



A review of seismic velocity response to variations in pore pressure, pore-saturating fluid and confining stress

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Summary

Fluid injection during hydraulic fracturing treatments changes the in situ stress, pore pressure and fluid saturation. This abstract reviews how each effect changes P- and S-wave velocities.

Introduction

In the context of hydrocarbon recovery, hydraulic fracturing is the process of injecting fluids mixed with a granular solid or proppant into a reservoir under high pressure to induce fracture initiation and growth within the rock. As a hydraulic fracture is propagated and held open, several processes occur simultaneously that change the physical environment in the rock volume surrounding the fracture. These processes include pore-pressure diffusion, fracturing fluid invasion and rock matrix deformation (Warpinski, 1994; Warpinski et al., 2004; Cipolla et al., 2011).

In this abstract, we review how pore-pressure diffusion, fluid invasion and matrix deformation affect the bulk mechanical rock properties, such as density and fracture orientation, in the region close to a hydraulic fracture. Furthermore, we review how these changes in density and fracture orientation affect seismically observable properties such as seismic velocities. The following equations for isotropic P-wave, v_p , and S-wave, v_s , velocities apply:

$$v_p = \sqrt{\frac{K_{sat} + \frac{4}{3}\mu_{sat}}{\rho}} \quad (1)$$

and

$$v_s = \sqrt{\frac{\mu_{sat}}{\rho}}, \quad (2)$$

where ρ is the effective density, K_{sat} is the effective bulk modulus and μ_{sat} is the effective shear modulus of the fluid saturated medium.

Pore-pressure Diffusion

During a hydraulic fracture treatment the pressure in the rock matrix is raised. The shape of this spatiotemporal pressure gradient is controlled by many parameters including, the difference between fracture and reservoir pressure, the matrix and natural fracture permeabilities, matrix porosity, and the fracture and reservoir fluid densities and compressibilities (Warpinski, 1994). A highly-compressible gas saturated reservoir will exhibit a steep pressure gradient due to the inefficiency of a compressible gas in communicating pressure through the pore system. However, in an incompressible liquid-saturated reservoir the pressure gradient will be more gradual, and will extend a further distance from the fracture.

By considering the effect of elevated pore pressure in the region of a single fluid-filled pore we can understand the resultant changes in effective density and seismic velocities. Increased pressure within a pore tends to force the surrounding rock grains apart, thus tending to increase the volume of the pore. Effective density is a combination of the densities of the rock and fluid constituents of the porous medium (Jaeger et al., 2007). An increase in porosity results in a decrease in the effective density of the porous medium, as rock is generally more dense than fluid. As seen in equation (1), a decrease in effective density tends to cause an increase in S-wave velocity. The effect of increased pore pressure on P-wave velocity can be seen by considering Wyllie's time-average equation for P-wave velocity in porous, isotropic, fluid-saturated rocks under high pressure (Wyllie et al., 1956). Mavko et al. (2009) interpreted Wyllie's equation as the P-wave travel time through a fluid-saturated rock is equal to the sum of the travel time through the rock matrix and the fluid-filled pore. Typical sedimentary rocks have P-wave velocities that are significantly higher than fluid hydrocarbons and water (Batzie and Wang, 1992). Hence, increasing pore volume increases the relative contribution of travel time through the pore fluid, resulting in a lower P-wave velocity in the fluid-saturated rock.

Fluid Invasion

A hydraulic fracture is filled with a high-pressure fracturing fluid and is surrounded by a porous reservoir with lower-pressure pore fluids. The resulting pressure gradient drives fracturing-fluid flow through the surfaces of the fracture, replacing formation fluid with the fracturing fluid in a temporally expanding zone around the hydraulic fracture. This affects both density and elastic moduli of the saturated rock. The low frequency Gassmann-Biot theory predicts the expected change in the relevant elastic moduli. Mavko et al. (2009) give the Gassmann equations for effective bulk and shear modulus of a fluid saturated rock as:

$$K_{sat} = K_{dry} + \frac{(1 - \frac{K_{dry}}{K_o})^2}{\frac{\phi}{K_{fluid}} + \frac{(1 - \phi)}{K_o} - \frac{K_{dry}}{K_o^2}} \quad (3)$$

and

$$\mu_{sat} = \mu_{dry}, \quad (4)$$

where K_{dry} is the bulk modulus of the dry rock, K_{fluid} is the bulk modulus of the pore fluid, K_o is the bulk modulus of the matrix material, ϕ is the porosity, and μ_{dry} is the shear modulus of the dry rock. Combining equations (1) and (3), we see that S-wave velocity is only affected by the change in fluid density. In the case of a higher-density fluid replacing a lower-density fluid, for example water replacing hydrocarbons, S-wave velocity decreases. Conversely, in the case of increasing gas saturation, a low density fluid replacing high density fluid, S-wave velocity increases. By considering equations (2) and (4), we see that P-wave velocity is affected by variations in both fluid density and bulk modulus, with the effect of the bulk modulus being the dominant contributor. Landro (2001) used the Gassmann equations to show increasing water saturation tends to result in increasing P-wave velocity.

Matrix Deformation

When a hydraulic fracture is opened under pressure a volume of rock is displaced in a direction normal to the face of the fracture. This displacement induces changes in the confining stress distribution surrounding the fracture. Analytic solutions to model the changes in stress have been developed for several simple crack geometries (Sneddon, 1946; Green and Sneddon, 1950). Warpinski et al. (2013) use the pressurized 3D elliptical crack model of Green and Sneddon (1950) to calculate the perturbation of confining stress in the three principle directions. In a direction normal to the crack face the total normal stress is increased, with the largest increase in compressive stress experienced in the direction normal to the crack face. In contrast, in a direction parallel to the crack at the crack tip, the change in confining stress is tensile in both

horizontal principle directions and nearly zero in the vertical direction. There will be a zone of shear stress between the compressive and tensile zones (Cippola et al., 2011).

If we assume an originally isotropic (random) distribution of microcracks within a rock matrix. After the fracture is opened, microcracks that are parallel or nearly parallel to the hydraulic fracture face will be closed in the compressive-stress region, increasing the rock density (Mavko et al., 2009). In contrast, closure of all other microcracks is proportional to their angle with the hydraulic fracture face, creating an anisotropic microcrack distribution, and consequently an elastically anisotropic matrix (Nur, 1971; Nur and Simmons, 1969; Sayers et al., 1990; Scott et al., 1993). In general, P-wave velocities are largest parallel to the preferential fracture planes, whereas S-wave velocities also depend on their polarization.

Several methods have been developed to model the effects of microfractures and aligned fracture sets on the elastic properties of an effective medium. Sayers and Kachanov (1991), Sayers and Kachanov (1995) and Schoenberg and Sayers (1995) describe the fourth order compliance tensor of a fractured medium as a sum of the compliance tensor of the uncracked medium and an additional compliance tensor representing the contribution of the aligned cracks or fracture system. The additional compliance tensor is described in terms of the normal and the tangential compliances of all microcracks in the volume of rock. Alternatively, Zatsepin and Crampin (1997) and Crampin and Zatsepin (1997) develop the anisotropic poroelasticity model to describe the elastic anisotropy behaviour of a pervasively microcracked medium in response to perturbations in local state of effective stress. Using this model, the change in the elastic moduli of a fluid saturated rock can be expressed as the sum of variations in the elastic moduli due to changes in microcrack orientations and variations due to changes in the geometry of individual microcracks.

Combined Effects

To consider the combined effect of elevated pore-pressure and increased differential confining stress on density, seismic velocity, and fracture orientations we need to introduce the effective stress concept. Effective stress is the difference between the confining (lithostatic) stress and the pore pressure (Mavko et al., 2009). Rock density is proportional to effective stress. The relation between effective stress and microcrack orientation is more complex, also depending on the magnitude of the closing stress of individual cracks. The closing stress is the minimum stress required to collapse a crack applied in the direction normal to the crack face. If the effective stress in a particular direction is equal to the closing stress, any microcracks with face normals aligned in the same direction will collapse and microcracks with face normals oriented in any other direction will remain open. Fracture anisotropy, and consequently elastic anisotropy, will develop. Alternatively, if the effective stress in any direction is less than the closing stress then microcracks of all orientations will remain open and no fracture anisotropy will develop. The Hertz-Mindlin grain contact model can be utilized to show the connection between effective stress and the reservoir dry-rock bulk modulus and shear modulus, hence the P-wave and S-wave velocities (Mavko et al., 2009). In general, seismic velocities increase with increasing effective stress (Landro, 2001).

The net effect of pore-pressure diffusion, fluid invasion and matrix deformation is the creation of five spatiotemporal zones of relative influence surrounding a hydraulic fracture (Figure 1): the fluid invasion zone (FIZ), the pressure/stress balance zone (PSBZ), the pressure/stress dominance zone (PSDZ), the tensile zone and the shear zone. The extent and relative importance of each zone of influence depends on both reservoir matrix and saturating fluid parameters, as well as hydraulic fracture fluid properties, as seen in Figure 1.

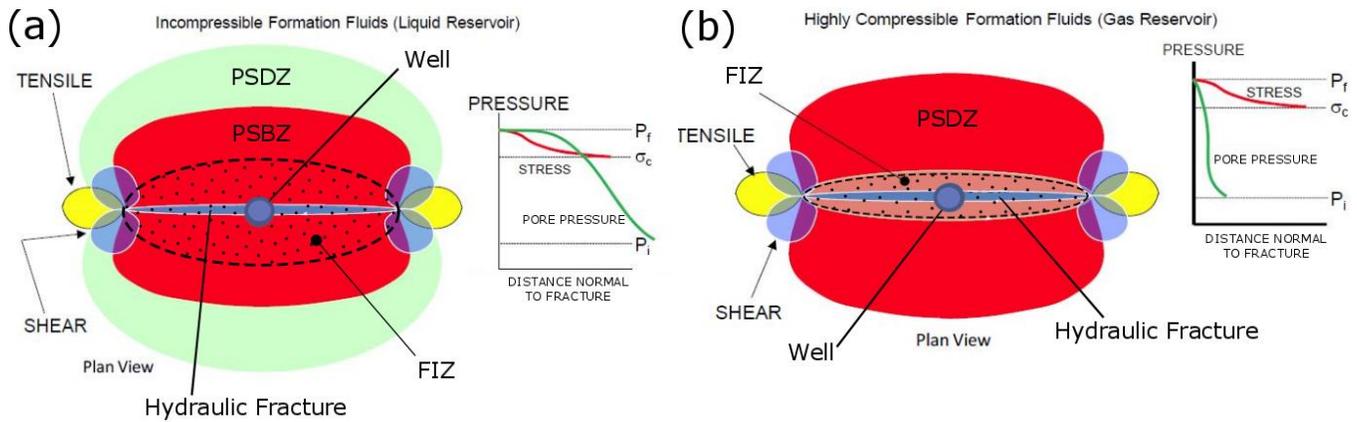


Figure 1. Illustration of the relative zones of influence for fluid invasion, pore-pressure increase, and confining-stress increase in the region surrounding a vertical hydraulic fracture extending from a vertical well, modified from (Cipolla et al., 2011). Panel (a) Shows the case of a fluid-saturated reservoir with moderate permeability. Panel (b) shows the case of a gas-saturated reservoir with low permeability.

The FIZ is the region directly adjacent to the hydraulic fracture face that experiences fluid replacement, the largest pore pressure increase and the largest lithostatic stress increase. Fluid replacement will tend to increase the effective density, increase P-wave velocity and decrease S-wave velocity. If pore-pressure diffusion effects dominate then seismic velocities will tend to decrease and stress-induced fracture and velocity anisotropy will not develop. However, if lithostatic stress effects dominate then microcracks with face normals perpendicular to the hydraulic fracture face will tend to close, resulting in the development of stress-induced fracture and velocity anisotropy.

The PSBZ is the compressive region from the outer surface of the FIZ to a variable distance from the hydraulic fracture face. Like in the FIZ, both pore pressure and lithostatic stresses increase and compete here, but without the effects of fluid invasion. An increase or decrease in effective stress determines variations in elastic velocities and densities here.

The PSDZ is the compressive region starting at the edge of the PSBZ and beyond. It will experience either pore-pressure increase or lithostatic stress increase, not both. Changes in elastic parameters are again determined by the change in effective stresses. The tensile zone is a small region at the tip of the hydraulic fracture which experiences tensile stress and the shear zone is a relatively small transition region between the tensile zone and the zones exhibiting compressive stress, where shear stresses dominate (Cipolla et al., 2011; Warpinski et al., 2013).

Conclusions

The volume of rock surrounding a hydraulic fracture experiences fluid invasion, pore-pressure increase, and confining stress increase. These three processes combine to change the in situ P- and S-wave velocities, creating five zones of influence of varying size. Rock physics principles can be used to forward model the expected changes in P-wave and S-wave velocity, as well as the development of velocity anisotropy in each of these zones. Consequently, close examination of different sources of seismic data, including microseismic, reflection seismic, and VSP datasets, can reveal temporal and spatial variations in stresses, pore pressures and fluid contents during hydraulic fracturing treatments.

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References

- Batzle, M., and Wang, Z., 1992, Seismic properties of pore fluids: *Geophysics*, **57**, no. 11, 1396-1408.
- Cipolla, C., Maxwell, S., Mack, M., and Downie, R., 2011, A practical guide to interpreting microseismic measurements: SPE North American Unconventional Gas Conference and Exhibition, **144067**.
- Crampin, S., and Zatsepin, S.V., 1997, Modelling the compliance of crustal rock – II. Response to temporal changes before earthquakes: *Geophysics Journal International*, **129**, no. 3, 495-506.
- Green, A.E., and Sneddon, I.N., 1950, The distribution of stress in the neighbourhood of a flat elliptical crack in an elastic solid. *Mathematical Proceedings of the Cambridge Philosophical Society*, **46**, 159-163.
- Jaeger, R.C., Cook, N.G.W., and Zimmerman, R.W., 2007, *Fundamentals of rock mechanics*, 4th edition: Blackwell Publishing.
- Landrø, M., 2001, Discrimination between pressure and fluid saturation changes from time lapse seismic data: *Geophysics*, **66**, no. 3, 836-844.
- Mavko, G., Mukerji, T., and Dvorkin, J., 2009, *The rock physics handbook*, 2nd edition: Cambridge University Press.
- Nur, A., 1971, Effects of stress on velocity anisotropy in rocks with cracks: *Journal of Geophysical Research*, **76**, no. 8, 2022-2034.
- Nur, A., and Simmons, G., 1969, Stress-induced velocity anisotropy in rock: An experimental study: *Journal of Geophysical Research*, **74**, no. 27, 6667-6674.
- Sayers, C.M., and Kachanov, M., 1991, A simple technique for finding effective elastic constants of cracked solids for arbitrary crack orientation statistics: *International Journal of Solids and Structures*, **27**, no. 6, 671-680.
- Sayers, C.M., and Kachanov, M., 1995, Microcrack-induced elastic wave anisotropy of brittle rocks: *Journal of Geophysical Research*, **100**, no. B3, 4149-4156.
- Sayers, C.M., Van Munster, J.G., and King, M.S., 1990, Stress-induced ultrasonic anisotropy in Berea sandstone *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, **27**, 429-436.
- Schoenberg, M., and Sayers, C.M., 1995, Seismic anisotropy of fractured rock: *Geophysics*, **60**, no. 1, 204-211.
- Scott, T.E. Jr., Ma, Q., and Roegiers, J.C., 1993, Acoustic velocity changes during shear enhanced compaction of sandstone: *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, **30**, no. 7, 763-769.
- Sneddon, I.N., 1946, The distribution of stress in the neighbourhood of a crack in an elastic solid: *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, **187**, no. 1009, 229-260.
- Warpinski, N.R., 1994, Interpretation of hydraulic fracture mapping experiments: SPE Tulsa Centennial Petroleum Engineering Symposium, **27985**.
- Warpinski, N.R., Mayerhofer, M.J., Agarwal, K., and Du, J., 2013, Hydraulic-fracture geomechanics and microseismic-source mechanisms: *SPE Journal*, **18**, no. 4, 766-780.
- Warpinski, N.R., Wolhart, S.L., and Wright, C.A., 2004, Analysis and Prediction of Microseismicity Induced by Hydraulic Fracturing: *SPE Journal*, **9**, no. 1, 1-24.
- Wyllie, M.R.J., Gregory, A.R., and Gardner, L.W., 1956, Elastic wave velocities in heterogeneous and porous media: *Geophysics*, **21**, 41-70.
- Zatsepin, S. V., and Crampin, S., 1997, Modelling the compliance of crustal rock – I. Response of shear-wave splitting to differential stress: *Geophysical Journal International*, **129**, no. 3, 477-494.