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CROSS-WELL SEISMOLOGY - A TOOL FOR RESERVOIR GEOPHYSICS

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I. BACKGROUND

Today it is common that 60 to 70 percent of the mobile oil is left in the ground when an oil reservoir is considered economically depleted (DOE, 1986). The large percentage of mobile oil left in the ground is due, in part, to macroscopic inhomogeneities in the oil reservoirs. This is illustrated in Figure 1. An oil well taps only a small fraction of the reservoir due to impermeable layers, which effectively transforms a large oil pool into a number of noninteracting pockets of oil. This fact is known in the oil industry, but little action has been taken so far because few tools are available to define the precise location of the untapped mobile oil. Simple infield drilling with increasingly smaller spacing between the oil wells will eventually drain all the small oil pockets in an oil field. This is a common route taken today. However, it is a very expensive way to drain an oil reservoir because of the limited amount of information available to determine the location of the new wells. This also results in many unnecessary and misplaced wells. Given the cost for an oil well of $0.3M to $10M, better reservoir definition currently receives high priority in the oil industry.

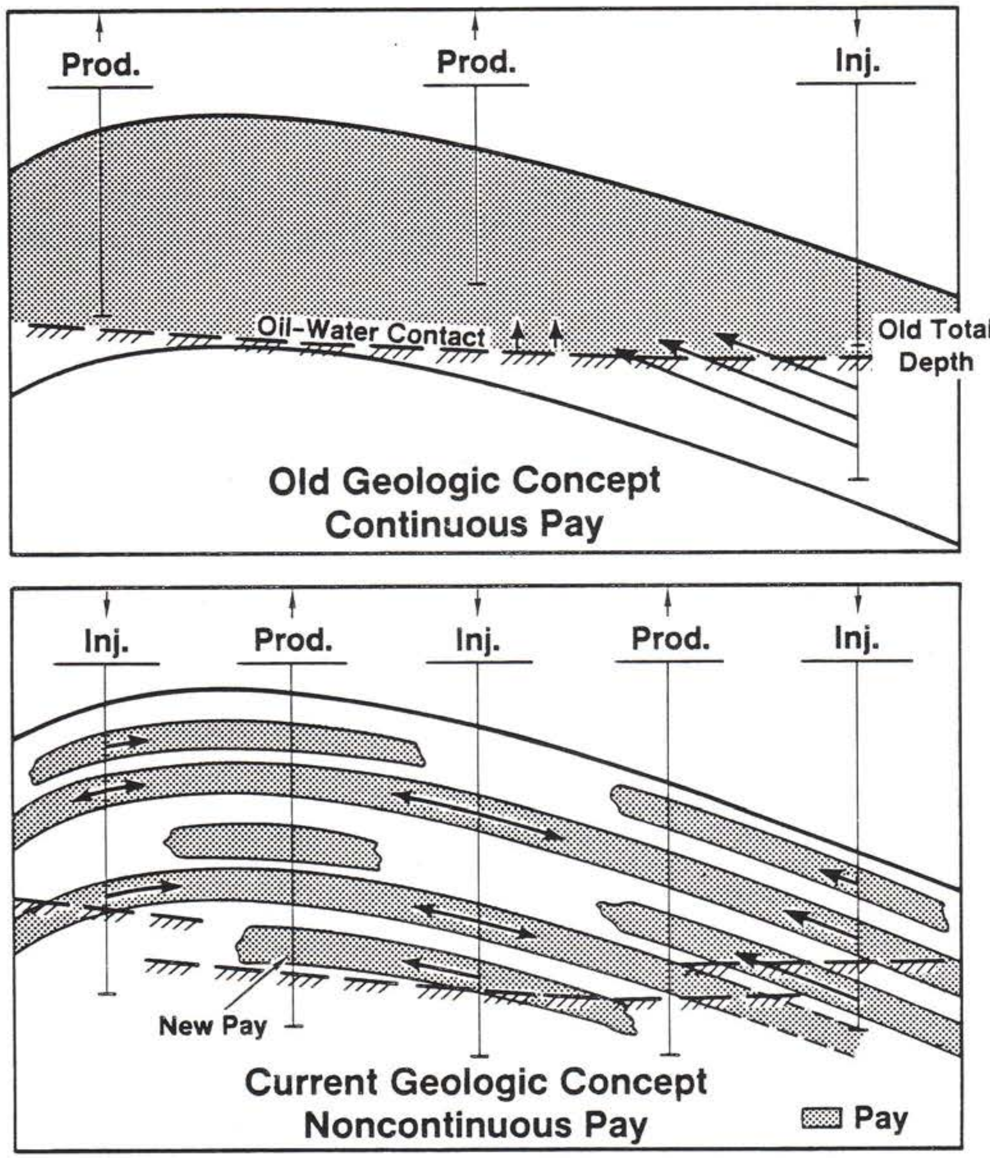

Figure 1. Old and Current Concepts of the Continuity of Oil Reservoirs.

II. INTRODUCTION

Seismic techniques in the oil industry are commonly deployed on two different scales: one, a 3-D, seismic scale which covers square miles; and a 1-D, well logging technique which covers a few inches around the well bore. The

3-D seismic survey covers more terrain but commonly lacks resolution to be effective on the reservoir scale. The seismic- or acoustic- logging technique has tremendous resolution but covers a limited amount of terrain, so that anomalies away from the well bore are not sampled.

Surface reflection and refraction techniques use the surface of the earth for both the seismic source and the receivers. The drawback with this configuration is that the sensors are far from the targets and seismic energy has to penetrate the slow and highly attenuating near surface layer both going down and coming up. Furthermore, the available energy in surface seismic sources is mainly converted into undesirable surface waves (Miller and Pursey, 1955).

The surface seismic techniques for monitoring and characterizing oil or gas reservoirs are shown in Figure 2. The common frequency range for surface-recorded reflected events, 10 to 50 Hz, makes imaging of thin beds and other thin features difficult or impossible. Surface seismic techniques also have to contend with a highly attenuating weathered layer, which decreases the signal/noise ratio. Surface noise compounds this signal/noise ratio problem, especially when surface seismic data are collected in oil fields.

The seismic well logging technique samples the geology surrounding the well. In the near well zone one can find both a borehole generated anomalous stress field as well as mechanical property and porefluid changes, generated by the process of drilling. In most cases the near well zone is a poor representation of stress conditions, geology and saturation conditions of oil reservoirs.

Cross hole seismology, shown in Figure 3, is emerging as a promising technique to evaluate and delineate oil reservoirs. This technique has several advantages because downhole seismic sources and multilevel receiver strings are used for reservoir characterization. One of the advantages is the potential for using an order of magnitude higher seismic frequencies than surface techniques due to lower attenuation in the sub-weathered layer formation. This, together with the relative closeness of the cross-well transducers to the target, indicates that the potential of an order of magnitude improvement or better in the resolution of the reflected events in well to well data as compared with conventional surface seismic data. In cross-well seismology it is also possible to use transmitted seismic arrivals, which make it possible to perform P- and S-wave cross-well seismic transmission tomography,

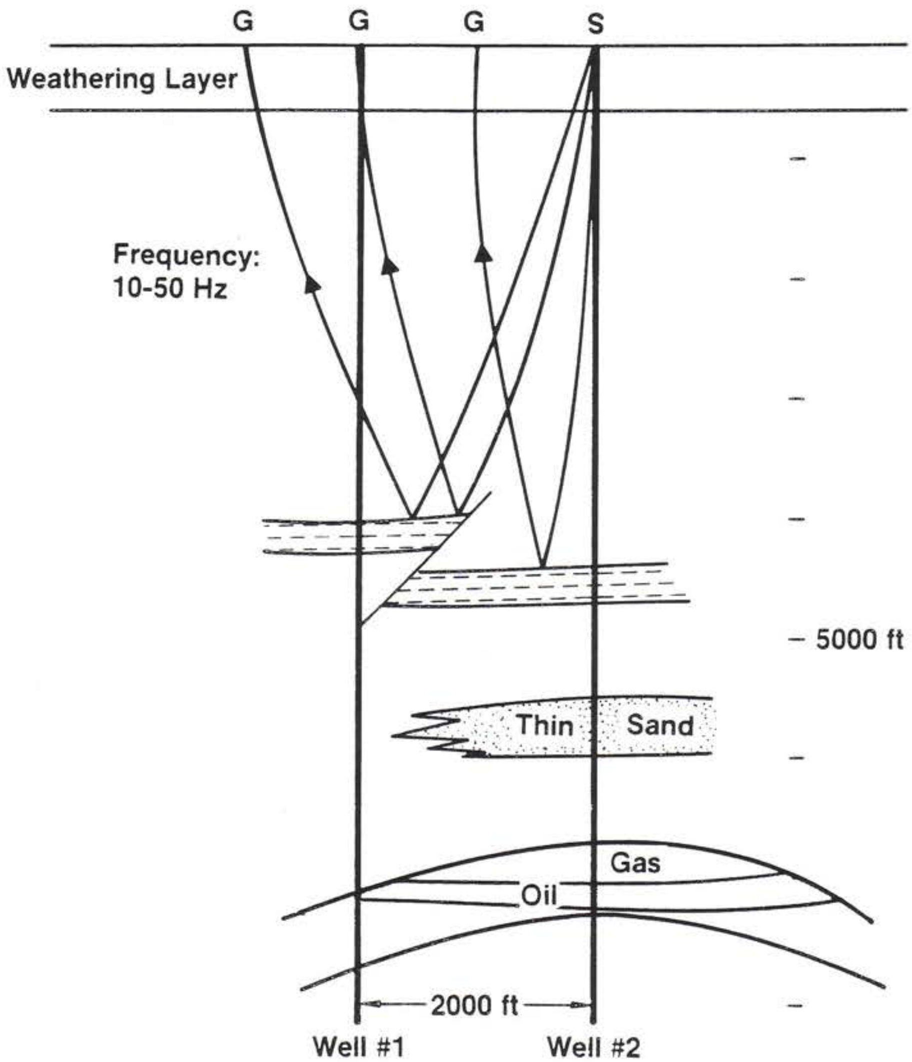

Figure 2. Reservoir Characterization Using Surface Seismic Techniques.

which provides data for an accurate reconstruction of the velocity field.

The 2-D cross-well seismic survey fills the void between the 3-D surface seismic and the 1-D logging techniques both in terms of spatial coverage and the seismic frequency band width. The cross-well seismic technique can thus be seen as a complimentary tool to existing techniques for the exploration and development geophysicist. The cross-well configuration allows the

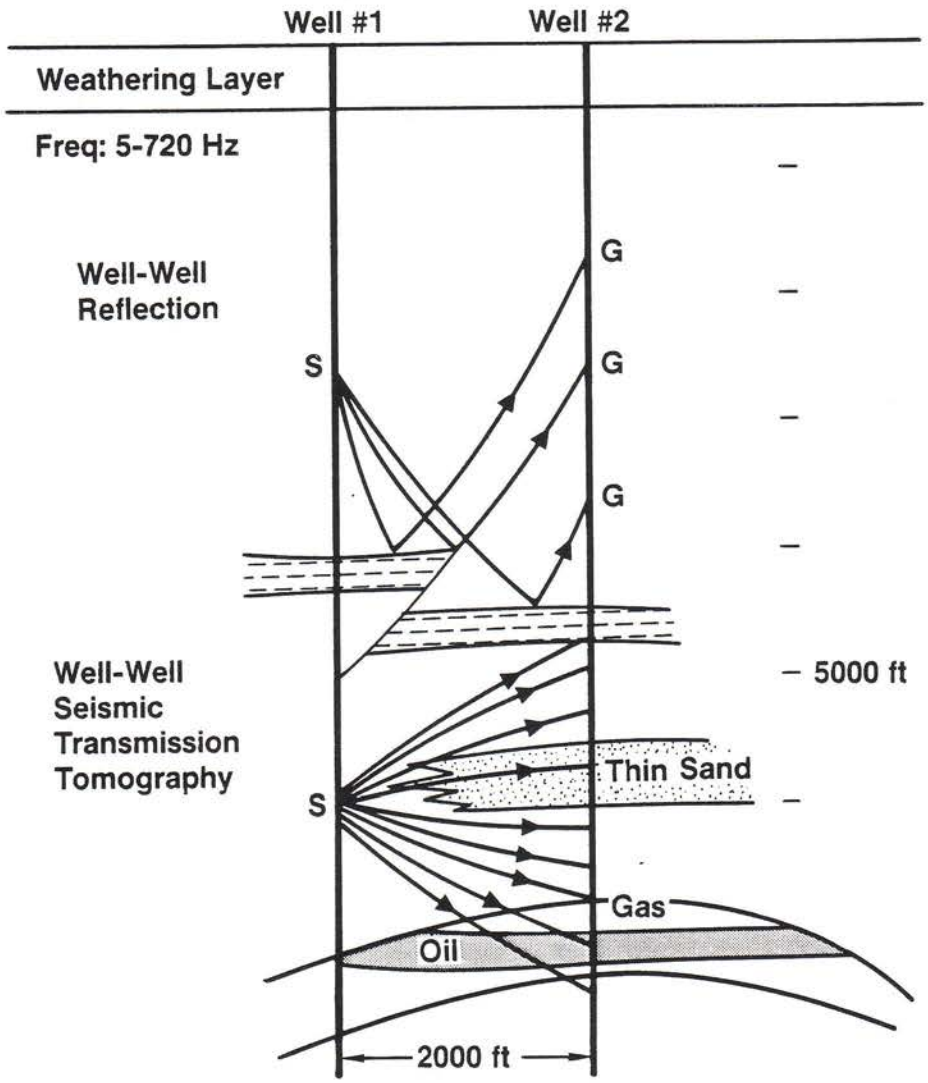

Figure 3. Reservoir Characterization Using Cross-Well Seismic Techniques.

use of transmitted together with reflected waves. This allows the construction of an image using a combination of migration of cross-well reflected events and tomographic velocity analysis using the transmitted seismic energy. Figure 3 shows how both these techniques can be used when seismic transducers are placed in wells. The downhole source can also be used in a reverse VSP mode. This is an attractive alternative when only one well is available. If a reverse VSP survey is done in a noisy environment, it may be possible to place the geophones below the weathered layer. This allows the use of much higher seismic frequencies in the reverse VSP mode than for a conventional VSP using a surface source. One of the most significant advantages gained by a reverse VSP operation is that it is possible to perform multi-offset VSP's with only one run in the well with the downhole source. These data allow imaging between the well and the surface in as many cross sections as is desired without additional expense except for positioning the surface geophones. Naturally, the cross-well survey can be combined with a reverse VSP to generate both a detailed 2-D image from the cross-well data and a 3-D image from the VSP data. If the cross-well reflected energy is used, it is possible to extend the imaged zone below the wells and still maintain an order of magnitude higher frequencies than for surface seismic techniques.

In some cases, wells are drilled with little a priori information about the geology of the drill site because severe surface noise or weathered layer problems have prevented adequate surface seismic surveys. If nearby wells are available with a spacing less than 5,000 feet, it is possible in some cases to replace the drilling of an investigation well with a cross-well seismic survey. Most oil wells in the world, 80% reported in 1986, are drilled as development wells in existing fields. In these cases nearby wells exist and the cross-well seismic survey is an option to investigative drilling. In other cases such as areas with good surface seismic information, a cross-well seismic survey will give more detailed information of the cross-well geology for evaluating in-field drilling locations for optimizing field development.

One of the primary applications for cross hole tomography is the pre-EOR site evaluation for bed and shale continuity and for spatial and temporal monitoring of the process of Enhanced Oil Recovery (EOR). This can be done before the steam or gas has reached the production or observation wells and thus make it possible to take corrective steps early in the EOR process. Another important application for cross-well seismology is the evaluation of pilot EOR projects in new areas.

III. MODELING OF CROSS-WELL SEISMIC TOMOGRAPHY

Computer tomography modeling experiments have been performed using complex 2-D velocity sections constructed from real cross-well seismic data and well logs from the Kern River Oil field. The simulated, cross-well travel-time data were obtained by raytracing through sections with a well spacing of 200 and 400 feet and a well depth of 1,000 feet. The raytraced travel times were checked using elastic, finite difference modeling through the same section. Travel times for the finite difference and the raytracing modeling for the same source-receiver pair were generally found to be within the sample rate of 1/2 millisecond.

Figure 4 shows the flow of processing cross-well seismic tomography data from both field and modeling experiments. A ray tracing algorithm described by Cerveny (1985), was used to obtain both the geometric raypaths through the cross-well velocity fields as well as the total travel time along these paths. The velocity section was reconstructed using an Algebraic Reconstruction Tomography (ART) algorithm as described by Lytle and Dines (1980) and Peterson et al. (1985). The velocity imaging process is iterative with two loops: the inner one is the ART; and the outer, the raytracing loop. The ART algorithm used in this paper is using the difference between the observed travel times, real or model, and the travel times through the current model along specific ray paths. This algorithm converges to the minimum-norm, least-squares solution (Ivansson, 1983). The start model might be a constant velocity field, and the initial ray paths in that case would be straight lines. The outer loop is an iterative raytracing loop, which traces rays through an improved estimate of the velocity field after each ART reconstruction. In each step the estimate of the ray path improves, so velocity corrections which minimize the difference between observed and computed travel times are distributed along better estimates of the raypaths. An important feature in the processing is the smoothing of the reconstructed velocity field prior to any raytracing.

The result of modeling a section between wells separated by 200 feet is shown in Figure 5. This figure shows the input model (Earth), the starting model (Log Model) obtained from two-dimensional extrapolation of a velocity log, and the reconstructed section (Result). To the right of the Result section are velocity profiles taken at three locations from the Earth section, shown by heavy black lines, and velocity profiles from the reconstructed

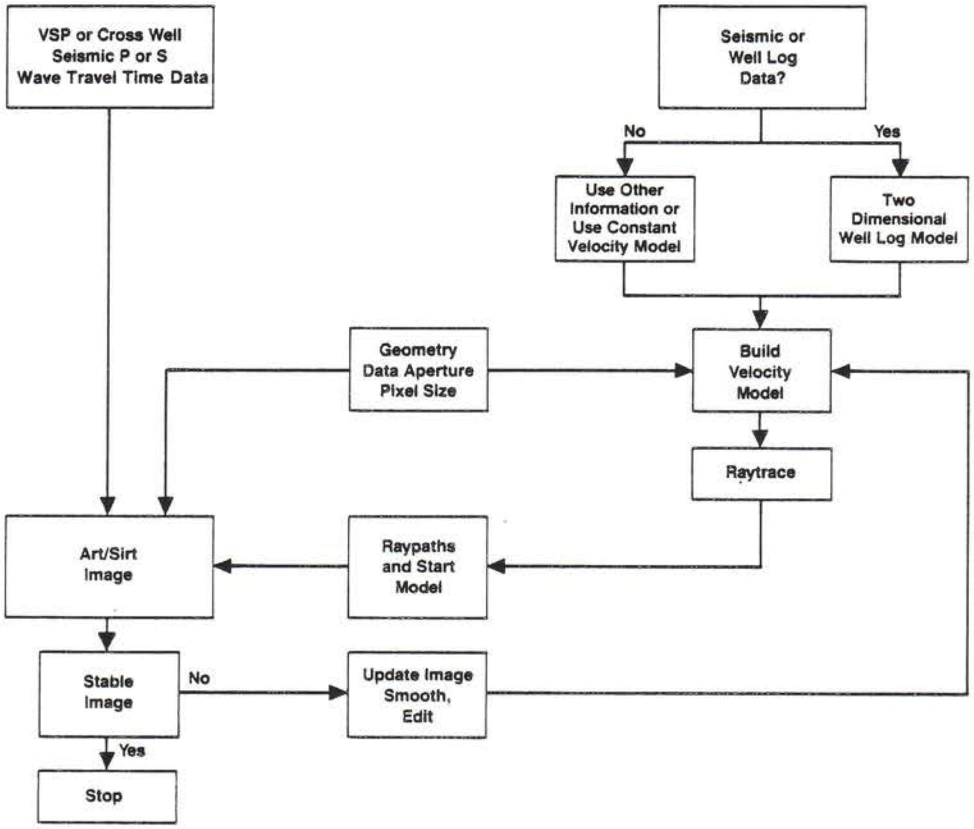

Figure 4. Flow Diagram for Processing of Tomographic VSP or Cross-Well Seismic Data.

section, shown by thin lines. The three velocity profiles were taken from pixel columns next to each well and in the middle of the section, respectively. To the right of the Vp Log are five, common source point gathers for raytraced travel times through the Earth and the Result. The small difference between the two travel-time data sets give an indication that, with limited a priori information about the structure between boreholes, a very good approximation of the true velocity distribution, can be obtained using travel times, ART tomography, and accurate raytracing.

In the work of tomographic velocity reconstruction the raytracing portion represents the vast bulk of the computing time. Without the raytracing the velocity image can be reconstructed fairly easily on a small computer in the

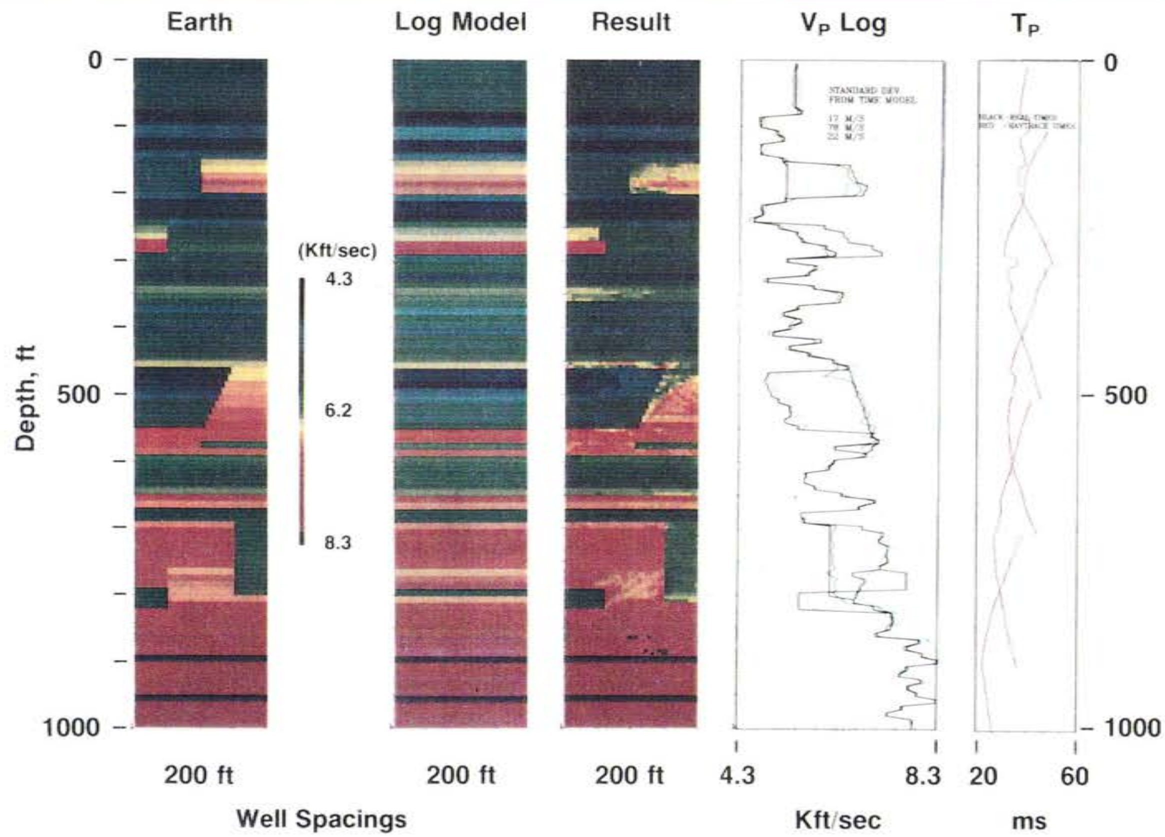

Figure 5. Modeling Cross-Well Tomography With a 200 ft (61m) Well Spacing Using Raytracing. Transducer Spacings and Pixel Size dimensions are 5 feet (1.5m).

field. This would have advantages in terms of quality control of the data and for making an informed decision on the spacing of the transducers in the wells.

In the discussion of the above model, shown in Figure 5, the vertical spacing between the transducer locations is 5 feet (1.5 m), resulting in 200 source points and 200 receiver points in the 1,000 feet wells. A data aperture of ±45° has been found empirically to be sufficient to produces good images and is used for all presented tomographic results. A data aperture of ±90° has been found to be very time consuming because the raytracing is through many more pixels. It was also found to introduce noise in the reconstructed section due to long rays, which are not necessarily the minimum time paths despite a successfully traced ray. The ±45° aperture generated over 12,000 rays for the 200-ft (61-m) model which was over 98% of all possible rays for this aperture. The commonly found distance between wells in the Kern River oil field is between 200 and 400 feet (61 and 122 m) so the size of this model is realistic.

It is clear from comparing the two sections Earth and Result in Figure 5 that Earth was successfully reconstructed using realistic model data. Even the thin truncated bed at 580 feet was successfully found. This figure shows the result of four consecutive smoothings, re-raytracing and reconstructions.

In a study of the influence of noise, it was found that random timing errors as high as the maximum travel time in one pixel, approximately 1 millisecond, could be added to the travel times without serious degradation of the images. Each pixel is intersected by many ray segments, so any random errors tend to be cancelled. A large, systematic shift in the picked travel times, due to incorrect identification of the arrivals, was, however, found to be more serious.

IV. TOMOGRAPHIC IMAGING OF AN EOR APPLICATION FOR HEAVY OIL

A field experiment was performed in January 1985 between pairs of three wells, which penetrated a steam-flooded sequence of oil sands in the Kern River Oil field in California. A plan of the field site is shown in Figure 6. The reason for conducting the experiment at this site was the expressed need for a detailed image of the steam- and water-flooded sequence of sands and the

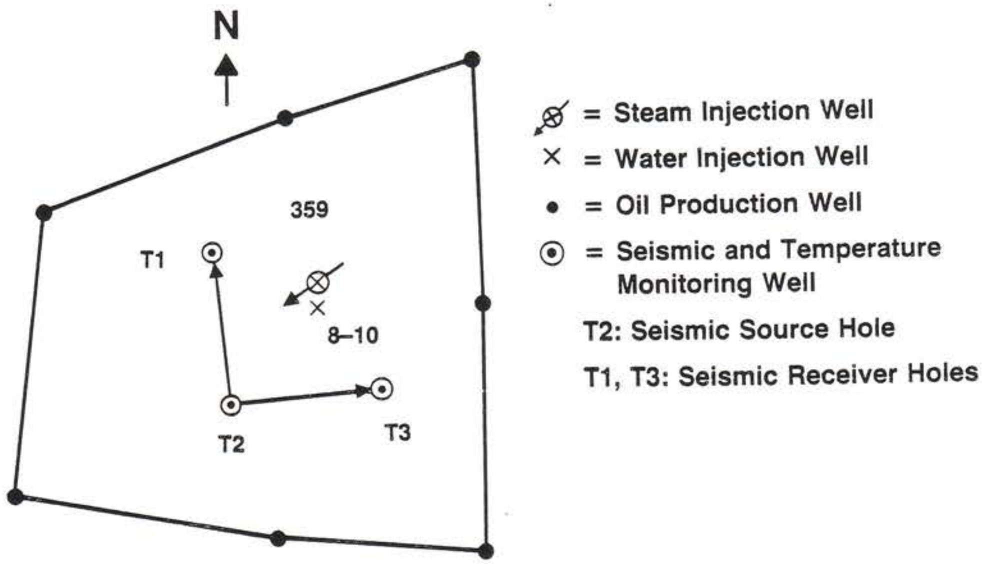

Figure 6. Planview of Seismic Cross-Well Tomography Experiment in Kern River.

anticipated large velocity changes from both the heating of the formation with heavy oil and the increase of gas saturation. Both these effects have been investigated by Tosaya et al. (1984) and Dunn (1986). Their results show that the P-wave velocity decreases sharply both with increasing the temperature and increasing the gas saturation in the core sample. By measuring the temperature in the wells, one can obtain an estimate of the gas saturation from the cross-well velocity images. The interest in imaging a thermal EOR situation is derived from the fact that, if the movement of steam can be predicted or monitored, methods exist to prevent steam breakthroughs and to guide the steam to unheated parts of the reservoir.

The depth of the wells where the experiment was performed is 1,000 feet (305 m) and they were separated by 100 feet (30.5 m). One well was used as a seismic source well (Well T2) and two wells were used as receiver wells (T1 and T3). The source used was a 40 cubic-inch downhole airgun from Bolt Technology, Inc., and the receivers were SSC clamped 3-component K-tools. In an early test during the experiment it was found that single pops with the airgun was sufficient to obtain good quality first arrivals.

The field data were of good quality in the beginning of the experiment but, as the data acquisition proceeded, the signal/noise ratio decreased substantially as a result of a combination of aeration of the well fluid (the well released air for several hours after the airgun operation stopped) and the airgun-induced damaged cement-casing bond in the source well. In a repeat of one receiver position at the end of the experiment, the amplitude of the arrived, horizontally traveling P-wave decreased from 0.2 units to 0.05 units, a decrease in the amplitude of 75%.

The source well was drilled between the two receiver wells so a section 1,000 feet (305 m) deep and 2x100 feet (2x30.5m) wide could be imaged, as shown in Figure 7. In this figure the field Velocity Log is shown for Well II (same as T2) in a heavy black line, together with three logs through one of the reconstructed sections between Wells T2 and T3. The 100-ft (30.5-m) wide images are divided into 10 pixel columns. The three logs are through pixel columns 2, 5, and 9, respectively. To the right of the velocity logs are shown four sets of raypaths for common source points between Wells I (T1) and II (T2). As can be seen in the figure, significant raybending occurred. These are the raypaths along which slowness is distributed as discussed in Peterson et al. (1985). Finally, to the right of the raypaths the travel times are shown for the same four common source points. Both the travel times picked from the field data and the travel times from raytracing the section between Wells I (T1) and II (T2) are shown. The difference between the two travel-time sets is small, which indicates that a velocity reconstruction fitting the field data was achieved.

When travel-time data are used along straight raypaths, significant lateral and vertical smearing of the velocity field occurs because slowness differences between the model and the image are not distributed into the correct pixels. In Figure 8 the cross-well data from the previous figure were used to create a velocity image using only straight rays and no start model. The result shows that the boundary between the high- and the low-velocity zones is not as sharp as when traced rays were used. However, there is much useful information in this image, which could be obtained on a small field computer, for evaluating the survey in the field or for monitoring a rapidly progressing steam or gas zone.

The interpretation of the cross-well velocity image in terms of the status of different sands is shown in Figure 9.

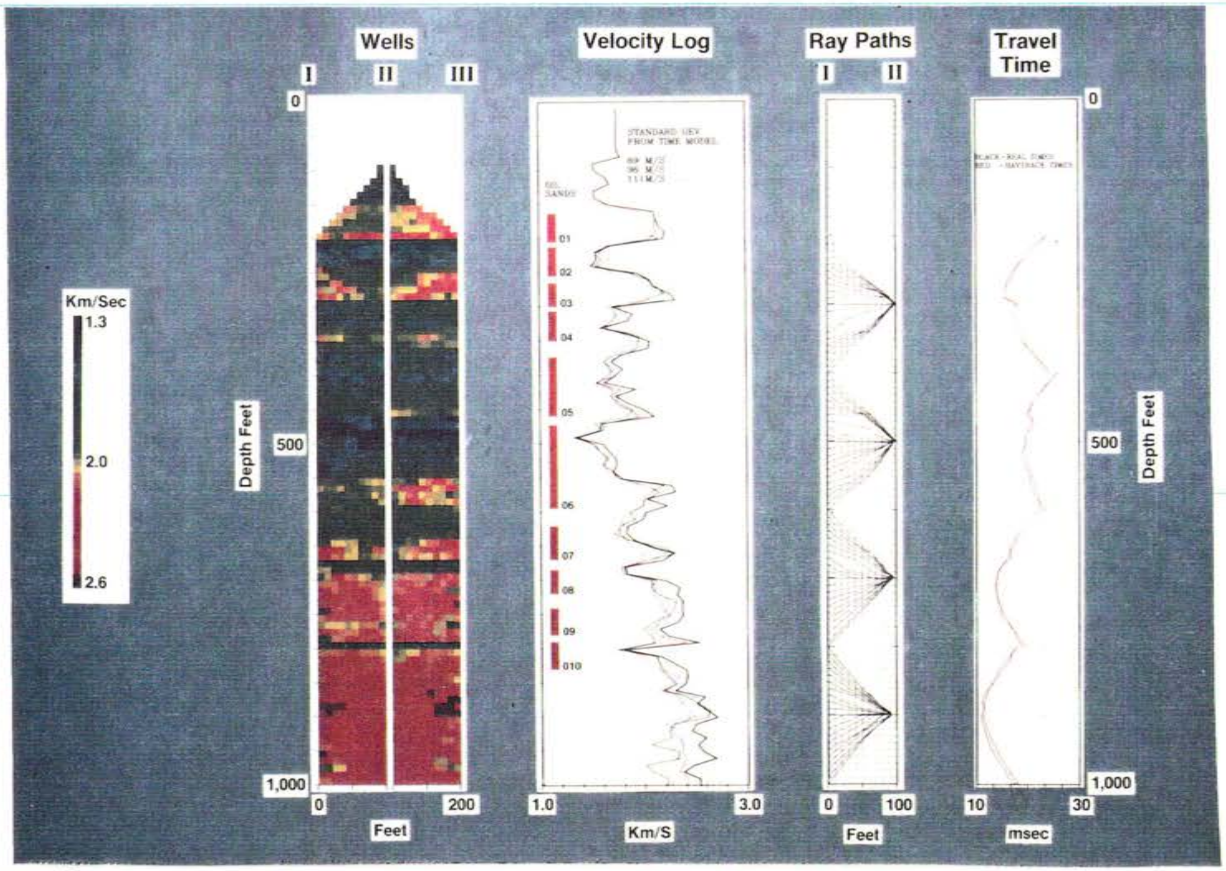

Figure 7. P-wave Velocity Image Between the Source Well II and the Two Receiver Wells I and III Using ART and Several Iterations of Raytracing. Transducer Spacings and Pixel Size Dimensions are 10 feet. A Model Derived From a Well Log was Used as Start Model.

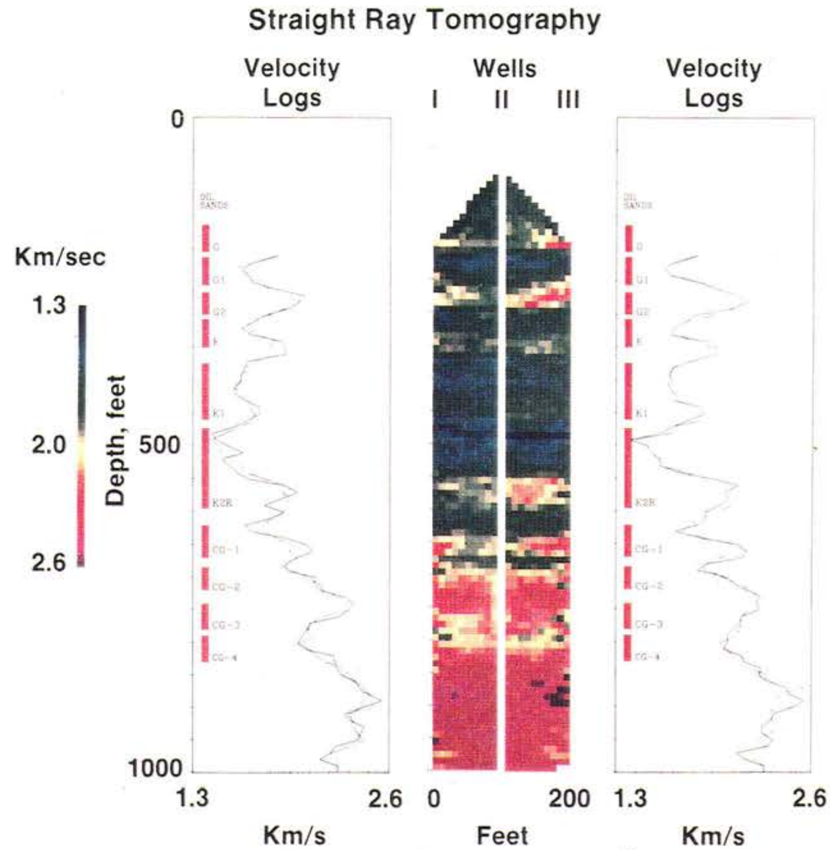

Figure 8. P-wave Velocity Image Between the Source Well II and the Two Receiver Wells I and III Using ART and Straight Ray Paths. No Start Model is Used.

In this figure the velocity section is interpreted in terms of fluid and gas saturations. The oil sands, as derived from the three well logs, are shown as short columns beside the velocity log and are numbered 1 to 10. The sands in the bottom of the section, #8 and #9, show up as high-velocity features due to high-water saturation from a prolonged period of water flooding. Other sands, #7 and bottom of #6, show a lateral change of velocity, which may indicate a lateral change in the fluid saturation. The reconstructed velocity section shows how sand #6 at a depth between 480 and 600 feet (146 and 183 m) is gas saturated in the top (low velocity) and oil saturated near the bottom (high velocity). Other sands, #4 and #5, are imaged as low-velocity zones. The low temperature logged in these

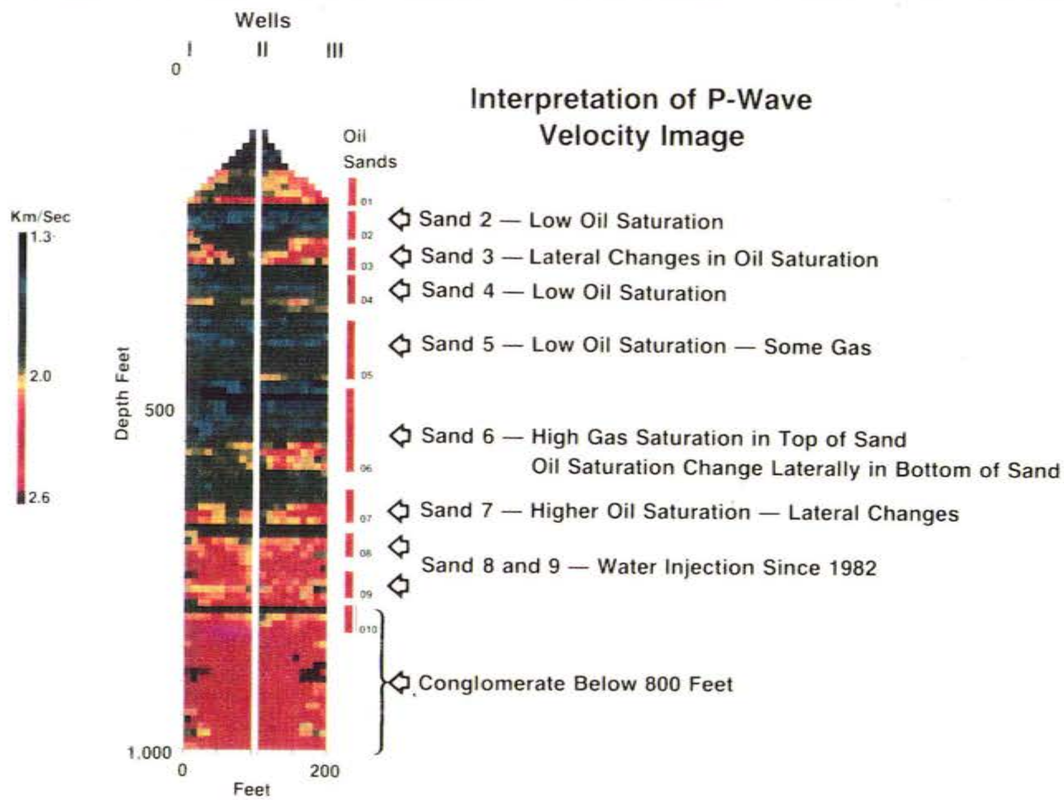

Figure 9. Interpretation of the P-wave Velocity Image in Terms of Oil, Water and Gas Saturations.

two sands, 80°F (27°C) versus 250°F (121°C) in sand #7, indicates that the low velocity is due to high-gas saturation rather than low viscosity from high temperature.

We also recorded an early steam breakthrough, using monthly temperature logs in Well 359 T1 at the depth of the recorded low-velocity zone. This confirms that little oil was left in the sand and that steam permeated quickly through the sand. Steam broke through in 359 T2 well before it broke through in 359 T3, where the tomographic velocity image indicated that the gas zone was smaller compared with the other two wells. The thickest, low-velocity zone in the cross-well image in the K2R sand was found in Well T1, the next largest in Well T2, and the smallest in Well T3. This is consistent with well log data, which indicates a thicker gas-saturated zone in Well T1 compared to Wells T2 and T3.

Sands #6 and #7 were part of a Vertically Expanding Steam (VES) flood, which started after the conclusion of the tomographic experiment. The velocity image indicates that the fluid saturation in the two sands was low. Production results of the VES were disappointing, indicating that little oil was left in the two sands. This is also consistent with the velocity image.

V. CONCLUSIONS

Successful tomographic images using realistic model data provide strong indications that the reconstructed sections using field data are, indeed, realistic representations of the velocity distributions between pairs of the three wells.

The most important factor for obtaining a stable velocity reconstruction is good data. Random travel time noise of the order of 1 millisecond will not significantly deteriorate the tomographic image. It is, however, important that large systematic errors in the picked travel times be avoided.

The cross-well velocity sections obtained from field cross-well seismic data obtained in an oil field show that stable images can be generated with moderately good quality data. I have been able to correlate the resulting velocity images with both various well logs obtained before the well was cased and with monthly temperature logs used to monitor an advancing steam front. The images are also consistent with production results following the cross- well experiment.

These results show that cross-well seismic techniques and seismic tomography in particular potentially are powerful diagnostic and monitoring techniques for thermal EOR situations. These techniques, when fully developed and commercialized, will, because their spatial resolution, also have a large impact on other aspects of future oil reservoir management.

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