Bringing change to shale reservoir development

Tom Davis[1]* discusses how industry and academia are working together to bring about innovation in reservoir characterisation.

Seismic monitoring can bring changes in our quest to better develop shale reservoirs. Shale reservoirs are a renewable resource. The reason is the stimulation process, hydraulic fracturing, is a process that if repeated can increase recovery. Seismic monitoring is necessary to enhance the effectiveness of the process and to mitigate potential reservoir damage and environmental concerns.

"Why shale"? Shale is the dominant sedimentary rock here on Earth. From an energy viewpoint it contains organic compounds (carbon). Our future depends on carbon and the management of this valuable resource. There is much to learn and do in the future regarding carbon and 'shales'. The term shale is often used in improper scientific context. Our shale reservoirs are not strictly shale. In fact, at Wattenberg Field, the reservoir is mixed chalk and marl and would not be classified as a shale. Extracting or injecting carbon molecules into or out of 'shales' is not easy. The term 'unconventional' is often used as a term ubiquitous with shale, but it is a generality. Everything about shales and our science and engineering is unconventional, and therefore we need to change our entire perspective about shales. Communication, integration, innovation and education are the essential elements necessary to achieve sustainability in shale resource development.

Through the Reservoir Characterization Project (RCP) at the Colorado School of Mines, industry and academia work together to bring about innovation in reservoir characterisation. For 40 years, we have been conducting 3D and 4D multi-component seismic reservoir characterisation as a means of improving recovery by better understanding the reservoir and processes operating within. Monitoring enables us to visualise changes in the reservoir and to quantify those changes in terms of geomechanical properties ie, stress. The opportunity is to build an integrated geomechanical reservoir model and to test various development scenarios for improving recovery. Opportunities exist for placement of more wells, refracturing of existing wells and testing the role that carbon dioxide may have in improving recovery. An integrated focus is required across the disciplines.

The opportunity

The opportunity exists because of technical advancements in seismic monitoring that can help us to develop shale reservoirs and at the same time reduce carbon dioxide emissions. The majority of wells drilled in the United States are shale wells, and we must improve recovery while preserving the environment.

The average recovery from our shale reservoirs averages 6% of the original oil in place. That recovery has the potential to triple or quadruple given the hydraulic fracturing process and the injection of methane and carbon dioxide (CO_2) as agents for improving recovery. To assure success, we need the ability to monitor these reservoirs. Permanent reservoir monitoring systems (PRM) enabling active and passive recording of the seismic wave-field will bring about change in shale reservoir development, provided the value of such monitoring can be embraced and utilised by all stakeholders in the development process.

The critical aspect of hydraulic fracturing is to enhance rather than damage reservoir permeability and connectivity to the wellbore. Combined with the use of CO_2 as an Enhanced Oil Recovery (EOR) process, it provides a means of storing CO_2 away from the atmosphere.

Geomechanical and geochemical changes can affect reservoir integrity and permeability. Changes must be understood from a chemical and geomechanical perspective, and the impacts of these changes on seismic wave-fields must be understood to obtain a clear understanding of the reservoir changes and the safety of storage.

Environmental stewardship is seen by the regulators and public as a key element of resource production. Monitoring is essential to assure all stakeholders of the appropriate stewardship. Social licence to operate will require mutual cooperation and understanding of all stakeholders. Sustainable development is an emerging area of significant importance and impact on scientific research and social engagement. Not only are we concerned with monitoring storage of CO_2, we are also interested in long-term effects of such storage, the potential of storage permanence, and community-building around carbon storage effects. Key mechanisms that control the flow of CO_2 through both shale matrix and fractures, the interactions between the fluid and the rock surface, and the mechanical response of shale caprock to CO_2 injection-generated stresses need to be determined.

Geoscience disciplines such as geophysics, petrophysics and geomechanics play a critical role in reservoir management and do so over the extended life of an unconventional reservoir. Seismic measurements comprising time-lapse seismic, vertical seismic profiles, and microseismic surveys provide a unique opportunity to monitor the flow of fluids and changing stress fields. These surveys are incredibly rich in information because

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the measured data vary with changes in mineralogy, porosity, fluid saturation, fracture attributes, pore pressure and external stresses. Because seismic data is so rich in information, an integrated approach is needed to understand the data. Integration is defined as the synthesis (bringing together) of multi-scale and multi-disciplinary data to solve complex multivariate problems. Failure to integrate the geoscience data with the engineering data has the consequence of misinterpreting time-lapse changes in one variable (e.g. stress) for changes in another (e.g. fluid migration).

Petrophysics quantifies the intrinsic properties of the formation such as mineralogy, porosity, fluid saturation, matrix permeability, elastic moduli, fracture attributes and rock strength properties. These properties can and do vary over time due to injected fluids and hydraulic fracturing. Geomechanics quantifies the pore pressure and external loads acting on the subterranean formations and estimates the formations response to engineering activities such as horizontal drilling and hydraulic fracturing. Since these activities cause changes to both intrinsic properties and earth stresses, the resulting seismic wave-field will vary with time. The geoscience disciplines analyse these acoustical changes and infer the cause or causes using an earth model coupled with engineering simulators. Thus, the monitoring of the reservoir using time-lapse acoustics provides critical input (e.g. fluid migration and critical stress loads) required for reservoir management decisions.

Hydraulic fracturing

Hydraulic fracturing is a technique used commercially since 1949 to enhance the recovery of oil and natural gas in various reservoir systems. There has been a significant increase in the use of the technique with the advent of shale reservoir development. Such reservoirs have extremely low permeabilities, making it difficult for reservoir fluids to flow to the wellbore, and hydraulic fracturing provides alternative paths for the fluids to drain from the reservoir system into the wellbore. In shale reservoirs, the technique is combined with horizontal wells to increase contact with the reservoir and to minimise the need for vertical penetrations. In any given horizontal well, up to 100 fracturing treatments will be applied along the wellbore.

As noted, even with the application of hydraulic fracturing, the reserve recoveries of these shale reservoirs is extremely low, usually less than 6%. If more reservoir rock can be accessed by additional hydraulic fracturing treatments over the life of the well by 'refracturing' of these wellbores, additional reserves can be produced and the use of these valuable resources can be maximised. Refracturing is of great interest to the industry as it comes without the large capital expenditure of drilling and completing new wells to access incremental reserves. Refracturing costs are likely to be only 20-30% of the cost of drilling and fracturing a new well.

Although refracturing has been performed previously in various reservoir types and has been part of the industry vernacular since the early 1950s, it has only recently been applied in shale reservoirs. One of the largest hurdles to such treatments is understanding where they should be applied along the wellbore. For refracturing to be most successful in shale systems, the new fractures need to access areas of the reservoir that were not adequately contacted by the initial fracturing treatments.

The monitoring will help to not only target areas rich for additional treatments, but it will also help us to understand how the rock reacted to (and possibly changed) the initial treatments. This information will help to optimise re-treatments and to determine how to best design and apply re-fracturing stimulations.

CO2 EOR and storage in shale reservoirs

The injection of carbon dioxide into shale reservoirs may enhance production, but currently there is not enough understanding about the geochemical and geomechanical changes that may be induced. Experimental studies on cores suggest that changes to pore structures and compositional fabric occur. Environmentally it is attractive to think that shale reservoirs could be a potential

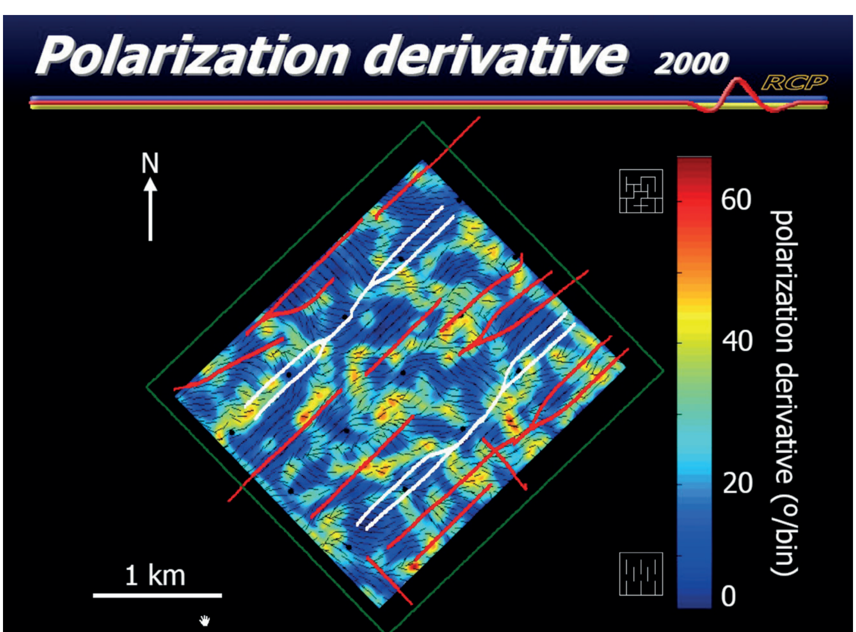

Figure 1 The spatial derivative of the fast (S1) polarisation as a means of showing the potential flow paths in the reservoir. The white horizontal wells are intended injectors, the red producers.

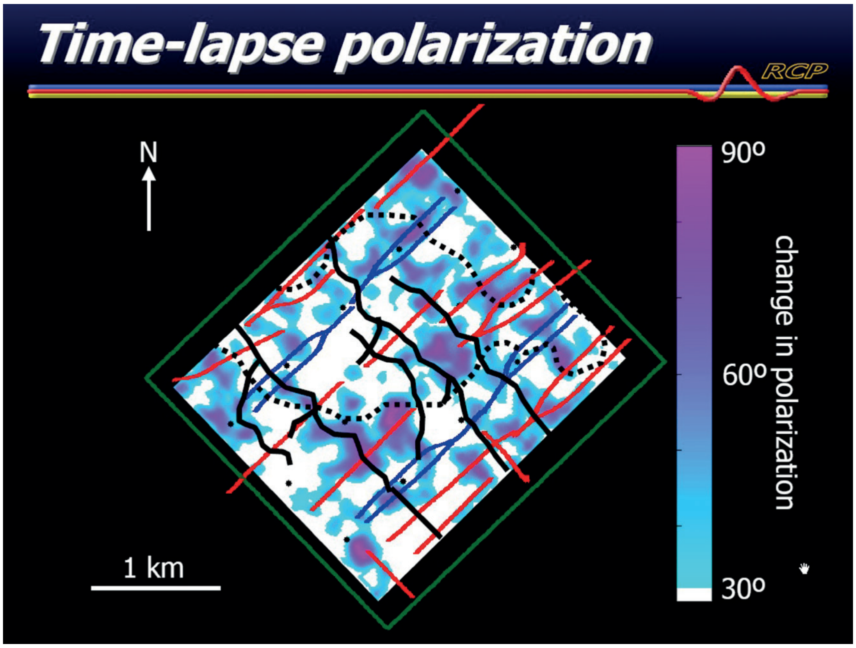

Figure 2 Polarisation change in the reservoir after two years of CO_2 injection. The injection wells are coloured in blue while the producing horizontal wells appear in red.

sink for CO_2 and that these reservoirs could be used for carbon capture and storage but the variability and heterogeneity in shales needs to be adequately studied to assure the injection process does not cause deleterious effects on the reservoir and damage to the environment. In essence, we are concerned that the hydraulic fracturing process in shale reservoirs may not be doing what we think it is doing. The concern is manifested in secondary recovery processes involving water injection as well. Most shale reservoir development to date involves primary recovery rather than secondary and tertiary recovery processes. To increase production, these processes need to be introduced.

Weyburn Field

As an example of stress monitoring in the subsurface let us review what our 4D, 9-C monitoring showed us at Weyburn and Wattenberg Fields. At Weyburn, we acquired three multi-component seismic surveys a year apart. The first was prior to CO_2 injection, the second one year later and then the third a year after the second survey. We used the spatial orientation of shear wave polarisation to map out potential flow paths in the reservoir over a 9 km^2 study area. In doing so we introduced a spatial derivative of shear wave polarisation (S1, fast). It showed that flow paths where not all parallel to the horizontal wells used for injection and production as previously assumed (Figure 1).

After a period of two years a time-lapse polarisation change was mapped in which polarisation flips of up to 90 degrees were shown. Note that the areas of strongest polarisation change do not necessarily correspond to the spatial position of the injectors but appear to coincide with the eastern producers (Figure 2).

What is going on? Firstly, the areas of greatest change correspond to highly fractured areas/volumes in the reservoir. Secondly, these fractured areas are areas of complex fracturing with multiple fracture sets and orientations. We refer to these portions of the reservoir as being stress-sensitive. These stress-sensitive zones are subject to the greatest change due to changes in effective stress.

Wattenberg Field

Wattenberg Field in the Denver Basin is the site of horizontal ‘shale’ development since 2008. The reserves in the field are enormous but the recovery is low. Many of the horizontal wells have been producing for years and the industry is looking at ways to increase recovery, including methane and CO2 injection along with refracturing. When many of the wells were drilled the mantra was ‘drill baby drill’ and the scheme of drilling and stimulation employed was referred to as ‘harvest’ production. The thought was simply ‘one and done’. That philosophy is changing and refracturing and gas injection are helping to bring about the change. But how can this change be effectively and economically brought about?

During the early development of shale reservoirs the engineers viewpoint was ‘We don’t need any of that seismic data’. The thought that the shale reservoir was layered and continuous changed when horizontal drilling showed that faults occurred and it was difficult to keep the drillbit in zone. Then the realisation occurred that the shales were not all the same in composition and mechanical make-up and that some zones were better to complete in than others. Seismic inversion was used to show and quantify these changes. Then some people (RCP) had this brilliant idea: ‘Let’s do time lapse seismic surveying during initial development’. What did we see? The answer turned out to be changes above, below and within the reservoir due in large part to stress changes introduced by hydraulic fracturing. The use of shear waves to show stimulated reservoir volume through time-lapse changes in shear wave azimuthal anisotropy for the two main zones that the wells were landed in was noteworthy (Figure 3).

To try to understand the changes we were seeing, Tom Bratton undertook finite element modelling of the reservoir(s) at Wattenberg Field (Bratton, 2018). He showed changes in stress occurred above, below and proximal to the wells he introduced into his model and that these changes occurred over time. Of importance, especially to the concept of refracturing, was the observation of shear wave polarity flips that occurred over time (Figures 4-6).

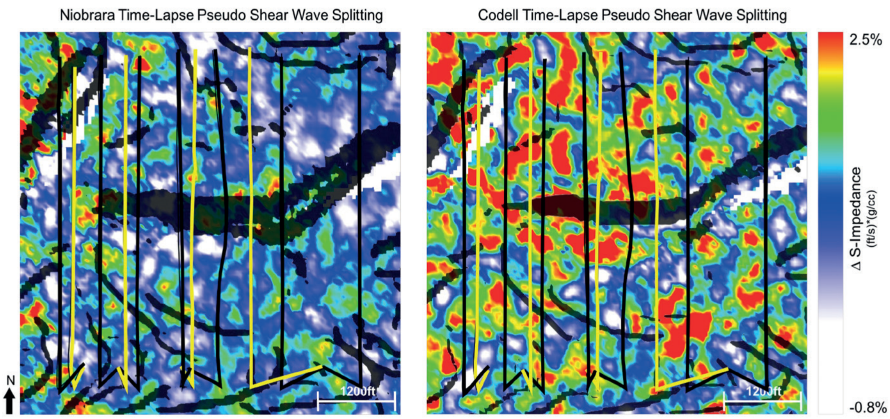

Figure 3 Time-lapse shear wave azimuthal anisotropy showing stimulated reservoir volumes in the Niobrara and Codell production zones in Wattenberg Field over 2.6 km^2. The black lines are horizontal wells in the Niobrara C Chalk. The yellow lines depict wells in the Codell.

What do these observations mean relative to injection and production in shale reservoirs? For one, hydraulic fracturing is prone to causing shear fracturing of the reservoir. Generally, the easiest rock to break is rock that has been broken before. The dominant sets of fractures in the Niobrara Chalk at Wattenberg Field are shear fractures. Many of these fractures are sealed with calcite but they are weak and can easily be opened. The most stress sensitive parts of the reservoir are where swarms of natural fractures already exist. The basis for this understanding is the Mohr circle (Figure 7). The increase of pore pressure moves the circle to the left until it hits the failure envelope and causes shear fracturing. Extensional fractures don't form until the Mohr circle moves past the vertical axis of the chart.

The lower effective stress areas are areas of more complex fracturing resulting in more surface area and if propped tend to be more productive, ie, have greater stimulated reservoir volume. Thus, early characterisation of the fracture network can assist the development of cost-effective stimulation practice in shale reservoirs. Seismic monitoring can be effective, especially with the use of shear waves. Shear waves can measure the stress changes in the reservoir as they measure volume changes and not interfaces as P-wave AVO does. In addition, shear waves can be used to monitor flips in the fast shear wave polarisation which when it occurs temporally and spatially can be used to time when refracking will be of benefit. These flips will occur in the higher permeable zones where there is a low contrast in horizontal stress magnitudes (Figure 8).

The characterisation of natural fractures and their interaction with hydraulic fractures is necessary for optimising drilling and stimulation in shale reservoirs. We are also learning that refracturing can increase reserves and production. Initially, refracturing targeted older wells completed with fewer, more widely spaced stages and low amounts of proppant and high amounts of gel. Now the characterisation of the interaction of natural fractures and hydraulic fractures with shear waves can aid in ways the earlier efforts could not. Generally, refracturing should not be viewed as a means to accelerate production. The greatest benefit comes from accessing new resource and to do so the direction

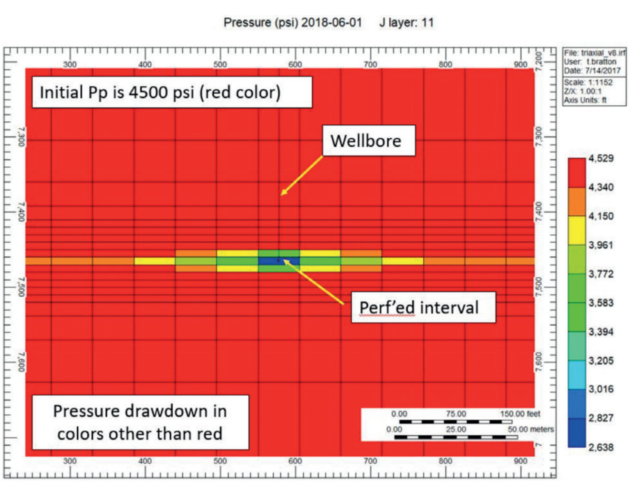

Figure 4 The finite element dynamic model.

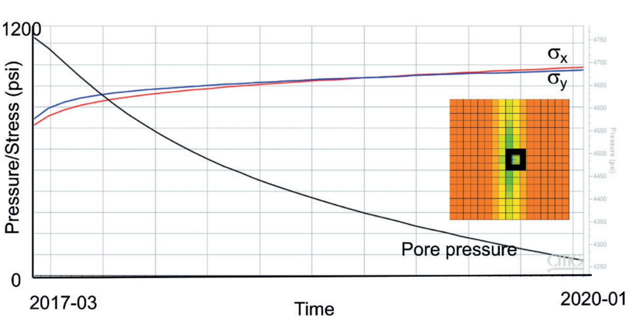

Figure 5 Lateral changes in magnitudes of horizontal stress as a function of time due to production. Even more prominent are the changes due to injection.

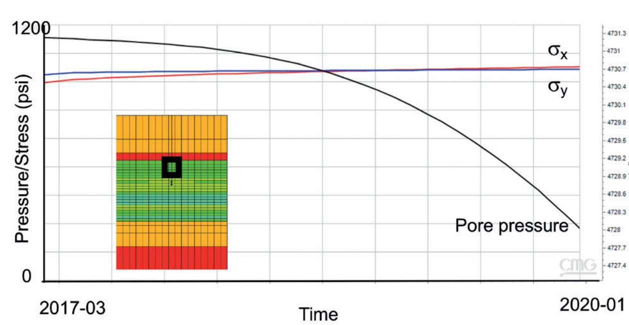

Figure 6 Changes also occur above the reservoir.

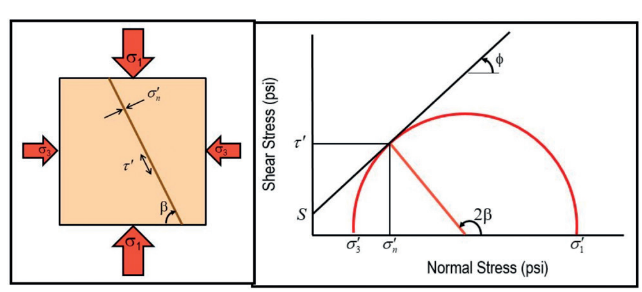

Figure 7 Mohr circle and the failure envelope.

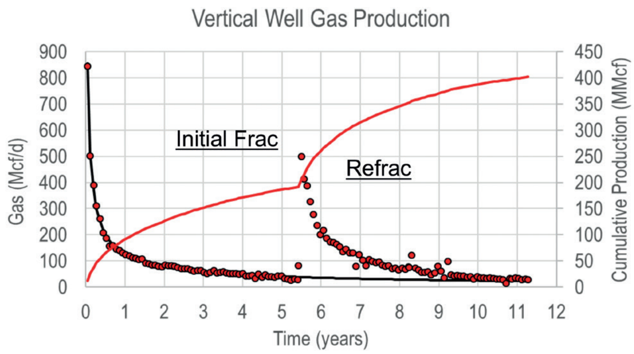

Figure 8 refracking of older wells can pay dividends.

of the hydraulic fractures needs to change and the extent of interaction and creation of complex fracturing. In effect, we see areas along the lateral where low effective stresses occur and use refracturing to maximise fracture surface area. In general, we can infer changes in stress from temporal changes in our seismic data and shear waves are more stress sensitive than compressional waves and have different attributes we can use.

We have used the reservoir model created at Wattenberg to conduct reservoir simulation under different scenarios of gas injection. The incremental recovery is significant and is predicated on the quantification of permeability in the reservoir and its changes with time as augmented by the time-lapse seismic data. The incremental recovery is predicted to be 5% higher with gas injection for a total of 12% recovery vs 7% primary (Ning et al, 2022). Under the combined use of CO_2 for enhanced recovery and decarbonisation compositional reservoir simulation indicated that the recovery factor would be 10% and provide a carbon neutral oil assessment (Ning et al, 2023).

Conclusions

A change in shale reservoir development can be brought about by incorporating time-lapse multi-component seismic monitoring. New technologies are starting to evolve to make permanent reservoir monitoring faster and more affordable. These technologies could have a significant impact by increasing production and reserves from shale reservoirs while providing avenues for carbon management and sequestration.

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