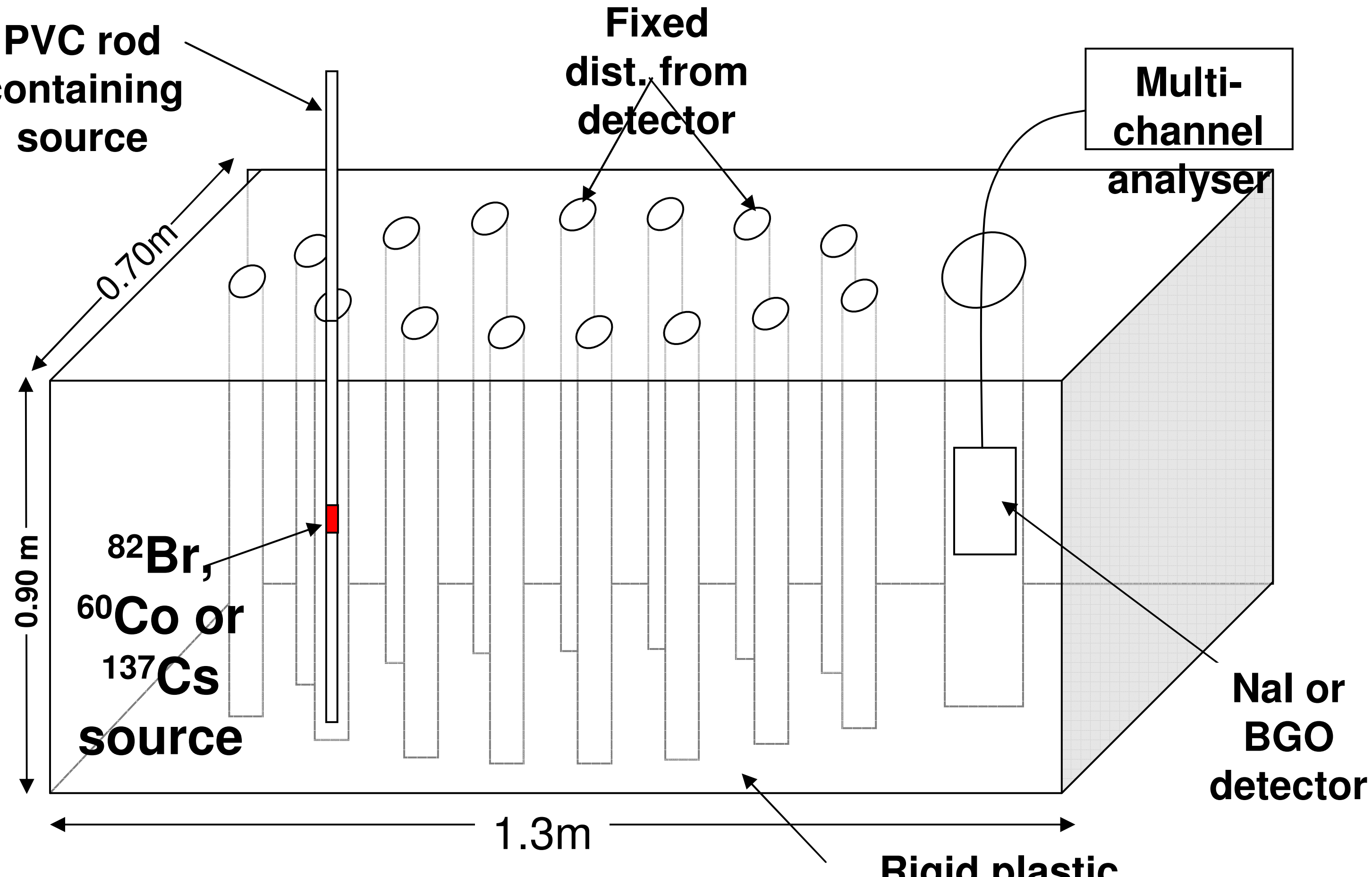
•Activated Gamma emissions at low energies are attenuated more by transmission through rock & water than high energies

•Hence changes in the ratio of the tracer emissions is a function of the distance the tracer has moved away from the injection bore ie Cl 1.95 / 6.1 MeV

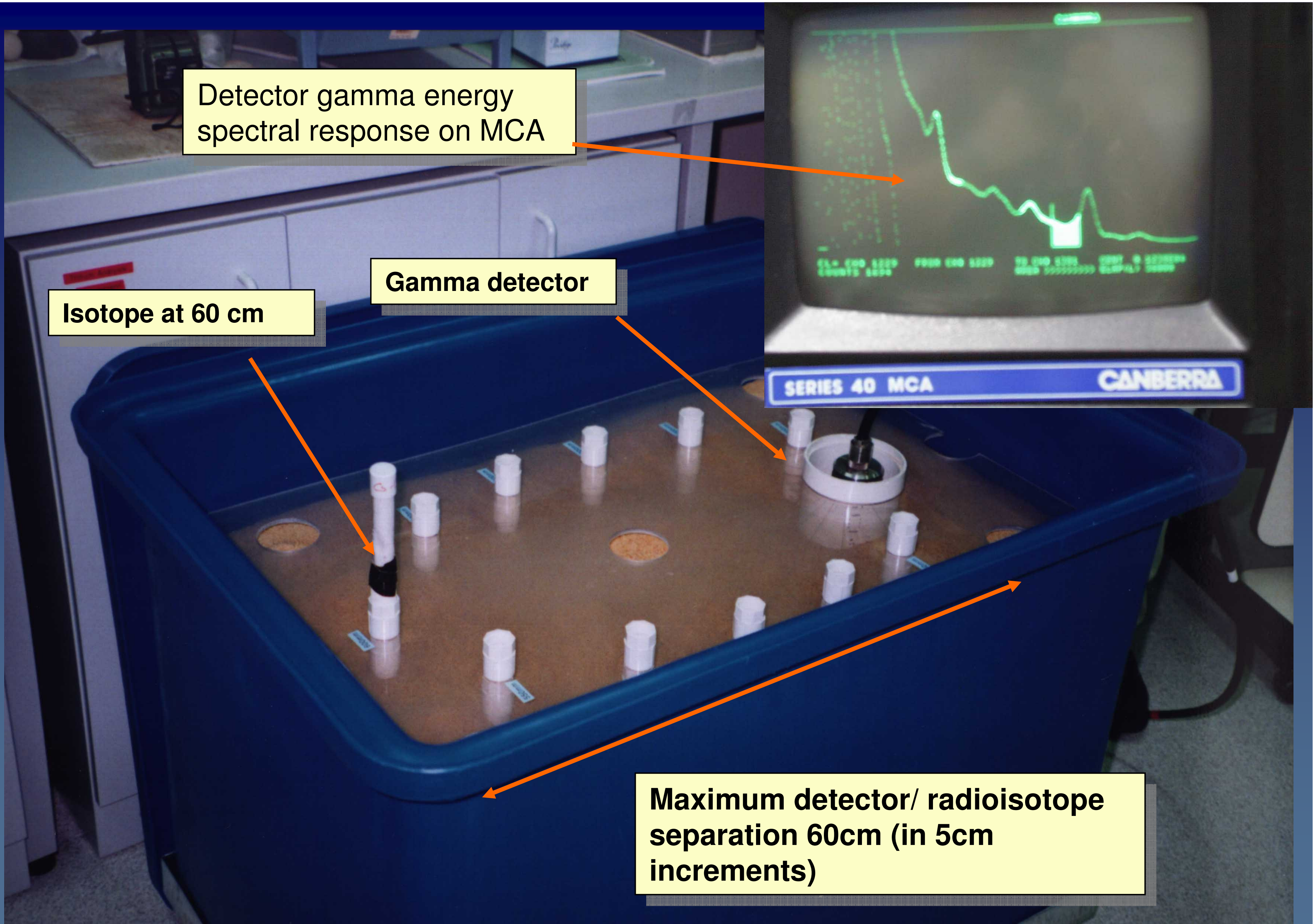
•This distance function is established by experiments

Differential attenuation of gamma energy studies: detector at known, fixed distance from source

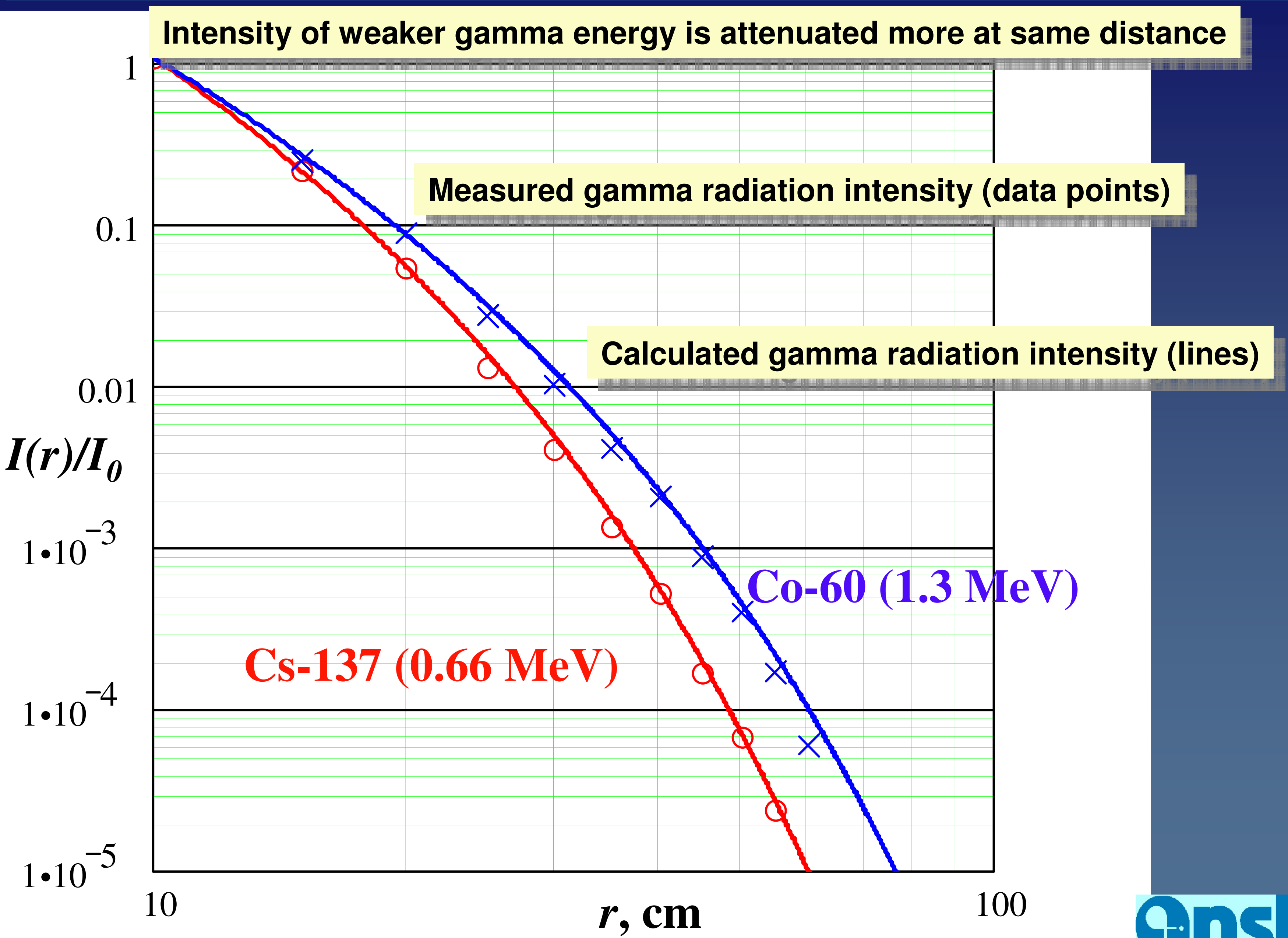
Laboratory studies to provide mathematical algorithms to convert gamma spectral data to effective distance moved, using long and short half-life radiotracers with suitable energies



Provides attenuation coefficient data for various gamma energies, and by differential; a solution for the mean distance moved by a tracer with 2 energies

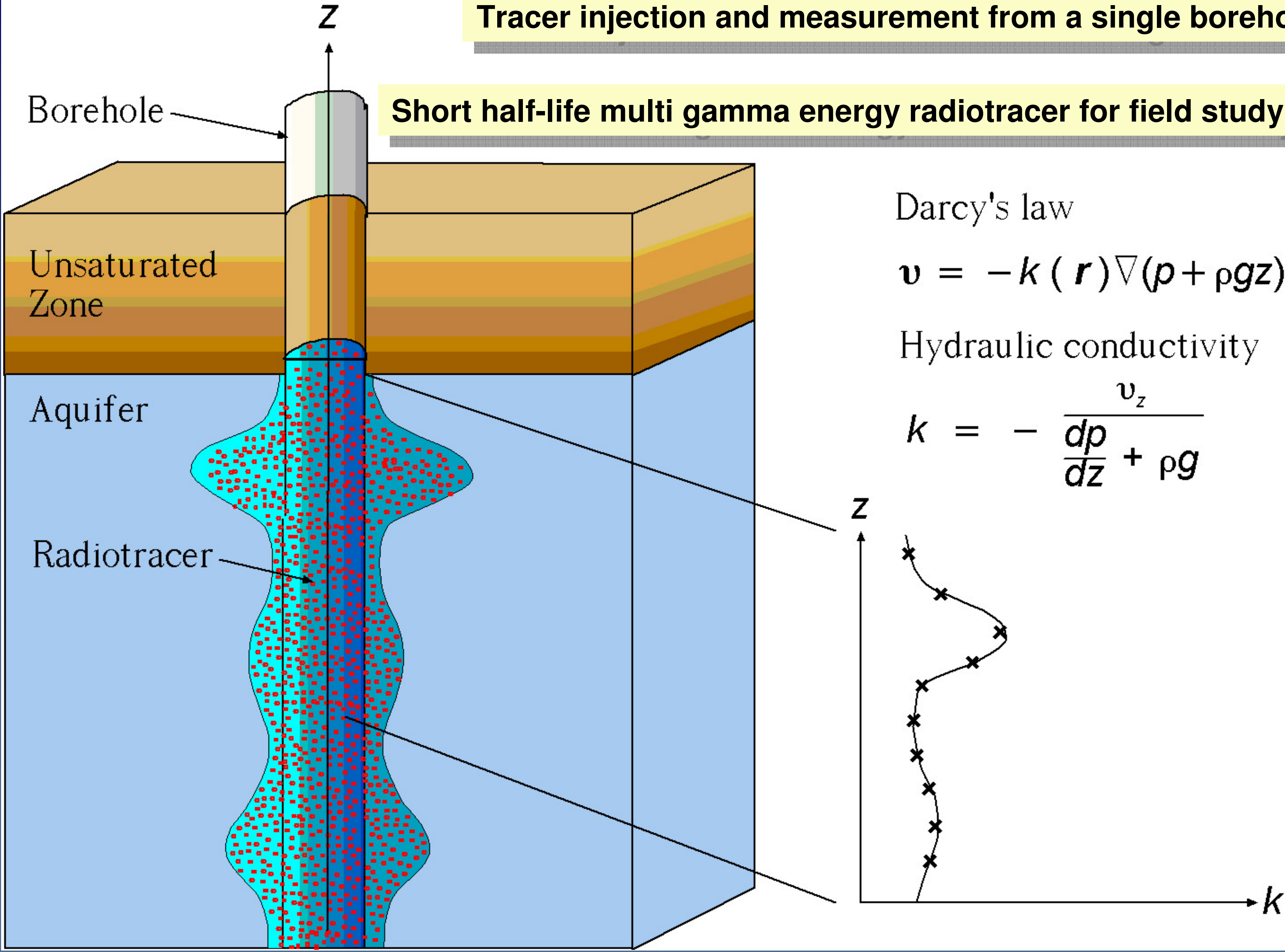

Detector gamma energy spectral response on MCA
Gamma detector
Isotope at 60 cm
Maximum detector/ radioisotope separation 60cm (in 5cm increments)
SERIES 40 MCA
CANBERRA

Calculated Gamma-Radiation Decay in Saturated Sand



Tracer injection and measurement from a single borehole

Short half-life multi gamma energy radiotracer for field study

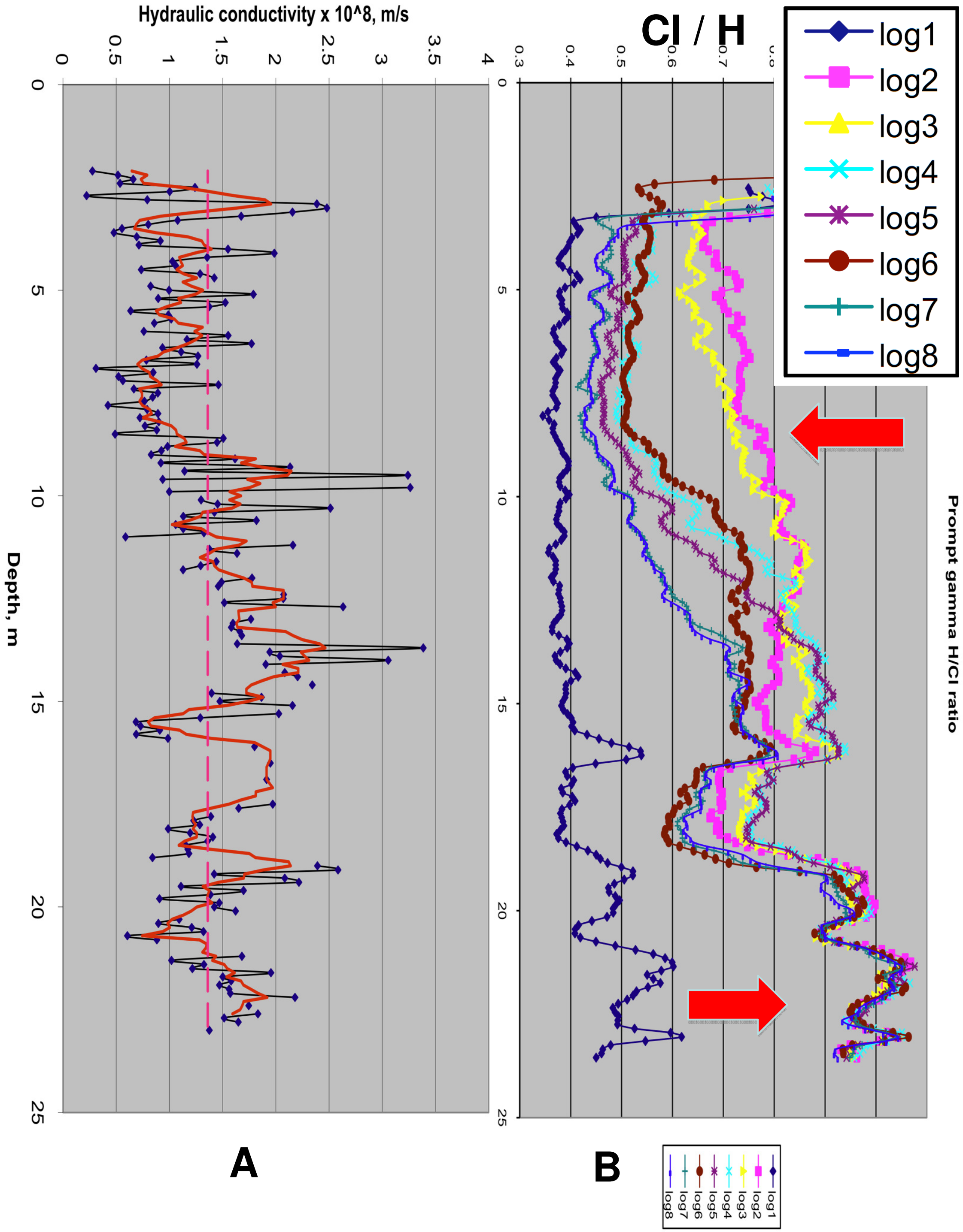


Darcy's law

$$\boldsymbol{\upsilon} = -k(\boldsymbol{r})\nabla(p + \rho g z)$$

Hydraulic conductivity

$$k = -\frac{\upsilon_z}{\frac{dp}{dz} + \rho g}$$



A

Hydraulic conductivity calculated from distance NaCl tracer moves beyond borehole

B

Sequential PGNAA log of tracer movement

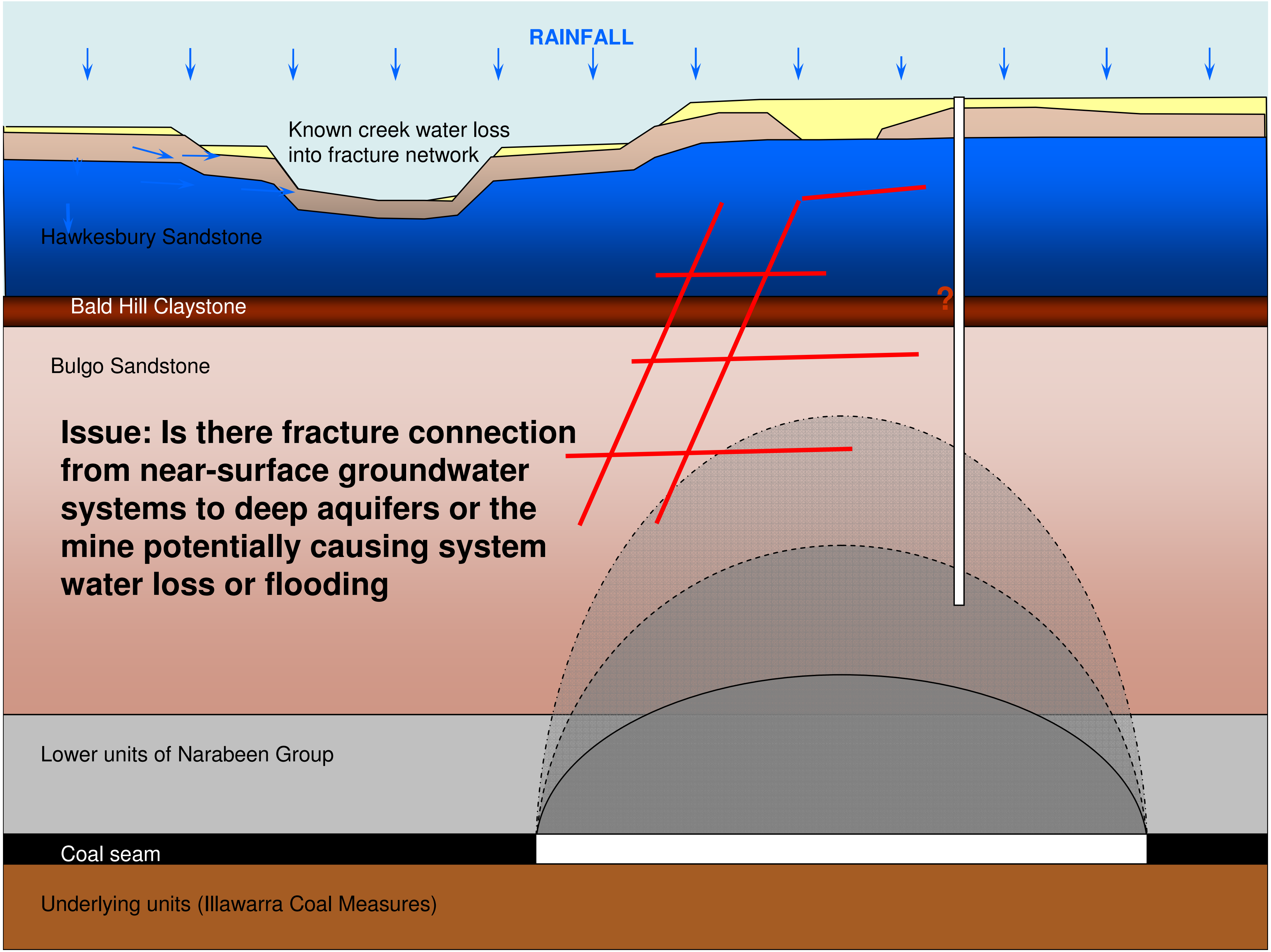
Log 1 = no tracer

Log 2 = pink

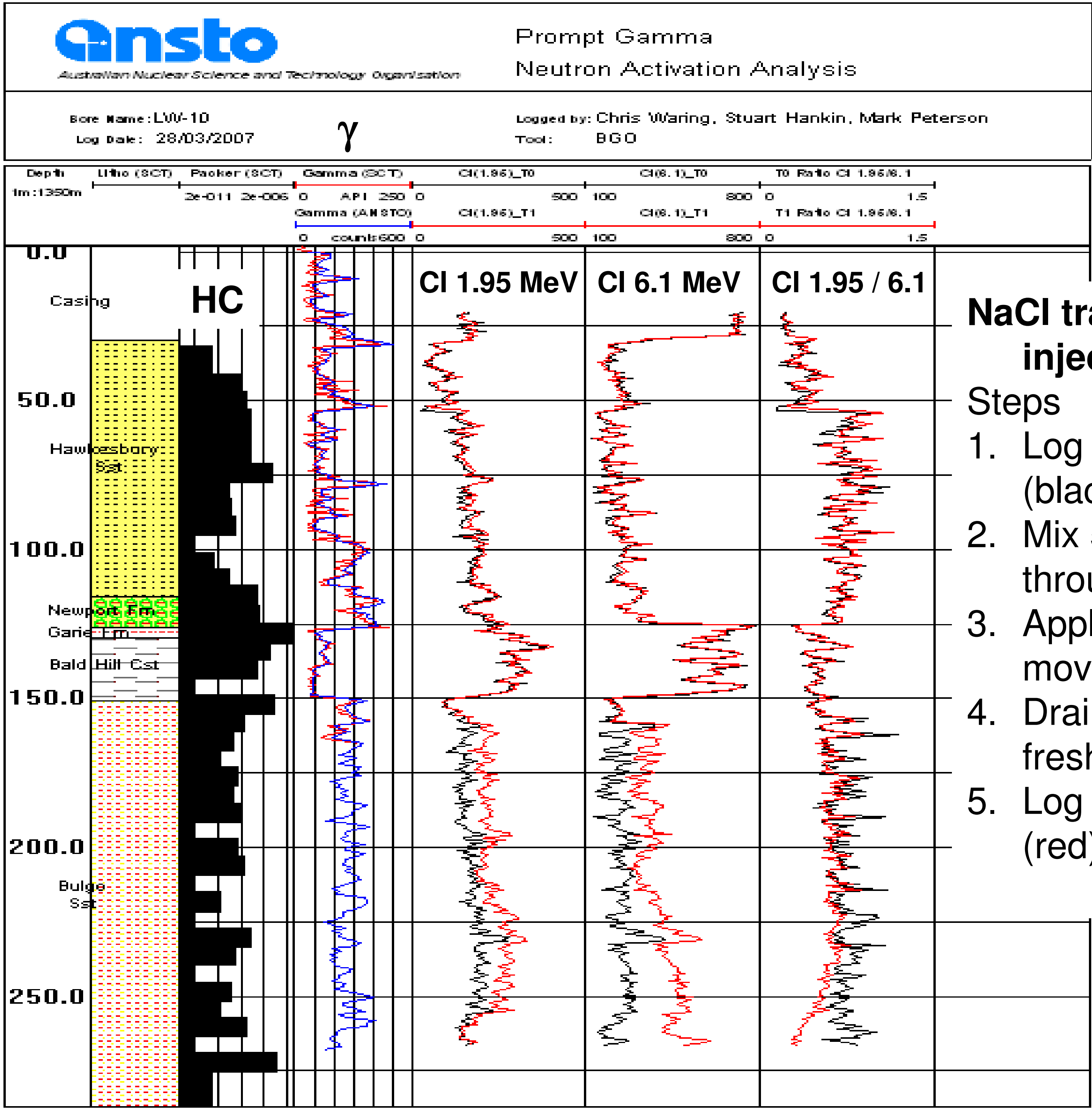
Apparently less tracer in top of borehole with time

Dense NaCl tracer moving away from borehole at the base

Lowers SWL, causes flow into borehole at top



RAINFALL
Known creek water loss
into fracture network
Hawkesbury Sandstone
Bald Hill Claystone
?
Bulgo Sandstone
Issue: Is there fracture connection
from near-surface groundwater
systems to deep aquifers or the
mine potentially causing system
water loss or flooding
Lower units of Narabeen Group
Coal seam
Underlying units (Illawarra Coal Measures)



Borehole into goaf leaking at base

NaCl tracer injection & migration

Steps

1. Log bore with PGNAA (black)
2. Mix 5% NaCl tracer through bore
3. Apply P (head) to tracer to move tracer into rock
4. Drain 2x bore volume freshwater from top of bore
5. Log bore with PGNAA (red)

Summary hydraulic parameter logging

Porosity and hydraulic conductivity

- PGNAA borehole logging is capable of detecting subtle variations in relative porosity.
- A new method for measuring high spatial resolution increments of hydraulic conductivity in a borehole is described and demonstrated in practice.

Vertical hydraulic connection

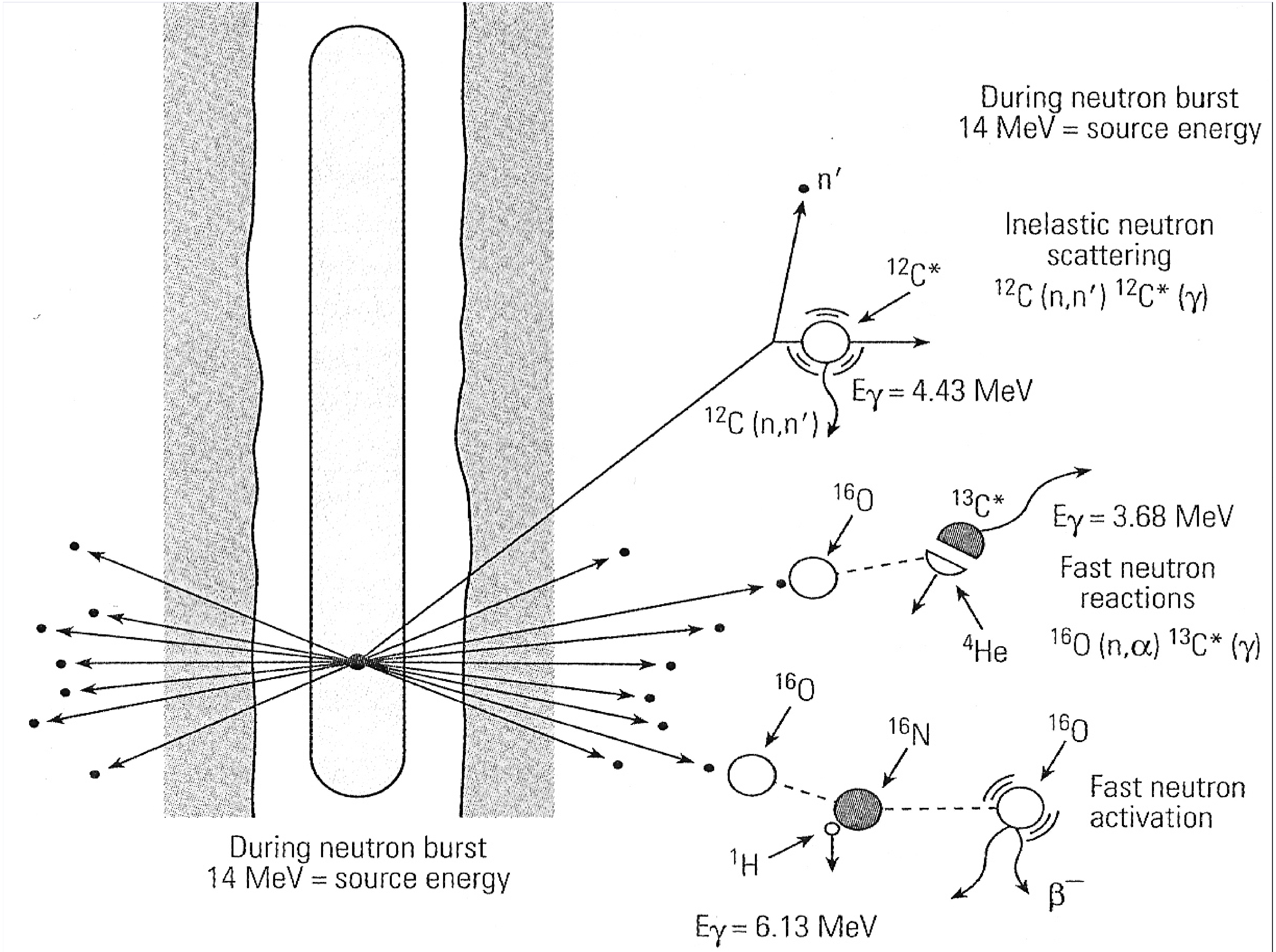
- Sequential tracer injection and PGNAA logging can identify induced advective circulation cells in sandstone adjacent to a borehole.
- Establishing vertical hydraulic connection can be very useful in assessing the impact of longwall mining on groundwater hydrology.

Nuclear Glossary

- Slow neutron interaction
- Radiative capture; when a slow or thermalised neutron (<1MeV) activates a nucleus and emits multiple gammas at fixed energies
- NAA Neutron Activation Analysis usually applied to reactor based delayed gamma measurements
- PGNAA Prompt Gamma Neutron Activation Analysis very rapid gamma emission
- DGNAA Delayed Gamma Neutron Activation Analysis delayed gamma emission (variable ½ life)

Fast neutron interaction

- INS Inelastic Neutron Scattering fast neutron (> 4 MeV) interaction with gamma
- Elastic neutron scattering neutron is slowed (heat) without gamma emission



During neutron burst
14 MeV = source energy
n′
Inelastic neutron scattering
^{12}C*
^{12}C (n,n′) ^{12}C* (γ)
Eγ = 4.43 MeV
^{12}C (n,n′)
^{16}O
^{13}C*
Eγ = 3.68 MeV
Fast neutron reactions
^{4}He
^{16}O (n,α) ^{13}C* (γ)
^{16}O
^{16}N
^{16}O
Fast neutron activation
^{1}H
β⁻
Eγ = 6.13 MeV
During neutron burst
14 MeV = source energy

Neutron Generators

- Use either DD, DT, or TT reactions (or all 3)
  - $_1H^2 + _1H^2 \rightarrow _2He^3 + _0n^1$ (DD 2.5MeV neutron)
  - $_1H^2 + _1H^3 \rightarrow _2He^4 + _0n^1$ (DT 14.1 MeV neutron)
  - $_1H^3 + _1H^3 \rightarrow _2He^4 + 2_0n^1$ (TT ~0.5-~10MeV neutrons)
- Techniques
  - Hot Cathode [target device]
  - Cold Cathode (Penning) [target device]
  - Inertial Electrostatic Confinement (IEC) device
  - RF Ion source
- Size Limitations
  - Usually caused by HV supply size ~ 120mm

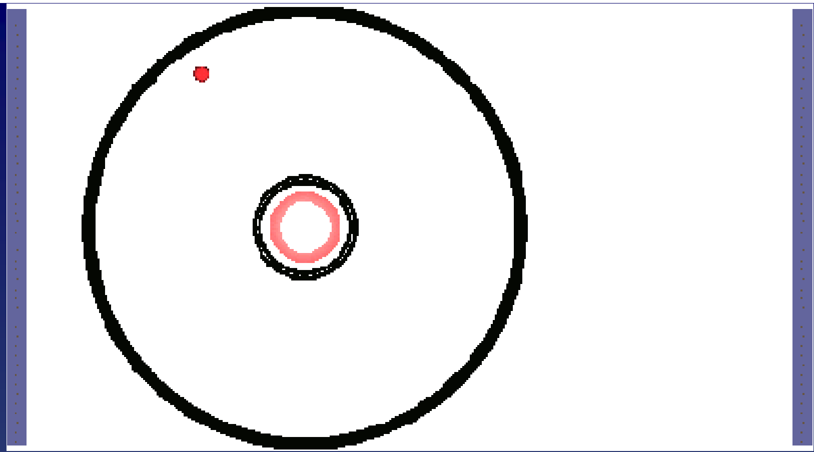
Neutron Generators

- ANSTO selected NSD-Fusion ;

  high flux 10^{10} n/s, long lifetime, low relative cost

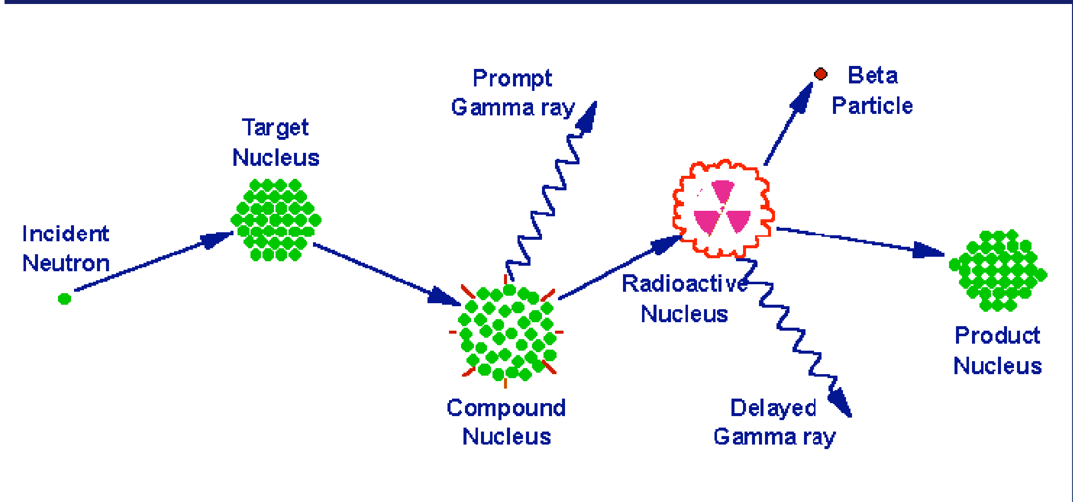
  - BNL uses THERMO neutron generator with relatively low flux $7*10^7$n/s & short lifetime
  - Oil field service companies are restricted to Penning type (THERMO & Sodern) by size

Supplier	Country	Neutron Generator Design	Neutron Flux D-T 14MeV n/s	Lifetime hrs	Cost AUD$ x ,000	Application
VNIIA	Russia	Penning	1.E+07	400	$100	Borehole
THERMO	USA	Penning	7.E+07	600	$100	Borehole
		Penning	5.E+09	600	$350	On-belt
Sodern	France	Penning	1.E+07	2,000	$150	Borehole
		Penning	1.E+08	??	$250	Borehole
		Penning	1.E+09	2,000	$360	On-belt
Adelphi	USA	RF	1.E+08	10,000 ?	$160	On-belt
		RF	1.E+09	10,000 ?	$256	On-belt
		RF	1.E+10	10,000 ?	$512	Lab-Fusion Res
		RF	1.E+11	10,000 ?	??	Lab-Fusion Res
NSD-Fusion	Germany (Aus)	IEC	1.E+08	20,000 +	$120	On-belt
		IEC	1.E+09	20,000 +	$165	On-belt
		IEC	**1.E+10**	**20,000 +**	**$200**	**Lab-Fusion Res**
		IEC	1.E+11	20,000 +	$240	Lab-Fusion Res



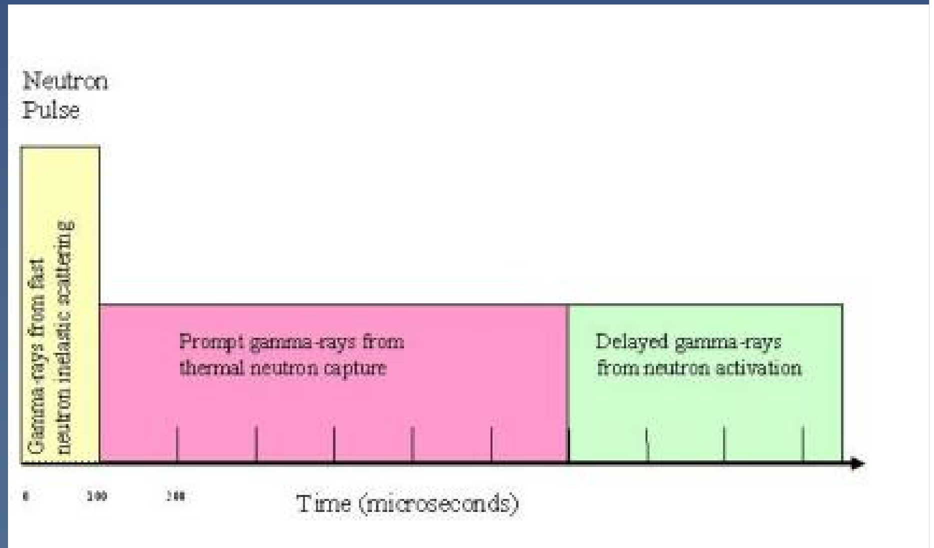
http://www.nsd-fusion.com/

Neutron Generator Activation Physics

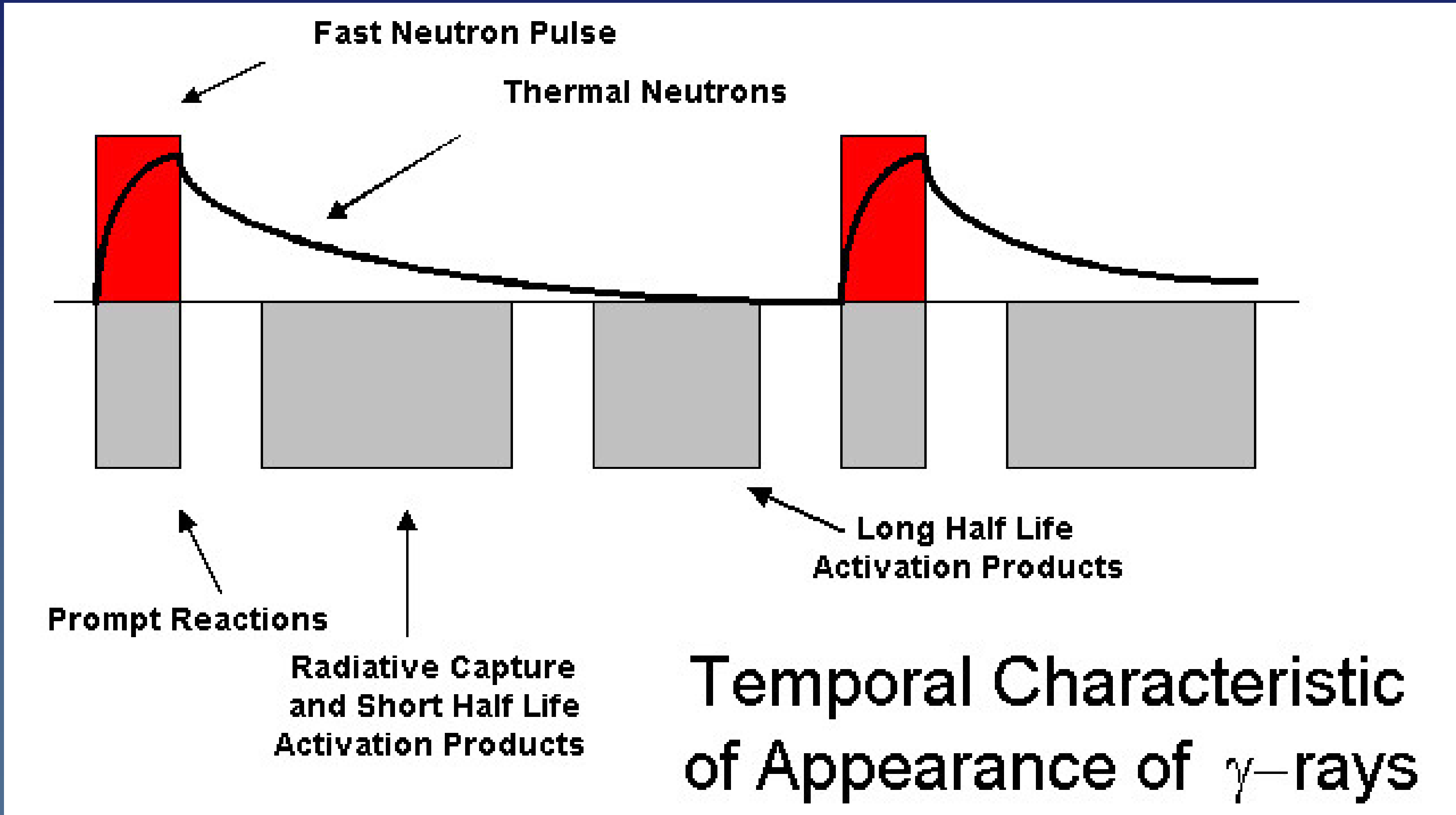


An Overview of Neutron Activation Analysis
by Michael D. Glascock
University of Missouri Research Reactor (MURR)

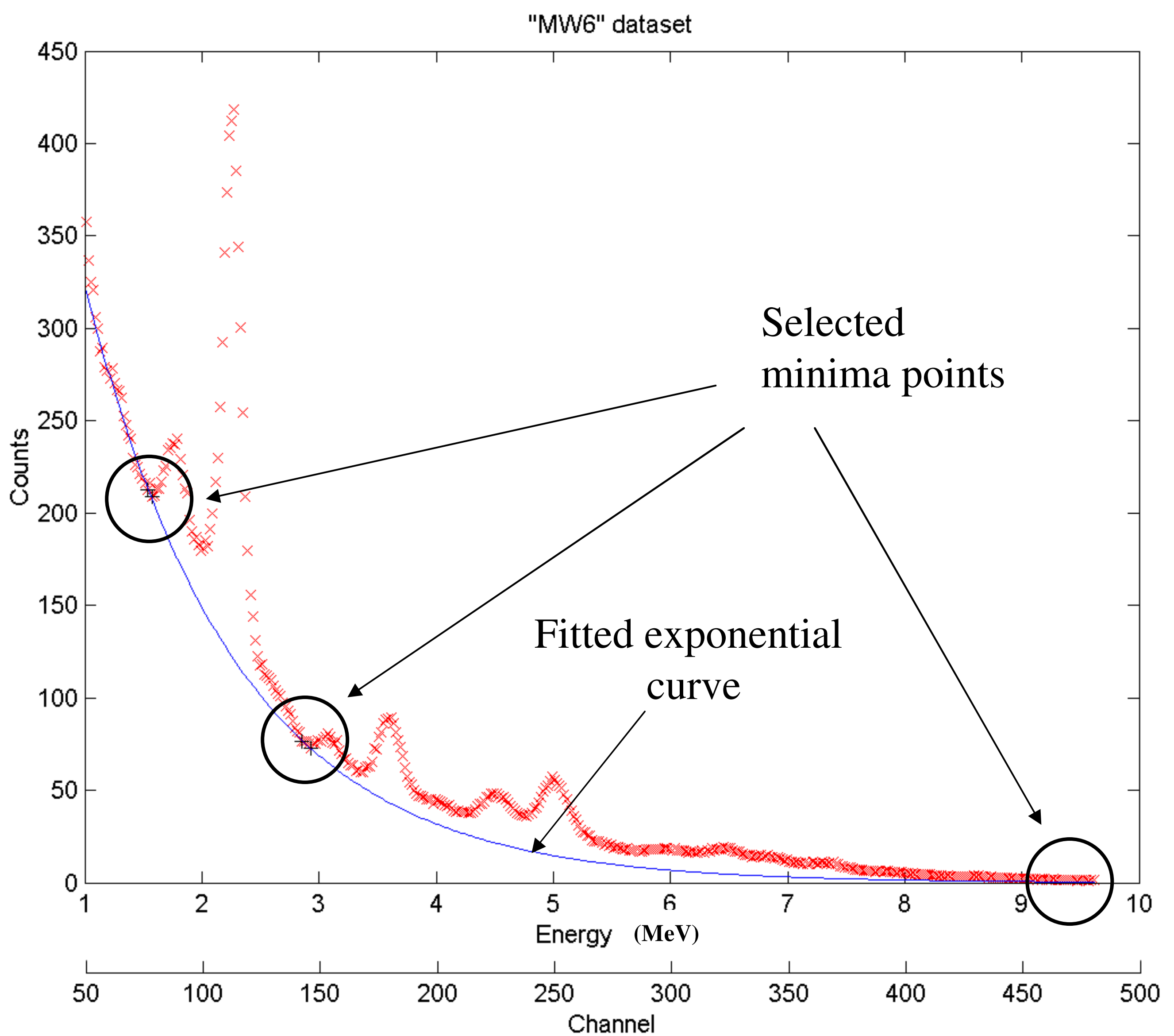
- Inelastic Neutron Scattering Gamma Ray Analysis (INS)
- Prompt Gamma Activation Analysis (PGNAA)
- Delayed Gamma Activation Analysis (DGNAA)
- Activated Neutron Analysis (long timescales)



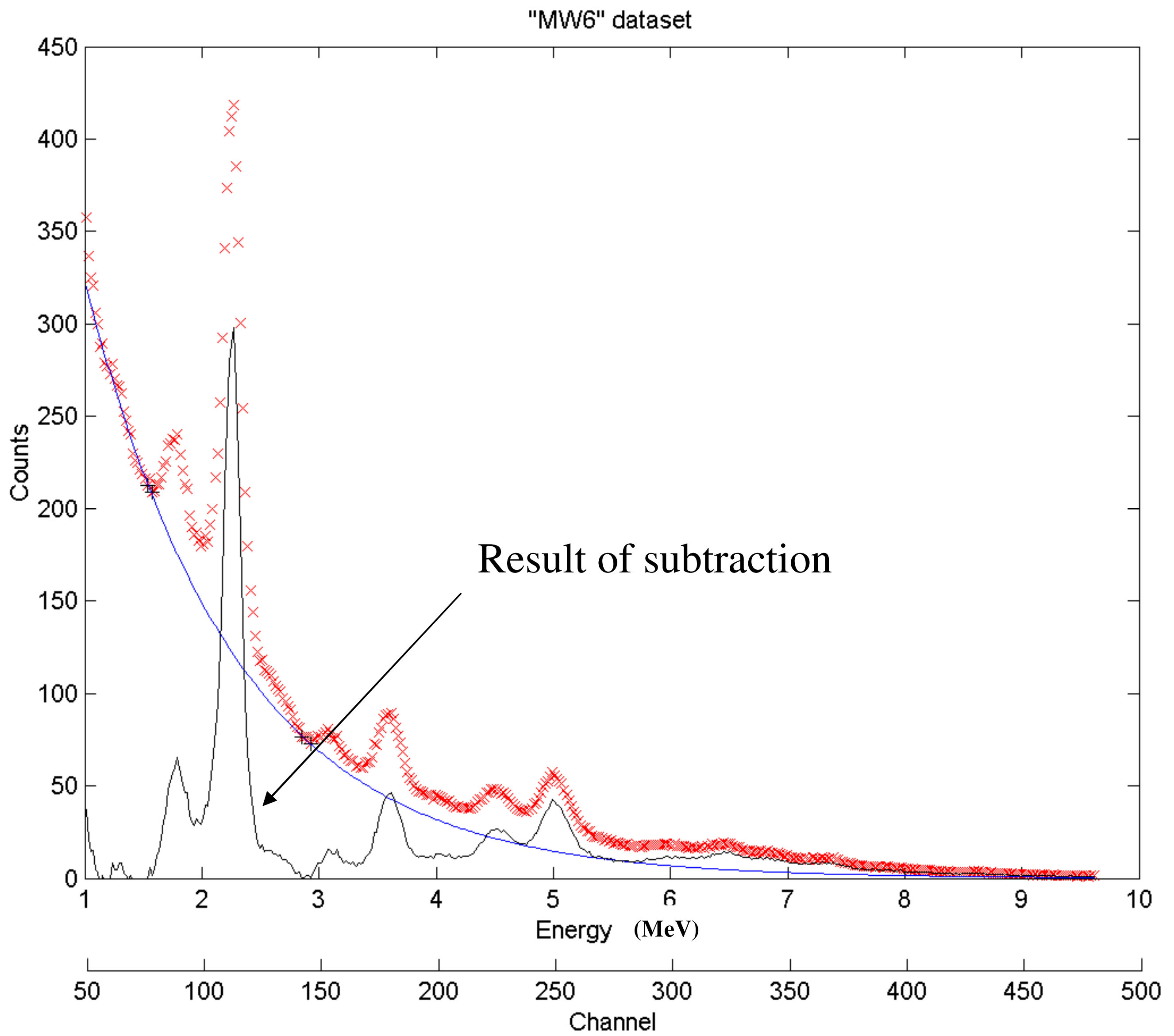
Timing

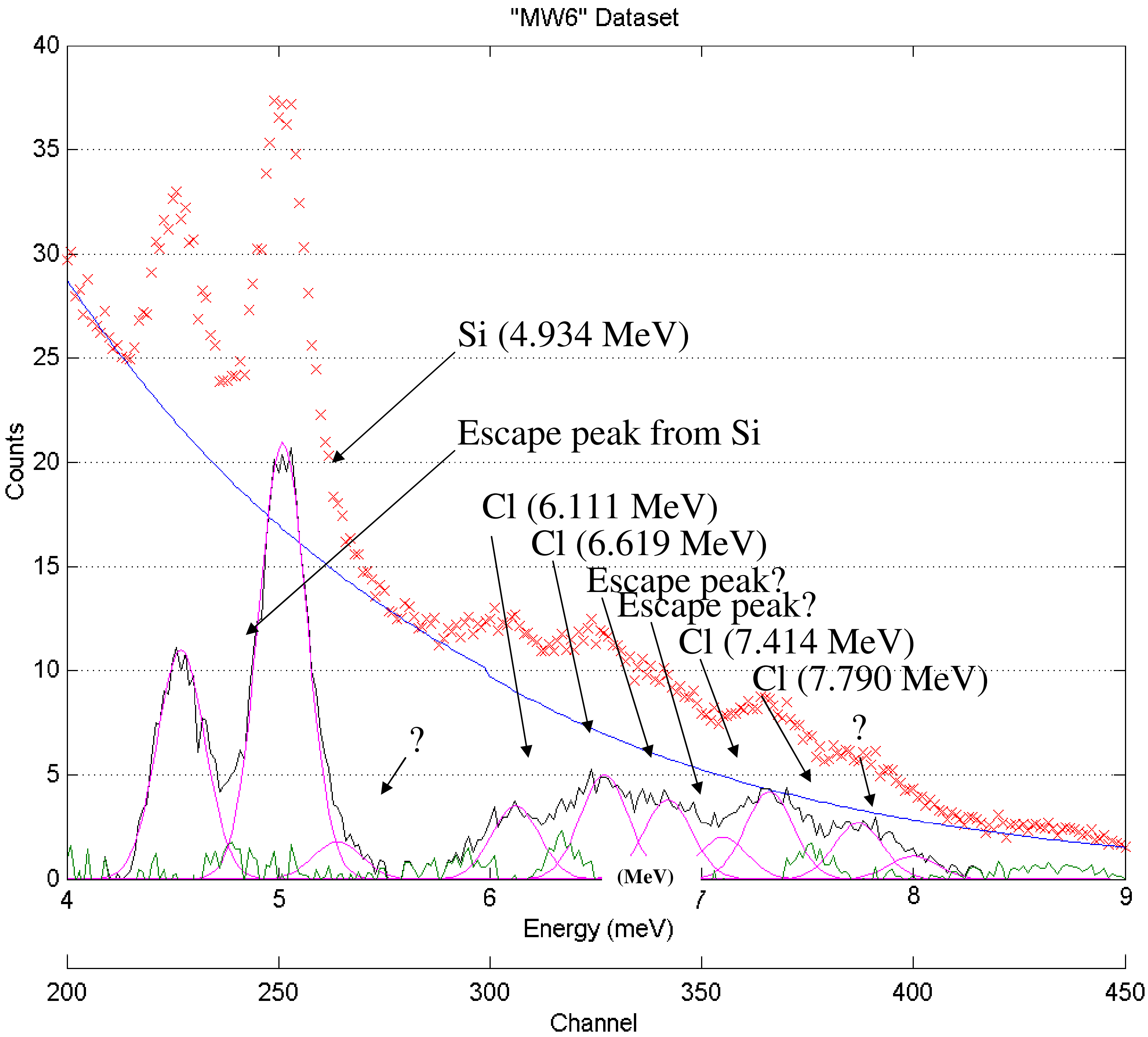


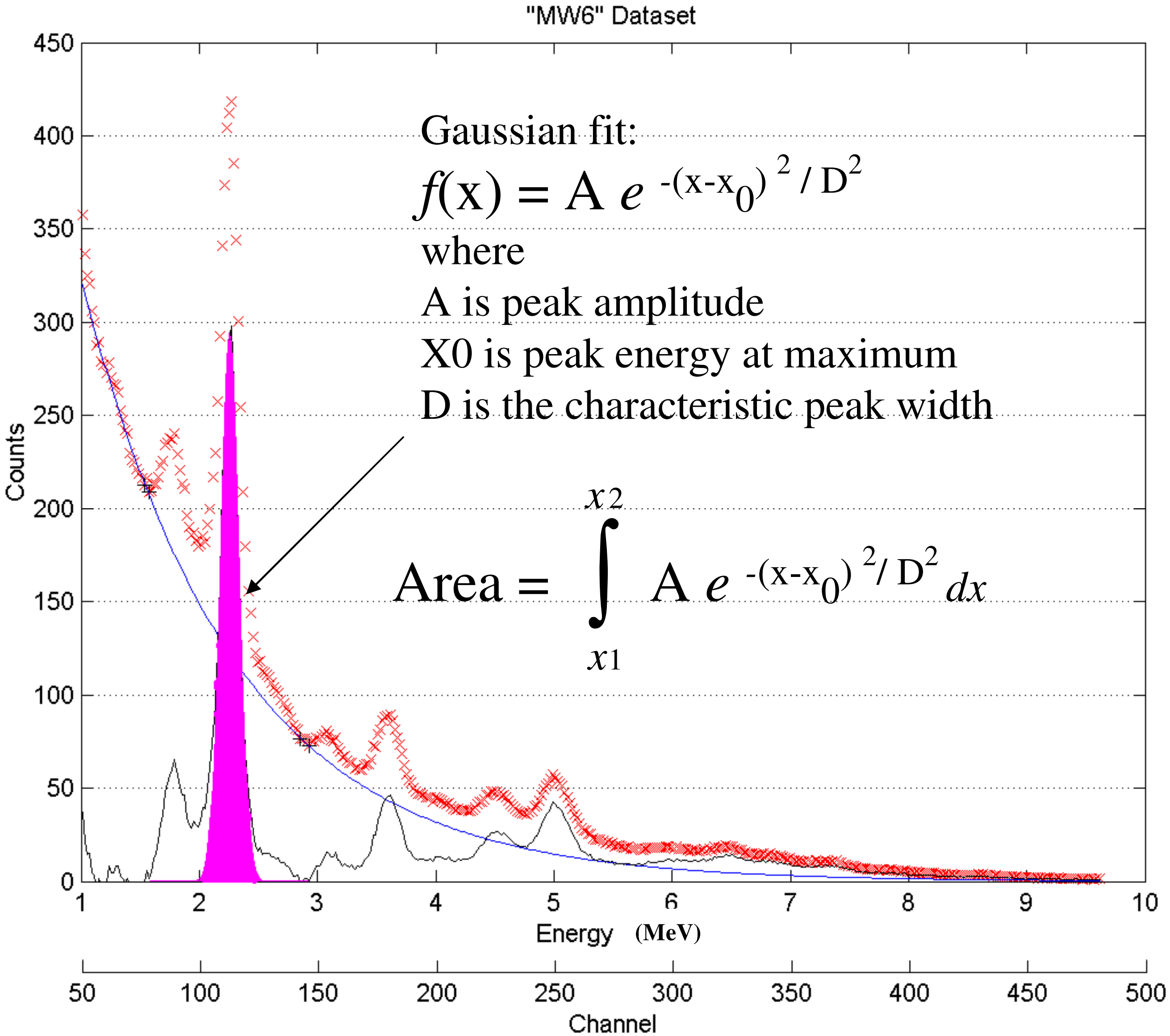
Fast Neutron Pulse
Thermal Neutrons
Long Half Life
Activation Products
Prompt Reactions
Radiative Capture
and Short Half Life
Activation Products
Temporal Characteristic
of Appearance of γ–rays



"MW6" dataset
Counts
Energy (MeV)
Channel
Selected minima points
Fitted exponential curve


"MW6" dataset
Counts
Result of subtraction
Energy (MeV)
Channel
450
400
350
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
50
100
150
200
250
300
350
400
450
500


"MW6" Dataset
Counts
Energy (meV)
Channel
Si (4.934 MeV)
Escape peak from Si
Cl (6.111 MeV)
Cl (6.619 MeV)
Escape peak?
Escape peak?
Cl (7.414 MeV)
Cl (7.790 MeV)
?
?
(MeV)



"MW6" Dataset
Counts
Energy (MeV)
Channel
Gaussian fit:
$f(x) = A\,e^{-(x-x_0)^2/D^2}$
where
A is peak amplitude
X0 is peak energy at maximum
D is the characteristic peak width
$\text{Area} = \int_{x1}^{x2} A\,e^{-(x-x_0)^2/D^2}\,dx$

Detector spectral resolution

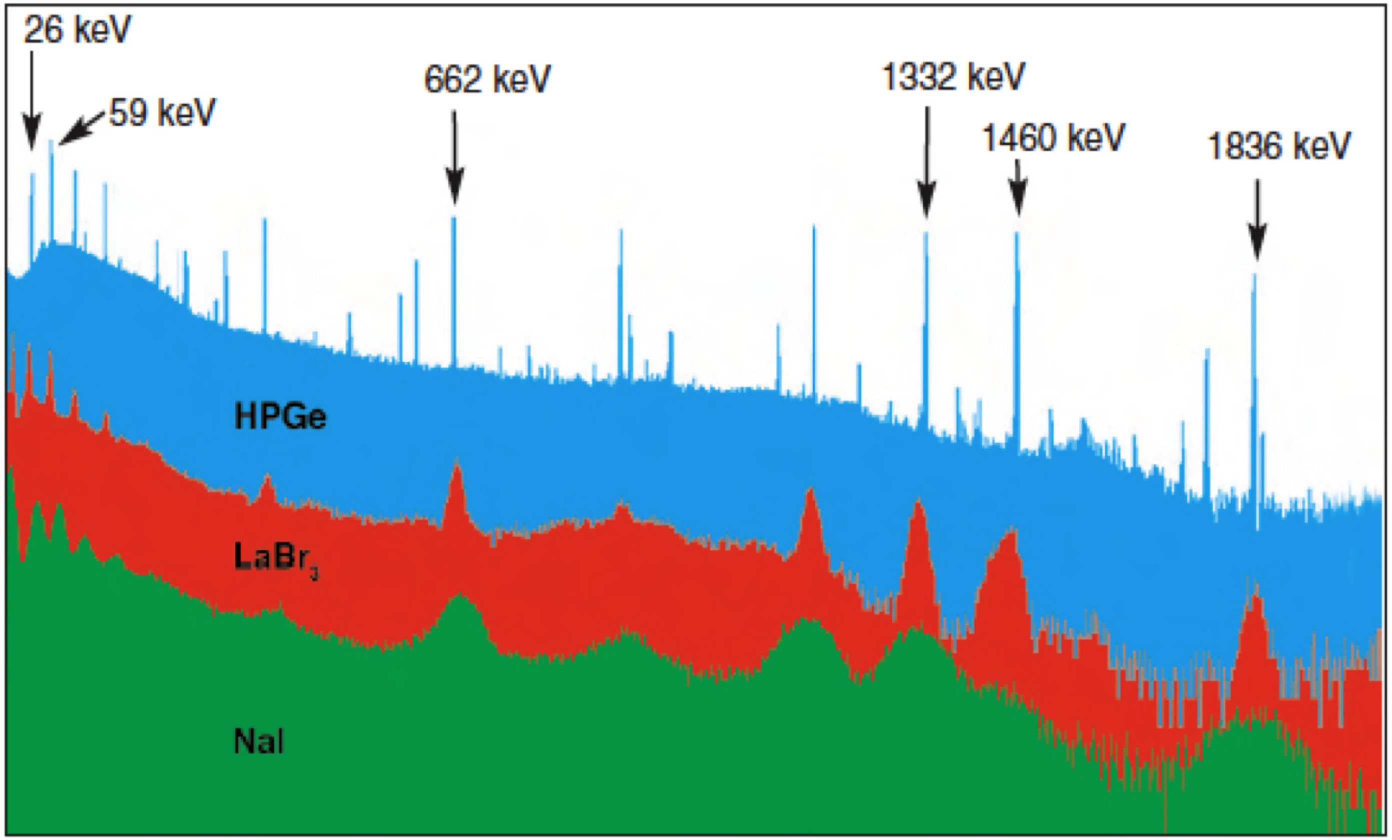
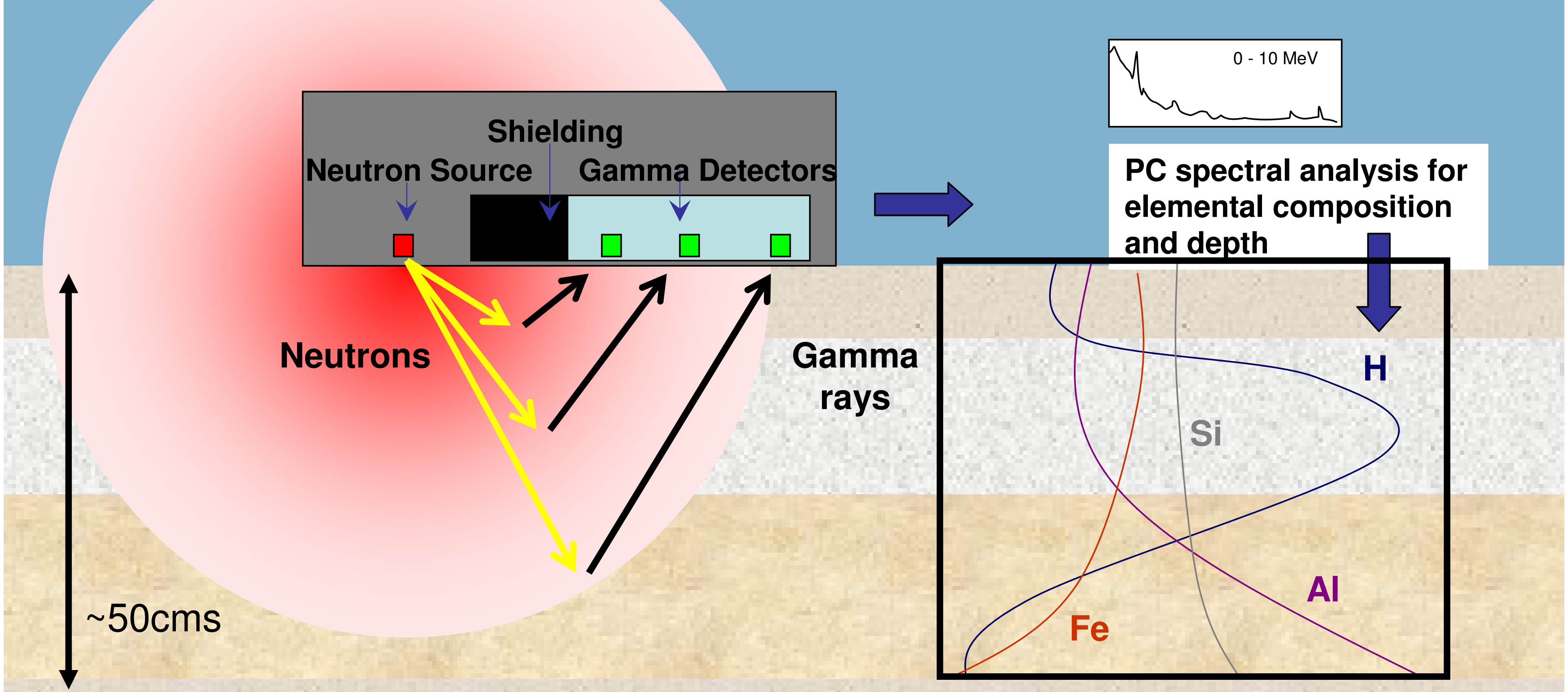


Figure 1. Comparison for $LaBr_3(Ce)$, NaI(Tl), and HPGe spectra.

- HPGe or $LaBr_3Ce$ are the only realistic possibilities for low detection limits of C
  - ORTEC HPGe 9 * GMX 60 $556,000 + cryo-cooling
    St Gobain $LaBr_3Ce$ 6 * 3*3 inch $376,000 + PMT- electronics

Neutron Activation C, soil moisture and composition by surface scanning



Carbon requires neutron generator (D-T fusion, 14 MeV neutrons, INS not PGNA)

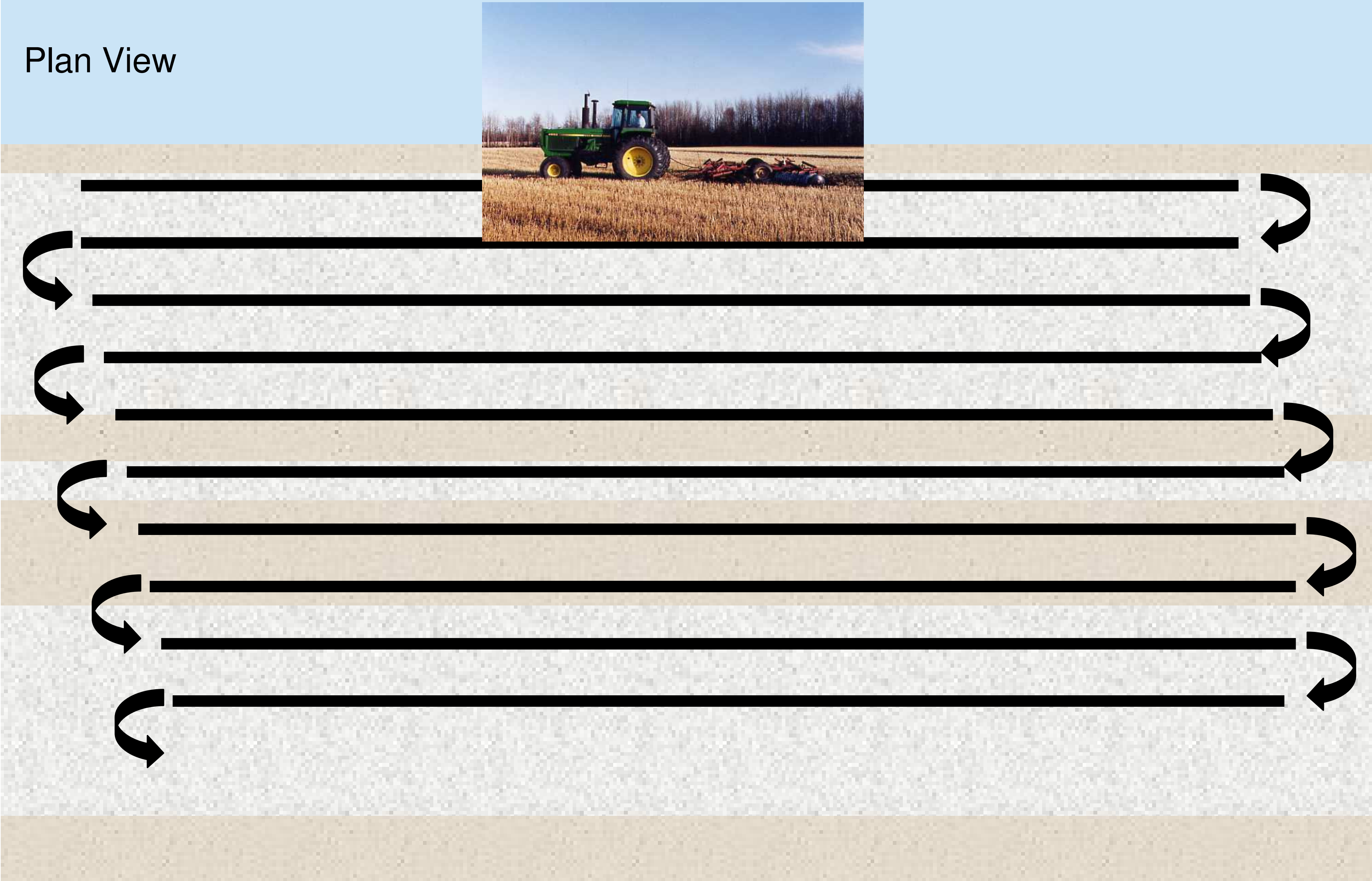
Unique instrument for remote soil geochemical measurement

Brookhaven National Lab. has built proof of concept soil C instrument

ANSTO to build next generation instrument with CSIRO support

2D Surface Mapping

Plan View



What is possible?

- Design surface system for rapid soil moisture and composition
- Build a surface system for H, Si, Al, Fe, Na, K, Ca, Mg, S, N, P, C, + with multiple BGO, LaBr3, HPGe detectors, shielding and neutron generator (fusion source)
- Capability ;
  no radiation when switched off, less OHS radiation concern
  source ~ 10^9 n/s
  linear acquisition speed ~ 20 m / min
  high and low spectral resolution detectors matched to range of elements (major and trace elements)
  depth distribution for element
  trace elements to ppm range

Technology

- Brookhaven National Laboratory has built a proof – of – concept soil C apparatus
  - BNL's apparatus uses low flux neutron generator 10^8 n/s & low resolution detectors (NaI, 3 * 5inch)
  - Oil field service companies build and operate C/O tools, restricted by size, power, temperature to similar specs.

- ANSTO proposes to use new high flux neutron generator 10^9 – 10^{10} n/s, high resolution LaBr3Ce or HPGe detectors and improved gamma spectroscopy

- CSIRO E&M cannot build such an instrument because of BHPB & Sodern contract
- CSIRO L&W's Earth Rover under development

NASA-C automation & ARPANSA

- Neutron generators do not emit radiation when switched off
  - May be transported easily without declaration or signage
  - Radiation risk to operator or public minimised by controlling operating conditions
- An automation strategy removes radiation risk
  - CSIRO team at QCAT has experience building robotic vehicles and is willing to automate NASA-C for 2D soil mapping, collision avoidance, and automatic shut-down if perimeter is breached
  - CSIRO is building a similar soil mapping platform for Raphael Viscarra-Rossel (CSIRO L&W)
- No existing ARPANSA regulation for “mobile” accelerator facilities
  - ANSTO SRP advises developing internal procedures for safe operation (SAC approval) then seeking ARPANSA approval

Continuous 3D Scan-matching with a Spinning 2D Laser

Michael Bosse and Robert Zlot
CSIRO ICT Centre

Applied science

- Improves certainty of C storage or release from soil under land use change and climate change
  - Current soil CO_2 emissions are 10x greater than all anthropogenic CO_2 emissions (amplification of spatial, temporal, geomorphic, & climatic uncertainties)
  - Can verify claims of soil C sequestration (C trading $)
    eg Soil Sequestration in Victoria parliamentary inquiry

- Quantifies soil composition and hydraulic function under intensive agriculture (H, C, N, O, S, P, Si, Fe, Al,)

- Geochemical prospecting for mineral deposits (Fe, Al, Ti, ….)

- Identification of unknown buried objects