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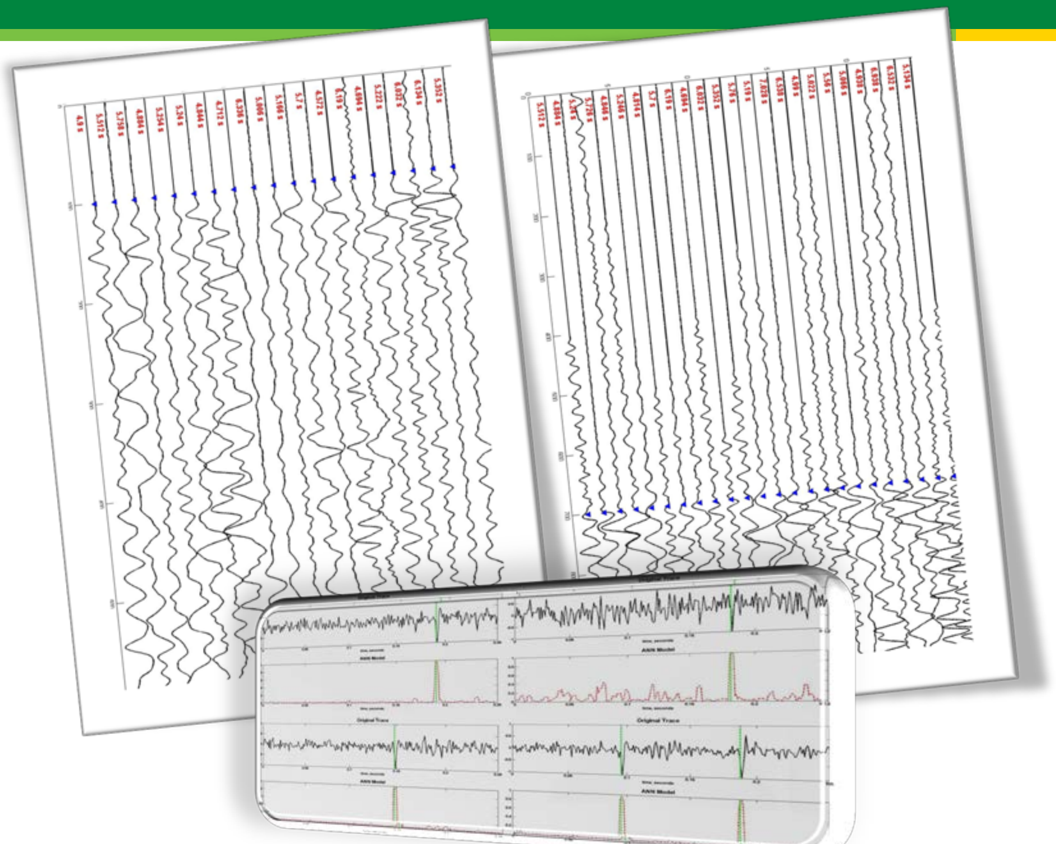
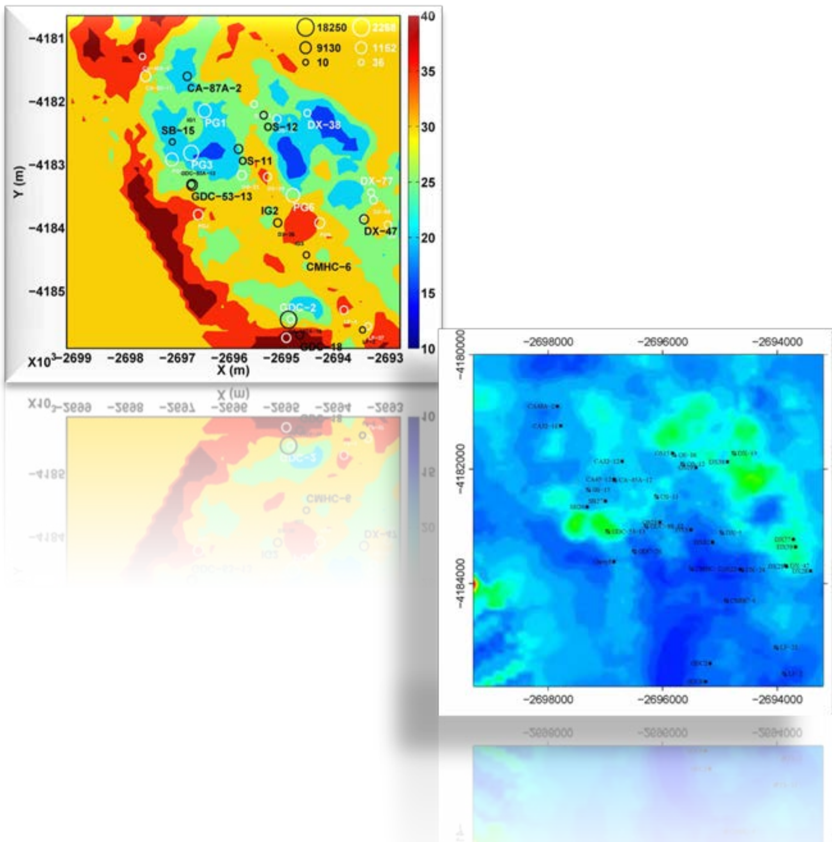

Sample trace with trained model output



Characterizing Fractures in the Geysers Geothermal Field by Micro-seismic Data, Using Soft Computing, Fractals, and Shear Wave Anisotropy

Project Officer: xx
Total Project Funding: $2,150K
April 23, 2013

Fred Aminzadeh
University of Southern California

DOE Grant DE-FOA-0000075-23

Relevance/Impact of Research

Challenges we address	Project Impact	Innovative Aspects
Efficient Use of MEQ Data	Auto-picker	Soft Computing
Triggered vs induced seismicity.	Fracture Mapping	Fractal Dimensions
Hot dry rock fracture regime	Monitoring Fluid/Temp	Dynamic Velocity field
Fracture Direction / Type	Correlating fracture & V	Azimuthal Velocity /Rock property

Contribution to Geothermal Technologies Program

Better use of MEQ data and its analysis will help better understanding of the fracture system and how it is changing with time as a results of injection and production

Scientific and Technical Approach

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ANN autopicker

- Use noise based classification for fuzzy segmentation and hybrid Neuro-fuzzy autopicking
- Improved applicability and efficiency

Fractal Analysis

- Find the correct fractal dimension of seismicity distribution
- Map the fractal structure of the fracture network from MEQ data
- Correlate "b" value with fractal dimension
- Investigate the triggered versus the induced seismicity

Velocity Modeling

- Velocity and stress anomalies comparing with production/injection data confirmed application of tomographic inversion for fracture characterization

Rock and fracture property mapping

- Map rock properties and correlate them with fracture properties to investigate the type and distribution of fracture network.

Anisotropy mapping

- Azimuthal polarization verified from all stations for multiple events, orientation and density mapped for the station locations. Studied the seismic effects of changing crack populations at The Geysers, particularly shows the results independent of fluid content.

Accomplishments

- ➢ Developed a new neural networks first arrival auto-picker for MEQ data and validated its superior performance against other picking programs. Implemented a noise based segmentation approach to validate the requirement for Neuro-fuzzy approach to autopicking
- ➢ Confirmed the induced (as opposed to triggered) nature of seismicity at the Geysers field from the b values and the fractal dimensions of MEQ's
- ➢ Based on the raw velocity fields generated by our project partners at LBNL, developed a smooth velocity, stress, and rock property field by Kriging and analyzed the changes in velocities with time to establish the impact of high temperature fluid movement in the rocks on the velocity field.
- ➢ Derived rock and fracture properties to identify the fluid flow type and monitor changes in reservoir
- ➢ Extend the simplification from the elastic moduli, useful in elastic wave propagation, to the elastic compliances anisotropy. This study will lead us to better the interpretation of that velocity field. Studied the seismic effects of changing crack populations at The Geysers, particularly shows the results independent of fluid content.

Challenges

- ➢ Ability to perform data transfer, formatting and software engineering across different platforms: Matlab, Zmap, RGRAP, OpendTect and SGeMS
- ➢ MEQ data quality and consistency of velocity estimates using seismic events of different size

Workflow

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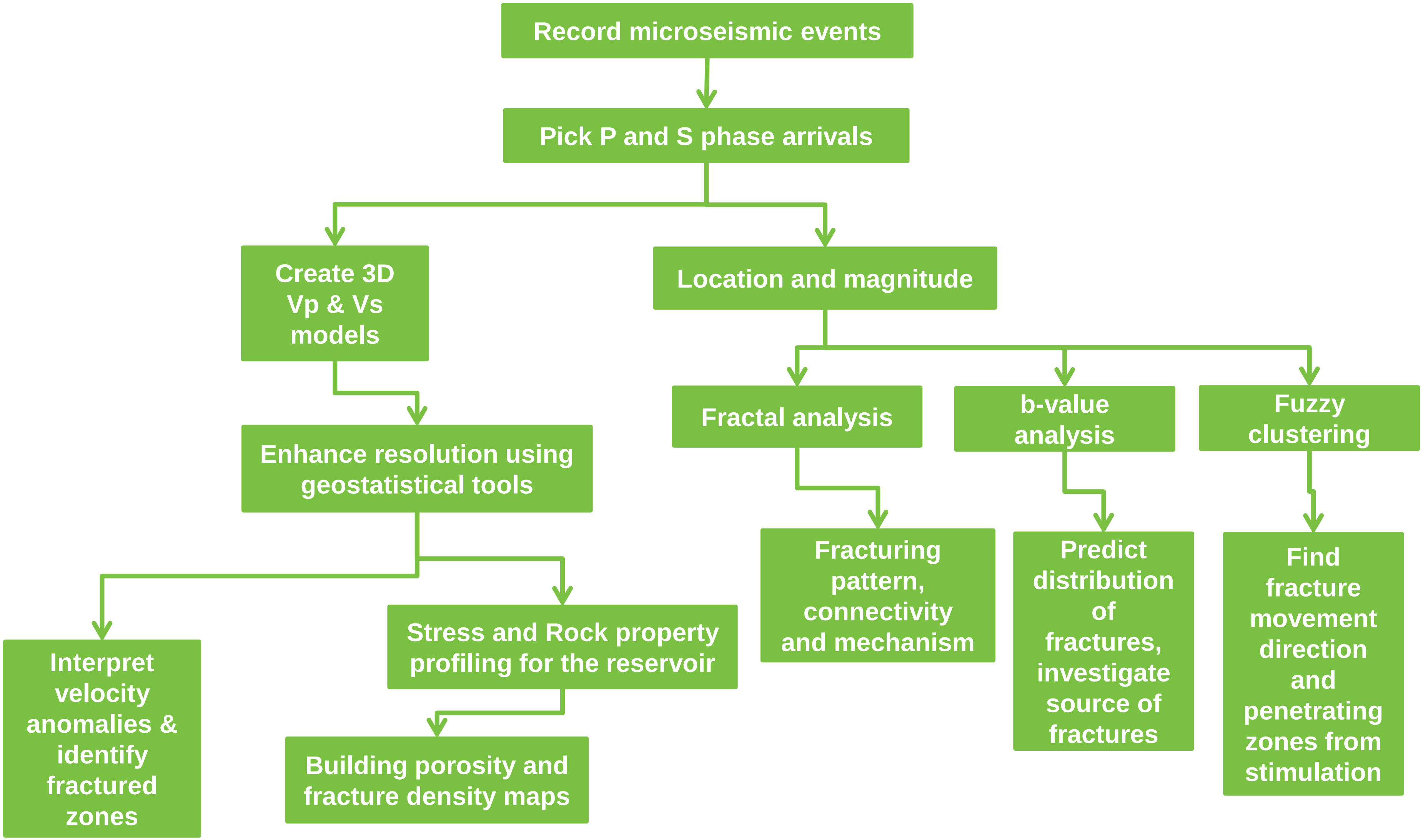
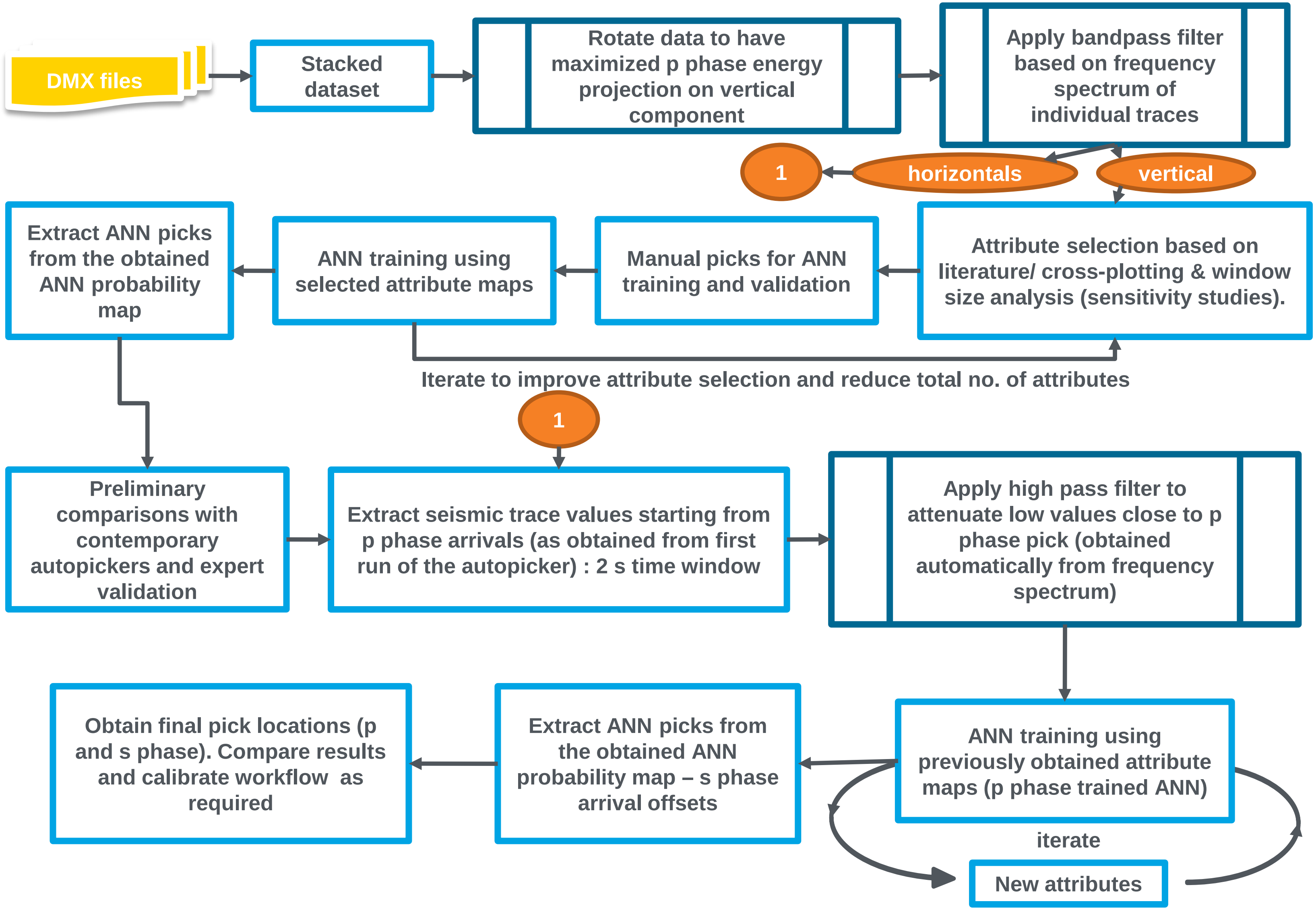
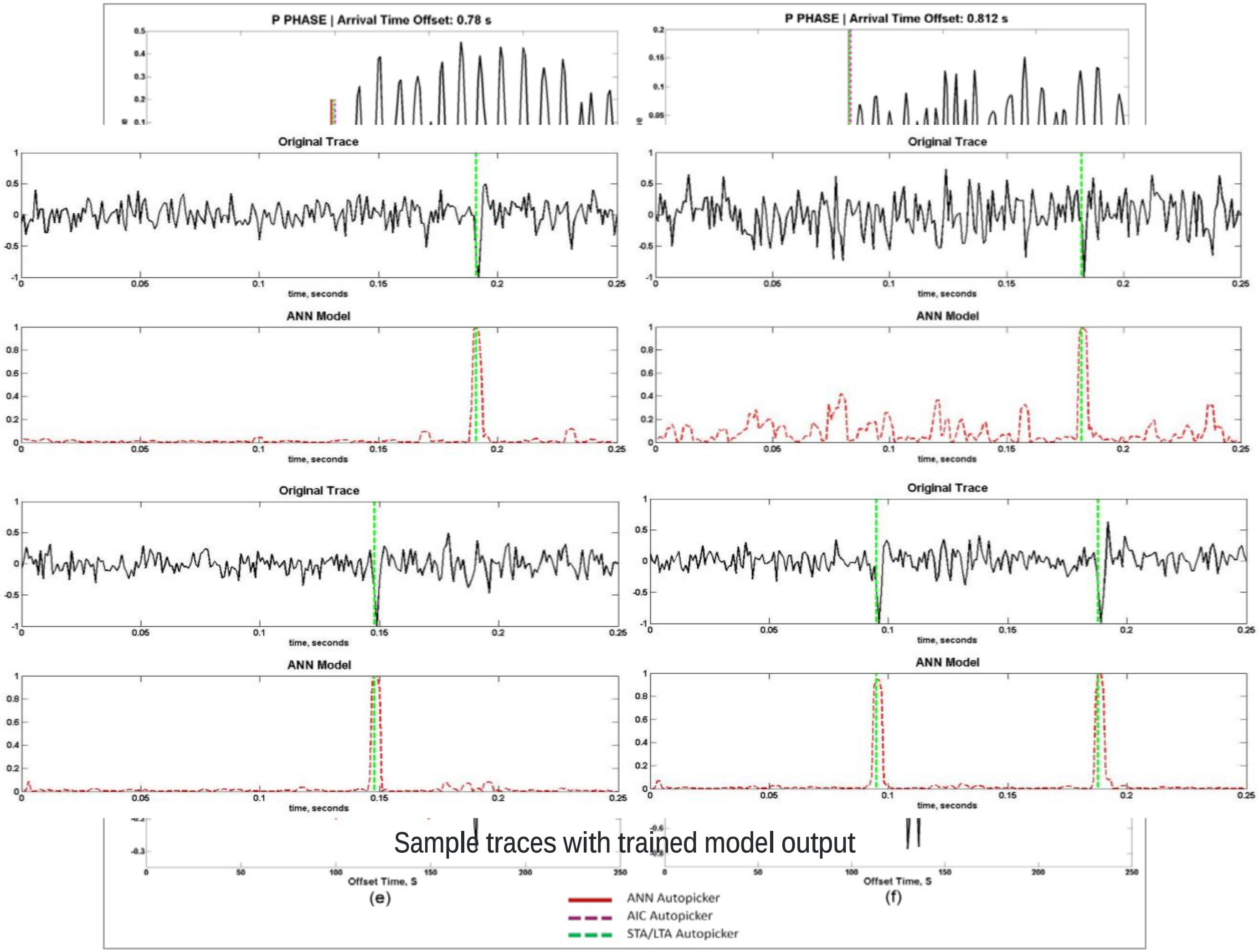


ANN Autopicker Methodology



ANN Autopicker Sample Results



Sample traces with trained model output

Comparisons with contemporary algorithms

Velocity modeling / Rock property mapping

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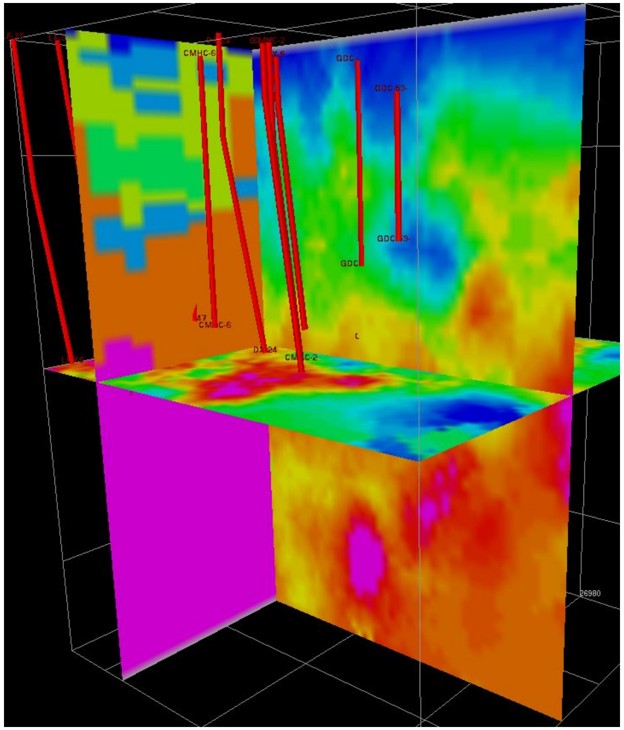
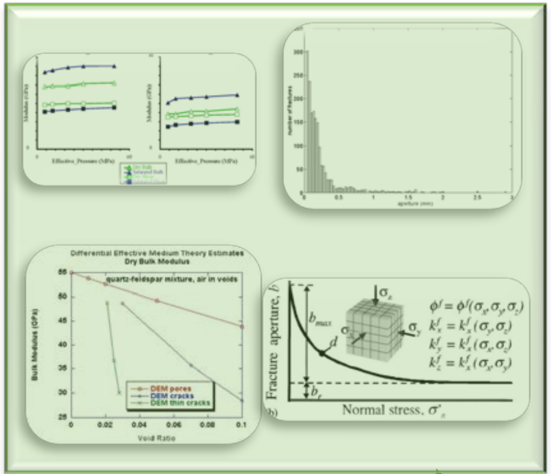


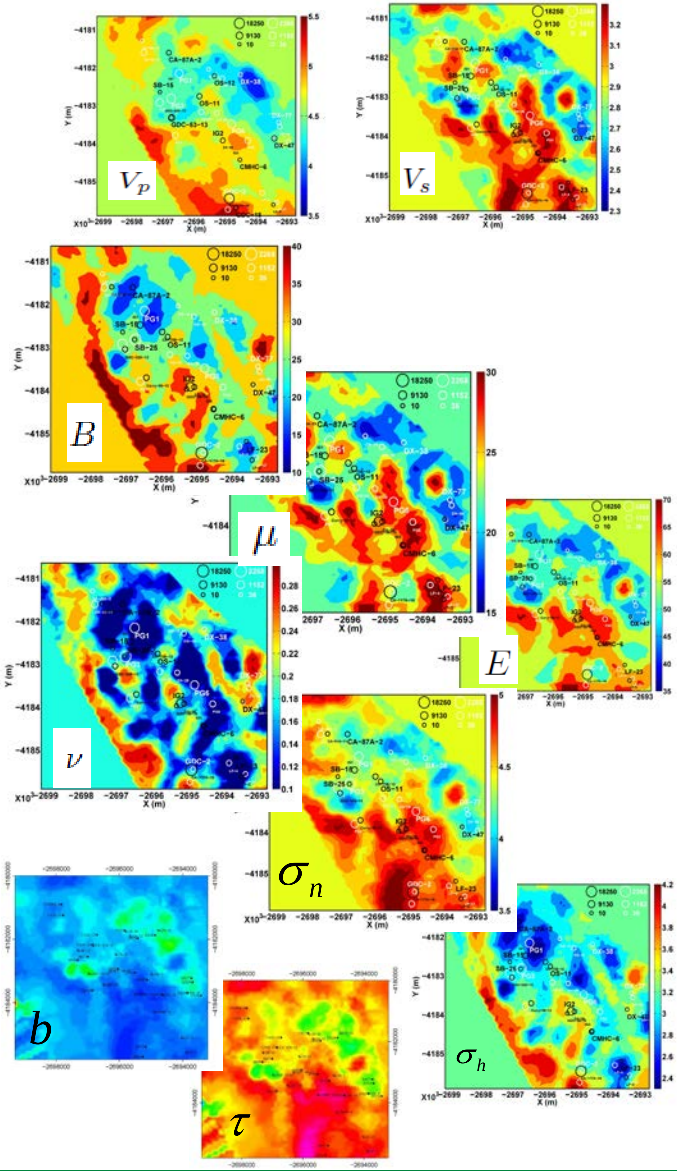


$$\nu = \frac{V_P^2 - 2V_S^2}{2\left(V_P^2 - V_S^2\right)} \qquad \sigma_h^2 = V_P^2 - \frac{4}{3}V_S^2$$

$$\mu = \rho V_s^2 \qquad B = \rho V_p^2 - \frac{4\mu}{3}$$

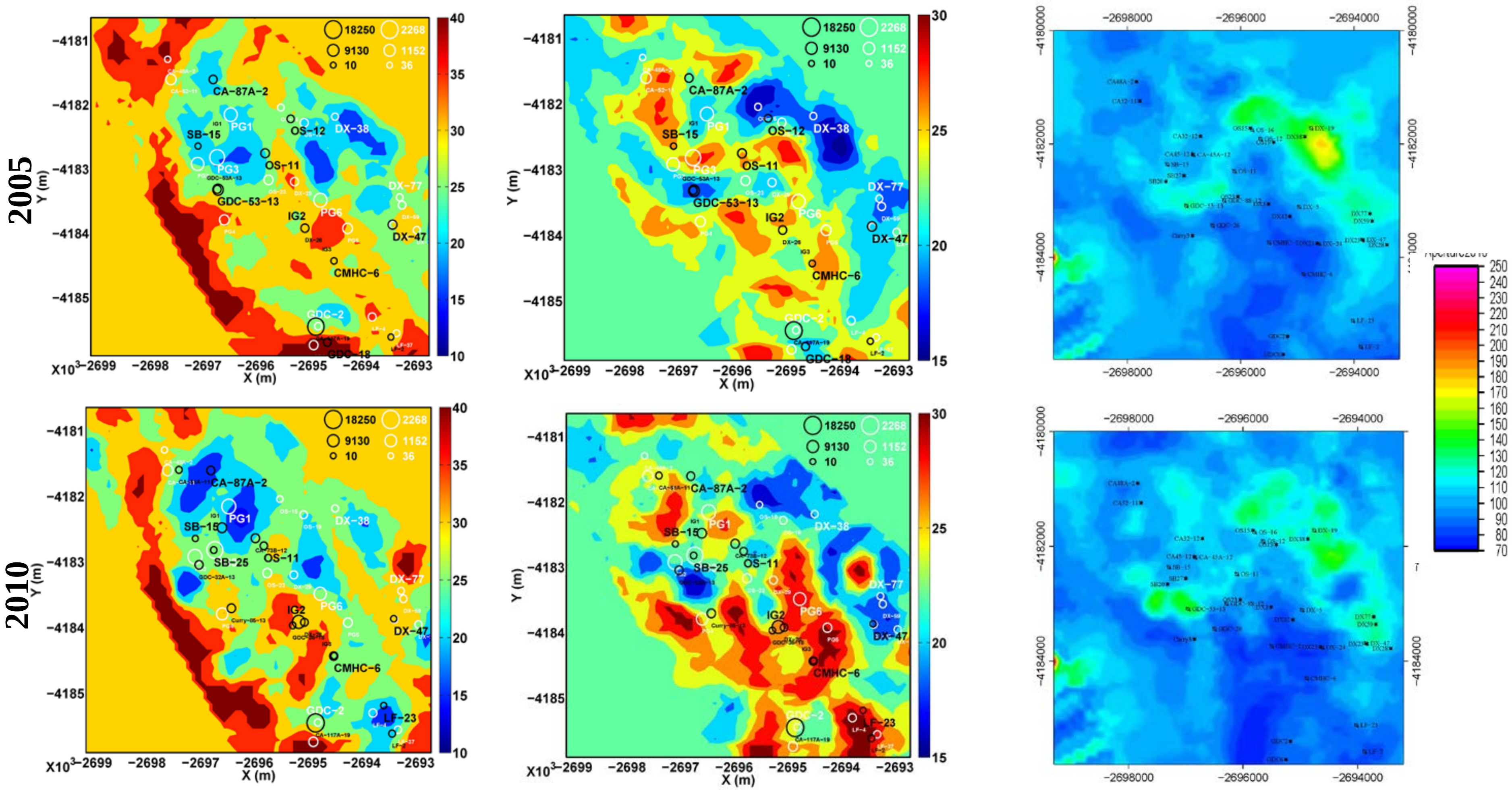
$$\sigma_n^2 = \frac{V_S^2(3V_P^2 - V_S^2)}{(V_P^2 - V_S^2)}$$

$$b = b_{\mathrm{r}} + b_{\mathrm{m}} = b_{\mathrm{r}} + b_{\max}[\exp(d \times \sigma_n')]$$



Note: These equations are primarily developed for sandstones. More appropriate relations may need to be used for the rock types in the Geysers

Identify the fluid flow type and monitor changes in reservoir



bulk modulus | shear modulus | **Fracture Aperture**

Project management activities or approaches

- ➢ Upon the project funding (with about 4 month delay from the original project proposal, received approval from the university to advertise for a post doc position.
- ➢ After several job posting and contacting faculty in different universities was not able to hire a qualified post docs
- ➢ Different measures were taken to complete the project (hiring additional graduate students, part time faculty and getting additional help form our project partners (LBNL)
- ➢ Established weekly meetings and technical exchange with our partners
- ➢ Coordinated our work with the industry and academia through our monthly distinguished lecture program, followed by discussions with the project team.

Variance from original project plans

- ➢ We expect to have a shift of two quarters (6 months) for much of our deliverables.
- ➢ With the corrective measure (item 3 above) we expect to deliver all the deliverables within the original budget.

Data Sharing

- This project does not generate any new MEQ or well data. It uses the data collected by LBNL and Calpine funded by other DOE grants or independently collected data.
- We have shared our results through publications (at GRC, SEG, and AGU meetings) with the general public.
- We have also provided copies of these publications to the "DOE Geothermal Data Repository". We intend to provide them with the copies of all the developed software and reports (with maps, numerical data, seismic attribute volumes, and images) we generate under this project.

Collaborations

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➢ Project Team

USC

Fred Aminzadeh (PI), Mo Sahimi (Petroleum Engineering), Charles Sammis (Earth Sciences)

LBNL

Ernie Majer, Leon Thomsen, Larry Hutchings and Katie Boyle

Calpine

Mark Walters, Joseph Beall, Alfonso Pingol and Julio Garcia

Collaboration was enhanced through frequent regularly scheduled conference calls with the team members. In addition, through USC Center for Geothermal Studies (CGS) monthly distinguished lecture series, further communication and knowledge sharing both within the project team and the outside researchers was accomplished.

➢ Jobs

Two full time and one part time graduate students were hired to work on this project.

Future Directions

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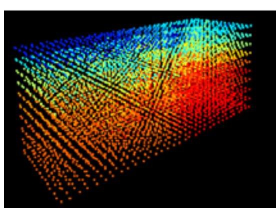
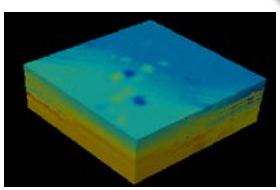
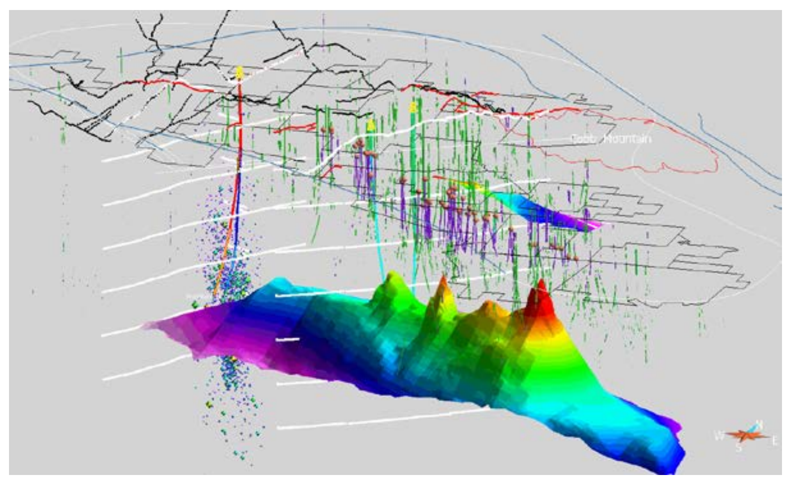
- We intend to deploy our auto-picker at LBNL and provide a copy of our software to the "DOE Geothermal Data Repository". Current implementation includes GUI based implementation with all necessary options for the users.
- Provide the high resolution velocity models with derived properties to both Calpine and DOE Geothermal Data Repository.
- We plan to populate GOCAD generated geobodies with the velocity fields which have derived after kriging of the raw velocities. The goal being to validate the velocity fields and establish a correlation with the interpreted faults.
- Planned milestones are the same as those in the original work plan (slide 2).







Summary

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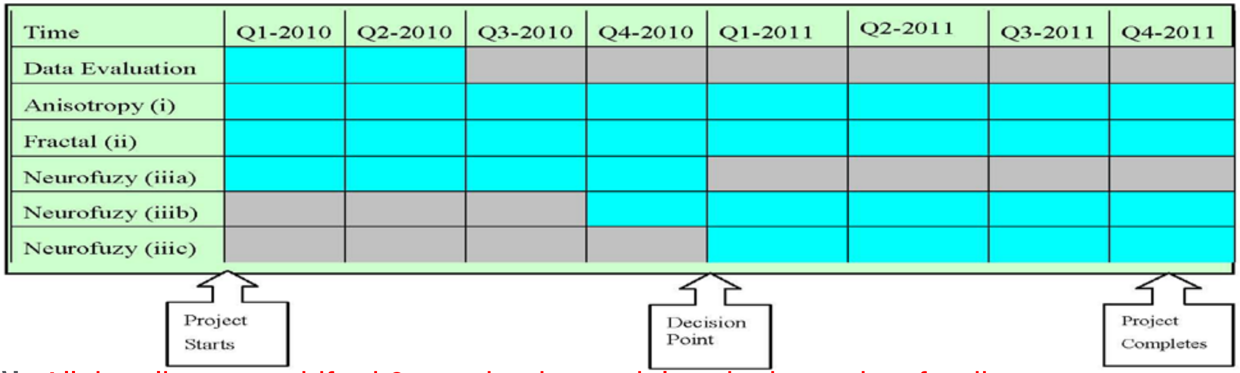
	FY2010	FY2011	FY2012
Target/Milestone	ANN autopicker	Neuro-Fuzzy autopicker	Neuro-Fuzzy autopicker
Results	Implemented.	Implemented, Working on improvements as discussed	Implemented, Working on improvements as discussed
Target/Milestone	Fractal & b value analysis	Integrated evaluation	Integrated evaluation
Results	Induced nature of events verified.	Map the fractal structure of fracture network	Confirm the fracture network in area of interests
Target/Milestone		velocity modeling, stress, and rock property profiling	Time lapse velocity modeling and stress profiling
Results		Area with higher fracture density in both NTR and HTZ has been identified	Identify the fluid type and monitor change in reservoir
Target/Milestone			Anisotropy mapping
Results			Under implementation

Project Timeline and Budget

Characterizing Fractures in the Geysers Geothermal Field by Micro-seismic Data, Using Soft Computing, Fractals, and Shear Wave Anisotropy

Original Project Time line



Revised Project Time line(1): All time lines are shifted 6 months due to delays in the project funding .

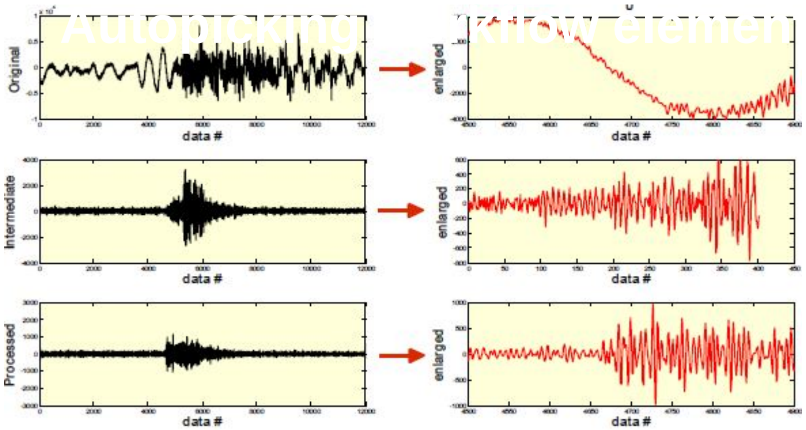
Revised Project Time line(2): Aside from (1), the entire project time line was extended (NCE) through Q3-13 through to allow for further refinements and complete work with project partners .

Original Budget

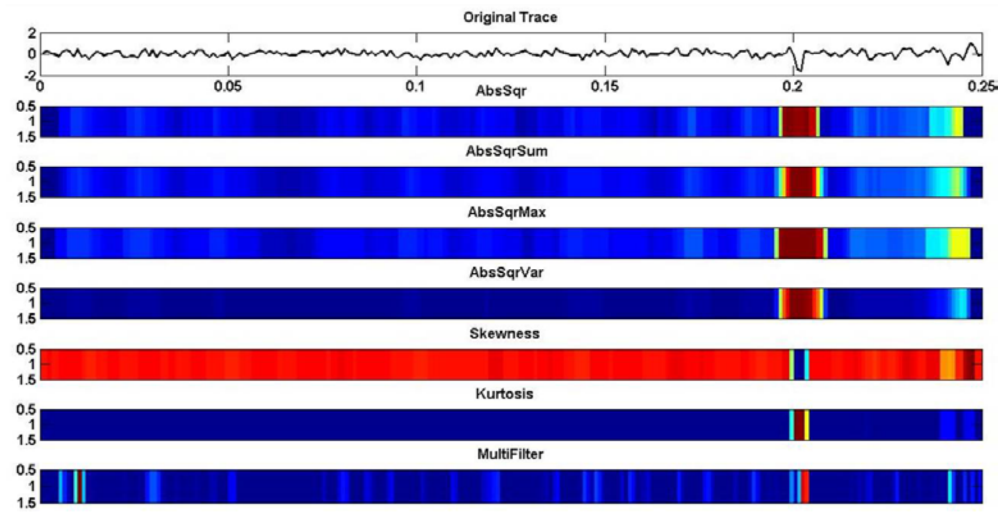
DOE Funding	$1,500K
Matching and Other External Funding	
USC	$200K
LBNL	$150K
Calpine	$300K
Total	**$2,150K**

Budget Variance and % spending- The project is expected to be completed on budget. The expenditure is roughly proportionate to the project time line.

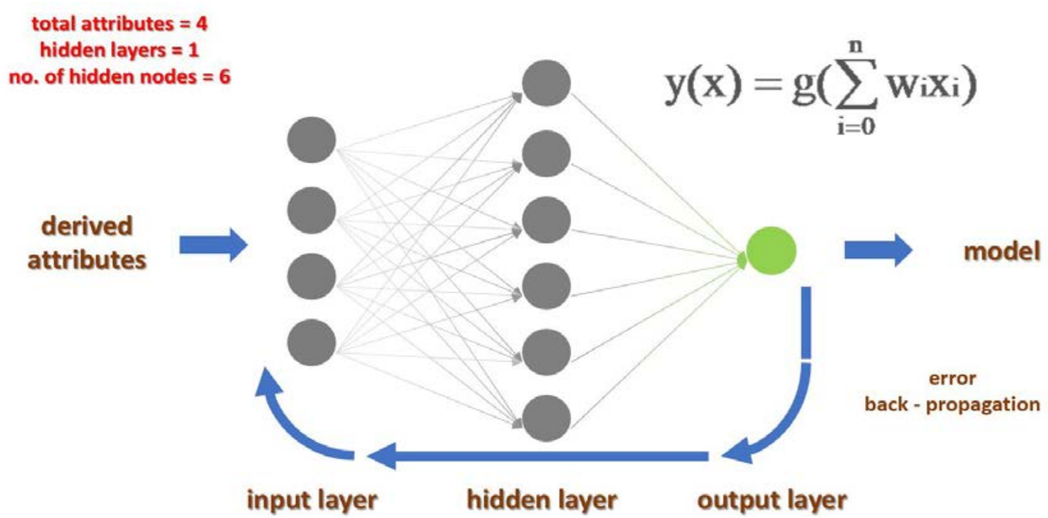
Autopicking workflow elements
Supplemental Slide 1



Noise removal using band pass filtering



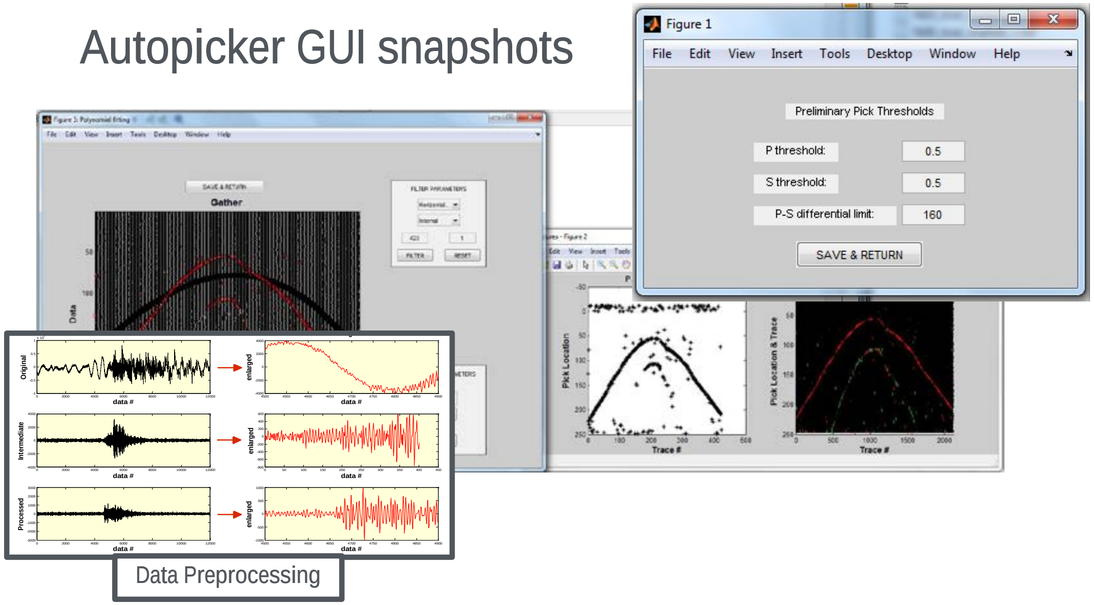
Sample attributes for selection



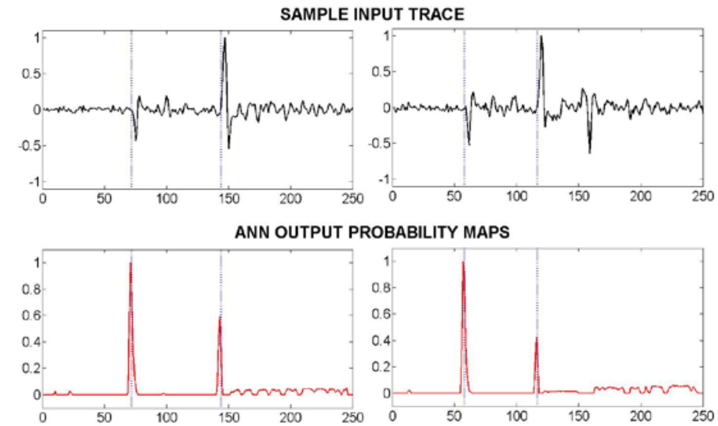
ANN design elements

Autopicker implementation
Supplemental Slide 2

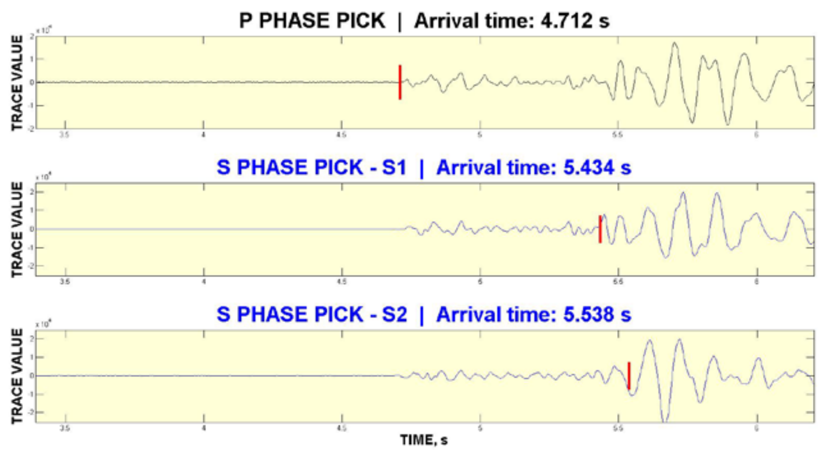
Autopicker GUI snapshots

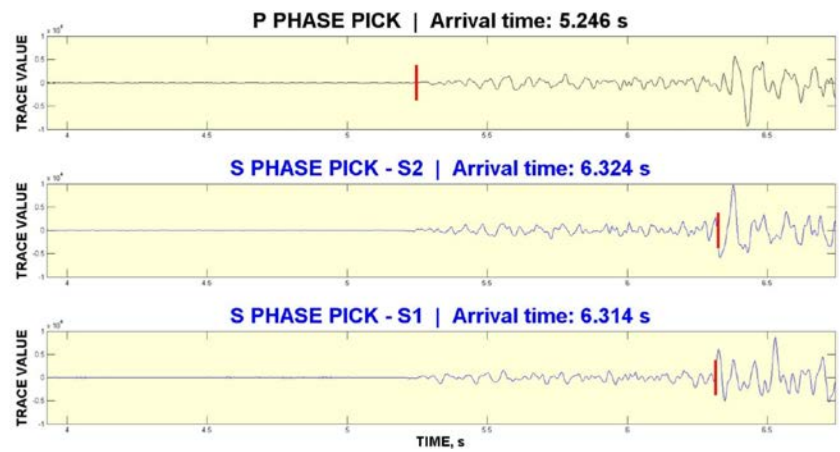


Results with synthetic data

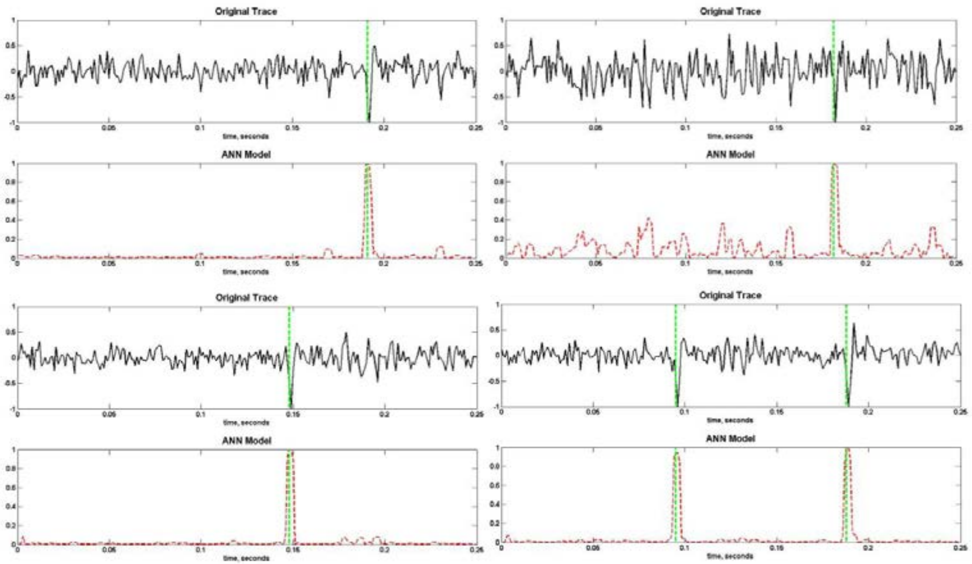


Results with actual data





Autopicking (Pick QC) **Supplemental Slide 3**

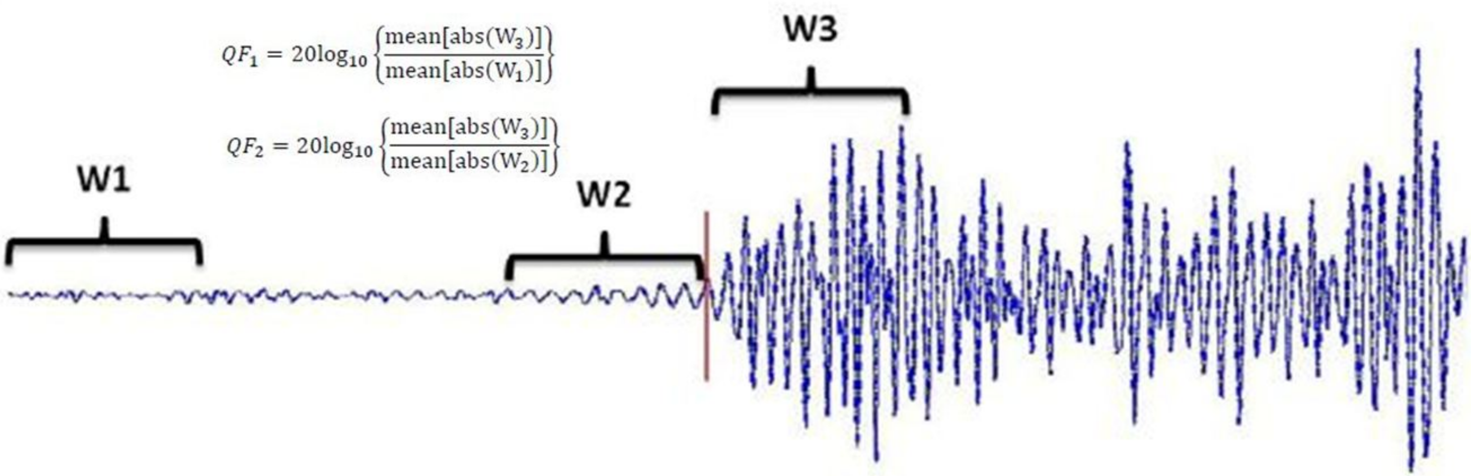


Sample trace with trained model output

Pick QC methodology

$$QF_1 = 20\log_{10}\left\{\frac{\text{mean}[\text{abs}(W_3)]}{\text{mean}[\text{abs}(W_1)]}\right\}$$

$$QF_2 = 20\log_{10}\left\{\frac{\text{mean}[\text{abs}(W_3)]}{\text{mean}[\text{abs}(W_2)]}\right\}$$



Pick quality control

ANN Picker Attributes Supplemental Slide 4

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AbsSum

$$A1_i = \sum_{i-N}^{I+N} |x_i|$$

AbsSumMean

$$A2_i = \frac{1}{N}\sum_{i-\frac{N}{2}}^{I+\frac{N}{2}} A1_i$$

AbsSumMax

$$A3_i = \max\left(\sum_{i-\frac{N}{2}}^{I+\frac{N}{2}} A1_i\right)$$

AbsSumVar

$$A4_i = \mathrm{var}\left(\sum_{i-N/2}^{I+N/2} A1_i\right)$$

Skewness

$$A5_i = \frac{\frac{1}{N}\times\sum_{i-\frac{N}{2}}^{i+\frac{N}{2}}(x_i-\bar{x})^3}{\left(\frac{1}{N}\times\sum_{i-\frac{N}{2}}^{i+\frac{N}{2}}(x_i-\bar{x})^2\right)^{\frac{3}{2}}}$$

Kurtosis

$$A6_i = -3 + \frac{\frac{1}{N}\times\sum_{i-\frac{N}{2}}^{i+\frac{N}{2}}(x_i-\bar{x})^4}{\left(\frac{1}{N}\times\sum_{i-\frac{N}{2}}^{i+\frac{N}{2}}(x_i-\bar{x})^2\right)^{2}}$$

BIC

$$A7_i = N\times\ln\left(\frac{1}{N}\times\sum_{i-\frac{N}{2}}^{i+\frac{N}{2}}(x_i-\bar{x})^2\right) + k\times\ln(N)$$

InstPha

$$A8_i = \tan^{-1}\frac{H(t)}{x(t)}$$

InstFreq

$$A9_i = \frac{d}{dt}A8_i$$

Wavelet

$$H = \left\{\frac{1+\sqrt{3}}{4\times\sqrt{2}}, \frac{3+\sqrt{3}}{4\times\sqrt{2}}, \frac{3-\sqrt{3}}{4\times\sqrt{2}}, \frac{1-\sqrt{3}}{4\times\sqrt{2}}\right\}$$

$$G = \left\{\frac{3-\sqrt{3}}{4\times\sqrt{2}}, \frac{-3+\sqrt{3}}{4\times\sqrt{2}}, \frac{3+\sqrt{3}}{4\times\sqrt{2}}, \frac{-1-\sqrt{3}}{4\times\sqrt{2}}\right\}$$

$$YH(i) = x_{2i}\times G(4) + x_{2i+1}\times G(3) + x_{2i+2}\times G(2) + x_{2i+3}\times G(1)$$

$$YL(i) = x_{2i}\times H(4) + x_{2i+1}\times H(3) + x_{2i+2}\times H(2) + x_{2i+3}\times H(1)$$

where $i = 1$ to $M/2$

$$A12_i = \min\left\{\min\left(YH\left(i-\frac{n}{2}\text{ to } i+\frac{n}{2}\right)\right), \min\left(YL\left(i-\frac{n}{2}\text{ to } i+\frac{n}{2}\right)\right)\right\}$$

FilterCF

....
....
....

ESM

$$E_i = \sqrt{x_i^2 + \tilde{x}_i^2}$$

$$A14_i = \frac{\frac{1}{N}\sum_{j=i}^{j=i+N-1} E_j}{\frac{1}{5N}\sum_{j=i-5N}^{j=i-1} E_j}$$

Fractal

$$A10_i = \frac{1}{\log F}\times\log\left(\frac{\max(\Delta x)_{i-\frac{N}{2},i+\frac{N}{2}}}{\sqrt{\frac{1}{N}\times\sum_{i-\frac{N}{2}}^{i+\frac{N}{2}}(x_i-\bar{x})^2}}\right)$$

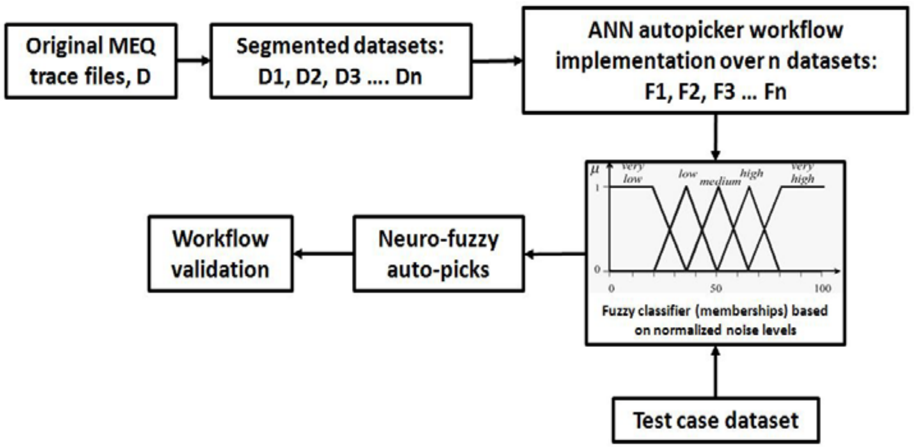
14

BKM

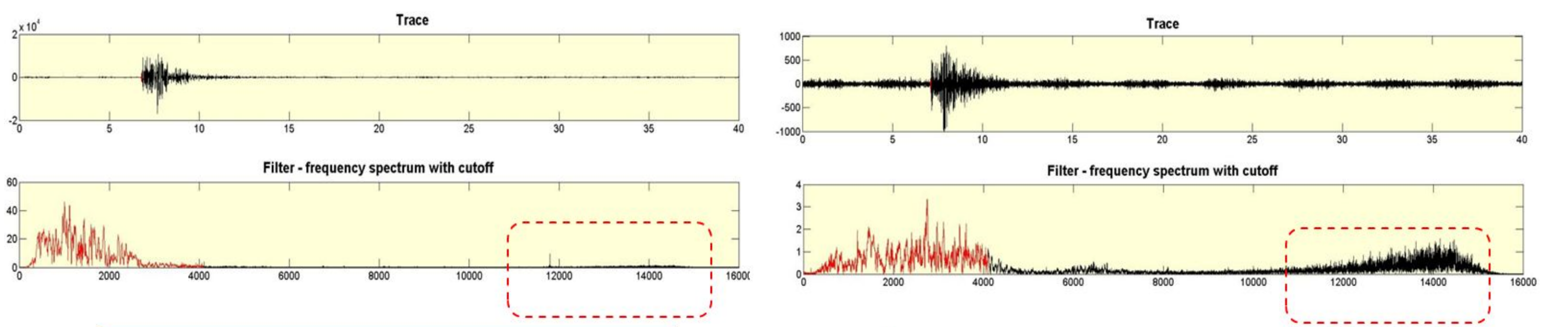
$$E_i^2 = x_i^2 + (x_i - x_{i-1})^2\times\frac{\sum_{j=1}^{i} x_j^2}{\sum_{j=1}^{i}(x_j - x_{j-1})^2}$$

$$A13_i = \frac{E_i^4 - \bar{E}_i^4}{\sigma(E_i^4)}$$

Hybrid Neuro-fuzzy Workflow

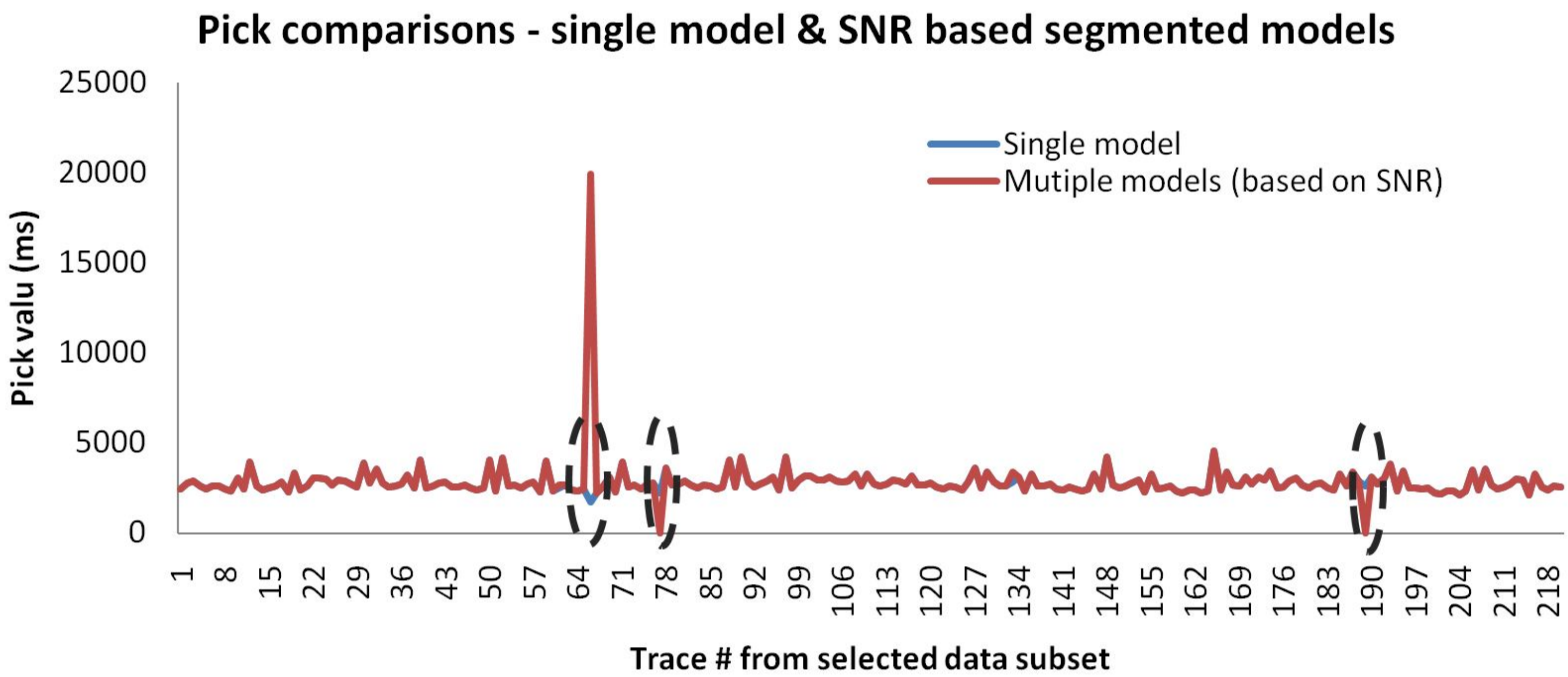


Noise based data stream segmentation

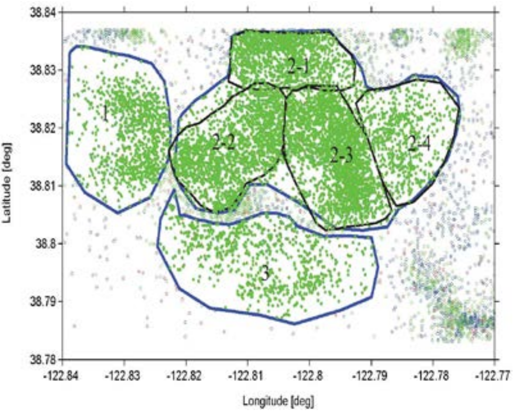


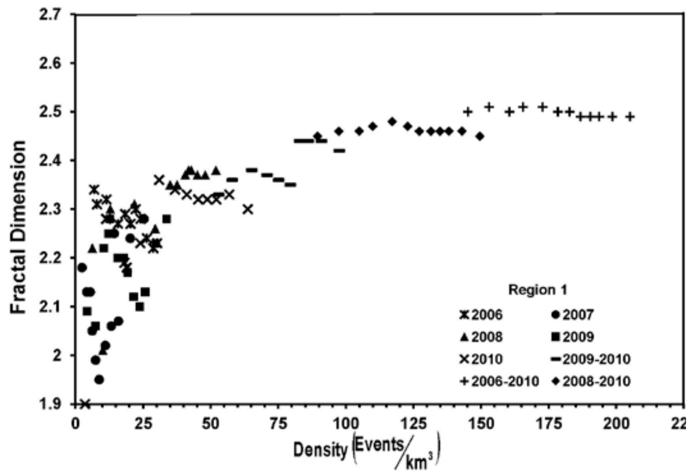
Absence of high frequency noise

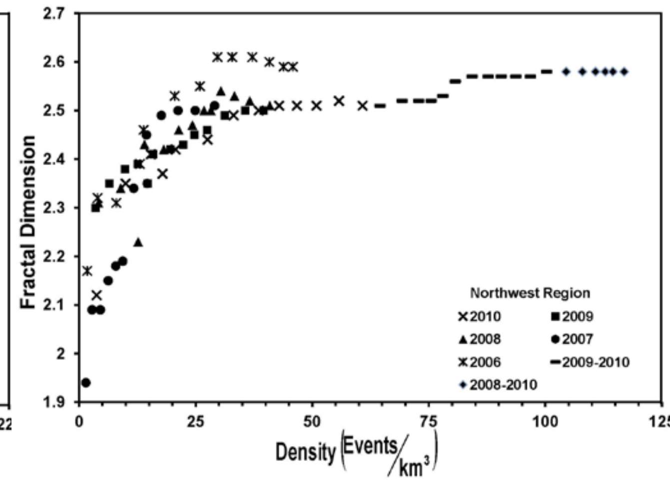
High frequency noise artifacts



Comparison of picks made using two models. Segmentation based on SNR. The results for the Geysers dataset indicate insignificant effect of noise based segmentation on final pick results. This is primarily a result of improved noise removal before picking. HYBRID NEURO-FUZZY METHOD DEEMED UNNECESSARY.

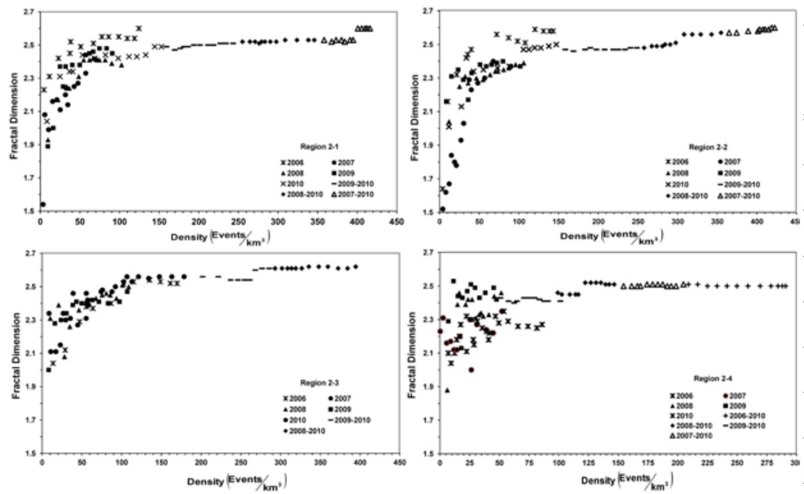






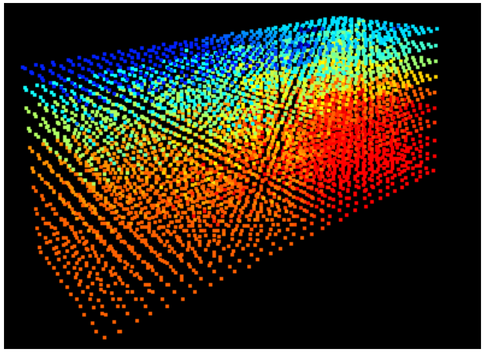
The results indicates that the seismicity distribution has the fractal structure with the dimension of 2.6 which is identical to the fractal dimension of nucleation and growth of fractures in random media. And b value of 1.3, D = 2b.

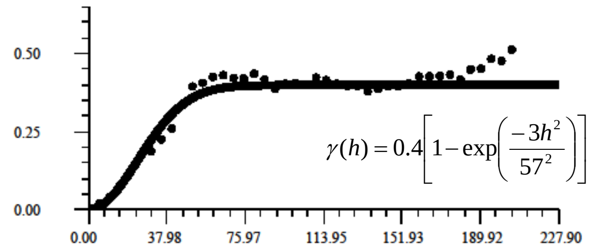
Confirmed induced seismicity



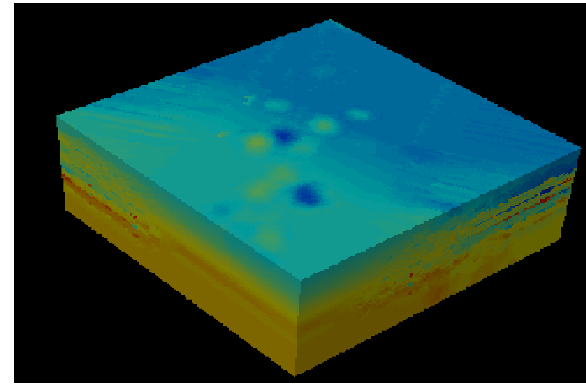
Region	True Fractal Dimension $D - C$	Estimated b-value
NW Geysers	2.58 ± 0.02	1.27
Region 1	2.5 ± 0.03	1.33
Region 2	2.63 ± 0.02	1.36
Region 3	2.58 ± 0.02	1.28
Region 2-1	2.6 ± 0.02	1.2
Region 2-2	2.6 ± 0.02	1.1
Region 2-3	2.62 ± 0.02	1.2
Region 2-4	2.51 ± 0.03	1.17

Velocity Modeling **Supplemental Slide 8**





Ordinary Kriging



$$V(approx.) = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}}$$

$$V_p = \sqrt{\frac{B + \frac{4\mu}{3}}{\rho}}$$

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

Poisson's ratio

$$\nu = \frac{V_P^2 - 2V_S^2}{2\left(V_P^2 - V_S^2\right)}$$

Shear modulus

$$\mu = \rho V_s^2$$

Young's modulus

$$E = 2\rho V_S^2(\nu + 1)$$

Bulk modulus

$$B = \rho V_p^2 - \frac{4\mu}{3}$$

Confining Stress

$$\sigma_h^2 = V_P^2 - \frac{4}{3}V_S^2$$

Normal Stress

$$\sigma_n^2 = \frac{V_S^2(3V_P^2 - V_S^2)}{(V_P^2 - V_S^2)}$$

Shear Stress

$$\tau = c + \sigma_n \tan\varphi$$

Fracture Aperture

$$b = b_r + b_m = b_r + b_{max}[\exp(d \times \sigma_n')]$$

Note: These equations are primarily developed for sandstones. More appropriate relations may need to be used for the rock types in the Geysers

Stochastic density modeling

Supplemental Slide 9

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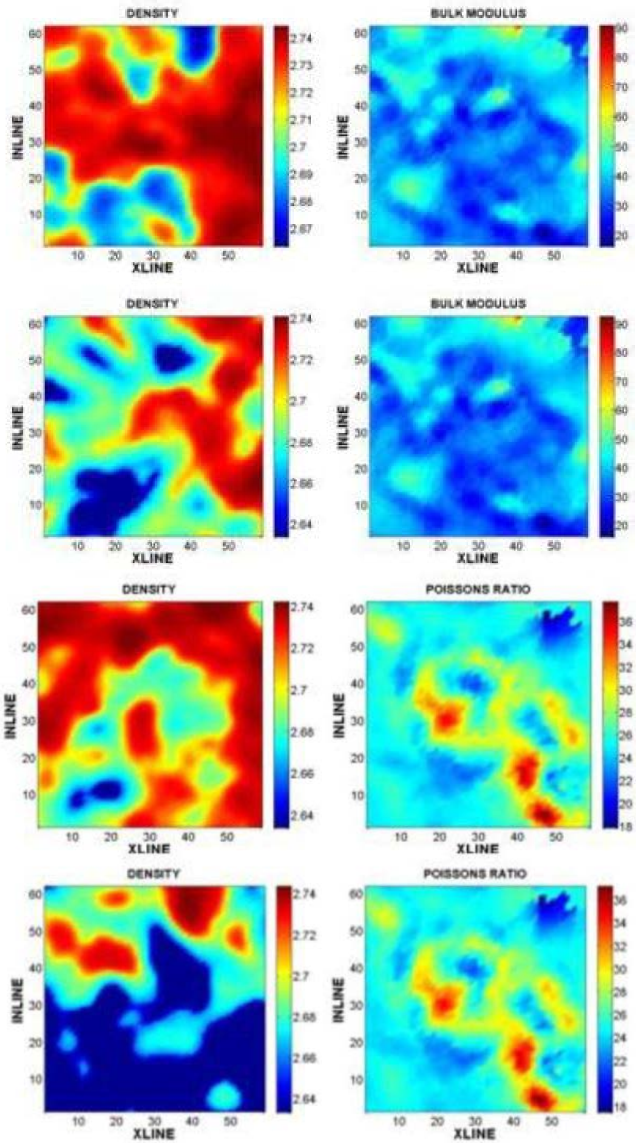

Nearly constant density assumed for rock property evaluations.

Density **modeled based on known lithology (felsite ↔ greywacke)**

Method used: *Sequential Gaussian Simulation*

No. of density realizations: 1000

Maximum density variability: ± 2.1%

Maximum property variability: ± 5.5%