Framework for time lapse fracture characterization using seismic, microseismic & well log data

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Summary

Extensive work has been done in the recent years involving use of conventional and passive seismic data for fracture characterization. This is particularly the case with unconventional reservoirs such as shale gas, shale oil and geothermal fields. The purpose of our study is to combine the benefits of conventional seismic data that provides relatively higher resolution reservoir characteristics with the relatively low resolution property estimates available from inversion of micro-earthquake data. Given the lower cost of the latter, we propose a cost effective dynamic reservoir characterization approach using a self-sustaining evaluation framework. The resulting time lapse fracture characterization technique is most suitable for those developments which involve the use of low cost passive seismic data acquisition arrays for reservoir monitoring. Our proposed method should allow for optimal use of microseismic data generated as part of passive seismic arrays common in unconventional field developments and thereby provide time lapse reservoir property predictions without having to carry out relatively expensive 4D seismic surveys.

Introduction

In recent years a lot of work has been done to look into integrated analysis schemes which make use of both conventional and micro-earthquake data. Maxwell *et al.* (2011) has shown how seismic attribute maps from conventional seismic data analysis can be used to better interpret observations based on induced seismicity seen in hydraulic fracturing programs. Cipolla *et al.* (2012) has shown how anisotropic stress fields from geomechanics can be integrated with induced seismicity and seismic derived attribute mapping to understand fracture network complexities. Passive seismic data is frequently used as a tool to characterize fractured reservoirs. Boyle *et al.* (2011) has shown how extensive MEQ catalogs can be used to better understand the subsurface at The Geysers geothermal field including time lapse changes within the zones of interest. Ouenes *et al.* (2004) has shown how seismic attributes from conventional seismic data can be used to characterize reservoir properties and how impedance can be used as an important constraining tool in that process.

One of the major limitations with small micro-earthquake sensor arrays is the limited phase arrival data available for property inversion workflows. However, they provide a very useful tool particularly when we consider the low deployment and operational costs associated with microseismic data when compared with conventional seismic surveys. Therefore there exists an opportunity to utilize reservoir properties interpreted from conventional seismic data analysis as a tool to enhance the resolution of the velocity models obtained from microseismic data. This provides a framework involving use of a single conventional seismic survey as a baseline mapping tool and the use of temporally catalogued phase energy arrival data to carry out time lapse velocity inversion.

Based on theories developed under rock physics, various elastic rock properties can be predicted using high resolution velocity models and these properties can in turn be used as a tool to characterize the reservoirs. We applied this approach in a geothermal field to validate its use in a highly data constrained environment with the view to maximize the benefits from a small micro-earthquake monitoring array by using available well control and seismic survey data. We used an integrated framework to understand how different properties can be used to better understand reservoir continuity as well as potential zones of interest for future developments. While the work shared here deals with results over a single time frame due to lack of adequate phase data (a result of the limitations with the micro-earthquake sensor array and processing methods used), it provides a broad framework for time lapse analysis provided adequate micro-earthquake data density is observed. Figure 1 shares a broad outline of the workflow we followed for our analysis. In this discussion, we would focus on high resolution property estimates from baseline velocity estimates using microseismic data.
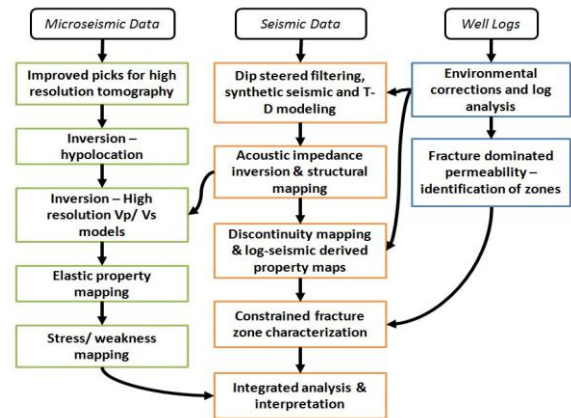

Figure 1: Integrated workflow

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Method

Based on the available dataset and initial analysis of data characteristics, a modified autopicker based on an ANN based workflow (Aminzadeh *et al.,* 2011) was used to generate necessary first break arrival data (both p and s wave) and a catalog was generated. Hypoinverse (Klein, 2003) and SimulPS (Thurber, 1993) were used to invert for initial hypocentral estimates and velocity model refinement as well as relocation. The final velocity models (V_P and V_P/V_S) are used as the baseline low resolution velocity estimates for further improvement.

Based on available conventional seismic data for the study area, acoustic impedance was estimated based on seismic colored inversion workflow (Lancaster *et al.*, 2000). The impedance volume was used to refine the microseismic derived velocity models by using co-kriging with coarse gridded velocities as primary variables and seismic derived high resolution impedance volume as the secondary variable. Figure 2 shows co-kriged V_P model using the geostatistical approach as explained.
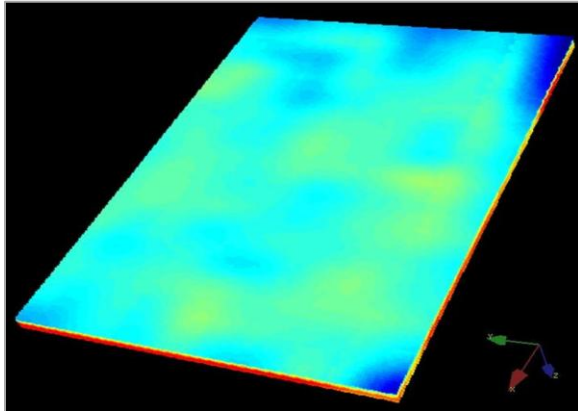

Figure 2: Co-kriged V_P model based on high resolution seismic derived impedance volume

Based on the velocity estimates, elastic properties were estimated using available framework to relate geophysical and geomechanical properties with reservoir characteristics such as fractures (Tokosoz, 1981). Based on velocities and density obtained from log-seismic property prediction from conventional seismic data (figure 1), Lame's parameters can be defined as follows:

$$\mu = \rho \times V_S^2 \tag{1}$$

$$\lambda = \rho \times V_P^2 - 2 \times \mu \tag{2}$$

Based on the Lame's parameters, elastic moduli can be estimated as follows:

$$K = \lambda + \frac{2 \times \mu}{3} \tag{3}$$

$$E = \frac{9 \times K \times \lambda}{3 \times K + \mu} \tag{4}$$

$$\sigma = \frac{\lambda}{2 \times (\lambda + \mu)} \tag{5}$$

Where ρ is the bulk density, K is the bulk modulus, E is the Young's Modulus and σ is the Poisson's Ratio. We can further calculate stress estimates (Tokosoz, 1981) and weakness estimates (Hsu *et al.,* 1993) which are used to further characterize fractures within the study area. Increased extensional stress estimates can be considered indicative of open fractures while high tangential weakness estimates are a function of crack density (Downton *et al.,* 2008). These parameters can be defined as follows:

$$V_E^2 = \frac{V_s^2 \times (3 \times V_p^2 - 4 \times V_s^2)}{(V_p^2 - V_s^2)} \tag{6}$$

$$V_K^2 = V_p^2 - \frac{4}{3} \times V_s^2 \tag{7}$$

$$\Delta_N = \frac{4e}{3g(1-g)} \tag{8}$$

$$\Delta_T = \frac{16e}{[3(3-2g)]} \tag{9}$$

$$\text{where,} \, g = \left(\frac{V_S}{V_P}\right)^2 \tag{10}$$

Where V_E is the extensional stress, V_K is the hydrostatic stress, Δ_N is the normal weakness, Δ_T is the tangential weakness and e is the fracture density. It should be noted that the weakness estimates are relative as they are based on the assumption of HTI anisotropic model and Hudson's effective medium theory (Hudson, 1994) for the study area. A more comprehensive analysis would require the use of anisotropic velocity models for the defined properties.

Figure 3 is a composite map which shows the elastic properties mapped at a reference depth of 1000 m for the study area. Figure 4 shows estimates of extensional stress and tangential weakness maps estimated at two reference depths of 750 m and 1250 m with injection and production well inserts for reference. We observe major extensional stress and tangential weakness anomalies (high values) within the central section of the study area at depths of interest. Most of the drilled wells also align with these anomalous zones and lie either at the periphery or within these zones of interest. As mentioned before, if anisotropic velocity estimates are available (using anisotropic inversion methods for passive seismic data), improved estimates of these properties can be obtained for better characterization.
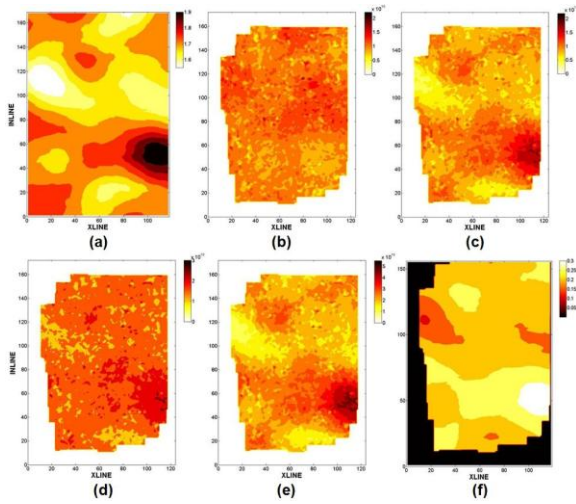
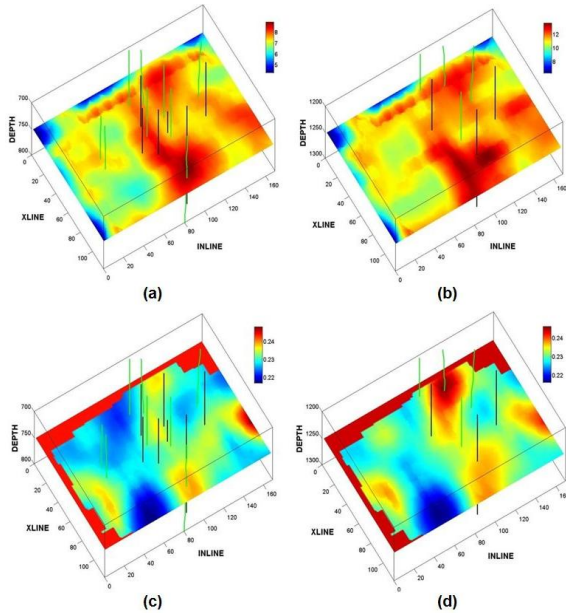Figure 3: (a) V_P/V_S, (b) μ, (c) λ, (d) K, (e) E & (f) σ at 1000m

Figure 4: Extensional stress maps at (a) 750 m and (b) 1250 m as well as tangential weakness maps at (c) 750m and (d) 1250m with well track inserts (green - injection & black - production) for reference

These properties can be directly used as tools to characterize the fractures within the study area based on the extensive rock physics framework available from literature (Martakis *et al.,* 2006; Berryman *et al.,* 2002; Berge *et al.,* 2001; Boitnott, 2003, etc). Just to give a brief overview, we would expect effective pressure increase to show up as high

compressional velocity or bulk moduli anomalies due to closure of cracks. Fractures should cause attenuation and lead to low velocity anomalies. Increased extensional stress and reduced bulk moduli anomalies should be indicative of open fracture systems. Tangential weakness is indicative of fracture density while normal weakness is indicative of fluid content. Increased cementation should lead to increased velocity ratio anomalies as well as shear and bulk moduli anomalies but should lead to low Poisson's Ratio anomalies. Presence of vapor phase causes similar affects as seen with fractures while increase in fluid saturation leads to increased velocity ratio anomalies and Poisson's Ratio due to increased compressibility.

We used some of these properties in an integrated mapping scheme where we used an artificial neural network (ANN) based non linear property prediction workflow with "a-priori" fracture zones (identified independently) as training data which we verified by analyzing available well logs. Equation 11 provides the basic model representation for the derived property (referred to as FZI in our study).

$$FZI = F\{ \phi_n, AI_n, V_{Pn}, V_{Sn}, \rho_n, V_{En,}\} \tag{11}$$

Where ϕ_n is the normalized log derived porosity estimate, AI_n is the normalized impedance values, V_{Pn} and V_{Sn} are the normalized phase velocities, V_{En} is the normalized extensional stress estimate and finally ρ_n is the normalized density estimate. The input nodal data for the ANN includes multiple seismic derived attributes including directional geometric attributes as well as seismic derived log property maps such as porosity, density and impedance estimates. The output provides estimates of zones within the reservoir having similar characteristics as per the ANN training workflow/ results.
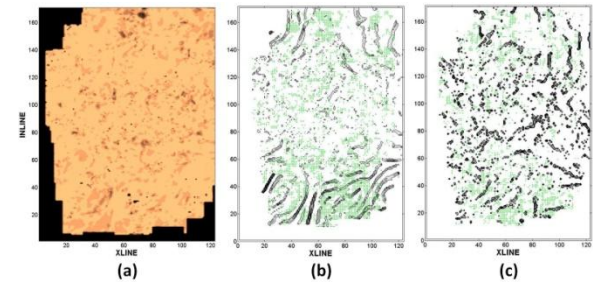
Results

Figure 5: (a) Sample depth slice map of fracture zone indicator (FZI) using seismic and microseismic derived properties (ANN framework), (b) integrated display showing threshold limited FZI with discontinuity at 1000 m and (c) at 1500 m

Figure 5 (a) shows a typical ANN derived output map based on the description of methodology in the previous

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section. Figure 5 (b & c) are integrated displays showing seismic derived discontinuity maps (derived independently using supervised ANN mapping framework based on conventional seismic data) to characterize identified fractured zones (FZI property derived from microseismic data). This allows better identification of possible zones of interest including intervals of interest within existing wells as well as new targets for future development. Moreover, it allows for better understanding of reservoir connectivity as well as improved identification of productive zones or other horizons of interest for enhanced reservoir management.

Figure 6 (a) provides an example of integrated analysis involving the derived fracture zone identification attribute (FZI) mapped with seismic derived discontinuity and enhanced edge maps. Figures 6 (b through e) show blowup sections of four sample zones of interest and we can identify connectivity based on FZI spread as well as mapped discontinuity or edge attributes.

Conclusion

We have demonstrated the possibility of using seismic derived high resolution impedance maps as a tool to improve the resolution of microseismic derived velocity models. This provides us with a framework for better constrained velocity models which we have then used to estimate elastic properties of the study area. Using rock physics framework, we have demonstrated how these properties can then be used to characterize the study area.

Based on our study, high resolution property estimates can be obtained in 4D using temporal micro-earthquake catalogs followed by temporal velocity inversion. These results can be used as the basis to study the time variant development of the fracture zones within the reservoir and how the injection and/ or production operations play a role in fracture zone development within the reservoir. This provides a cost effective time lapse characterization tool for unconventional reservoirs allowing for improved reservoir management.

Though this workflow has been applied for a geothermal field, a similar approach can also be used for other unconventional developments including tight reservoirs which involve microseismic monitoring. It also provides a valuable and cost effective tool to validate reservoir development programs and can also be used as a diagnostic tool to understand the overall impact of field operations such as injection programs on the reservoir.
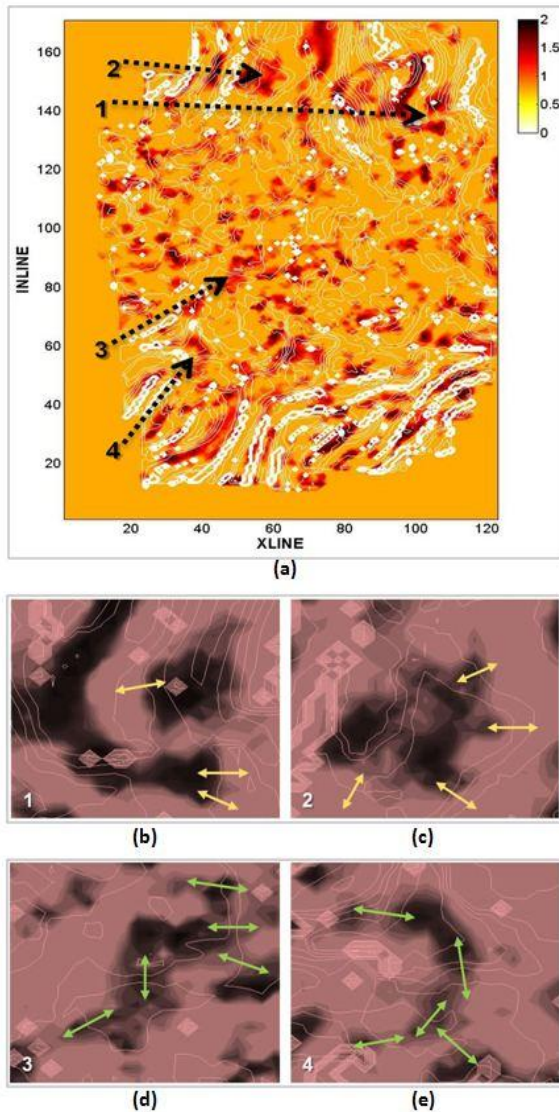
Acknowledgments

Figure 6: (a) shows a composite map with FZI, discontinuity and edge maps with blown up sections (a) through (d) with identified presence or absence of connectivity