

Direct Imaging Of Reservoir Fluid Changes: A New Tool For Managing Production

Cat scan technology can now be applied to the oilfield. Interwell imaging can produce high resolution 2-D and 3-D images of reservoirs and help track fluid movements. Chevron has used this technology in one of their cyclic steam flood operations with great success.

The optimization of production, especially in enhanced oil recovery (EOR) operations, could be enhanced significantly if fluid fronts and changes within the reservoir could be mapped. However, conventional monitoring technologies such as logs, pressure analysis, or surface seismic are typically unable to resolve changes inside the reservoir in sufficient detail. In many cases the effects of EOR and primary production have to be inferred from well production data, and specific questions such as flow conduits and local compartmentalization remain undefined.

Newly developed interwell imaging technology has been applied to produce high resolution 2-D and 3-D images of changes in the reservoir as the EOR technique progresses. As a result, new understanding of the actual reservoir structure and flow characteristics are available to the asset team to optimize the production. The application of the technology to a cyclic steam flood operation in California is described in this article.

Cymric Reservoir Cyclic Steam Flood

The Cymric oil field in California's San Joaquin Valley is typical of many of the oil fields of this region (Fig. 1). The reservoir rock is a siliceous shale (Opal A-CT diatomite-porcelanite) of high porosity and low permeability occurring at a depth of about 1,000 ft, with steep dips of up to 70°. Natural and induced fractures are the primary reservoir depletion channels, and prediction of the orientation of the induced fractures is key to development optimization. The heavy oils

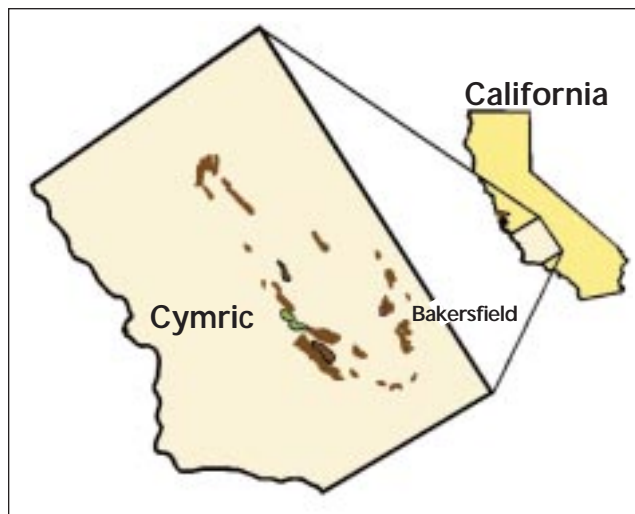


Fig. 1. This map of the southern San Joaquin Valley depicts the location of the Cymric oil field relative to Bakersfield, Calif.

contained in these reservoirs usually require an EOR process such as steam injection to increase production.

Chevron has been using a proprietary variant of cyclic steaming in Cymric for several years to increase the volume of reservoir rock being contacted by the steam while avoiding the need for surface pumping units. Steam is injected into a reservoir zone for 3 days at a pressure sufficient to induce the growth of fractures in the reservoir. This allows steam to

come in contact with a greater reservoir volume. When steam injection ceases, the well is allowed to “soak” for several days. During this period the rocks imbibe water and give up oil, and the transfer of heat to the heavy oil makes it possible for the oil to flow more freely. After soaking, the injector well is returned to production, and the oil flows into the well under the pressures created by the injection portion of the cycle. After about 30 to 45 days the induced pressure is depleted, production ceases, and a new injection phase begins.

The well spacing in Cymric is typically $\frac{5}{8}$ acre (about 110 ft). There is potential for communication between adjacent patterns as well as the possibility of an induced fracture damaging a nearby well. Reservoir heterogeneity and anisotropy can lead to non-uniform steam induced fracture migration. Premature steam breakthrough into nearby injector/producing wells is undesired and can lead to severe mechanical damage that can result in abandonment of the wells.³ The closer the well, the more likely it is to encounter this problem.

To manage the production cycle efficiently and avoid steam breakthrough, know the exact location of the steam and adjust the injection operation and new well locations accordingly. It is also useful to know the vertical and lateral extent of these induced fractures and the extent to which the reservoir oil is being depleted by steam. Additionally, on a broader scale, knowledge of the sweep efficiency allows changes to be made to the overall injection strategy that could be applied to both this and other patterns.

Crosswell Seismic Imaging

In order to provide detailed information on the steaming and production effects occurring inside the reservoir, Chevron decided to apply high-resolution crosswell seismic imaging technology in a sequence of time-lapse surveys. The crosswell seismic service provided by TomoSeis Corp. uses a borehole nondestructive acoustic source. In one well this source is rapidly hoisted on wireline and typically energized every 2.5 ft at a rate of roughly 10 ft/minute. A second (receiver) well contains an array of 10 hydrophone receivers which are spaced 5 ft apart and pulled up-hole, interleaving every station at a 2.5 ft spacing while the source is energized over the entire logged interval in the first well.

The magnitude of this acoustic data acquisition can be quantified by the number of traces collected; this survey technique typically will collect 160,000 traces over an interval of interest of 1,000 ft, and in a time frame of about a day and a half. These data traces are processed for travel time information, which is then used as input to an algorithm that results in a high-resolution velocity image. Additionally, the data can be processed to obtain a high resolution reflection image, although this has not been done at this time.

One advantage of crosswell seismic surveying for production monitoring is that very high resolution can be achieved. This, coupled with the fact that crosswell seismic data are directly referenced in depth (not time), means that the differences between repeat surveys can be easily computed and as a result, changes of 1%-2% velocity can often be resolved.

Fig. 2a shows a 3-D perspective of the wells involved in the survey. They include three temperature observation wells (in blue) which surround a nearby steam injector well (in

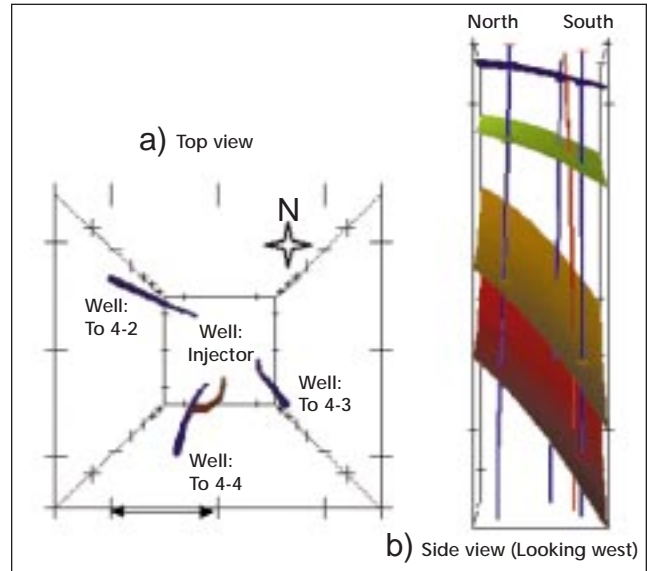


Fig. 2. The observation wells are relative to the position of the steam injector well and the relative dip encountered in this survey.

maroon). Fig. 2b shows the same wells projected into a N-S oriented cross section. The cross section includes several formation surfaces that show the severe structural dip within the survey area. For the majority of these time-lapse crosswell seismic surveys, the source occupied the TO4-4 well and the propagated acoustic energy was received in wells TO4-2 and TO4-3. The focus of this paper is on the results obtained from the TO4-4 to TO4-3 profile. The TO4-4 to TO4-2 profile yielded similar results.¹⁻²

The TO4-3 and TO4-4 wells are spaced 70 ft apart. The perforated zone in the injector well intersects the plane between the TO4-3 and TO4-4 wells. Based upon prior studies³⁻⁴ that used shear-wave birefringence, crossed-dipole anisotropy logs, and image logs, it was expected that an induced vertical fracture would grow along the strike direction during steam injection.

To monitor the cyclic steam process in the reservoir a series of five time-lapse crosswell seismic snapshots were collected throughout a 13-month period covering the different phases and several full injection/production cycles. Figs. 3-5 show the processed results of three snapshots and are tomographic images which can be likened to medical industry “cat scan” technology. These three snapshots were acquired at different times during an injection/production cycle. The image in Fig. 3 depicts the reservoir state just prior to the commencement of a steam injection cycle. Fig. 4 illustrates the reservoir conditions at the peak of an injection cycle, and the image in Fig. 5 was obtained from data acquired early in the production phase of a cycle.

Figs. 3-5 are shown with a horizontal exaggeration of roughly 3 to 1, so the true formation dip in the reservoir is considerably greater than illustrated. The color scale represents the reservoir acoustic velocity (P-wave) at all points in the reservoir between the two survey wells. The darkest blues are low velocities on the order of 4,000 ft/second and the light yellows and orange colors are higher velocities on the order

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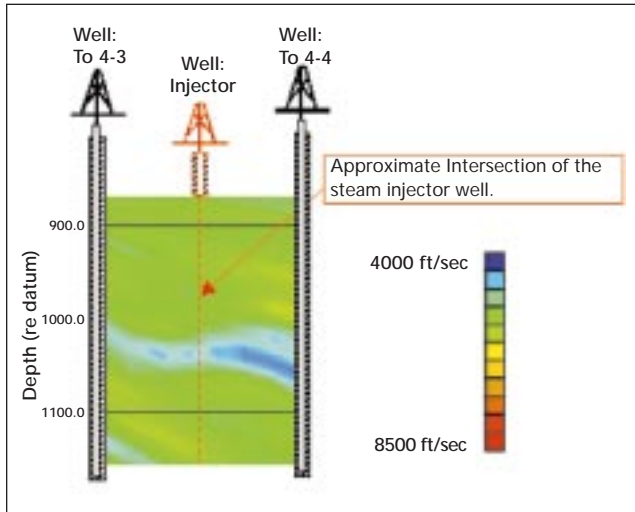


Fig. 3. This crosswell seismic velocity image of the reservoir is at the beginning of an injection cycle.

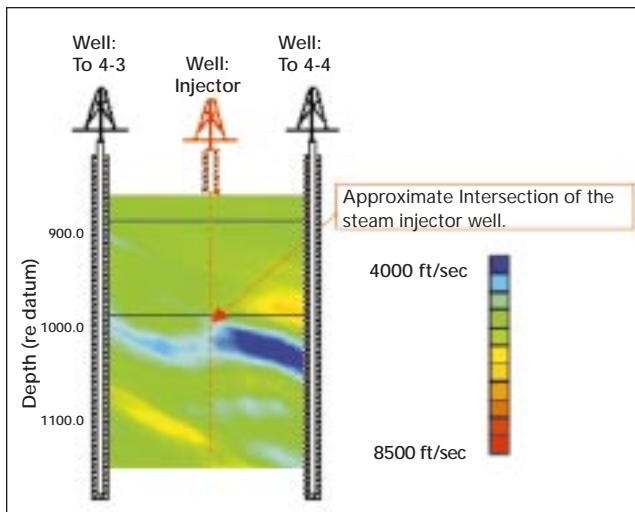


Fig. 4. This crosswell seismic velocity image of the reservoir is at the peak of an injection cycle. The image indicates an increase in the velocity suppression and shows a strong directionality and vertical confinement.

of 7,000 ft/second. Typical unheated reservoir velocities are 5,000 to 5,500 ft/second. Petrophysical measurements made at Chevron on two core samples from Cymric indicate that both increasing steam saturation and increasing sample temperature will decrease the seismic velocity by 10% to 20%.

Time Lapse Survey Results

The crosswell seismic surveys are able to image the reservoir velocity changes with very high resolution. The perforations in the injection-production well are between depths of about 1,060 ft and 1,150 ft. At the perforations, the injection well is nearly coincident with the plane of the TO04-3 to TO04-4 profile. The perforations in the well project onto the image along the dashed red line in Figs. 3-5.

The observed changes in the reservoir are not presently

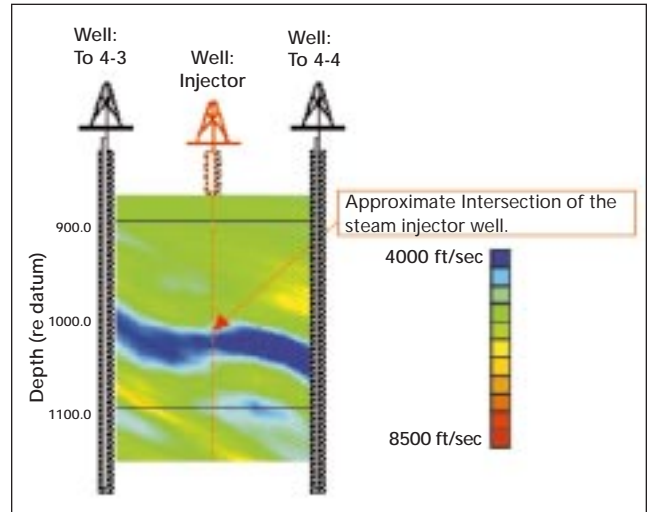


Fig. 5. This crosswell seismic velocity image of the reservoir is at the end of an injection/production cycle. The image indicates a velocity suppressed interval which extends in both directions from the steam injector well.

resolvable with conventional surface seismic 4-D, though the results of this study and other similar studies may provide insight as to how a surface 4-D program could be "tuned." However the reservoir changes can be clearly identified and located with crosswell seismic in this case.

In the first snapshot (Fig. 3), there is a 30-ft thick, low velocity zone (blue color) downdip of the injector, about 20 ft above the perforations. There is also a thin, low velocity zone updip of the perforations. These features suggest that there is steam entering the reservoir just above the perforations, and there may be a vertical fracture extending for at least 60 ft above the perforations. However, the downdip flow from this fracture appears to be starting at a slightly different point on the fracture than the updip flow. The bulk of steam appears to be flowing downdip (or as hot water, because the steam may be quenched at the end of a production cycle).

The second snapshot (Fig. 4) shows that the downdip low velocity zone has grown in intensity, but not in extent. These data were acquired during steam injection and the bulk of the steam may be moving either out of the plane of our image to the southeast, or further downdip.

The third snapshot (Fig. 5) shows that the low velocity zone has grown on the updip side and has further decreased in velocity. There is also a downdip decrease in velocity at slightly greater depth (1,100 ft). This coincides with the middle of the perforations. Interestingly, the vertical extent to which the reservoir is being swept is still rather small. (Note: These snapshots have been combined into a time-lapse "movie", which makes it far easier to visualize the dynamic nature of these processes in the reservoir.)

In these images, evidence is provided for a 100-ft vertical extent to an induced fracture near the injection wellbore. Additionally, most of the steam appears to be confined to thin zones coincident with bedding which suggests that there may also be an induced fracture (or fractures) along bedding.

Results

The crosswell seismic imaging technique resolved the locations and extent of the fluid changes occurring within the reservoir during the injection/production cycles. From the time lapse images, there is evidence of induced vertical fracturing as well as a preferential down-dip sweep direction. The 12%-15% changes observed in the acoustic velocity of the reservoir rock resulting from the steam injection are consistent with those predicted by rock physics studies. Cymric reservoir changes provided strong features imageable with the crosswell seismic surveys; so strong in fact that it has not been necessary to "difference" the repeat surveys in order to visualize the changes. (Figs. 3-5 show raw velocity not velocity change.)

Chevron is working with both surface seismic and crosswell seismic technologies for optimal reservoir monitoring. In the Cymric reservoir, the events described are not generally observable from the surface with seismic 4-D monitoring. Therefore in this and similar reservoir situations, crosswell seismic provides a unique way of imaging reservoir changes during production. In marginal cases, crosswell imaging can provide a basis for optimizing surface 4-D processing and surface monitoring on a wide area basis.

Acknowledgments

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