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Microearthquake Monitoring and Applications

Gregg Nordquist
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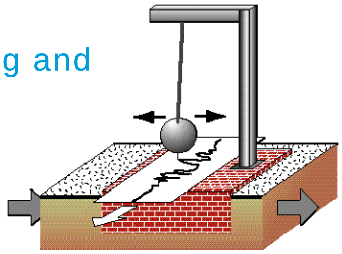
Presentation for Joint: International Geothermal Association and Indonesian Geothermal Association Workshop

Bali Indonesia April 2008

Microearthquake (MEQ) Monitoring and Applications

Gregg Nordquist



Dr. R. Uhrhammer, UC Berkeley

 DOC ID

Applications of MEQ Monitoring

- Introduction
- Applications
  - Oil and Gas
  - Engineered Geothermal Systems (EGS)
  - Other
- Conventional Geothermal
  - Salak Field, Java, Indonesia
  - The Geysers, California, USA
- The way forward – Topics of Research and Further Study
  - Array optimization for locations and sensitivity
  - Improvement of locations
  - Velocity tomography
  - S-Wave Splitting
  - Seismic moment analysis

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Can Passive Microseismic Data Be Used to Delineate a Permeable Fracture and in Targeting?

Yes

Is this routinely being applied in the "Energy Industry"?

Yes

Is this routinely being applied in the "Conventional Geothermal Industry"?

Not yet (Belum)

Why not yet in Conventional Geothermal?

Reasons include:

- Still on the learning curve
- Down hole instruments temperature stability
- Costs to implement

and

- "Its just not that easy"
  - Model resolution due to often sparse or poorly distributed data sets
  - Interpretations not always straight forward. For example, not all fractures are seismogenic, high permeable structures may not have MEQs
- But progress is being made

Passive Seismic Applications

Oil and Gas

- Water/steam flood management
- Hydrofrac monitoring
- Primary production monitoring
- Disposal and storage

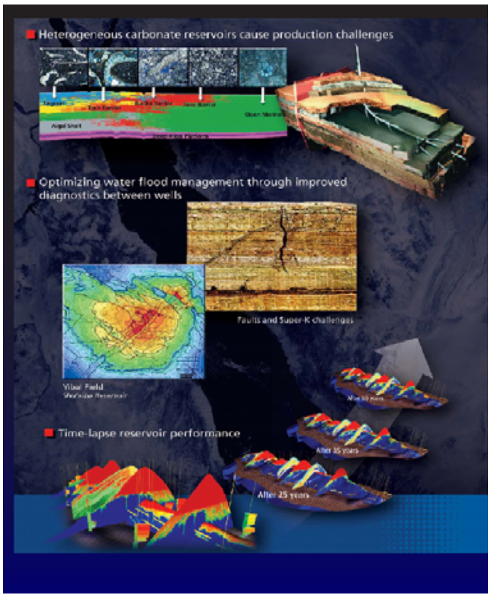
Mining

- Rock bursts

EGS (Engineered Geothermal systems)

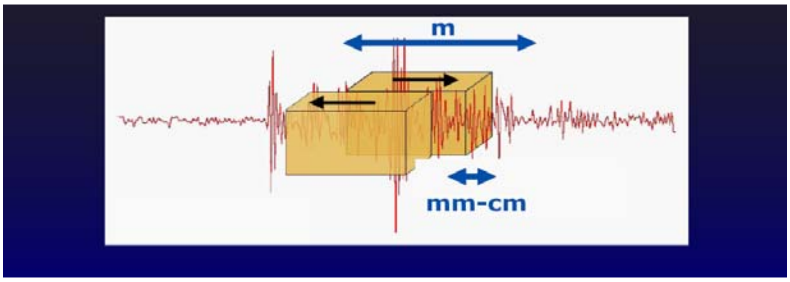
- Identify fractured volume

Conventional Geothermal



Oil and Gas - Monitoring

- Direct imaging of production, water/steam flood, and hydrofrac related micro-earthquakes (MEQ)
  - Magnitudes: -4 to 0
  - Fault size: meters
  - Displacements: mm – cm
  - Seismic frequencies: 10 – 1000 Hz



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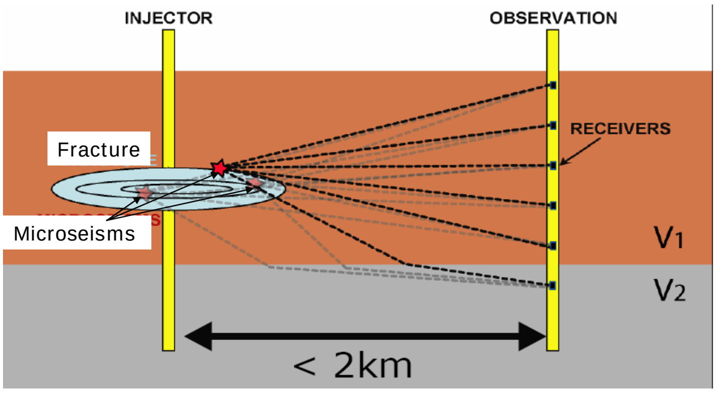
Oil and Gas – Hydrofrac monitoring



Microseisms are induced as the fracture propagates. Typically measured using a down hole array of instruments. Ideally the receivers are located above and below the zone of interest.

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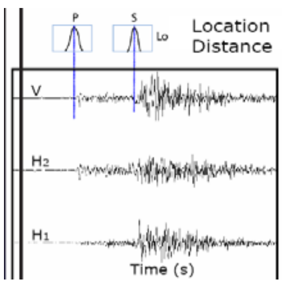
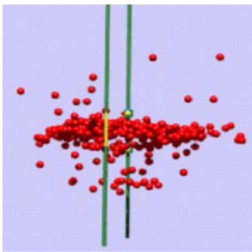
Oil and Gas – Hydrofrac monitoring

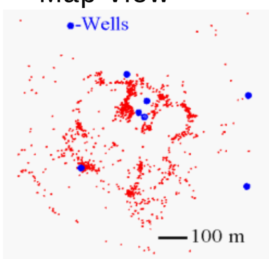
Signal



X-section view



Map view



After Maxwell, et al, 2001

Microseisms used in real time to image orientation, height, length, and temporal growth of induces fractures

Detailed post analysis of locations as well as seismic source parameter (magnitudes, stress release, etc.) may be used to infer effectiveness of fracing program.

Becoming a "common practice" major contractors engaged (Schlumberger, Halliburton, Pinnacle etc.)

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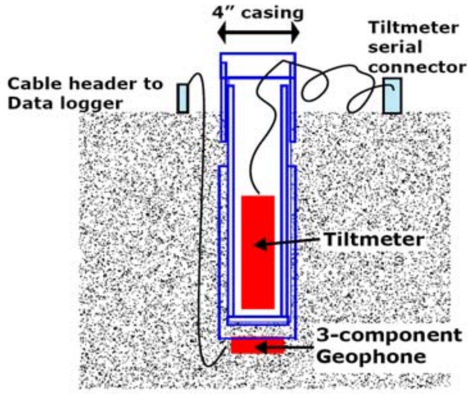
Oil and Gas – Reservoir monitoring – "Smart Oil Field" Permanent Arrays

Permanent highly sensitive monitoring arrays are now being installed around the world

Providing "real time" monitoring for field management including:

- Well/casing failures
- Fault mapping
- Fluid movements/water flood conformance
- Compaction strains
- Thermal fronts
- Fluid injection



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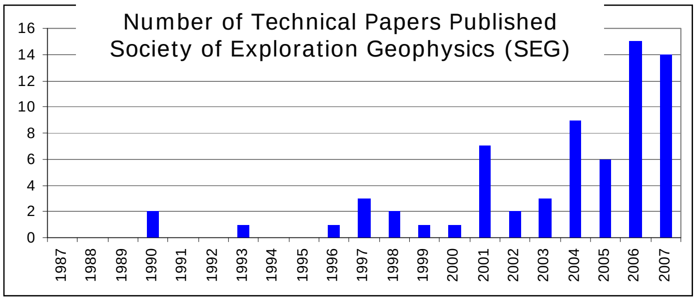
Oil and Gas – Summary

- Contractors and oil and gas companies are increasingly applying passive micro-seismic monitoring:
  - "Smart Oil Field" permanent arrays
  - Hydrofrac monitoring
- Still on the learning curve – but the levels of money and technical effort are increasing



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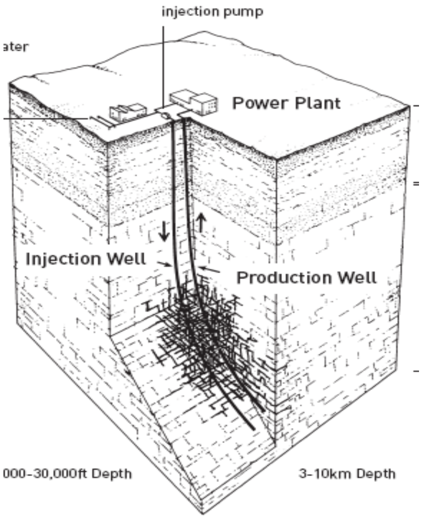
EGS (Engineered Geothermal System)

Energy is produced by extracting heat from deeply buried hot rocks by circulating water or other working fluid through an engineered, artificial reservoir or underground heat exchanger.

Reservoir is stimulated to improve permeability. Passive seismic monitoring is used to map the extent of stimulated volume.



After Tester et al, 2006

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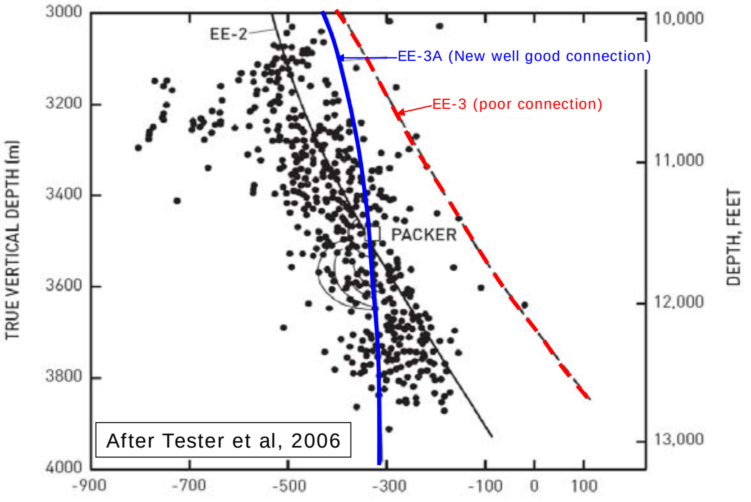
EGS (Engineered Geothermal System)



After Tester et al, 2006

Experience from Fenton Hill, USA showed well targeted into microseismic clusters encountered improved permeability.

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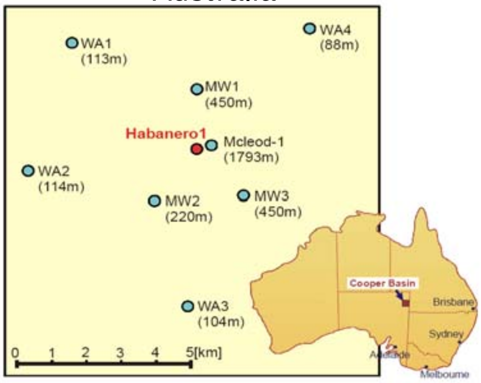
EGS (Engineered Geothermal System)

Seismic Array at Cooper Basin Australia

Monitoring of the fracture system during stimulation requires high sensitivity. Down hole sensors are typically installed to improve location resolution and to lower the detection limit.



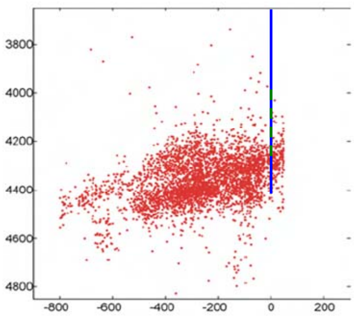
Red is stimulation well, blue are location and depths of sensors

After Asanuma et al, 2005

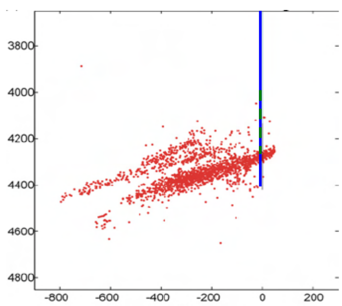
EGS (Engineered Geothermal System)

Application of Precision Relative Event Location Example from Cooper Basin Stimulation

Single Event Location



Double Difference



After Kumano, et. al, 2006

Double difference tightens up clusters of events allowing for definition of discrete areas which have been stimulated. This allows operators to better target and optimize the location of production wells.

EGS (Engineered Geothermal System) - Summary

- High definition MEQ monitoring is a Best Practice
  - Provides best available "picture" of the fractured reservoir
  - Production wells are targeted into MEQ clusters
- Implementation of precision relative event location algorithms such as "cluster analysis" and "double difference" improves resolution
- High stimulation injection pressures can result in felt events
  - Basel (magnitude 3.4) stopped project
  - Soultz felt events have delayed project

Other Applications – Microseismic Monitoring

- Monitoring of waste disposal
  - Ensure waste fluid or cuttings injections are going into target zones
- Mining
  - Used to determine if safe for miners to work underground
  - Mature technology

and

Conventional Geothermal

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MEQ Monitoring and Conventional Geothermal - Topics

- Introduction and Basics
- MEQ Monitoring Examples
  - Salak Field, Java, Indonesia
  - The Geysers, California, USA
- The way forward – Topics of Research and Further Study
  - Array optimization for locations and sensitivity
  - Improvement of locations
  - Velocity tomography
  - S-Wave Splitting
  - Seismic moment analysis

Passive Seismic Monitoring Conventional Geothermal

Injection

- permeability pathways
- injection management

Production

- distribution of reservoir permeability
- resource boundaries

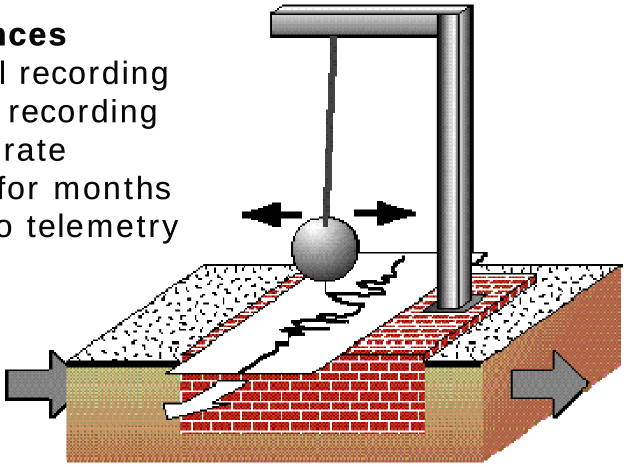
Hazard and Environmental

- civic responsibility

The Seismograph

Recent advances

- 24-bit digital recording
- Stand-alone recording systems operate unattended for months without radio telemetry



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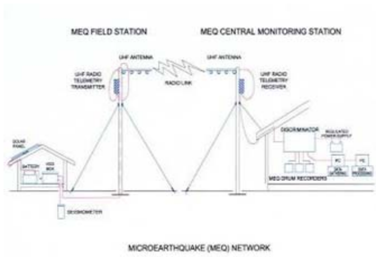
Passive Seismic Monitoring Systems

Telemetry or Hardwire

- Plus
  - Real time processing
  - One part time person can process
  - Costly
- Negative
  - Station deployment can be difficult
  - Line of site issue

Digital stand alone

- Plus
  - Station deployment easy/flexible
  - Easy to maintain
  - Relatively low cost
- Negative
  - No real time processing
  - Requires more manpower



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Induced Earthquakes Conventional Geothermal

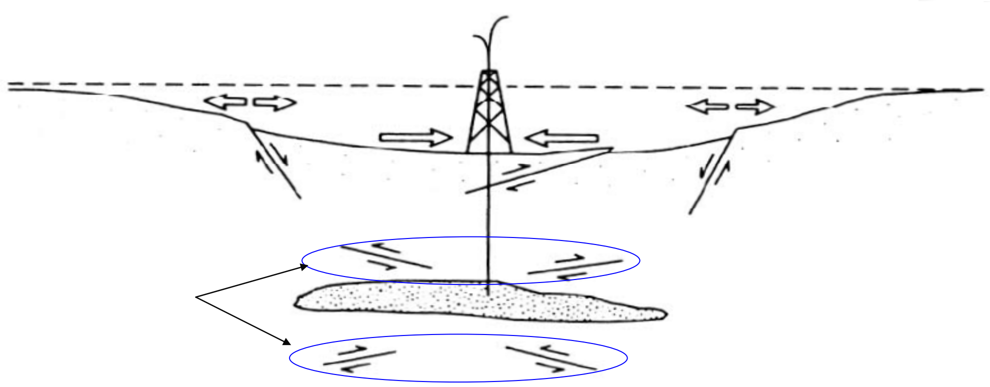
Induction Mechanisms

- Compaction related to pressure draw down
- Pressure and temperature changes

Located on pre-existing faults and fractures

- Compaction induced MEQs occur at or near margins of the reservoir
- Production induced MEQs occur along fractures connected to reservoir
- Injection induced MEQs along fractures connected to injectate pathway
- Majority of MEQs are too small to be felt at the surface, but there are "felt" events on occasion. The largest magnitude earthquake reported has been a M4.6 recorded in The Geysers in the mid 1980's.

Compaction and Seismicity Related to Pressure Drawdown due to Production



Increased stress may induce earthquakes at the margins of the compacting reservoir

After Segall and Fitzgerald, 1998

Seismicity Induced by Injection Pressure Increase

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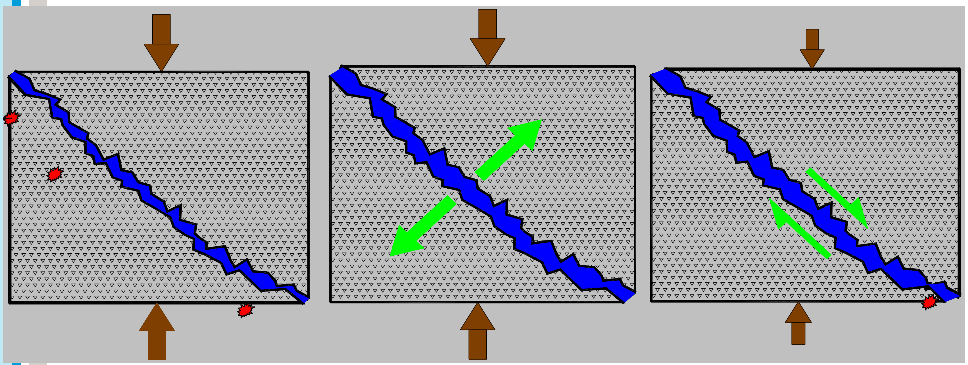
Explains earthquakes due to injection pressure increase which is below the frac pressure at which the rock fails.



Fracture stressed but locked by asperities | Increase in pore pressure drives fracture surfaces apart | Fracture surfaces slip until stopped by asperities

from Stark 2007 after Mossop and Segall 2004

Seismicity Induced by Cold Injection Cooling High Temperature Rock

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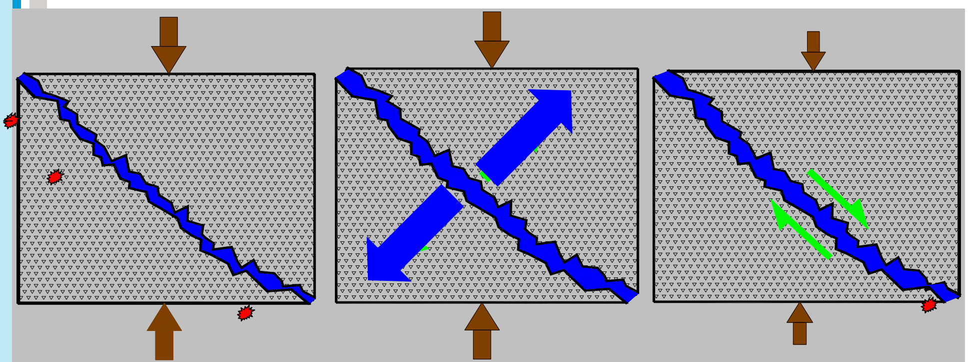
Explains earthquakes caused by rock shrinkage related rock shrinking due to cold injection chilling hot geothermal reservoir rocks.



Fracture stressed but locked by asperities | Increase in pore pressure drives fracture surfaces apart | Fracture surfaces slip until stopped by asperities

from Cumming 2008 after Stark 2007

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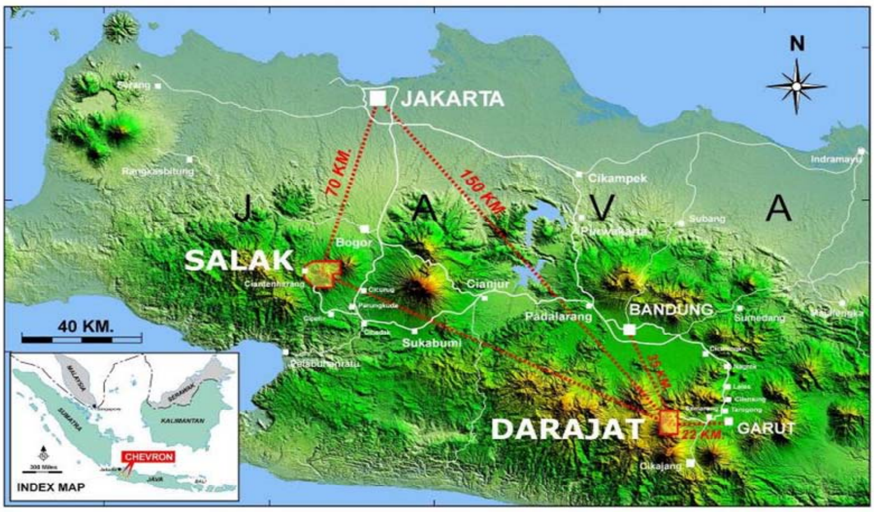
Conventional Geothermal Passive Seismic Monitoring Example

Salak Geothermal Field Indonesia

Salak Geothermal Field, West Java



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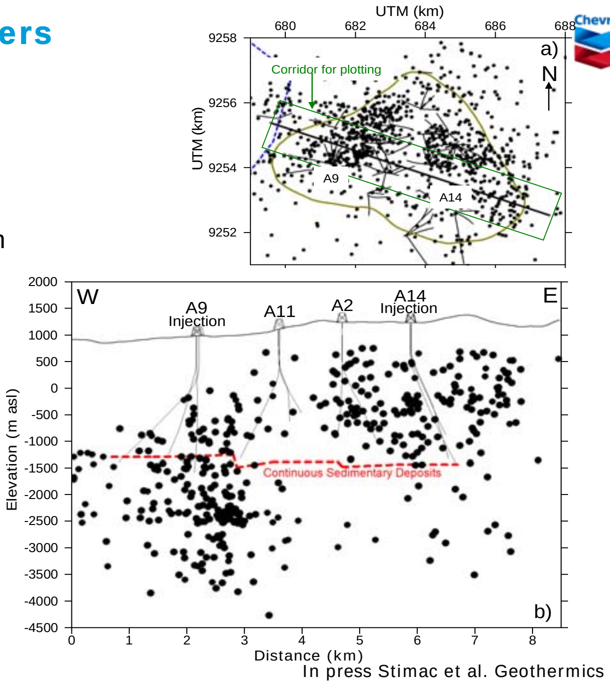
MEQ Epicenters Salak

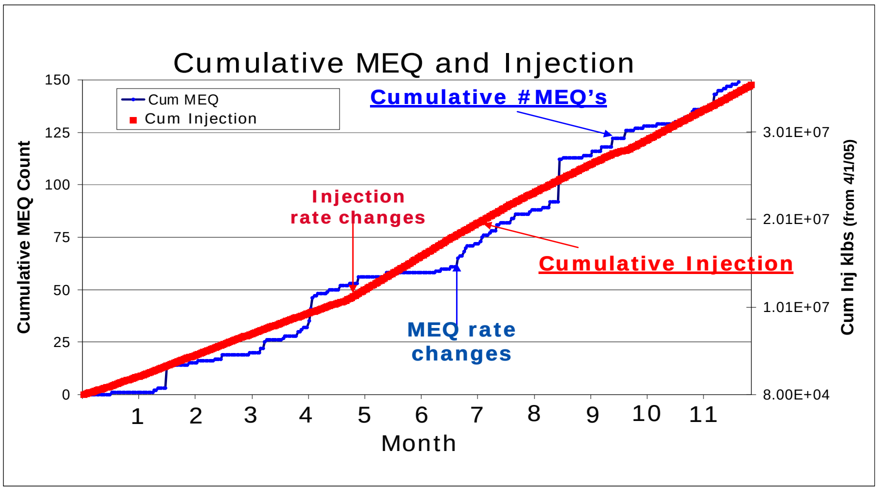
Majority of MEQ activity can be attributed to injection

Beneath A9 the deeply extending MEQs are located over an interpreted up flow zone. An area where locally enhanced vertical permeability is expected



In press Stimac et al. Geothermics

Injection monitoring



Rate of MEQ activity increased about 2 months after injection increased

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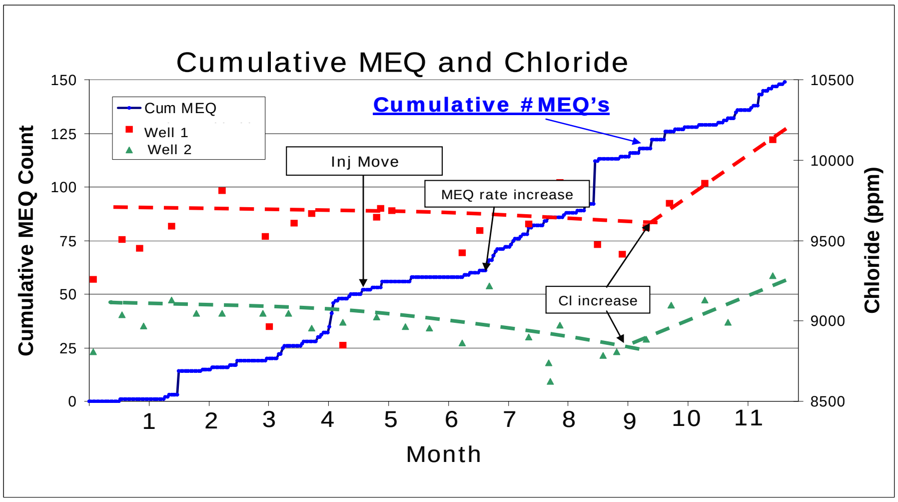
Injection Monitoring – MEQ and Chloride

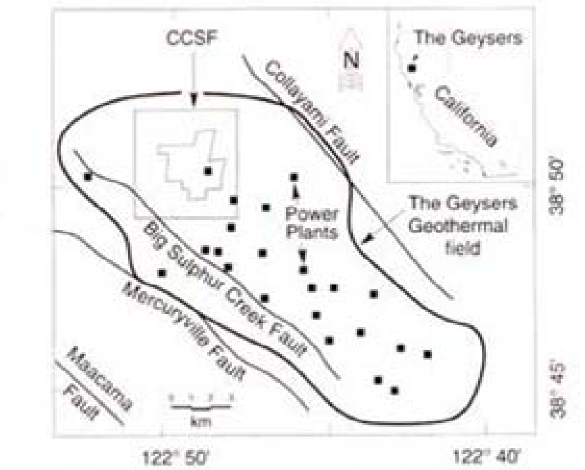


Chloride increases about 2 months later
(4 months after injection moved)

Conventional Geothermal
Passive Seismic Monitoring Example

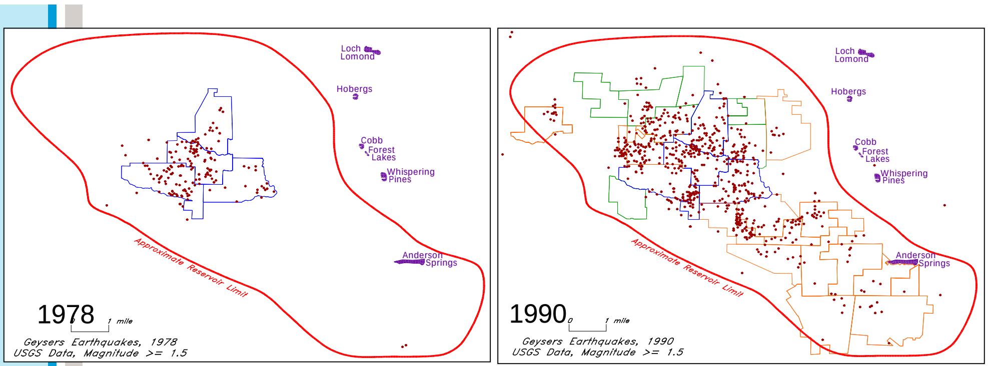
The Geysers Geothermal Field
California, USA

The Geysers Field California



After Romero, et al, 1995

The Geysers Field – MEQ Patterns as Field is Developed



Reservoir Limit (red outer line), microearthquakes (brown dots) and developed areas (multicolored lines)

After Eberhart-Phillips and Oppenheimer (1984)

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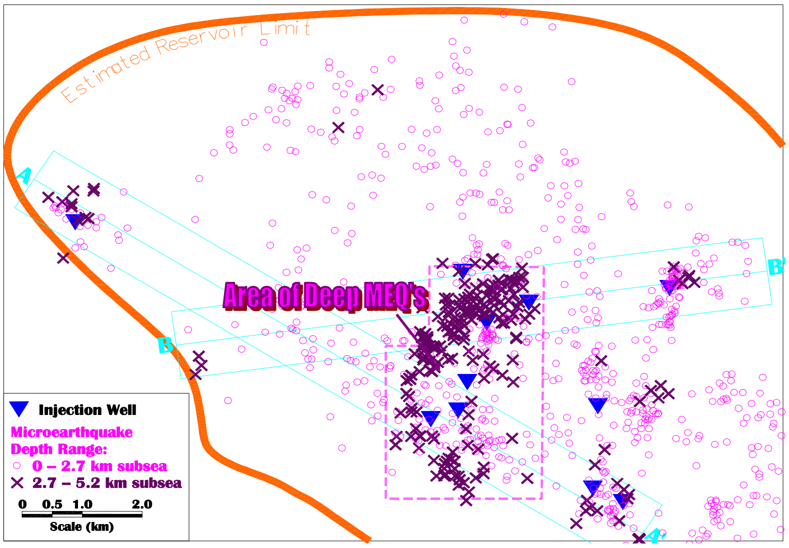
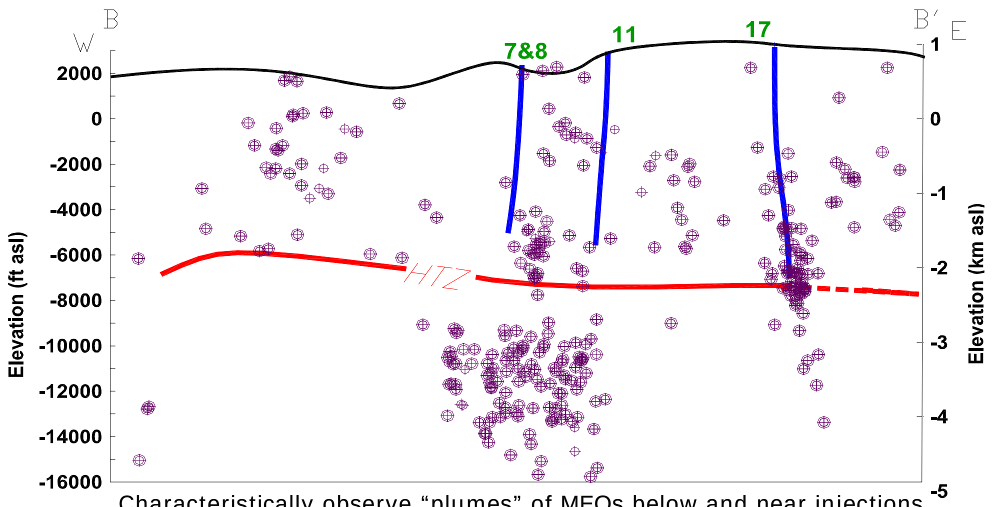
The Geysers Field – Reservoir Limit



Reservoir Limit Outside of Production defined by Well Pressure and MEQ Distribution (pers comm. M. Stark, Cal Pine, 2007)

Courtesy M. Stark, 2007

The Geysers Field – MEQs and Injection



Characteristically observe "plumes" of MEQs below and near injections wells (injection wells outline with blue – production wells are not shown).

Courtesy M. Stark, 2007

Summary – Case Histories

- Companies are getting "value" out of their MEQ monitoring efforts. Patterns of MEQs are used to:
  - Infer reservoir structure outside of drilled area
  - Monitor injection movement
- There is more that can be done to further add to the value of passive microseismic monitoring
  - – next slide please!

Conventional Geothermal - MEQ the Way Forward and Research Topics

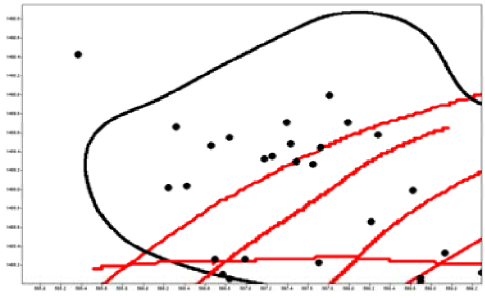
- Array sensitivity and optimization
  - Station location
  - Down hole and surface seismometers
- Improved location resolutions
  - Uncertainty analysis
  - Cluster analysis
  - Precision relative event locations (eg double difference)
- Velocity and Attenuation tomography
  - Improved resolution of velocity structure
  - Possible 4-D application (changes with time)
- S-wave splitting
  - Fracture trends and density
- Seismic moment analysis
  - Fracture and stress release characteristics

Sensitivity and Array Design

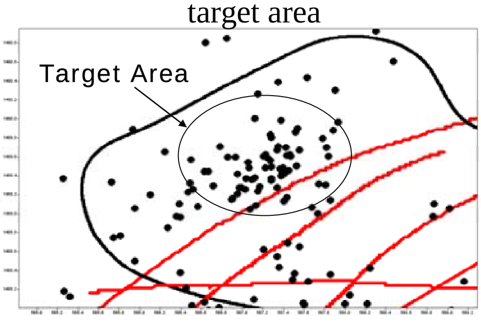
- 24 bit instruments
  - Costs coming down, easy to operate and maintain
- Commercially available software
  - Robust event detection and processing software is available. Companies have option to operate own arrays (lowers costs)
- Array optimization for location and sensitivity
  - Array design for focused monitoring
    - Locate instruments for best resolution
  - Downhole sensors where practical and possible

Focused Monitoring Improves Sensitivity
(example from Tiwi Field – Philippines)

Field Wide Array 10 stns monitoring entire field

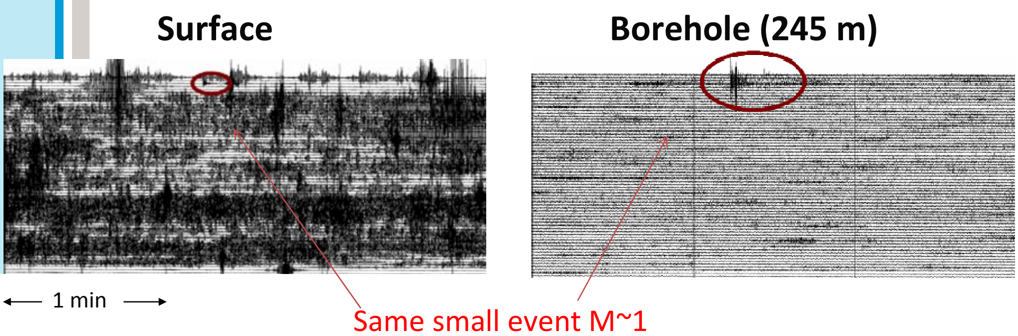


Focused Array 12 stns focused around target area



- Focused Array was ≈ 5 times more sensitive in target area
- MEQ locations more accurately determined

Down hole sensors can lower noise and improve array sensitivity



Station located near a road. Down hole instrument not as impacted by surface noise. Easier to identify and more accurately pick event phases. Able to further amplify signal from the downhole instrument to lower detection level. But going downhole adds expense.

(Courtesy Uni of Auckland IESE)

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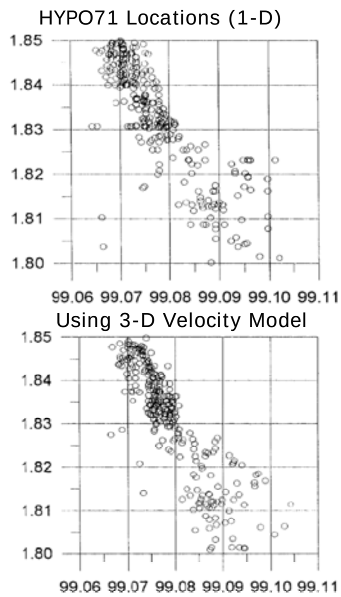
Improved absolute locations

Improved resolution of the velocity structure results in more accurate locations and better clustering of events



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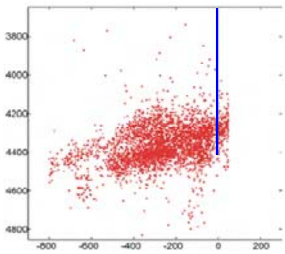
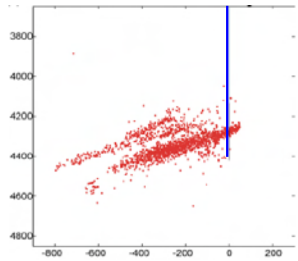
Precision relative locations

Precision relative locations determined with techniques such as double difference and cluster analysis can improve resolution of structures.

Single Event Location

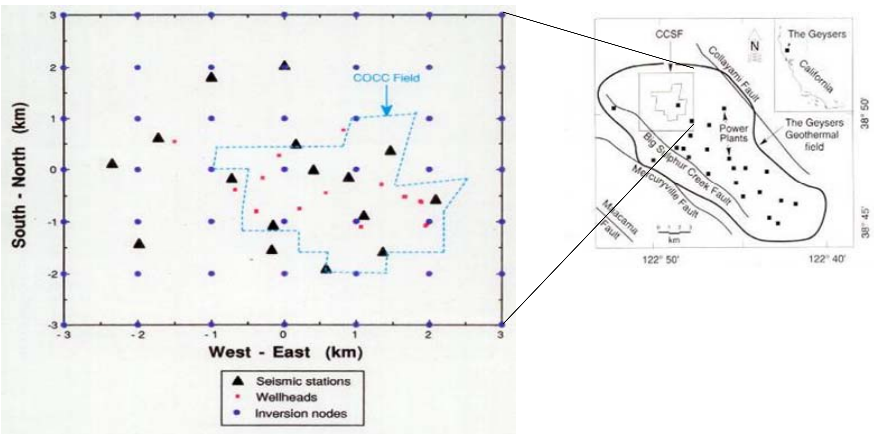


Double Difference



Asanuma et al 2007

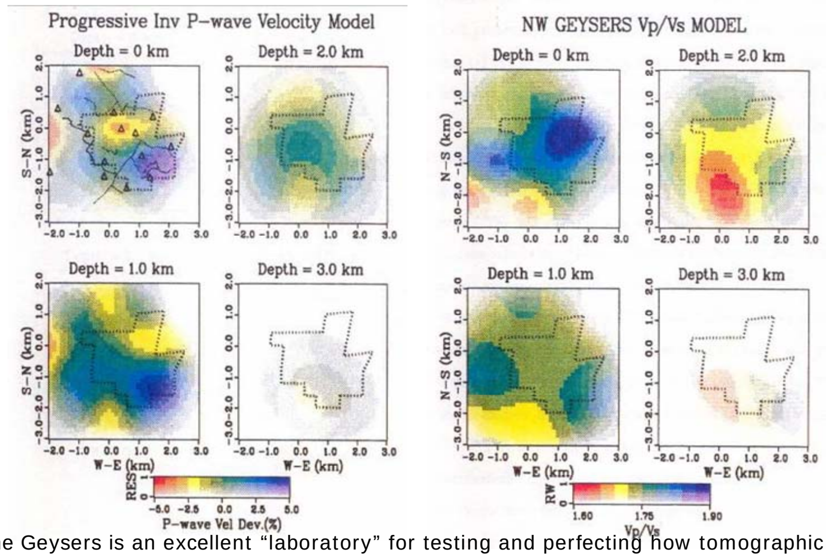
Tomographic Inversion – NW Geysers



Tomographic inversion provides a 3-D image of the velocity and attenuation structure. Resolution depends on the lateral and depth distribution of the MEQs. Typically this is not ideal and resolution and the level of uncertainty can be high.

After Romero, et al, 1995

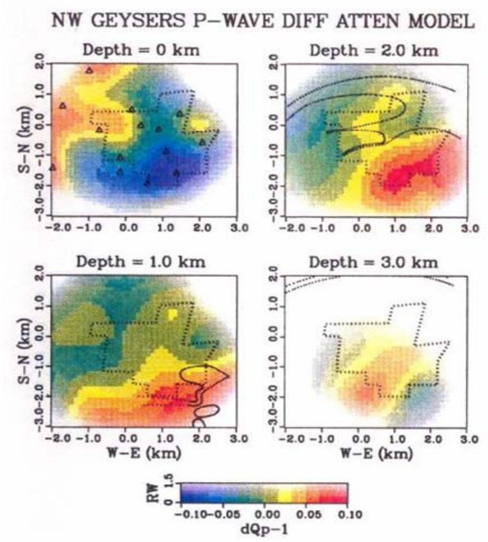
Tomographic Inversion – NW Geysers



The Geysers is an excellent "laboratory" for testing and perfecting how tomographic imaging can be applied in Geothermal. Researchers are working with field operators to test if changes with time can reliably resolve and detect saturation changes related to increased injection and help with field management decisions.

After Romero, et al, 1995

Attenuation Structure – NW Geysers



Seismic tomography can be applied to study the attenuation structure. When integrated with other data including the velocity structure (eg Vp/Vs) can highlight areas of higher relative fracture densities and changes in saturation.

After Romero, et al, 1996

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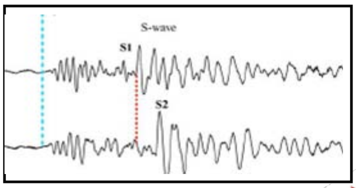
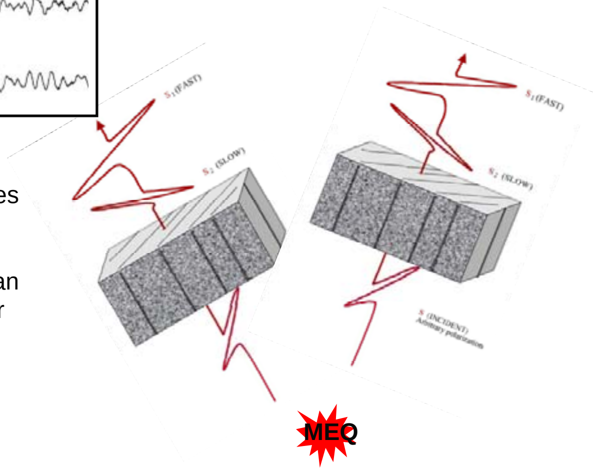
S-wave splitting

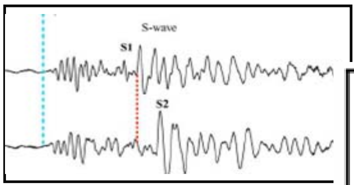


Cracks or layering causes S-wave polarization aligned with cracks or layers to travel faster than S-wave across cracks or layers. The difference in time and direction of polarization is recorded.



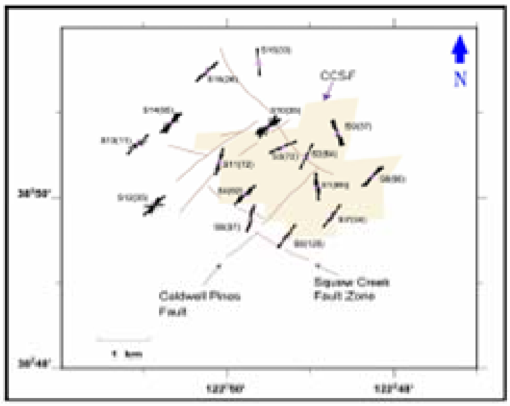
From Cumming, 2008 after Rial et al. 2005

S-wave splitting - Direction



The S-wave polarization alignment can be plotted for each station. For example, at the NW Geysers the polarization indicates micro-cracks are aligned NE, consistent to that observed in cores.

NW Geysers
Rose Diagrams

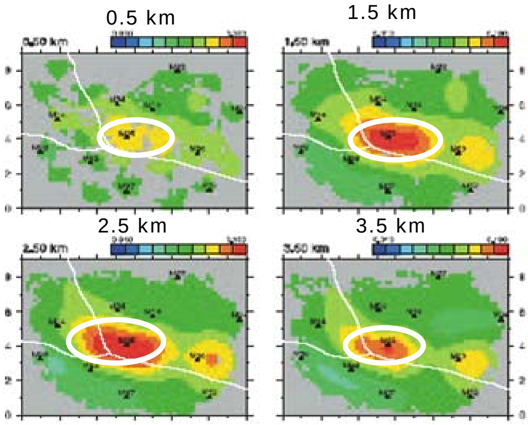


After Elkibbi and Rial 2003

S-wave splitting – Casa Diablo, California

High S-wave splitting (red) below area of Casa Diablo geothermal wells (white oval). The very permeable shallow outflow that is being produced by the wells is 1000 to 2000 m above this zone.

Interpreted Crack Density

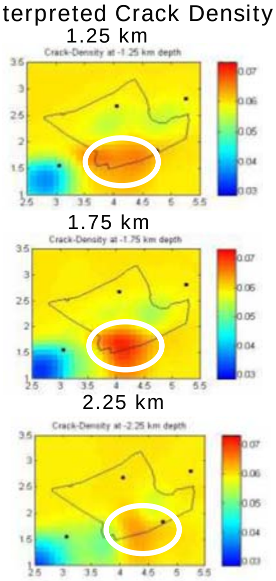


After Malin and Shalev 1999

S-wave splitting – Example 2

High S-wave splitting (red) in depth range of 1.25 to 2.25 km. Area shaded red is interpreted as high fracture density. This interpretation highlighted an area for the fields operator to investigate further and possibly target a well.

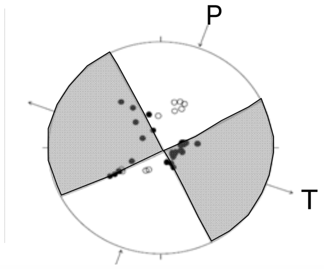
Interpreted Crack Density



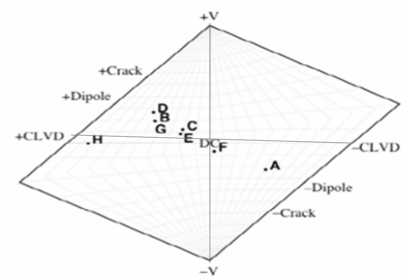
Courtesy: IESE, Uni. Of Auckland

Seismic Source Process Analysis

Focal Mechanism show nature of shear failure. Used to determine fault movement and principle stress directions



Seismic moment analysis can provide information on the relative strengths of the 3 orthogonal force dipoles.
Can identify non shear failure such of dilation and collapse



After Pramono et al, 2005

Summary

- Conventional geothermal companies are monitoring MEQ data to track injection and to infer reservoir boundaries and structures.
- MEQ monitoring in the Oil and Gas industry is increasing. The geothermal industry can benefit from their lesson's learned.
- But must be realistic: Hot water is not as valuable as oil. Budgets for application and testing are lower
  - Need to be creative to get the data and stay in budget
    - Stand alone recording systems for example
- Data – The more the better
  - Continuous or long term monitoring
  - Improve the sensitivity with optimized deployment of instruments and sensors
    - Balance of costs vs benefits (for example: number of stations and surface vs borehole sensors)
    - Temperature limitations of sensors
  - A well constrained and well distributed data set of MEQ data improves the chances of success of applying such techniques as time difference velocity tomography and S-wave splitting
- Interpretation - Integrate with other available data and "ground truth" results

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