High Resolution Reservoir Exploration and Modeling with Micro-earthquake & MT Data and Rock Physics

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利用微地震地電阻與岩石物理資料探測與模擬地熱儲集層

Outline

We Have developed an end-to-end solution for rapid and inexpensive exploration and modeling of reservoirs in active seismic areas.

Outline

Thoughts about Geothermal (甚麼是地熱?)

Instrumentation (設備)

Information from Seismic Recordings (地震資訊)

Automated Processing (自動處理)

Tomography (速度構造)

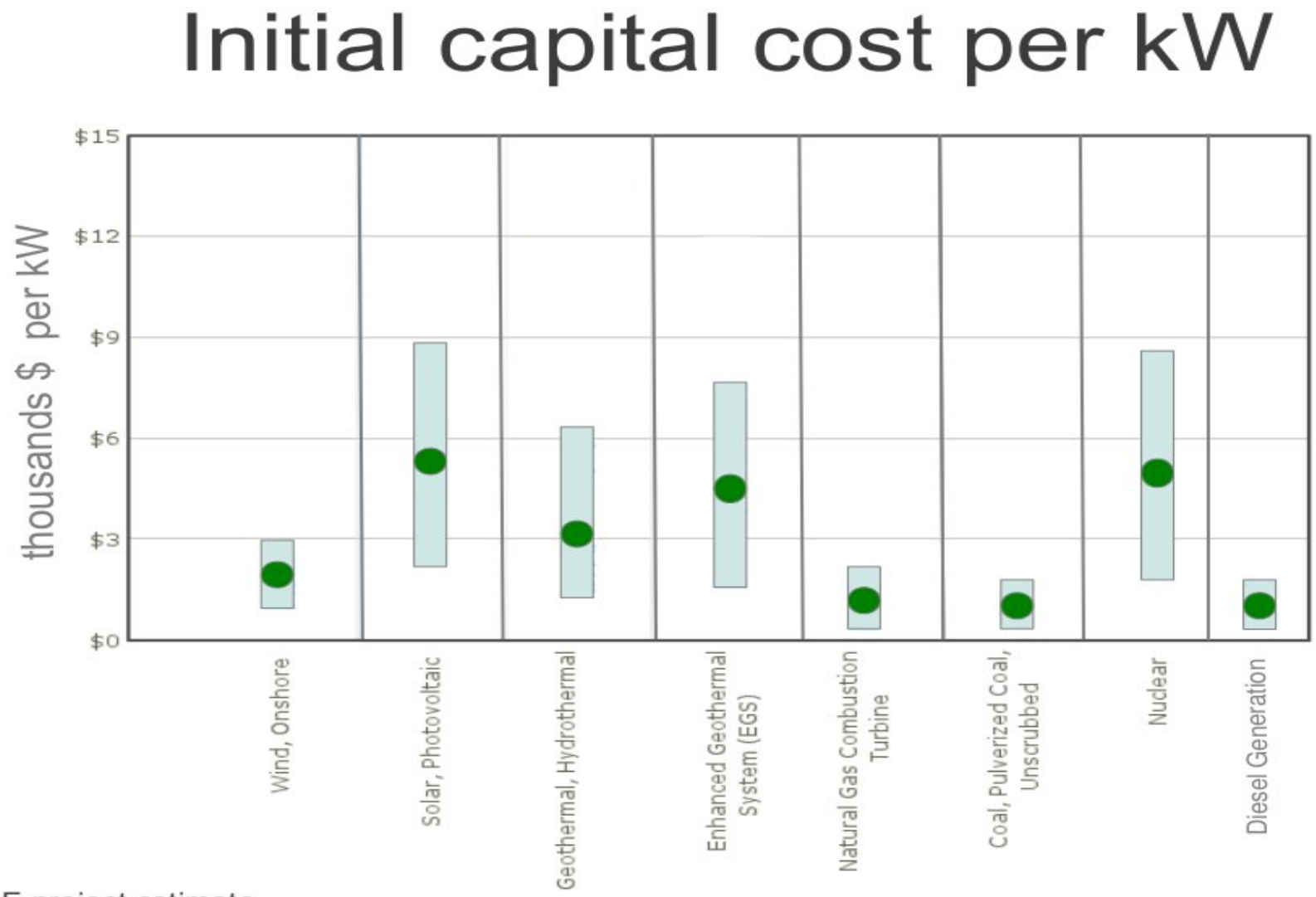
Rock Physics (岩石物理)

Case Studies – Geysers, proprietary (範例)

Geothermal as an Energy Source

Geothermal plants at the Geysers geothermal field, CA.

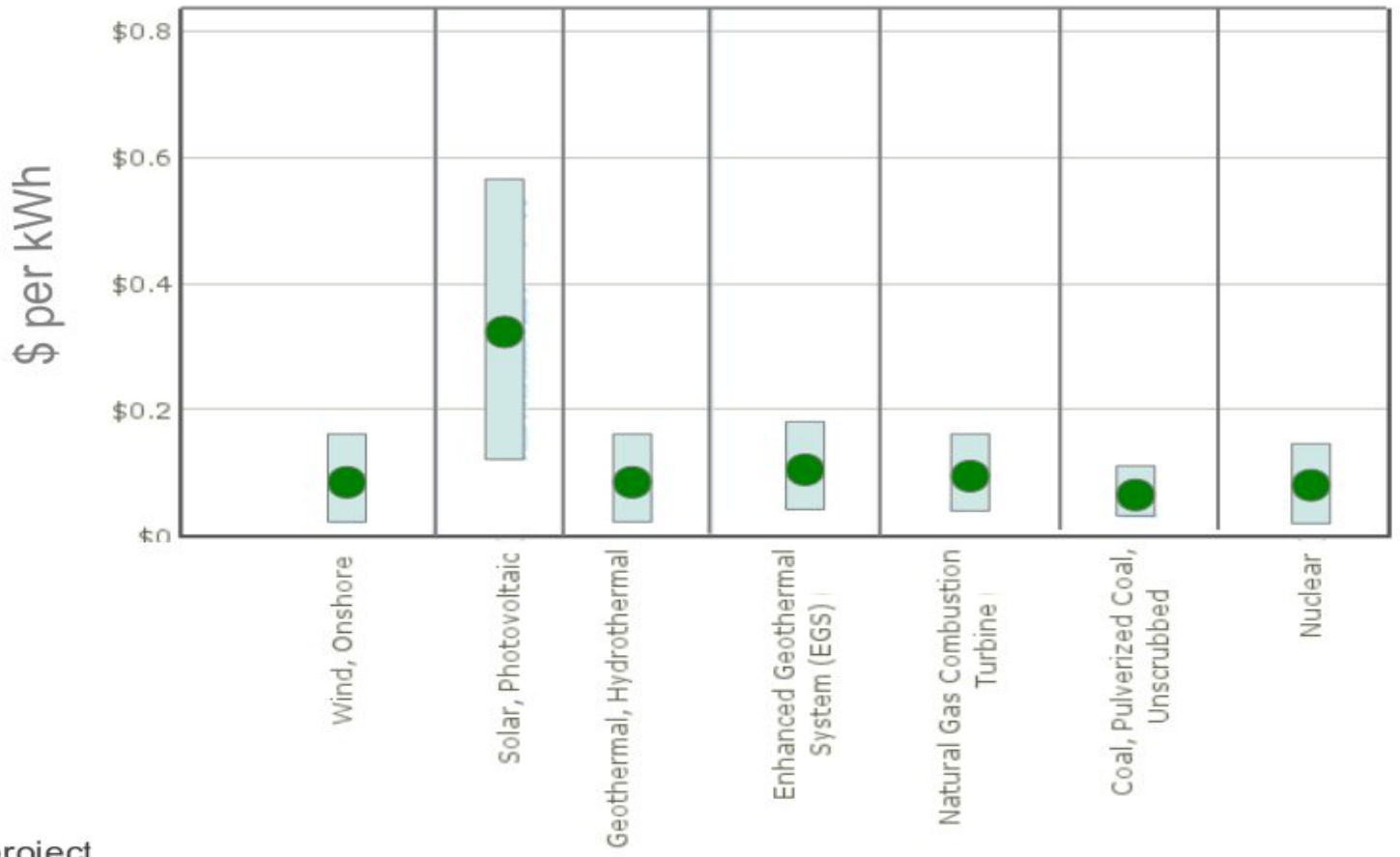
Geothermal as an Energy Source



Geothermal as an Energy Source

Levelized cost of energy $/kWh

Levelized cost is the price a plant must sell electricity at in order to break even.



◆ DOE project
▲ Other estima

http://en.openei.org/apps/TCDB/

Reservoir Exploration and Modeling

Goals

Accuracy
Resolution
Rapid
Cheap

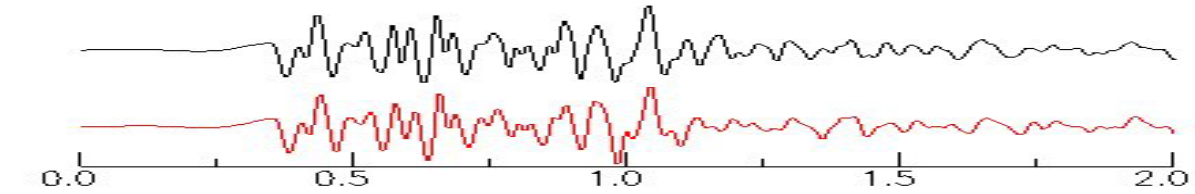
Approach

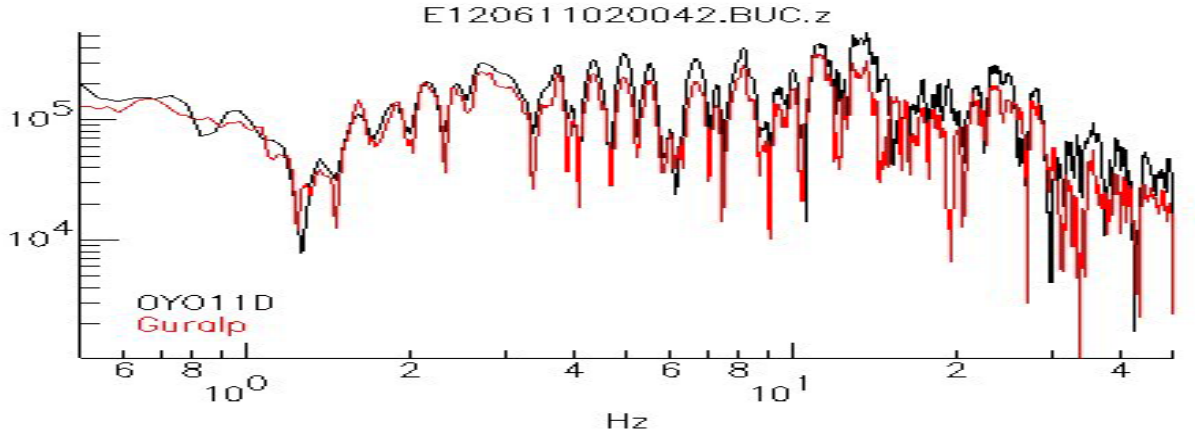
High-tech
Automation
Tomography
Rock Physics

Field Instrumentation

- 24 bit
- 250 sps
- 4.5Hz geophones
- GPS
- low power
- radio telemetry
- inexpensive
- deploy in one hour
- non-technician

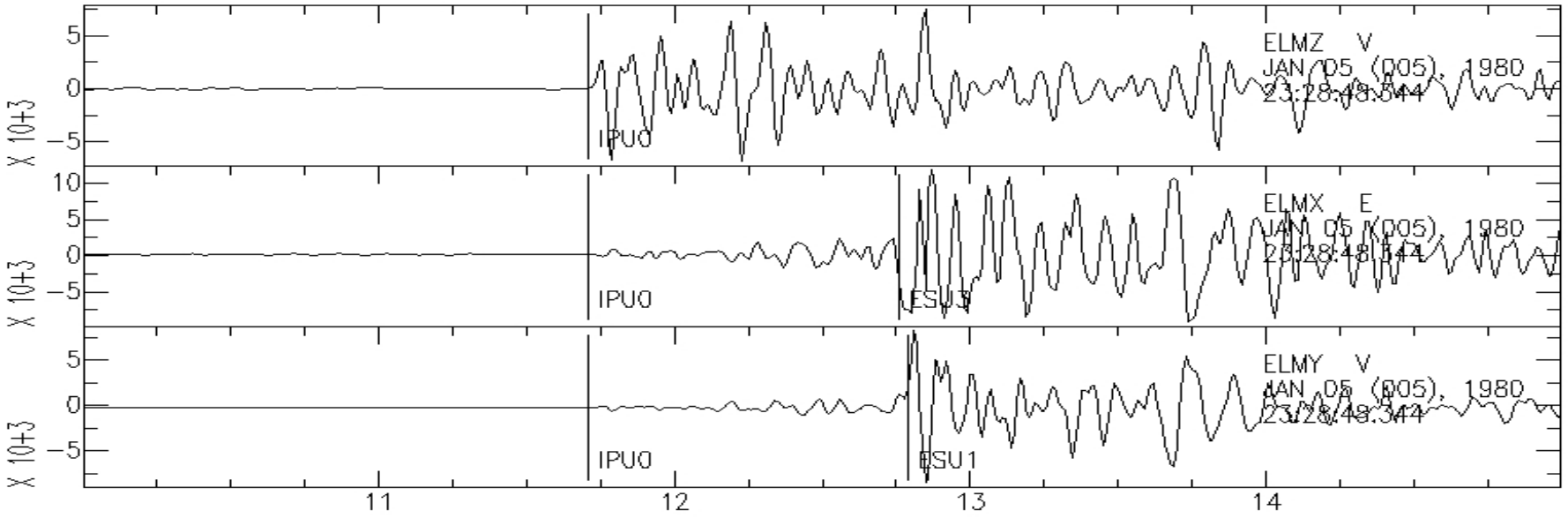
Huddle Test with Guralp



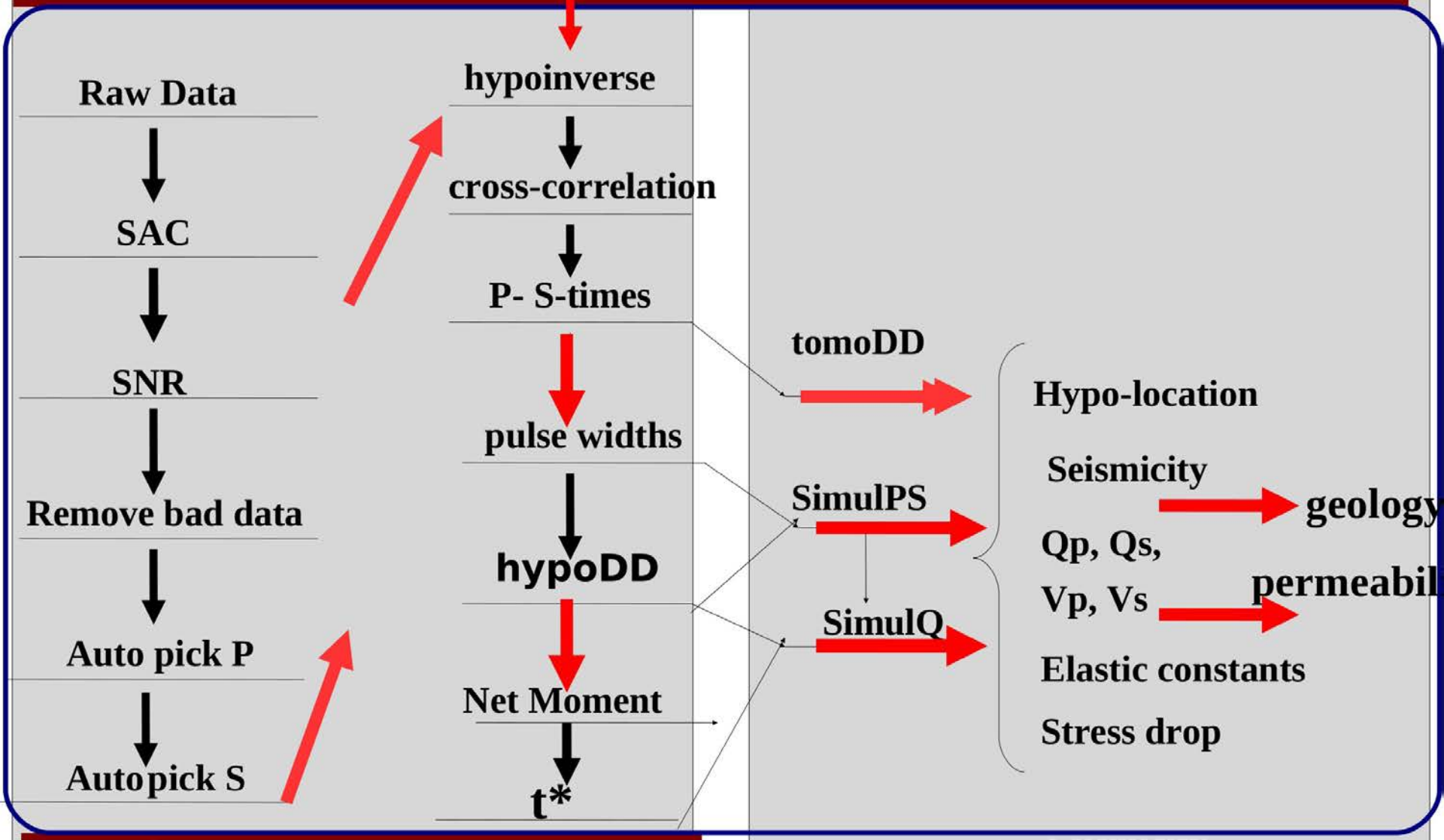


3-component seismograms

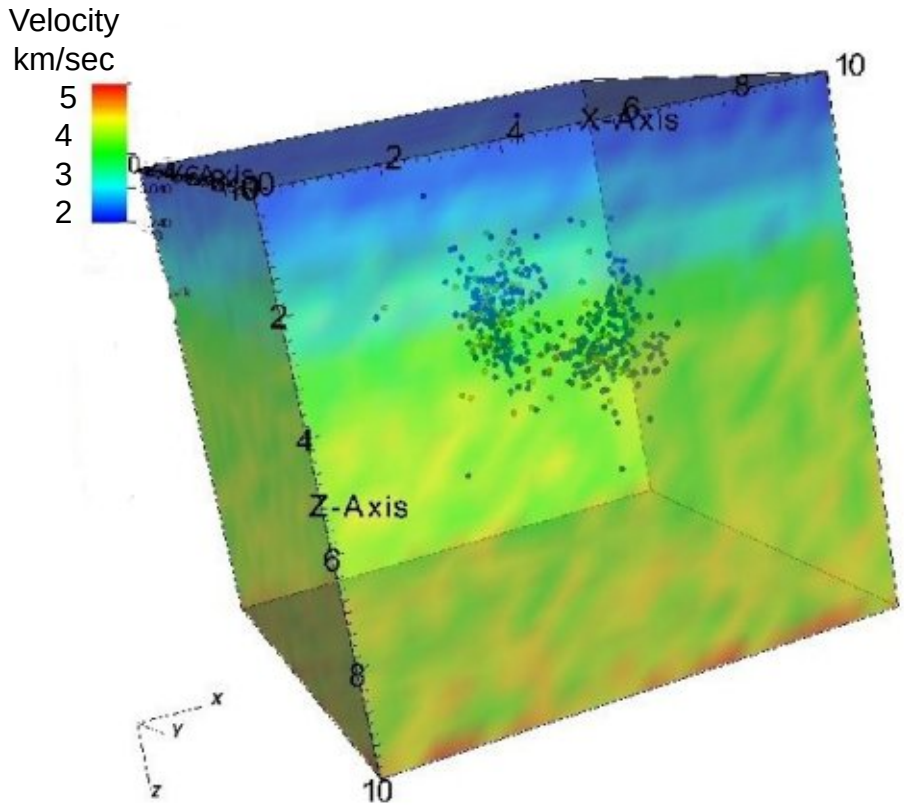
- P & S-arrivals → Vp & Vs tomograpahy
- Pulse widths → Qp & Qs “
- Rock physics → Elastic constants
- Moment tensors → Crack motions
- Q inversion → Moment, stress drop
- Magnetotellurics → Fluids



Automated Processing Programs & Analysis



Automated Earthquake Parameters
Rapid Tomography - updated daily



dots-earthquake locations

Accuracy & Resolution

DoF = number of P&S arrivals

- number of parameters

- Parameters = 2 x nodes + (4 x earthquakes)
- Data (P&S arrivals) = 2 x earthquakes x stations

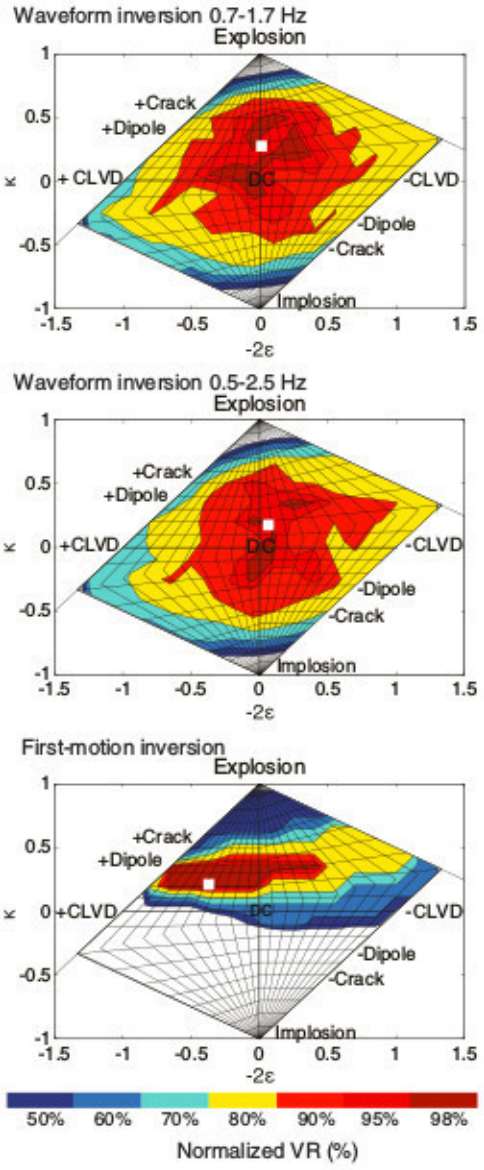
Better to increase number of stations
(測站越多越好!!)

Interpretation

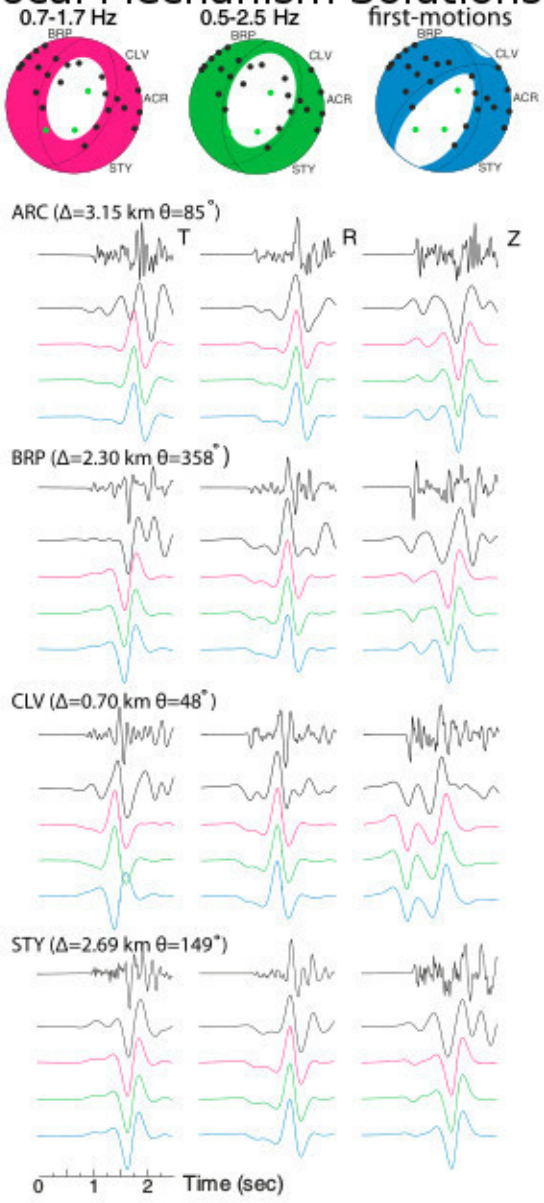
- *Vp, Vs, Qp & Qs from tomography*
- *Mo & Δσ from Q inversion*
- *Young's & Bulk moduli, Lambda, Poisson's ratio – derived*
- *Hypocenters – very accurate*
- *MT – 2 & 3D inversion*

Moment Tensor Inversion

Uncertainity Plots



Focal Mechanism Solutions



Rock physics

如何建立震波資料與岩石物理

- Develop quantitative relationships between reservoir properties and seismic data
- Utilize laboratory and well-log data
- Develop rock physics models of the reservoir
- Utilize 3D visualization software

仍需要更多探索，需要岩石物理專家的合作參與

Rock Physics Relationships

Seismic velocity

$$Vs = \sqrt{\frac{\mu}{\rho}} \quad \text{and} \quad \mu = v_s^2 \rho$$

$$Vp = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

- Use *Vs* to eliminate density

Poisson's ratio $\sigma = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$.

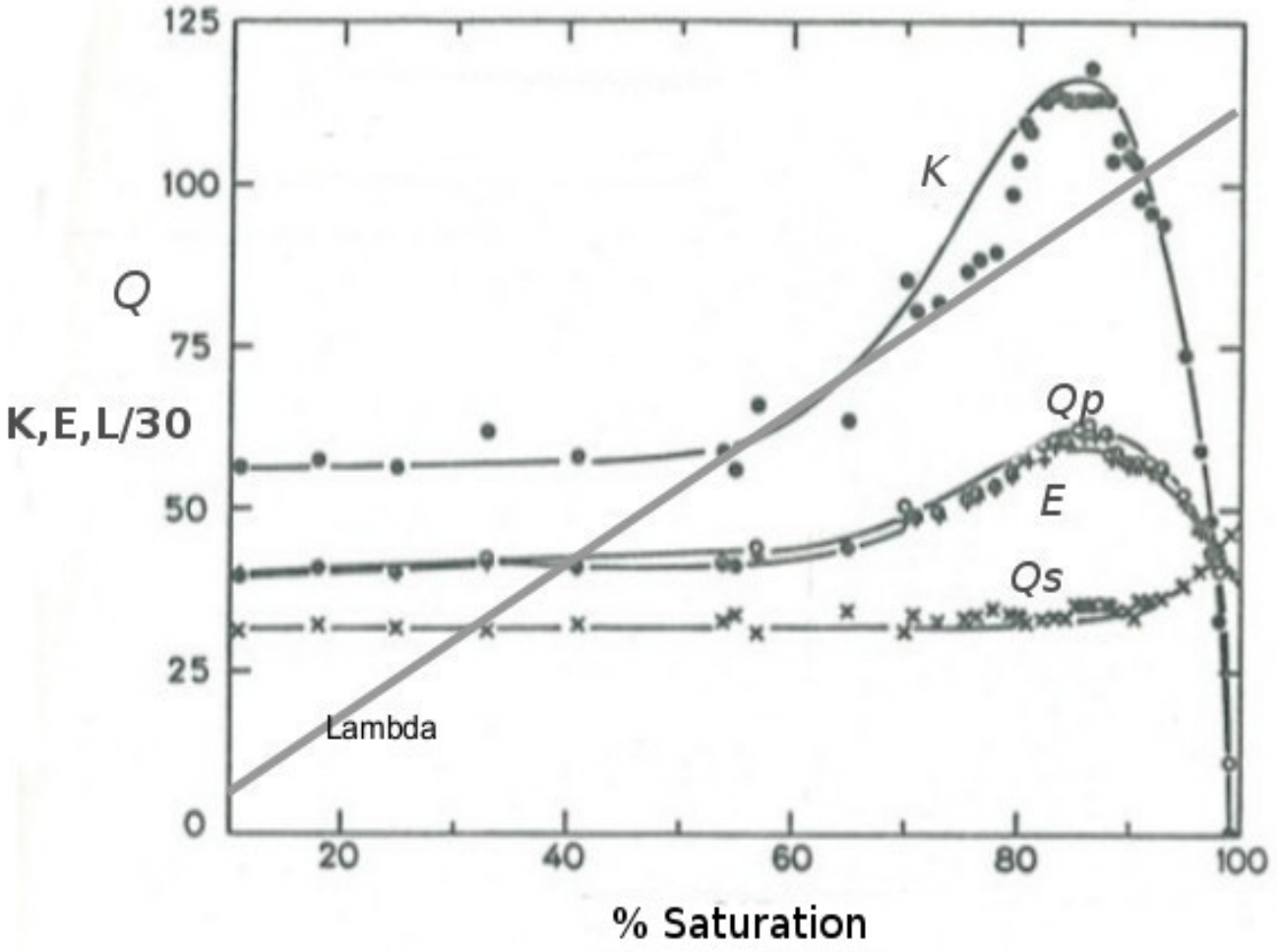
Lambda $\frac{\lambda}{\mu} = \frac{(V_p^2 - 2V_s^2)}{V_s^2}$

Bulk modulus $\frac{K}{\mu} = \frac{\left(V_p^2 - \frac{4V_s^2}{3}\right)}{V_s^2}$

Young's modulus $\frac{E}{\mu} = \frac{3\left(\frac{V_p}{V_s}\right)^2 - 4}{\left(\frac{V_p}{V_s}\right)^2 - 1}$

震波速度可推算彈性係數

Parameters vs. Saturation

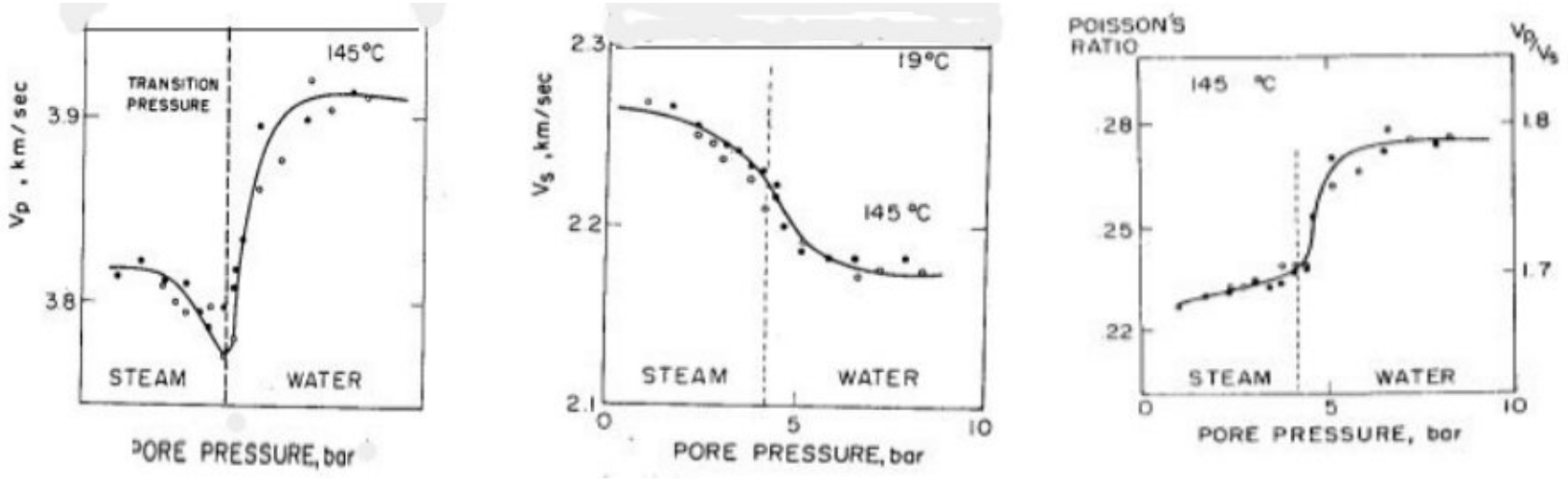


from Berryman and Bonner (2002) and Murphey (1982)

利用震波資訊與岩石物理可以探索儲集層

Laboratory Studies

Laboratory study at constant confining pressure and temperature, but changes in saturation



Vp, Vs and Poisson's ratio from Ito et al., 1979

利用震波資訊與岩石物理可以探索儲集層

Velocity and Q

INTERPRETATION

Basic axioms of rock physics

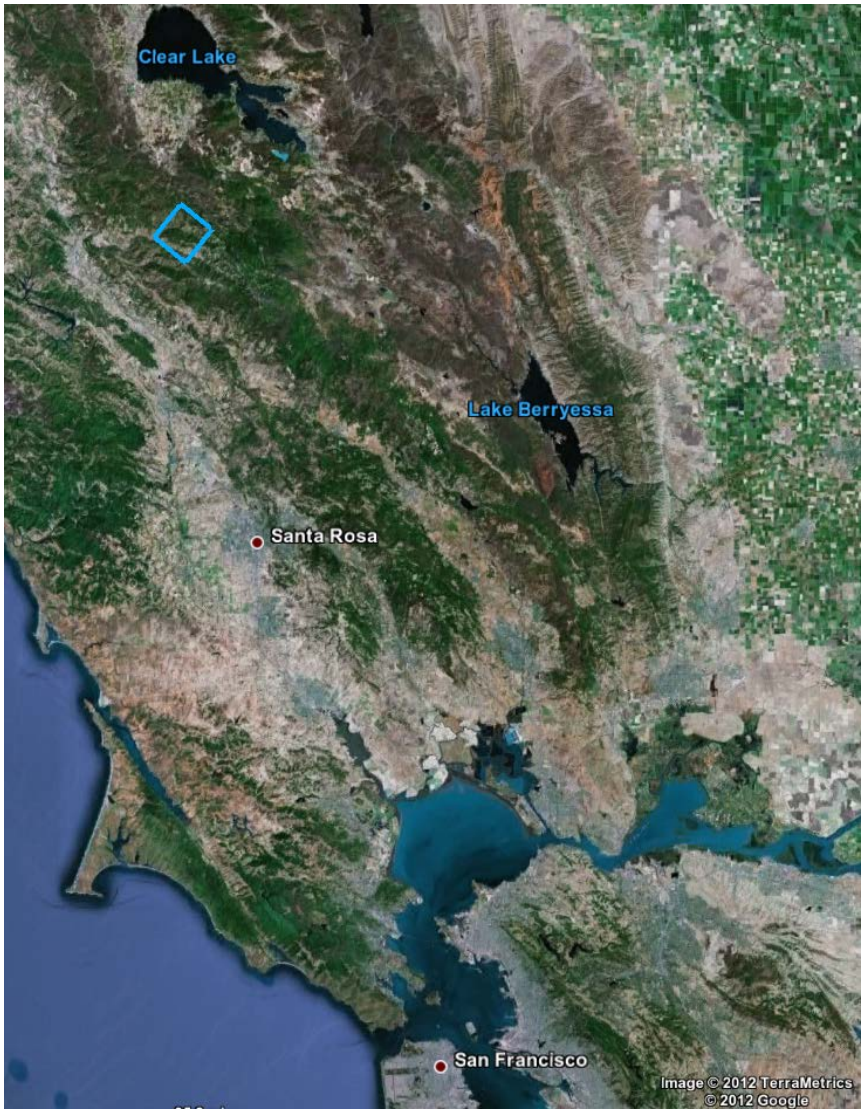
- Increase of velocity and decrease in attenuation with depth
- Decrease in velocity and increase in attenuation due to fracturing
- Decrease in velocity due to alteration
- Extreme temperature gradient works to decrease velocity with depth
- Fluid saturation stiffens pores; affects P-wave velocity, but not S-waves
- Attenuation due to scattering from fractures or heterogeneities (extrinsic)
- Attenuation also due to fluid migration at a range of scales (intrinsic)
- Attenuation and Vp changes (in space or time) can indicate saturation
- In a fully saturated homogeneous medium only extrinsic attenuation
- Saturation increases the density of the material and decreases both P- and S-velocity
- Shear modulus is independent of fluid in the absence of geochemical reactions
- Viscosity, porosity and permeability affects the degree of attenuation
- Dilatency can cause expansion and permeability
- Variation in lithology observed in elastic constants
- Decrease in Poisson's ratio occurs as porosity
- Compaction and lithification preferentially eliminate small aperture pores

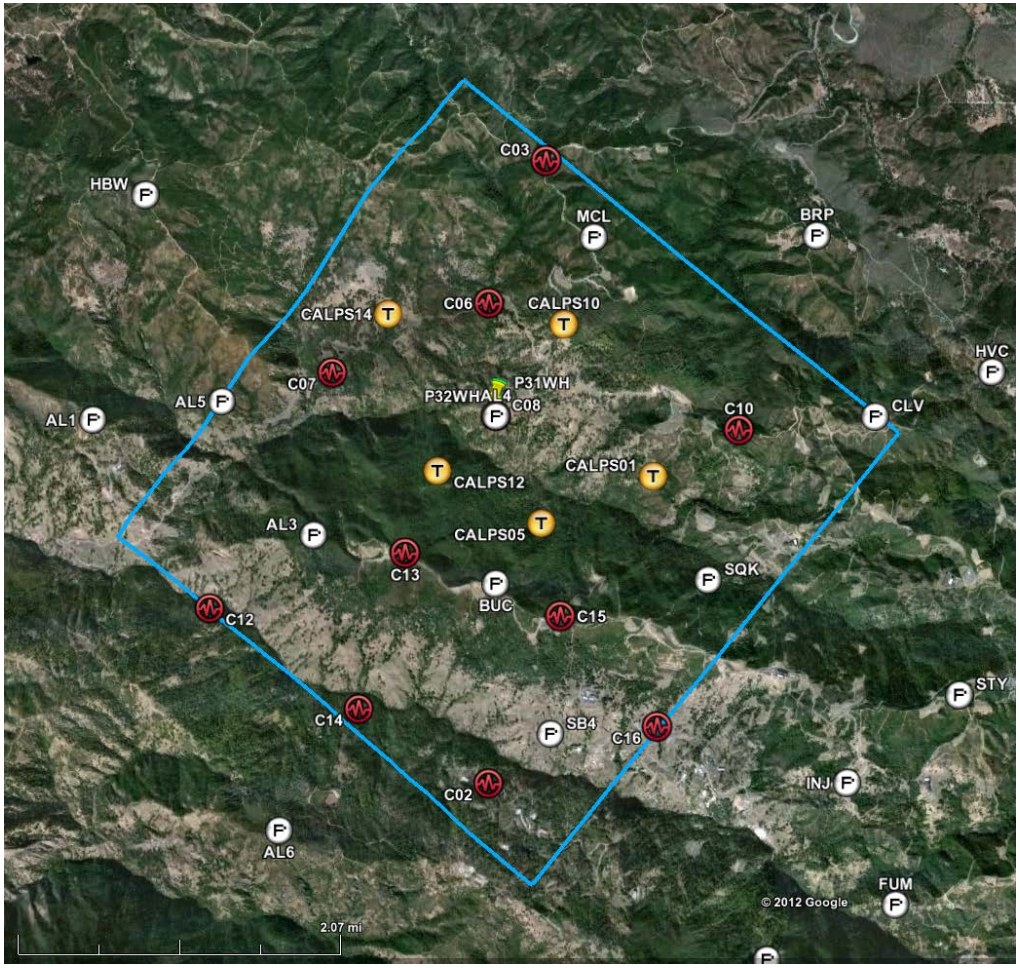
從震波數據可以獲得許多資訊來解釋

ESD EARTH SCIENCES DIVISION High Density Network

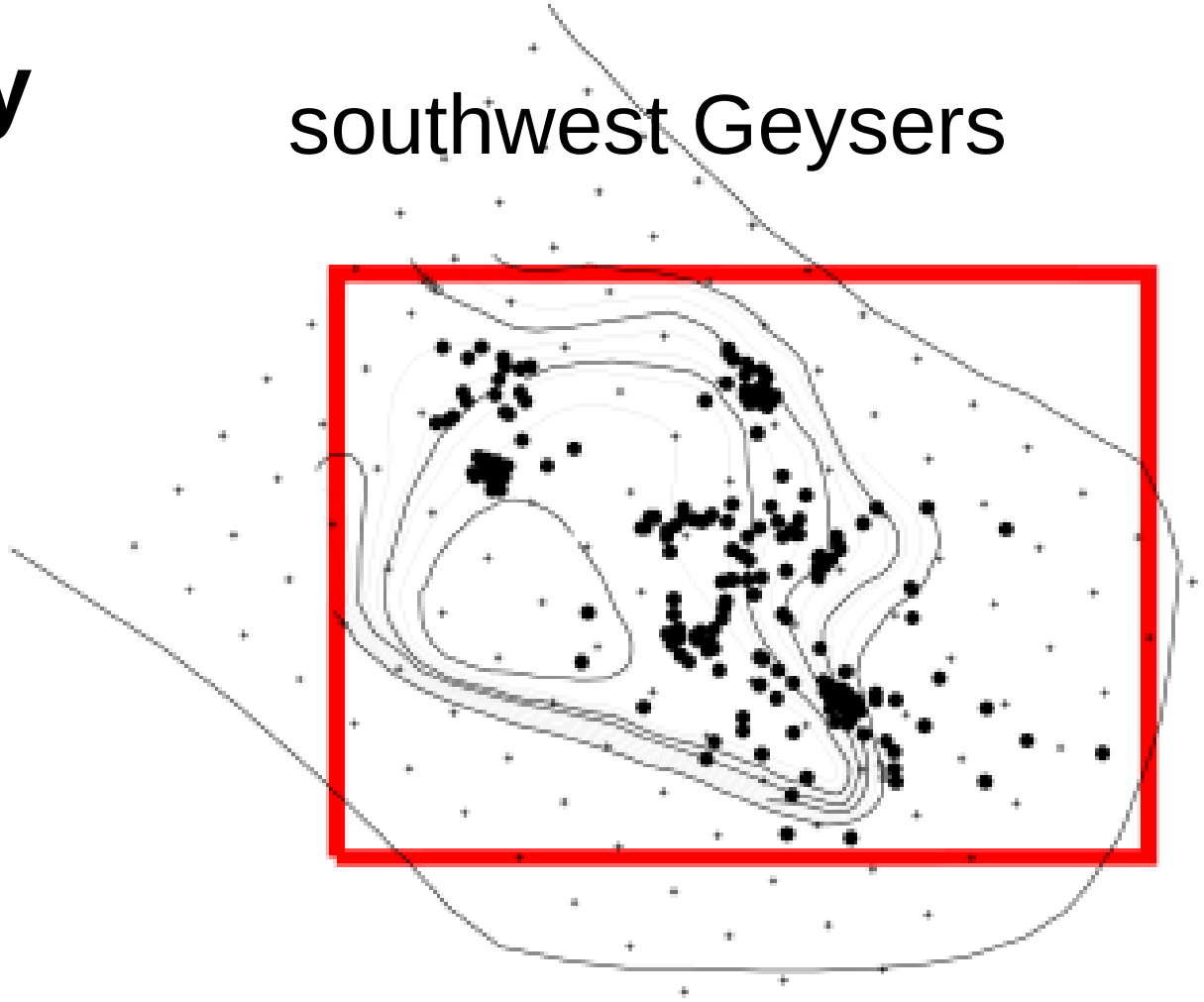
BERKELEY LAB

23 surface stations within 5.7km X 6.0km area around the EGS injection



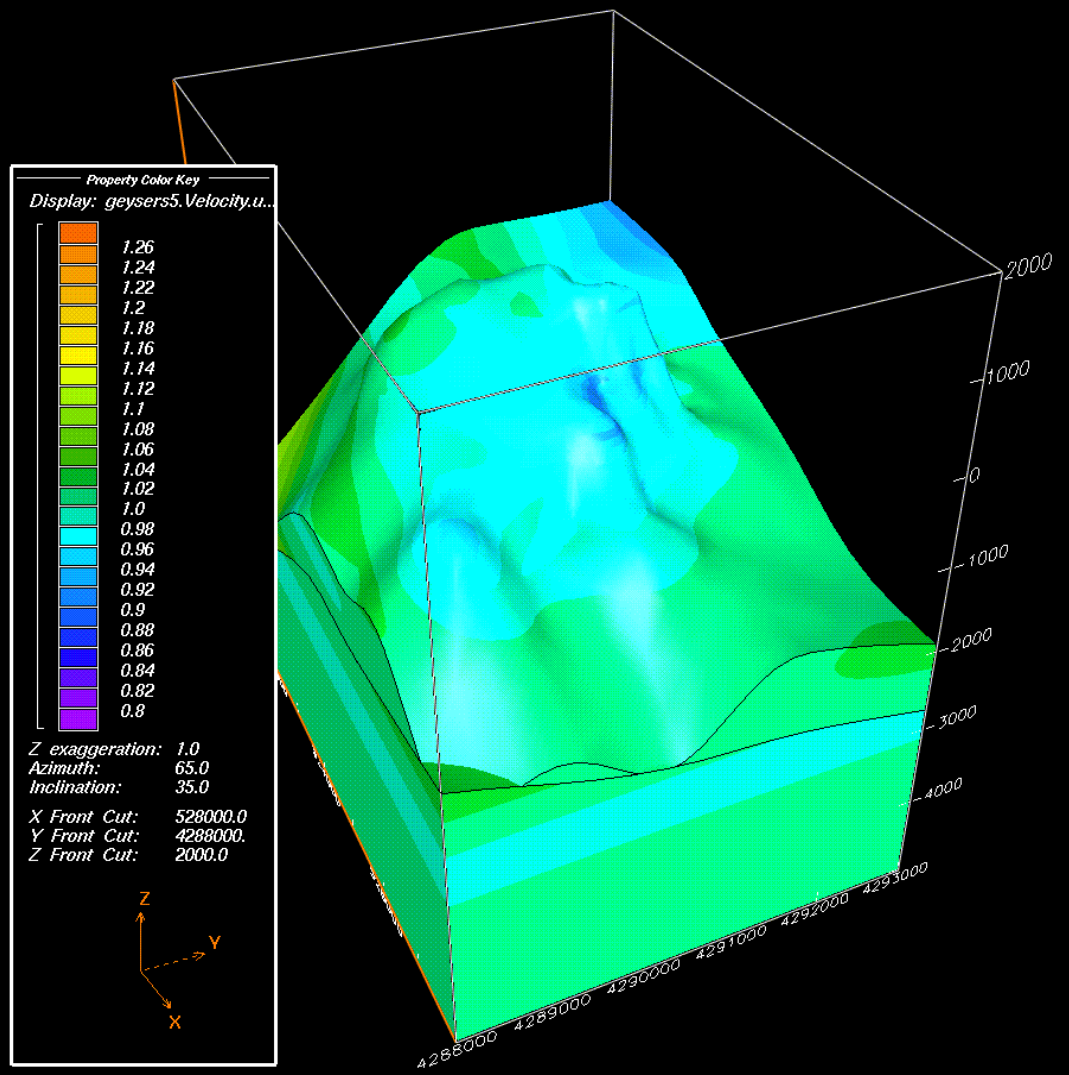


Study Area



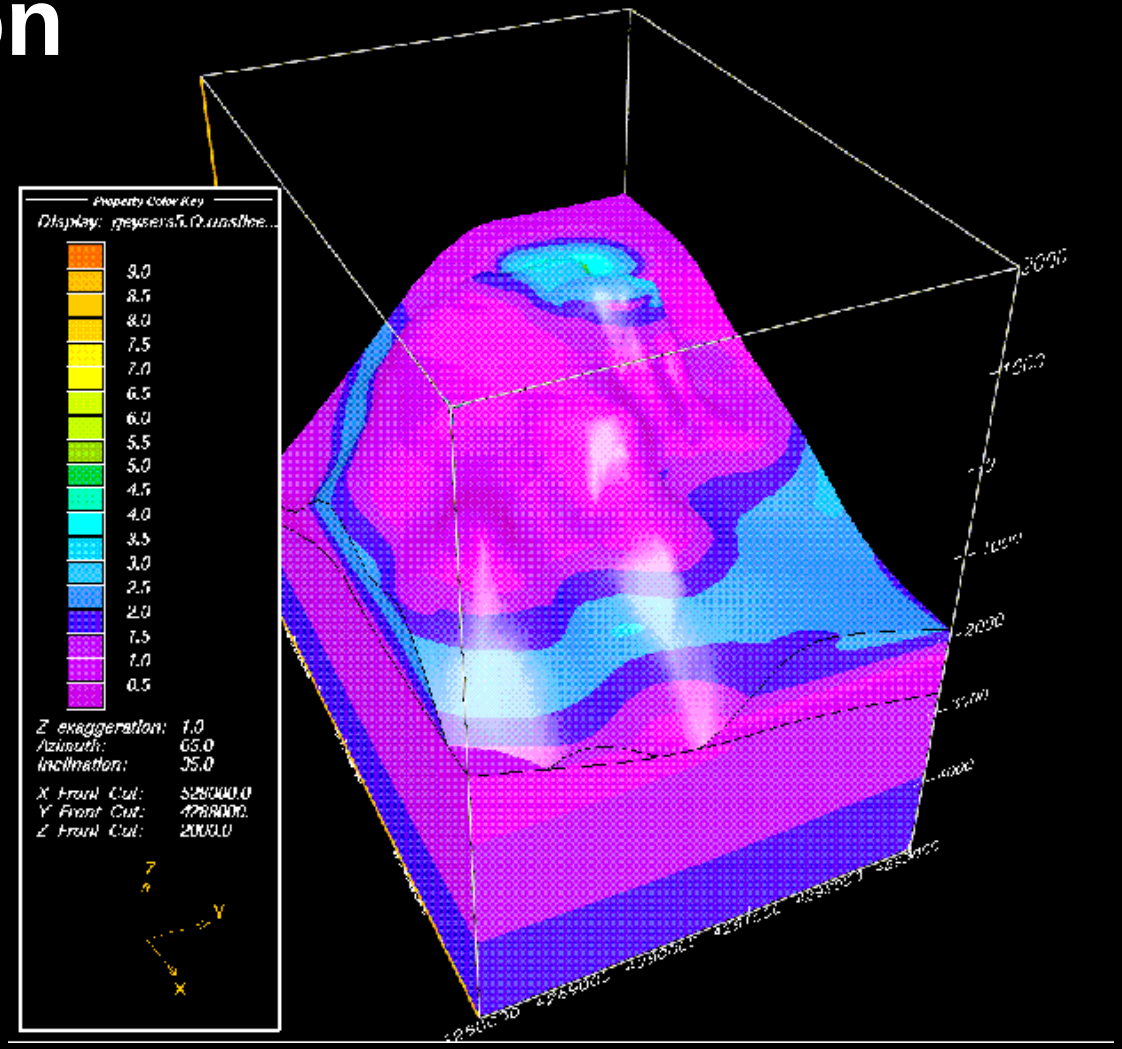
- microearthquake locations (black dots)
- nodes for inversion studies (small dots)
- pressure contours

Velocity Inversion Results



Variation of velocity inversion results from the “expected" model as viewed on the felsite.

Attenuation Inversion Results

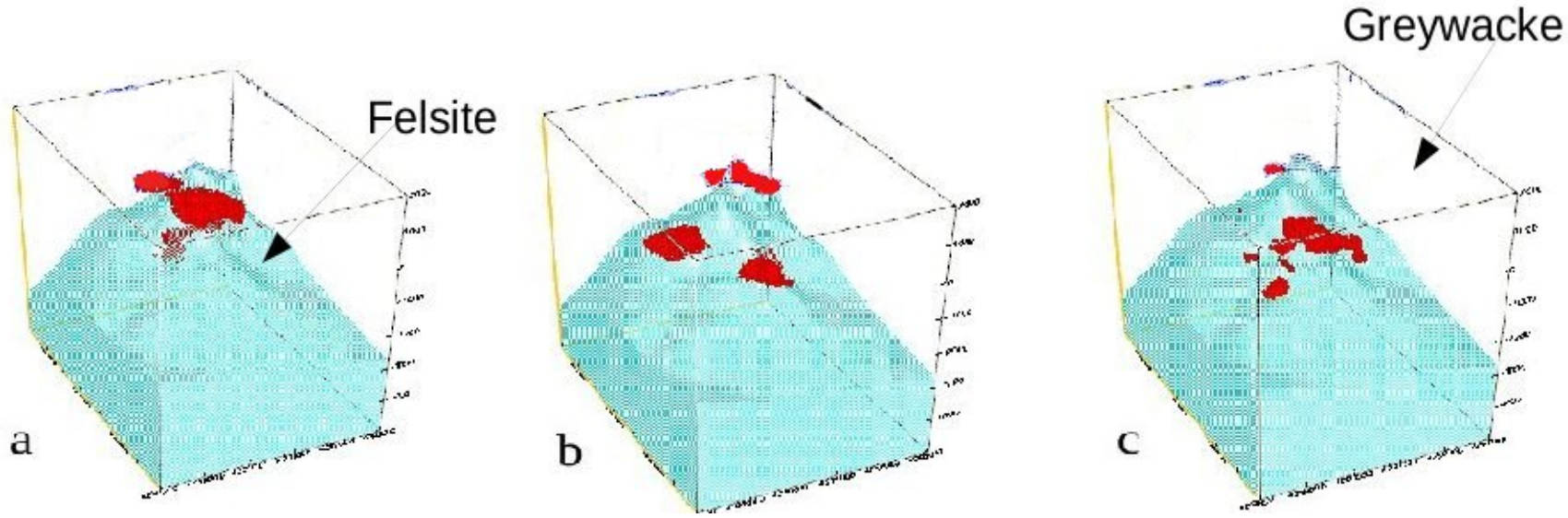


Variation of Qp inversion results from the "expected" model.

Identify reservoir fractures and permeability

找出在儲集層的裂隙與滲透率

Anomalous Zones



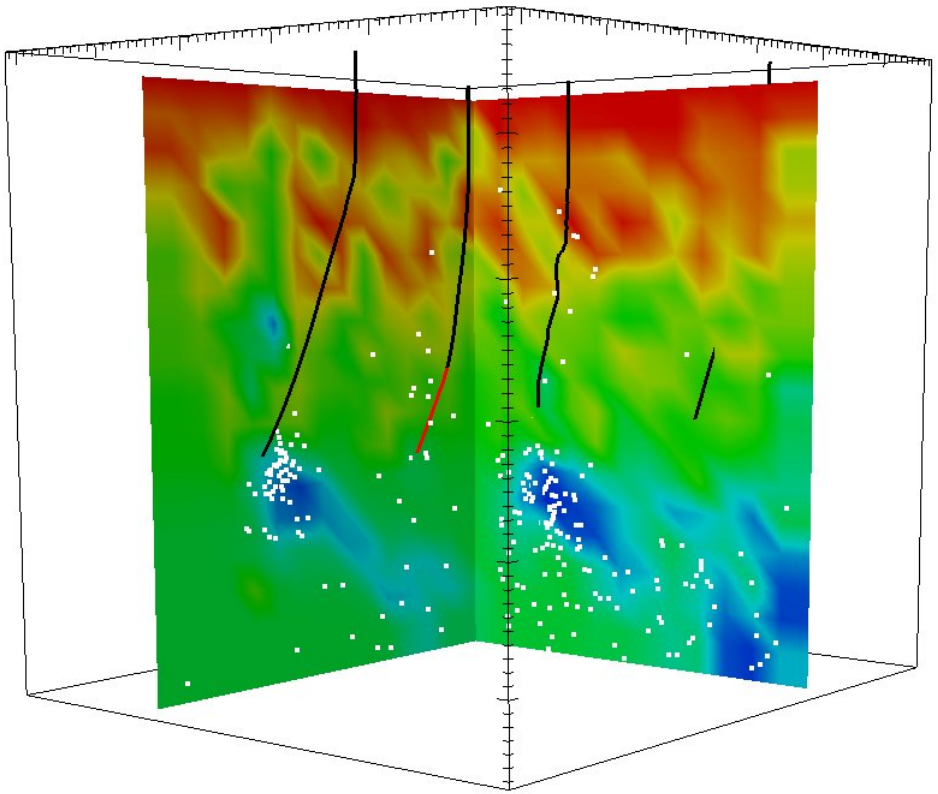
a) Qp > 50% and Vp > 5% above model ⟶ reduced fracture density

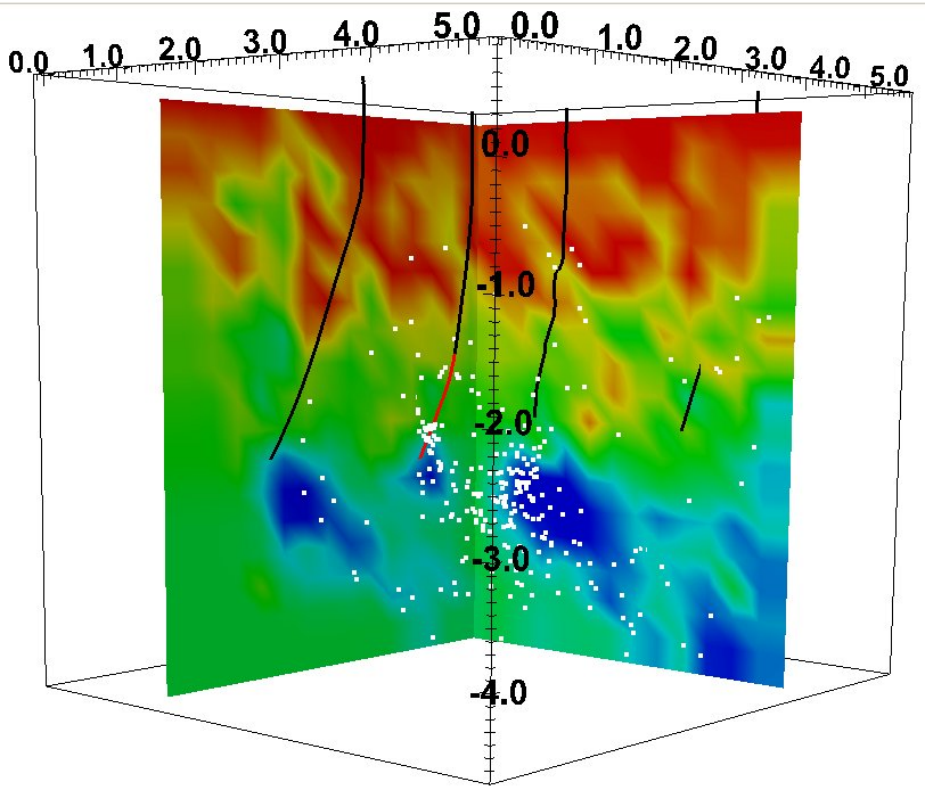
b) Qp > 50% and Vp < 5% from model ⟶ well cemented fracture medium

c) Qp < 50% and Vp < 5% from model ⟶ high fracture density

Vs Tomography for two Months

Injection at four wells



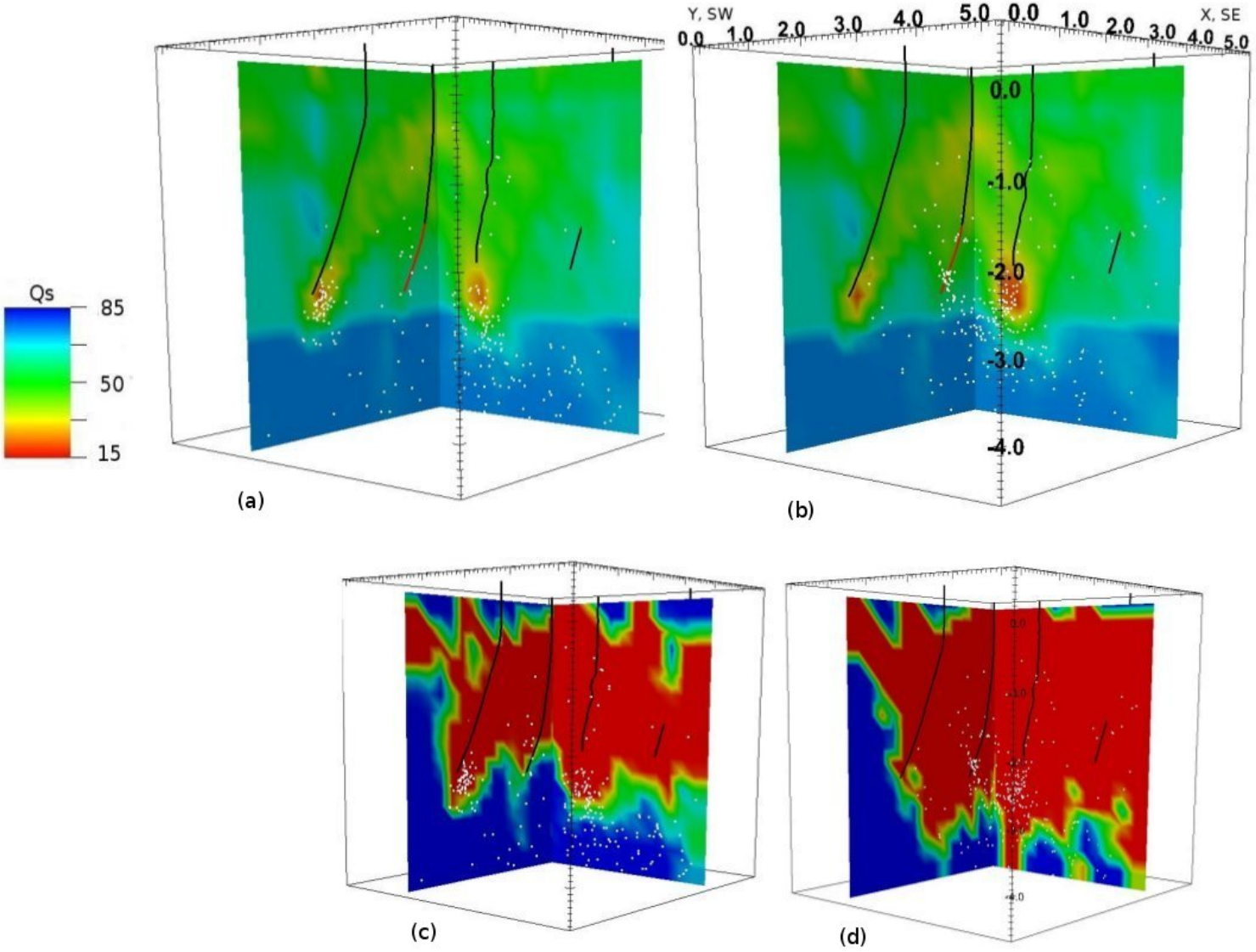


One month, plus seven events

Second month, injection increased

從灌注測試可以檢驗速度構造結果

Qs Tomography and Resolution




Taiwan
Philippines

5 km x 5 km with 25 stations and 220 earthquakes

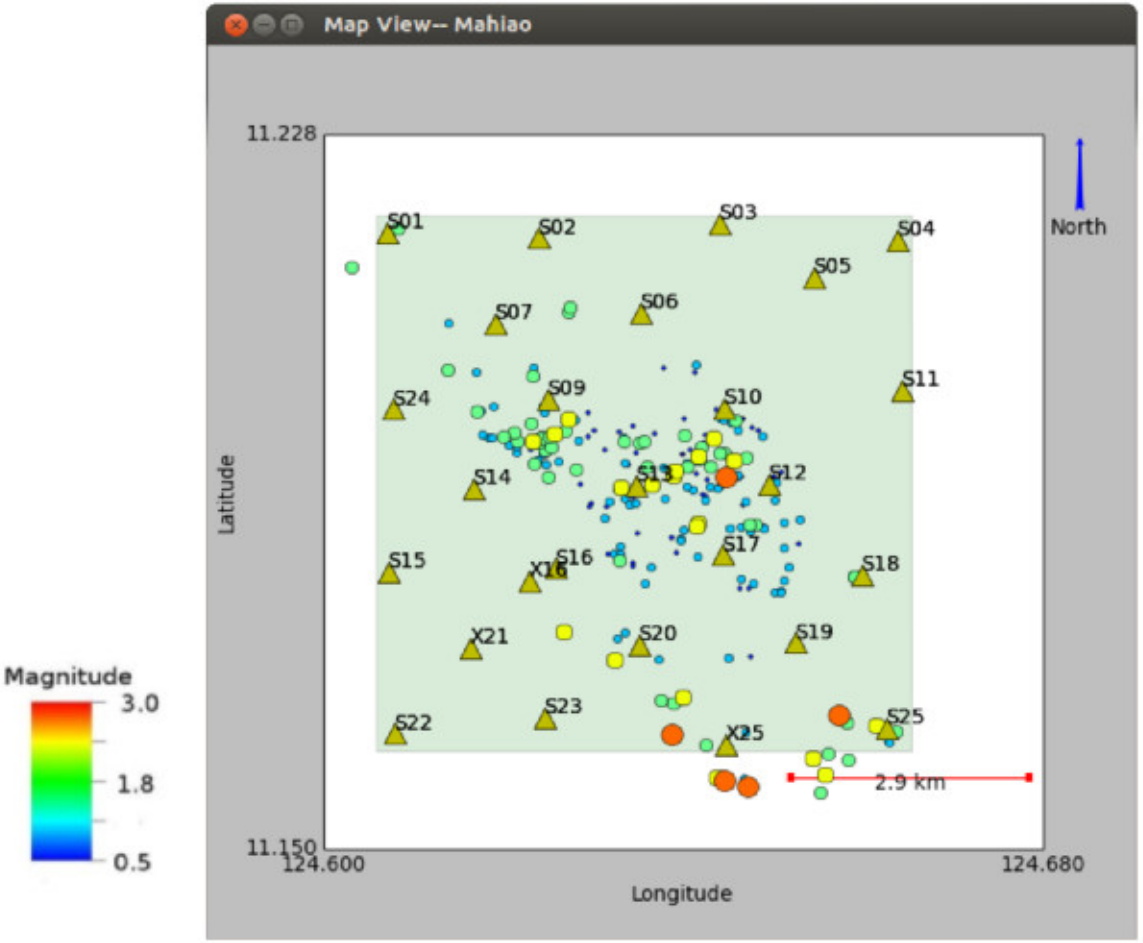


Figure 11. Surface projection of the study volume, station locations, and epicenters of micro-earthquakes analyzed.

Cap rock and heat source

蓋層與熱源

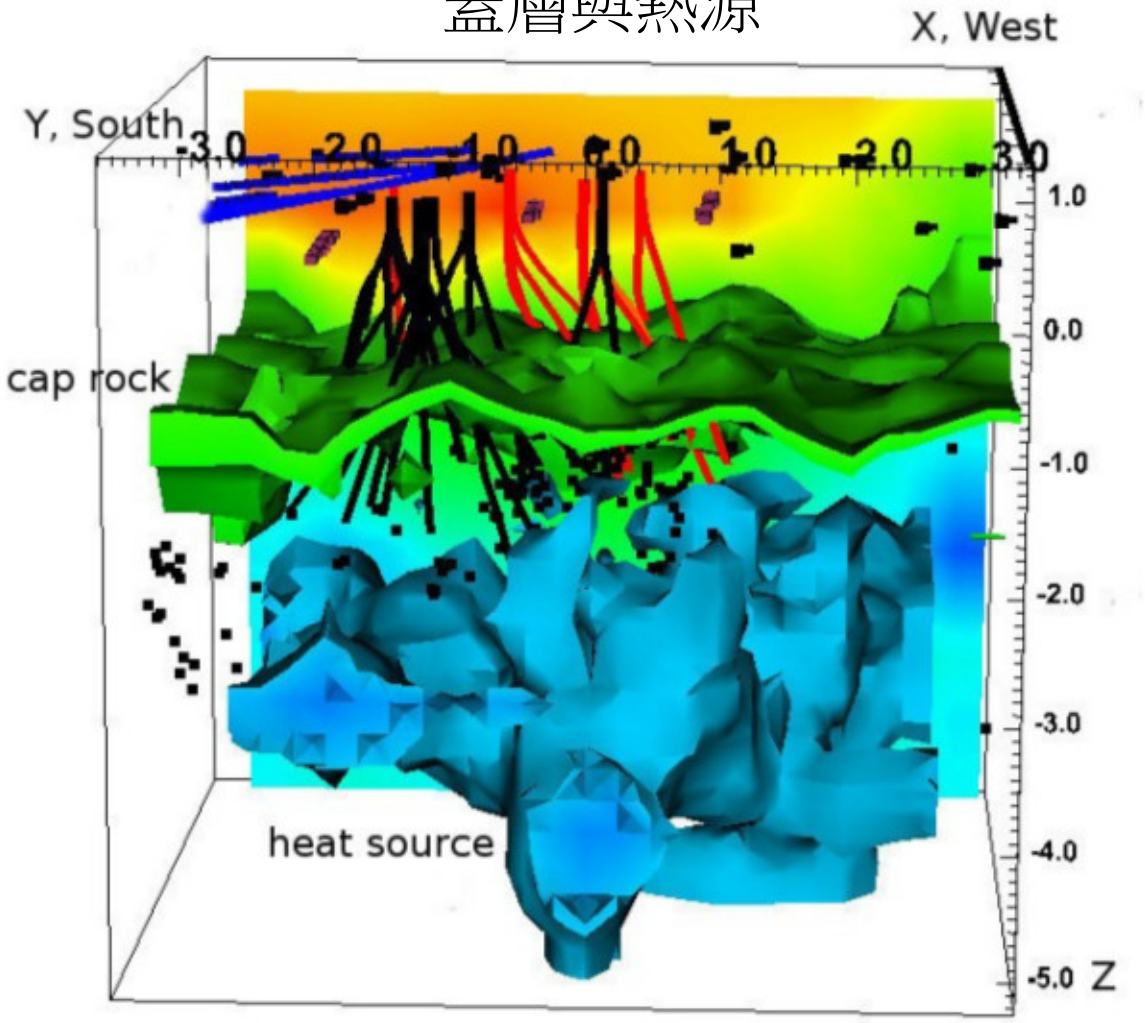
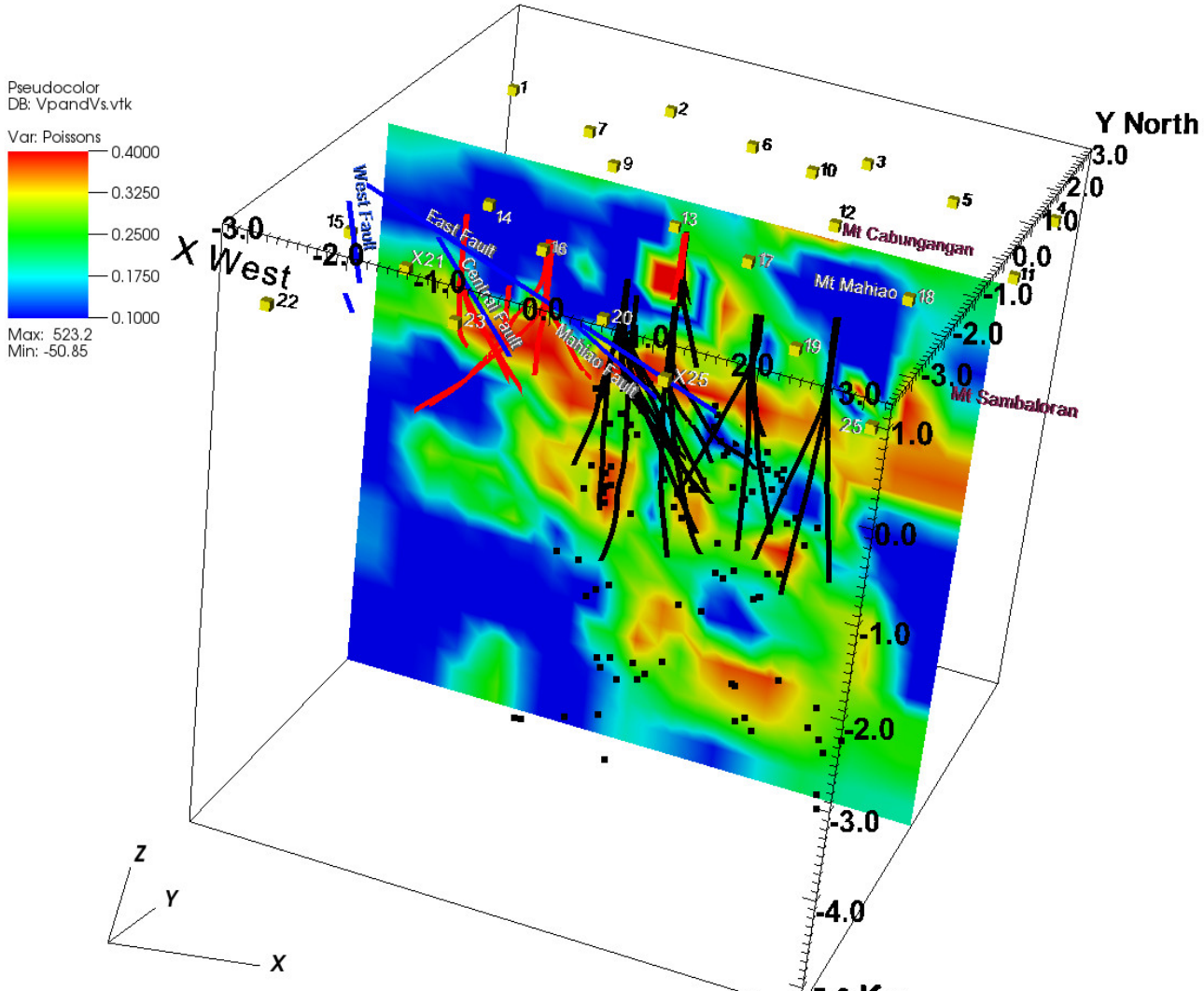


Figure 1. Cap rock and heat source

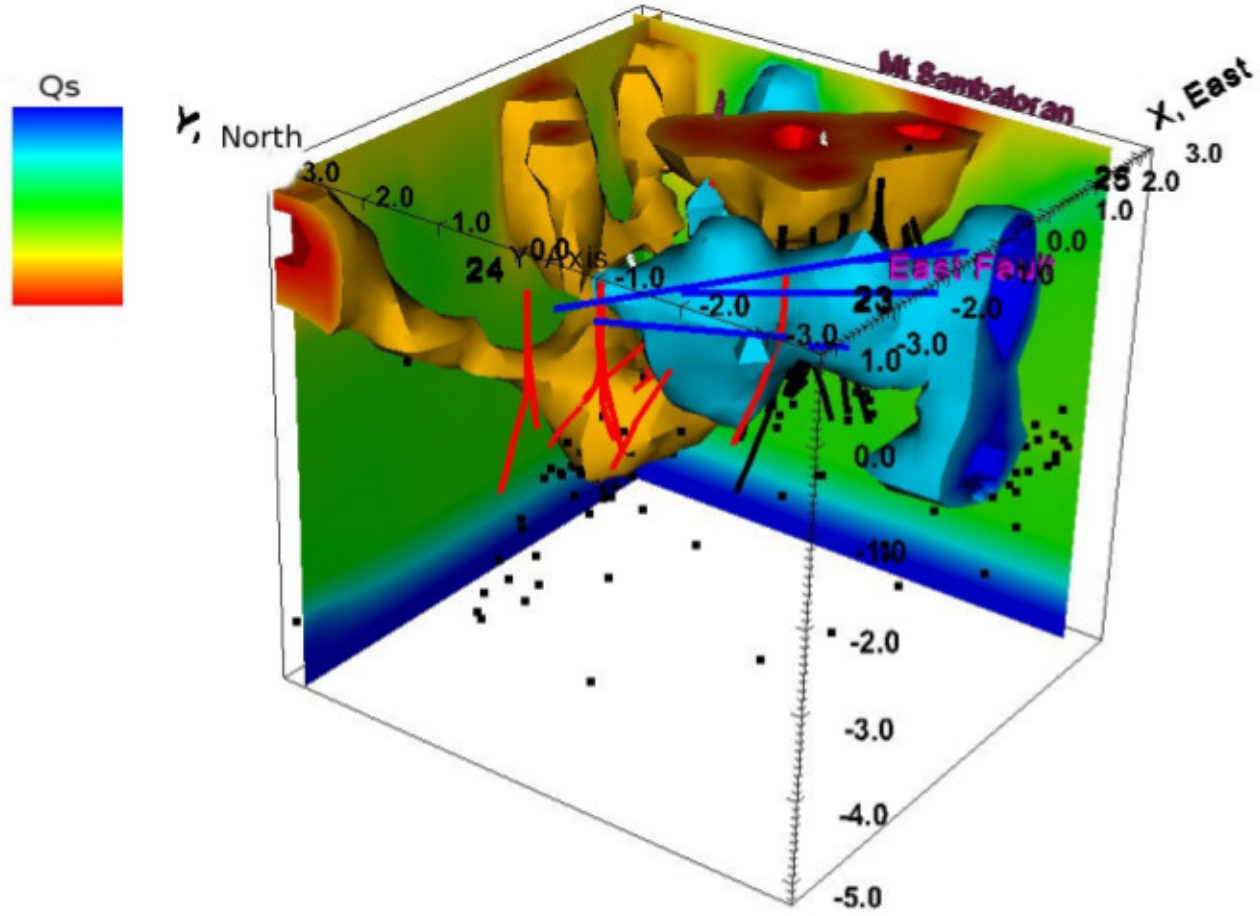
Anomaly at top of Reservoir

異常高柏松比解釋為液體存在

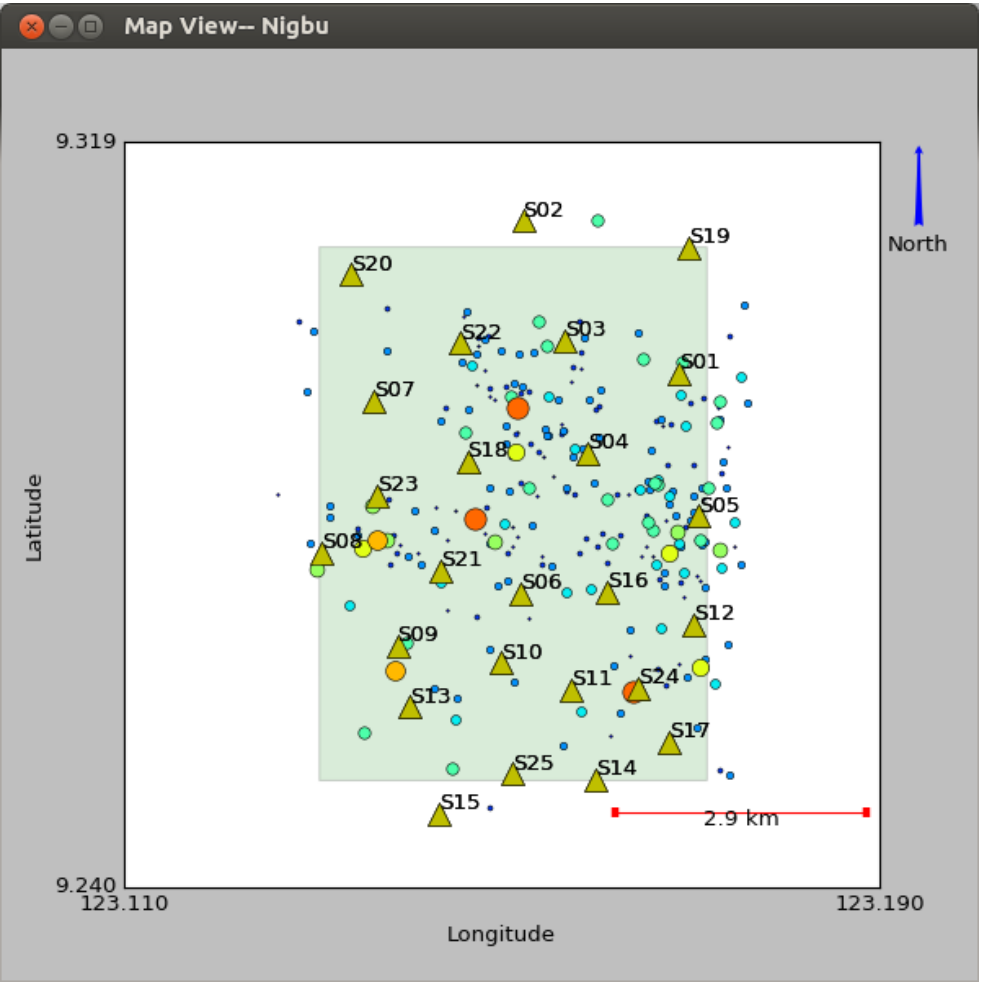


Qs observe outflow and reservoir

低Qs表示液體流出

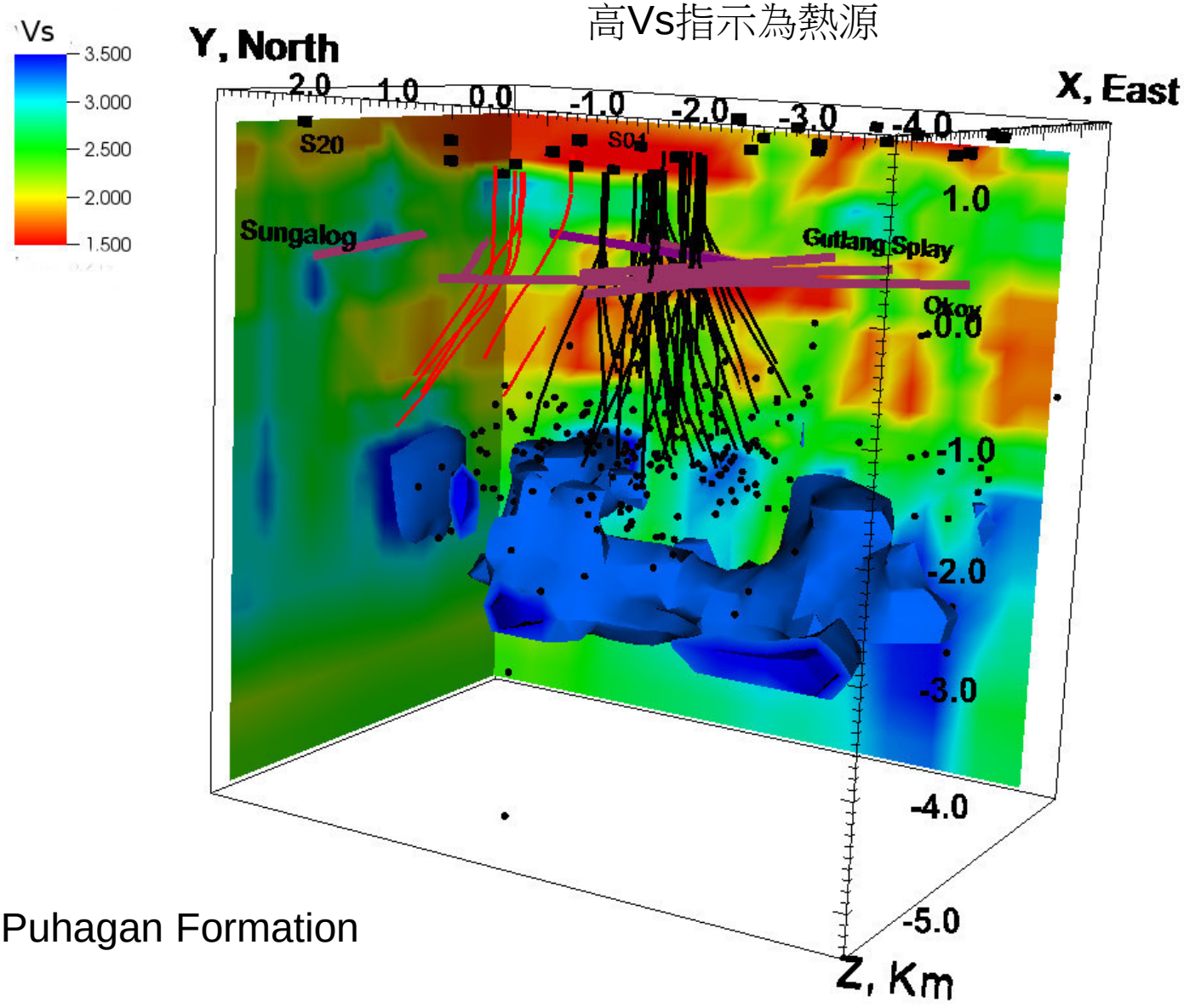


4 km x 6 km with 25 stations and 240 earthquakes



Heat Source observed by *Vs*

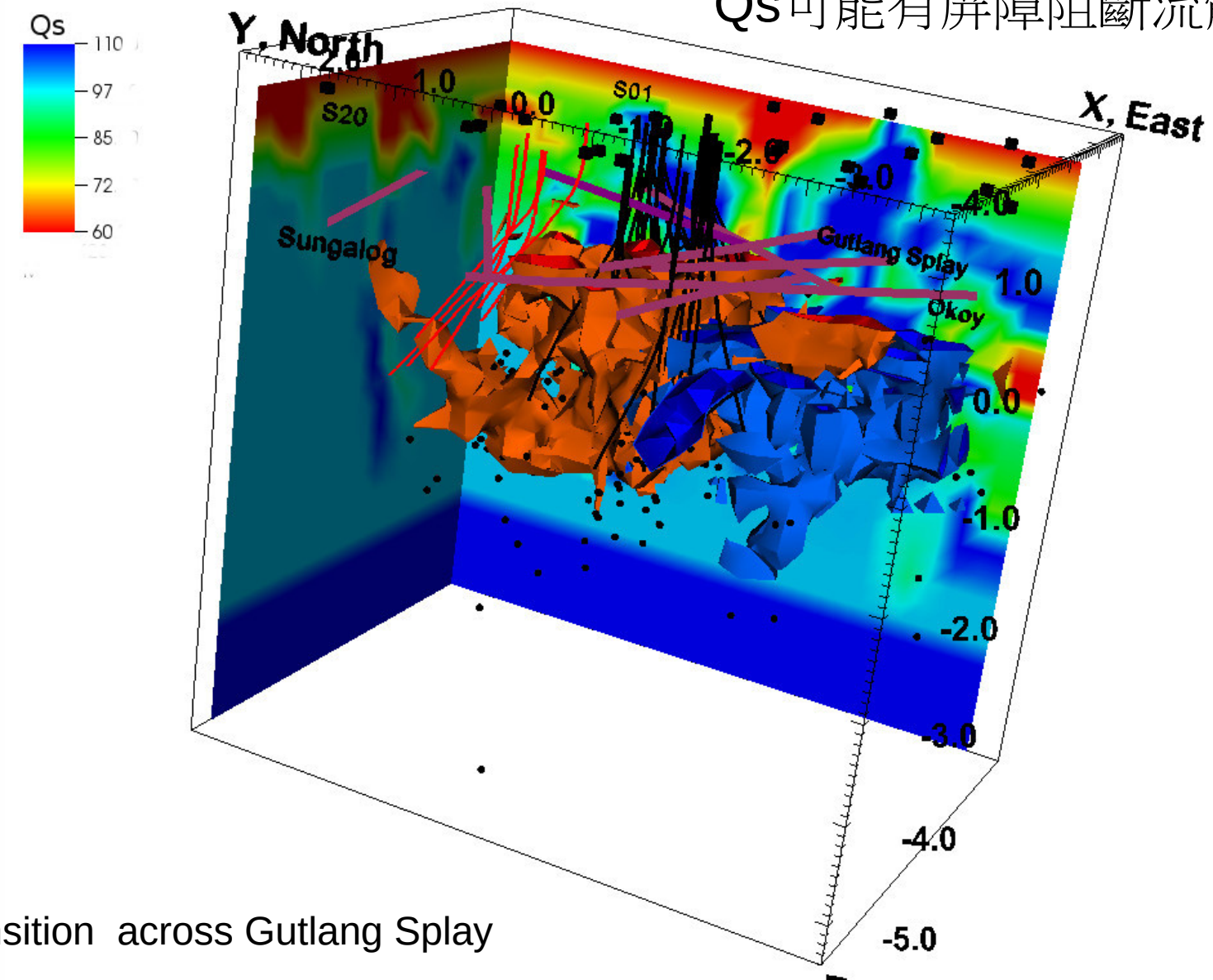
高Vs指示為熱源



Puhagan Formation

Reservoir as seen in *Qs*

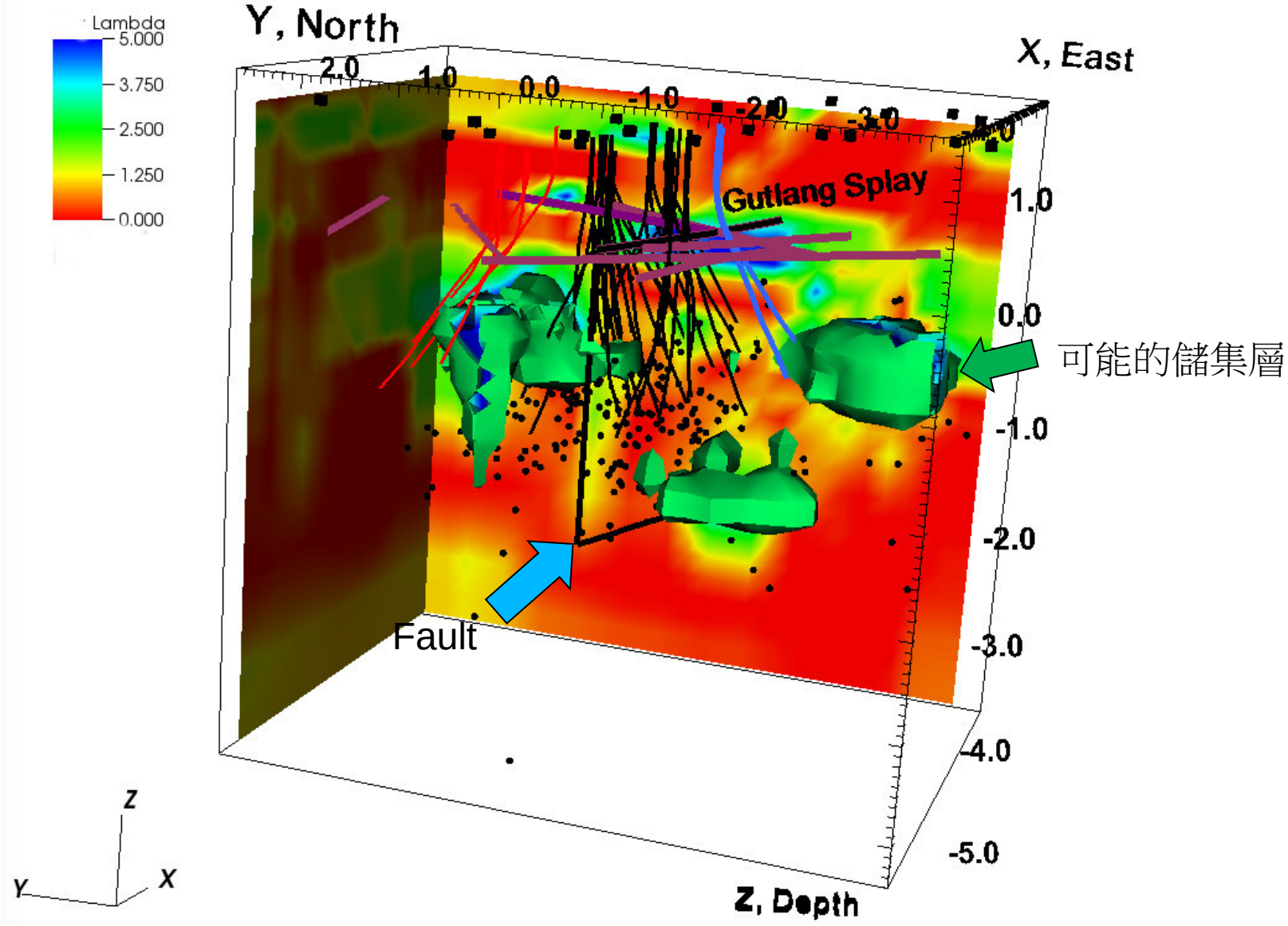
Qs可能有屏障阻斷流體流動



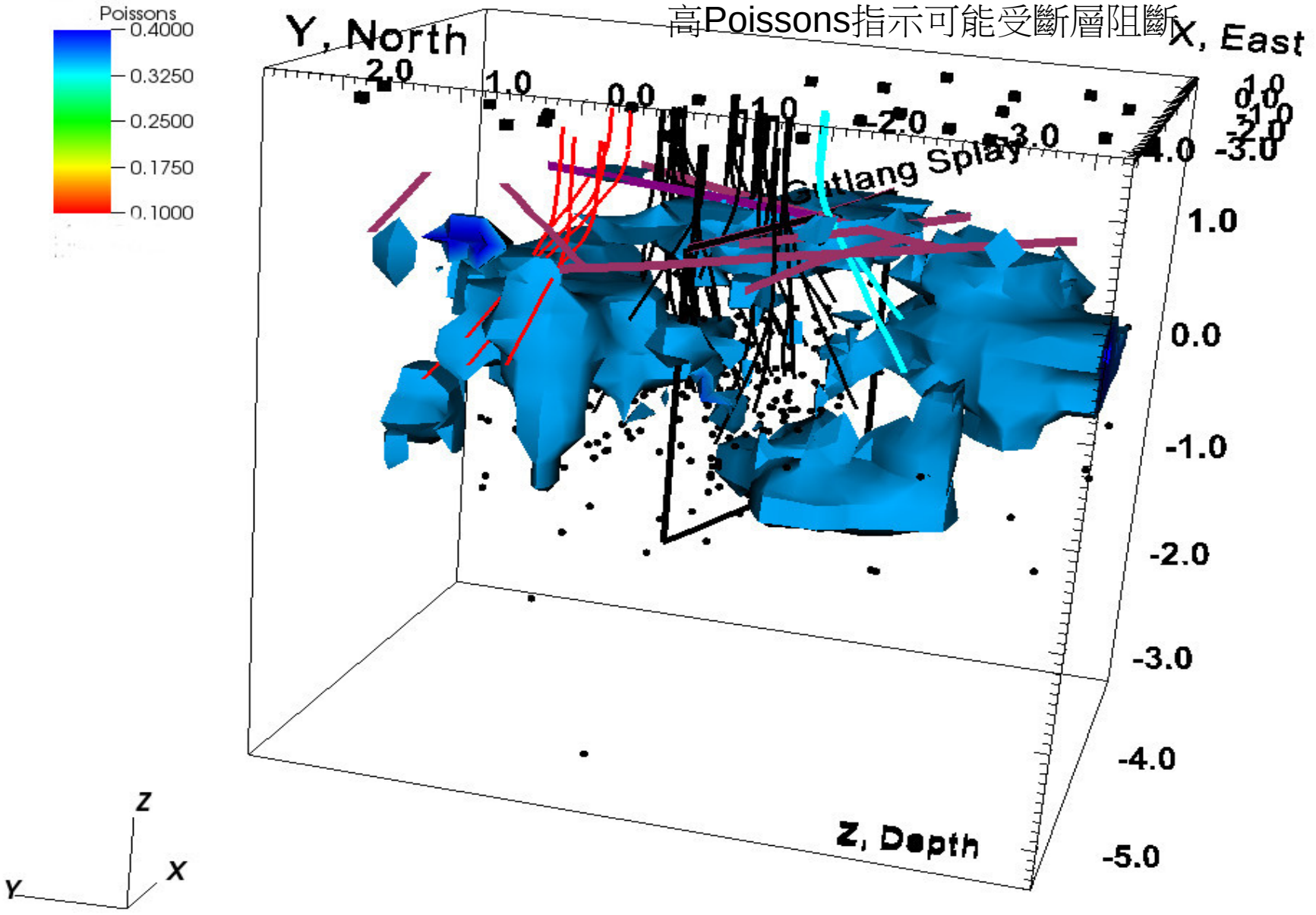
Transition across Gutlang Splay

Lambda Transition Across Gutlang Splay

高Lambda指示可能受斷層阻斷



Poisson's Ratio



Conclusions & Observations

- Improvements in data collection and processing can improve reservoir monitoring and modelling
- Reduced costs in labor and hardware for data collection
- Reduced time and labor for processing and analysis
- Allows for near-real time reservoir exploration and modeling
- Micro-earthquake data can be used to provide a basis for rock physics interpretations in geothermal fields