Downhole acoustic surveillance of deepwater wells

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Deepwater production increasingly relies on a few precious wells that are complex and expensive. Success is critically dependent on our ability to understand and manage these wells, particularly at the sandface. These wells are filled with expensive "jewelry" like sand control and production allocation systems that aim at maximizing production and minimizing risk. While this smart equipment can mitigate many anticipated dangers, it can easily fail when something unexpected happens. For example, repairing a sand control system that failed due to plugging can cost US $30–40 million, while the costs of lost production due to long-term well impairment can be even higher. Lower-than-expected production is often referred to as "well underperformance" (Wong et al., 2003) and can be caused by various impairments: a plugged sand screen, contaminated gravel sand, clogged perforations, damaged formation around the wellbore or larger-scale compartmentalization. While 4D seismic can address large-scale compartmentalization, it has insufficient resolution to address near-well issues. Scarce downhole data from pressure and temperature gauges also cannot unambiguously characterize the impairment. This limits mitigation opportunities and prevents us from finding more effective drawdown strategies for high-rate, high ultimate-recovery deepwater wells. We strongly believe that geophysical surveillance in boreholes has a big role to play in identifying sources of well impairment and optimizing production. Here we describe one possible avenue—real-time completion monitoring (RTCM)—that utilizes acoustic signals in the fluid column to monitor changes in permeability along the completion. In essence, this is a miniaturized 4D seismic survey in a well. We illustrate the capabilities of acoustic surveillance through a series of full-scale laboratory tests with realistic completion and discuss opportunities for deployment in deepwater wells.

Basic concept of evaluating permeability with acoustic waves. At low frequencies, acoustic signals in a fluid-filled borehole are mainly carried by tube or Stoneley waves. Inside the fluid column the tube wave mainly consists of a piston-like motion. When fluid is compressed, it attempts to expand radially and pushes against the formation or casing. When the borehole wall is permeable, then the tube wave can move the fluid through, which leads to a slowdown in velocity and an increase in attenuation (Figure 1). Currently, these principles are employed in estimating near-wellbore permeability from open-hole acoustic logging (Tang and Cheng, 2004). Conceptually similar principles may be extended to deepwater production wells with sand-screen completions. These wells contain multiple permeable layers (sand screen, gravel sand, perforated casing, formation) as shown in Figure 2.

In unimpaired wells, fluid can flow freely from the reservoir through all of these layers inside the borehole. However, reduction of permeability in any of these layers (impairment) may greatly reduce the fluid flow. Low-frequency tube waves can conduct instant pressure testing and therefore indicate whether fluid communication is blocked, thus providing valuable information about impairment location and strength. While this sounds conceptually similar to the open-hole case, the quantitative interpretation is quite different because wells with sand screens support two tube waves and their permeability dependence is more complicated (Bakulin et al., 2008). Initial experiments and modeling confirmed our ability to identify sand-screen plugging in completions without gravel packs. Here we present more realistic experiments with gravel-packed completions and examine other completion scenarios beyond screen plugging.

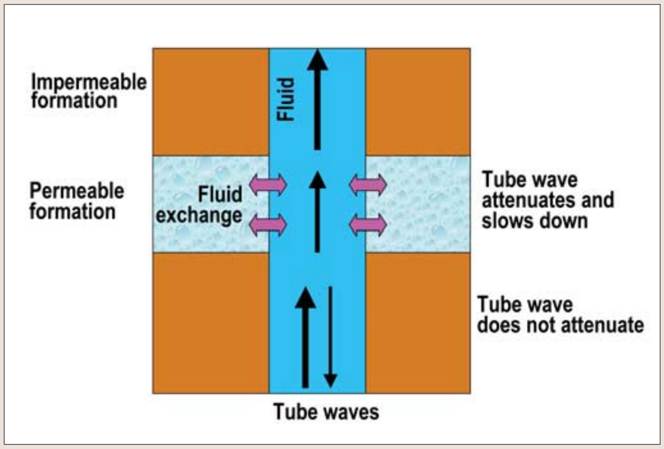


Figure 1. A tube wave attenuates and slows down when it encounters a permeable interval that can exchange fluids between borehole and formation.

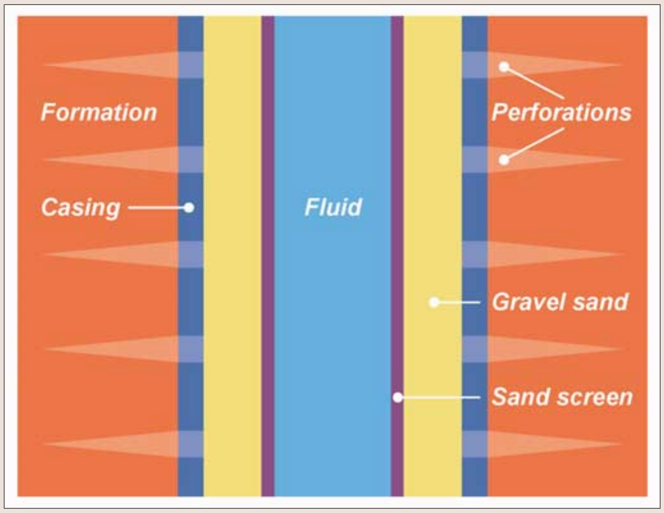


Figure 2. Schematic cross-section of a cased deepwater well with sand-screened completion.

Experimental setup. A sketch and photo of the full-scale laboratory setup of a completed horizontal well are shown in Figure 3. The outside consists of a 30-ft aluminum outer pipe (casing) with perforations, while the inside has a sand screen and gravel pack. Other details are pictured in Figure 4. An acoustic measurement is performed with 24 fiber-optic sensors (Figure 4a) wrapped around the outer pipe (casing) as described by Bakulin et al. (2008). The sensor spacing is 38 cm. On the outside of the pipe, the tube or "breathing" waves have mainly radial motion. Minute expansion or contraction of the pipe volume is reliably picked up by 10 m of the wrapped sensing fiber (Figure 4a). Wire-wrapped sand screen is placed inside the casing (Figure 4b) and consists of

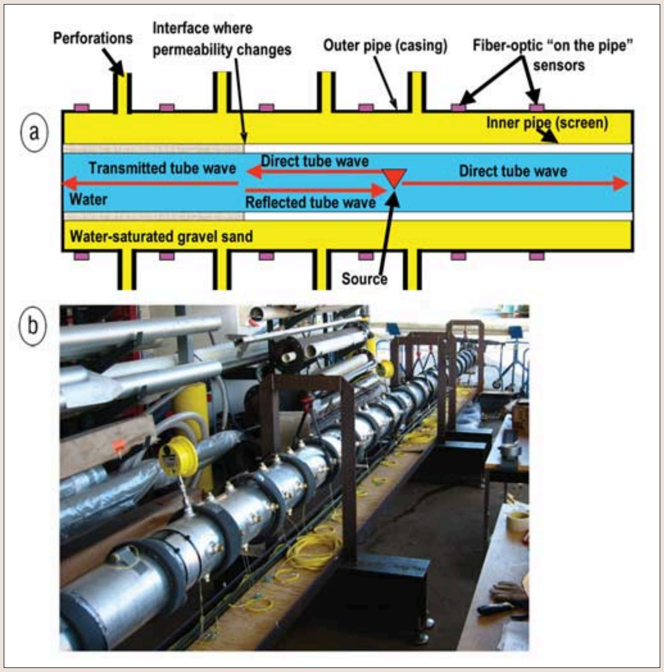


Figure 3. Sketch (a) and photograph (b) of the full-scale laboratory model of completed horizontal well.

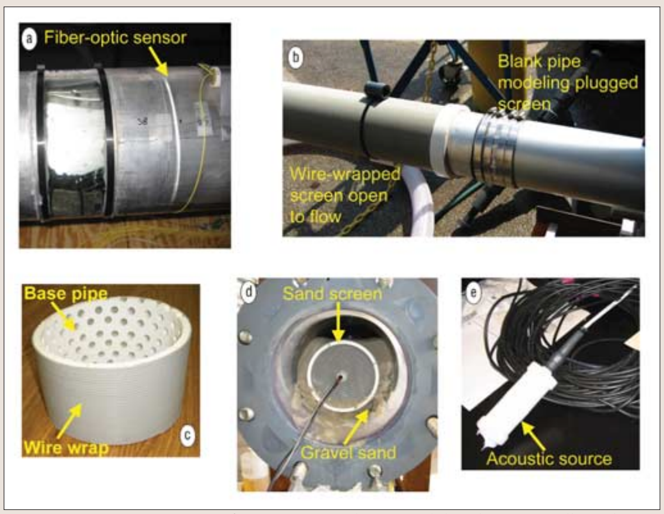


Figure 4. Components of experimental setup: (a) Fiber-optic "on the pipe" acoustic sensor. Glass windows were inserted every 5 ft to observe gravel packing process. (b) Wire-wrapped sand screen and blank pipe. (c) Cross-section of the screen showing wire wrap and base pipe (although plastic base pipe is shown, the aluminum one was actually used in the experiment). (d) Gravel-packed annulus. (e) Piezoelectric acoustic source.

an aluminum base pipe with perforations and a plastic wire-wrap with 0.008-inch gaps (Figure 4c). To model plugged sand screens, we used unperforated aluminum base pipe (Figure 4b). The gravel packing process fills the annulus between the sand screen and casing (as well as perforation tunnels in real wells) with high-permeability gravel sand. The sand screen and gravel pack prevent migration of reservoir sand into the wellbore as well as maintain the structure of the reservoir around the wellbore. Figure 4d shows a gravel-packed model where a small channel at the top remains free of sand to ensure that proper cleanout can be achieved. Acoustic signals are excited with a piezoelectric acoustic source placed inside the screen (Figure 4e).

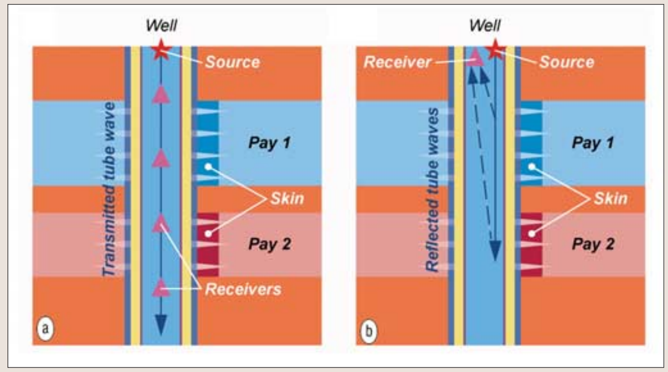


Figure 5. Conceptual design of RTCM configurations. (a) "Permanent or repeated log" (transmission configuration). (b) "Mini 4D seismic in a well" (reflection configuration). Acoustic source may be eliminated when noise sources are used.

4D well monitoring. The concept of completion monitoring with acoustic waves is a natural extension of 4D seismic ideas into the smaller scale, near-wellbore environment. In 4D seismic, we build time-lapse images of the subsurface and interpret changes in terms of various fluid-flow or production scenarios. In completion monitoring, tube waves repeatedly "illuminate" the completion and near-wellbore space, and we interpret changes in terms of important reservoir and completion parameters. In both instances, monitoring simply consists of measuring those parameters of the reservoir or producing equipment (for example, wells) that is needed to make the most critical (read: expensive and risky) reservoir management decisions. In 4D seismic, we can observe how a reservoir is drained and decide where to drill the next well. In completion monitoring, we can observe if and how wells are getting impaired and decide what kind of workover is required and when.

One can distinguish two RTCM configurations: "permanent or repeated log" (transmission) and "mini 4D seismic in a well" (reflection). In both cases, we detect changes in acoustic signatures of tube waves over time and infer changes of permeability along the completion. In the transmission configuration, we measure velocity and attenuation of the tube wave(s) along the completion, thus requiring sensors along the entire sandface (Figure 5a). In the reflection configuration, we may have sensors only above the completion and analyze the change in reflected arrivals from permeability interfaces (Figure 5b). The depth location of the change can be found by analyzing the arrival times just like in reflection seismic.

Similar to 4D seismic, one makes a decision about acquisition type and frequency. To characterize change in completion and near-wellbore properties in a nonpermanent transmission configuration, one simply needs to acquire time-lapse wireline acoustic logs across the sandface. For example, repeated "tube-wave reflection logs" (Medlin and Schmitt, 1994) conducted before and after treatment were used to evaluate quality of hydraulic fracturing in onshore wells through tight formations. However, just as in 4D seismic, it is difficult to replicate exactly the same survey. We expect repeatability of time-lapse logs to be suboptimal as well as information to be scarce and in nonreal time. In addition, well shut-in would be required for borehole monitoring. If permanent sensors are installed downhole, then we expect generally better repeatability and more rich real-time information. As an extra benefit, permanent systems can also be used for passive monitoring. In 4D seismic, this would be listening to microseismic events. In real-time completion monitoring, we can listen to flow, sand production,

Figure 6. *Acoustic response of open-to-flow sand screen (a) and unperforated base pipe (b) modeling plugged screen. Both displays are shown with equal magnification. Notice greatly increased attenuation of tube-wave signal in open screen.*

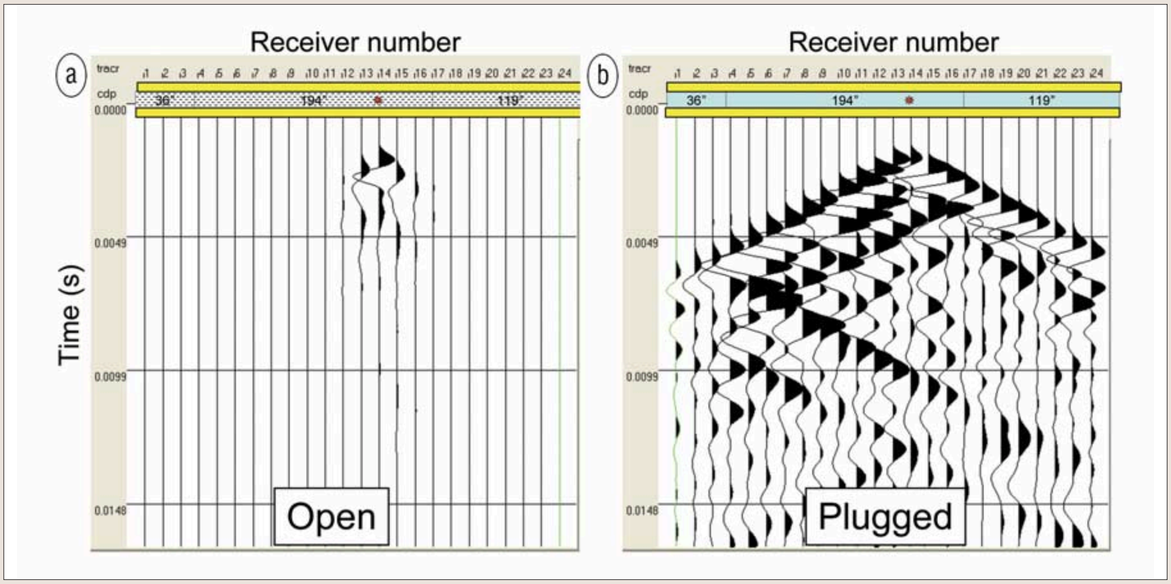
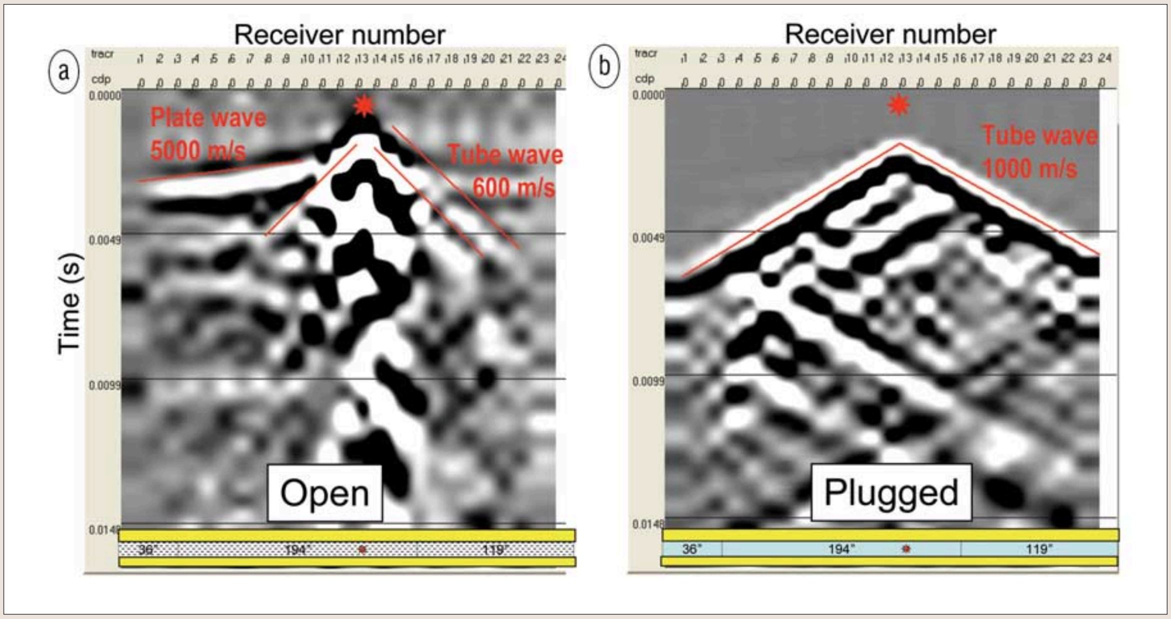


Figure 7. Same as Figure 6 but with variable density display and larger magnification. Notice slower velocity of tube-wave signals in open screen compared to the plugged one.



and any malfunctioning downhole equipment.

In the remainder of this paper, we adopt a 4D seismic approach: we experimentally create contrasting completion scenarios like impaired-unimpaired screens and analyze changes in the associated acoustic signatures. Thus, we concentrate on distinguishing these contrasting scenarios as opposed to inverting for absolute static values of the completion properties. While numerical modeling also reveals similar time-lapse signatures (Bakulin et al., 2008), we felt that full-scale experimental study would be more convincing. We show experiments suggesting that acoustic measurements can be performed while the well is flowing. In addition, the experimental approach brought many "4D surprises" in that we discovered we can monitor things that we did not expect to.

To summarize, we feel that real-time information about inflow ability of the well could be valuable to well engineers or production technologists that can potentially allow them to:

- detect changes in permeability in and around the well (and thus the inflow ability) in real time
- identify the well structure responsible for any problems (screen, perforation, etc.)
- help design best practices for drawing the wells without impairing them
- raise red flags before problems become acute, as opposed to major problems when intervention is unavoidable
- help characterize cross-flow and differential depletion in wells with multiple commingled producing intervals.

Detecting sand-screen plugging. One typical impairment that can restrict deepwater well production is plugging of sand screens. Figure 6 compares responses for an open-to-flow, wire-wrapped screen and a completely plugged screen modeled as a blank pipe (Figure 4b). The top of the plot contains a visual display picturing exact sand-screen assembly placed inside the casing. Plugged sections are shown in solid blue, while dashes depict open sections. Yellow strips around sand screen indicate that the completion is gravel-packed. Permeability of the wire-wrapped screen is estimated at ~250-1000 darcies, whereas permeability of the blank pipe is zero. Plugged screen supports tube-wave signals with small attenuation, whereas open screen has huge

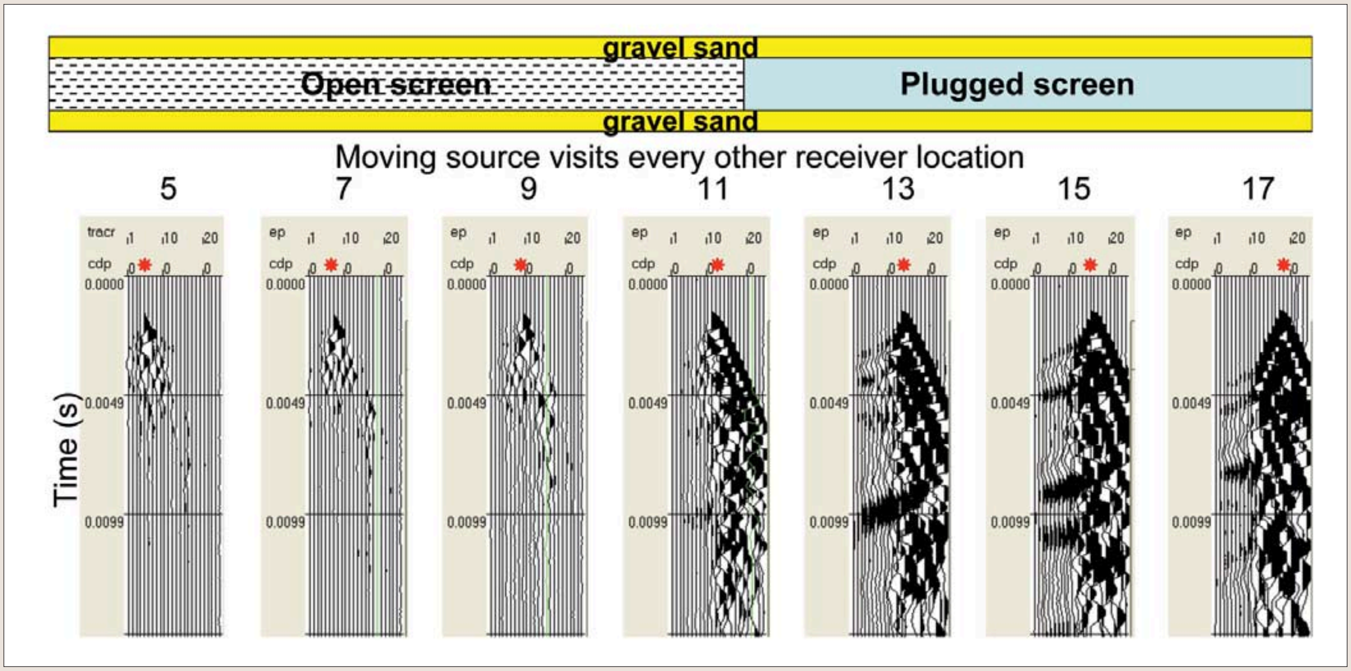


Figure 8. *Simulated wireline survey with a source moving from sensor 5 to sensor 17 with an increment of 76 cm in the gravel-packed completion with a open-plugged interface. Note that the location of the open-plugged interface (between receivers 11 and 12) is easily found by tracking attenuation and velocity attributes.*

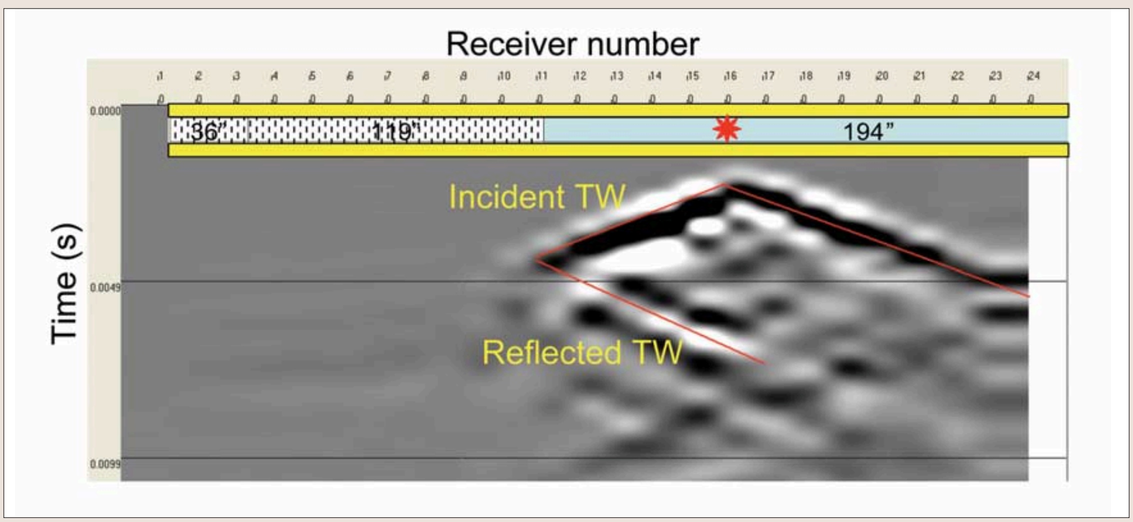


Figure 9. *Reflection of fast-tube wave from plugged-open interface inside gravel-packed completion.*

attenuation. Figure 7 shows that velocity of the fast-tube wave signal is greatly reduced in open screen. Therefore, we conclude that decreased velocities and large attenuation of the fast-tube wave characterize open screens. We stress that examples of plugged and open screens represent the end members with large (~1000 darcies) and vanishing (0 d) permeability, while partial plugging will manifest as an intermediate permeability, thus generating velocity and attenuation intermediate between the two extremes. Relatively large differences between signatures of plugged and open screens suggest that we can likely distinguish various levels of partial plugging or intermediate permeability of sand screens.

Figure 8 shows a simulated wireline survey conducted with a moving source in a model where the left part of the screen is open and the right part is plugged. Acoustic data can be interpreted easily by visual inspection. The location of the open-plugged interface is identified between sensor locations 11 and 12. When the source is in the plugged section, we observe a fast-tube wave velocity of ~1000 m/s and little attenuation, whereas highly permeable open screen reduces this velocity to ~600 m/s and leads to extremely high attenuation. Since simple visual interpretation by inspection is straightforward, one expects that tube-wave velocity and attenuation can be plotted as logging curves along the well depth. However, the presence of both fast and slow tube waves makes this task more challenging and requires delicate wave separation before reliable attributes can be extracted.

Another way to identify a plugged-open interface is by locating a strong reflected event of the fast-tube wave (Figure 9). This reflection accurately pinpoints the location of a plugged-open interface. Locating interfaces when the source is inside the open screen is more challenging due to severe attenuation.

Finally, let us examine a more complex and realistic scenario where a completion in a layered formation suffers a variable impairment in different depth intervals. Figure 10a

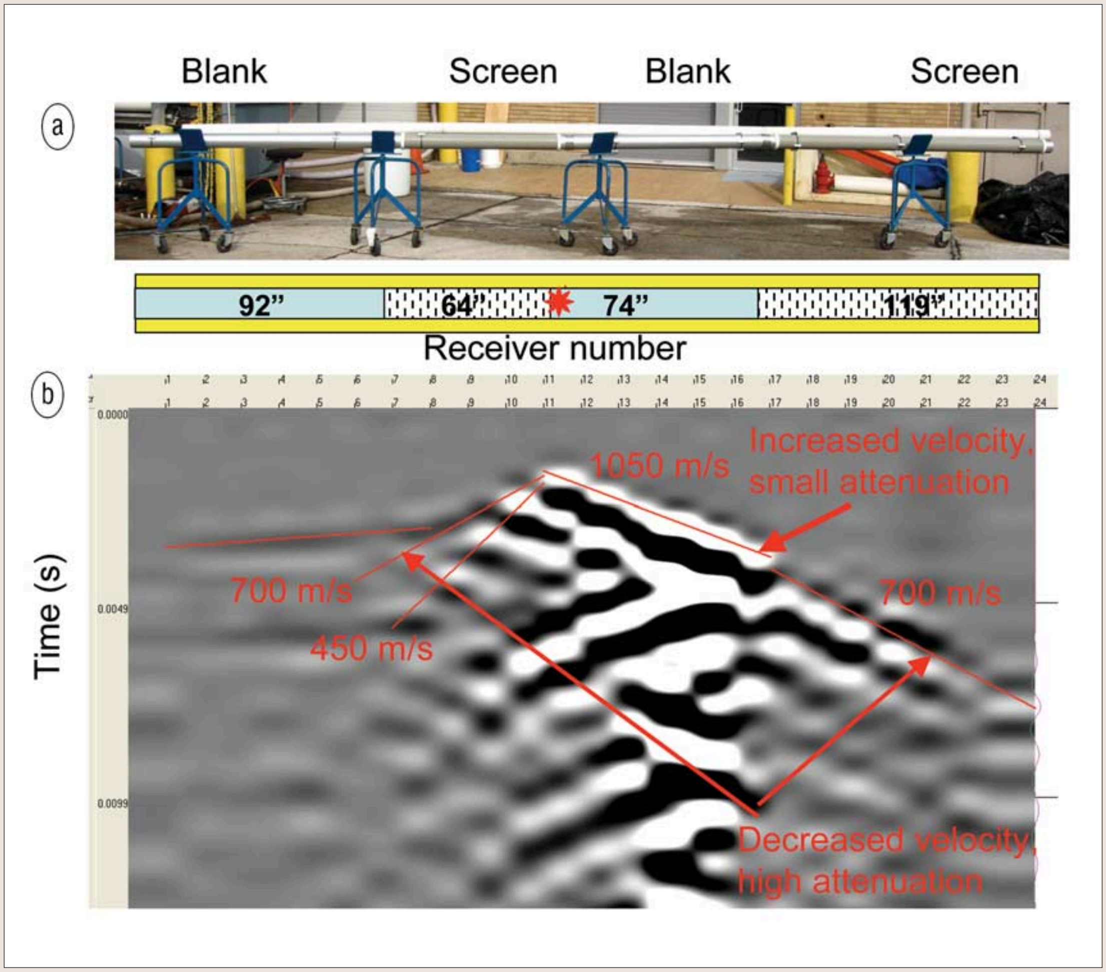


Figure 10. Alternating plugged and open sections of a sand screen (a) and corresponding acoustic response (b) from a source at receiver location 12 (inside the plugged section). Immediate interpretation is as follows. To the right of the source (between receivers 12 and 17), the fast-tube wave maintains high velocity (~1050 m/s) and little attenuation—this region is plugged. Upon reaching receiver 17, the signal slows down (~700 m/s) and attenuates—this is the open region. To the left of the source (between traces 7 and 11), signal is attenuated and slow —again indicating an open region. Further processing needs to be applied to reveal the presence of the plugged section between receivers 1 and 7.

shows an experimental model with alternating plugged and open sections of the sand screen. When the source is placed near the open-plugged boundary, the fast-tube wave propagates with high velocity (~1050 m/s) and little attenuation to the right of the source until it reaches the next boundary at receiver 17 (Figure 10b). In the open section between receivers 17 and 24, the fast-tube wave experiences a large slowdown (~700 m/s) and substantial attenuation. Likewise, to the left of the source, signal strength is greatly diminished due to the presence of another open section. Estimating impairment of the leftmost section (between receivers 1 and 7) is likely to require another position of the active or passive source close to this section. We conclude that sand-screen plugging can be reliably identified using tube-wave signatures.

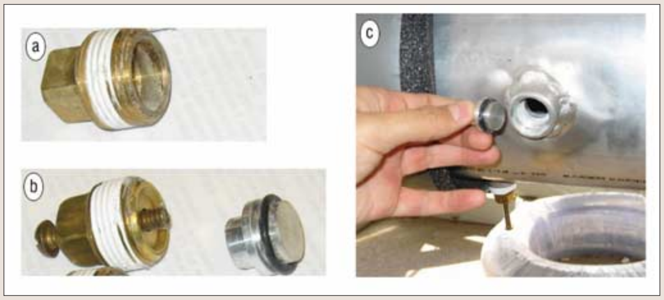


Figure 11. Two types of perforation plugs used in the experiment: (a) smaller plug that leaves part of the perforation tunnel open (height of ~2 cm); (b) large (two-component) plug that completely fills the perforation tunnel; (c) picture showing installation of the bottom component of the large plug.

Detecting open perforation tunnels. Another important impairment mechanism is related to perforation plugging. Production technologists expect that good perforation tunnels in deepwater wells extend several to dozens of inches into the formation and are filled with highly permeable gravel sand (hundreds of darcies). In reality, they may be filled with formation sand with much less permeability (few darcies or less) or plugged with fines.

In these conditions, flow from the reservoir bypasses impaired perforations and instead goes through the unimpaired ones. As a consequence, the depth interval with impaired perforations does not contribute to production. Open perforations are then overloaded—a condition that may lead to extremely high fluid velocity, gravel pack fluidization, and erosion of sand screen (Wong et al., 2003). Unraveling the detailed picture of perforation impairment may lead to improved completion practices, more focused workovers, and optimized well drawdown.

It is anticipated that tube waves can also sense permeability at the next boundary between gravel sand and formation. For this purpose, an array of 76 perforations with a density of eight perforations per foot was designed and implemented in the model. The experiments related to open and closed perforations are planned for the future, and in the meantime the perforation tunnels have been closed with the brass plugs shown on Figure 11a. Despite plugging, a measurement in the test setup with casing only has shown that tube waves sense the presence of perforated section as shown on Figure 12a. One can see an increased attenuation

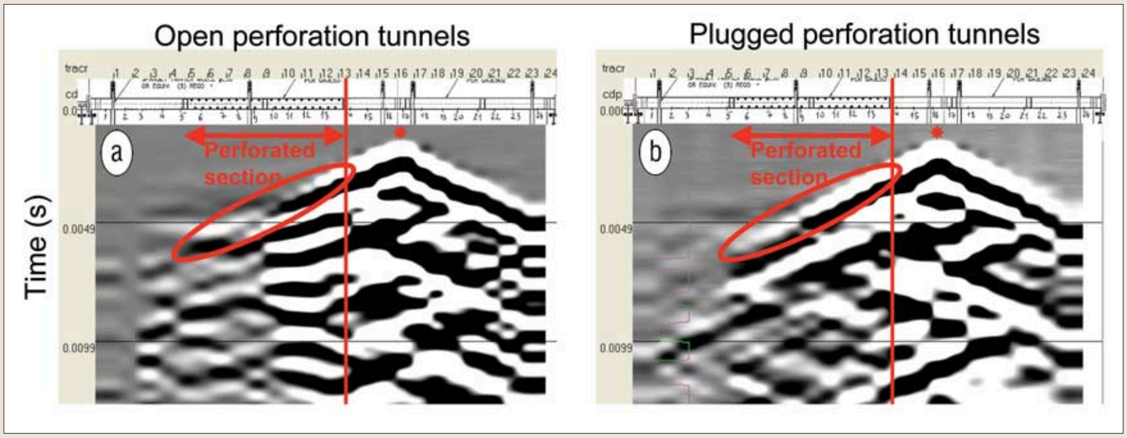


Figure 12. Acoustic response with and without water-filled perforation cavities between receivers 5 and 14. Model of a cased well without screen or sand. (a) Perforation cavities of ~2 cm height; (b) No perforation cavities. Note larger attenuation of first arrivals in the case of open perforation tunnels (a).

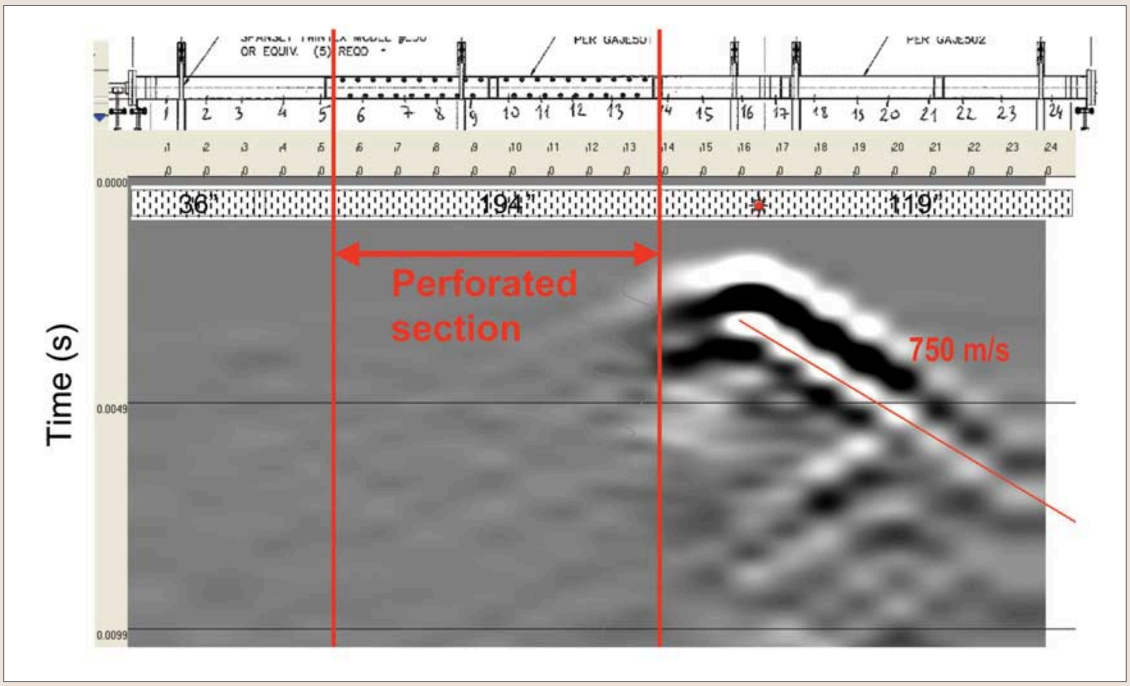


***Figure 13.** Effect of perforation cavities on attenuation of the fast-tube wave in the presence of sand screen (no sand). Note that signal propagating to the left and to the right of the source has identical velocity, but attenuation is greatly increased in the section with perforation cavities.*

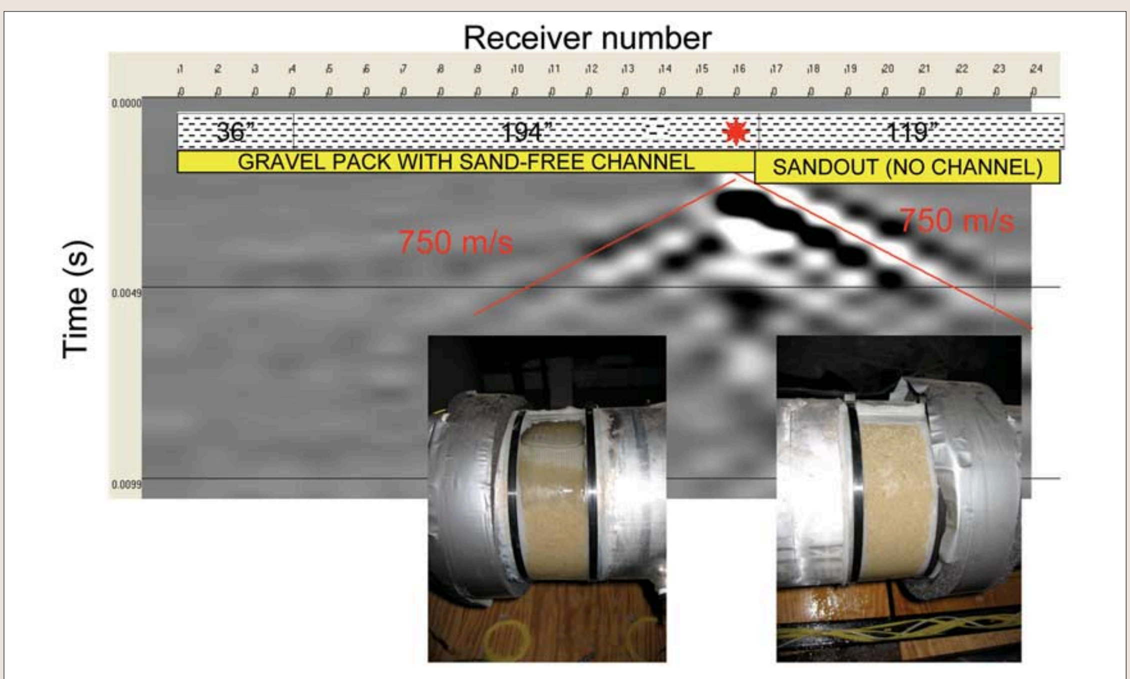
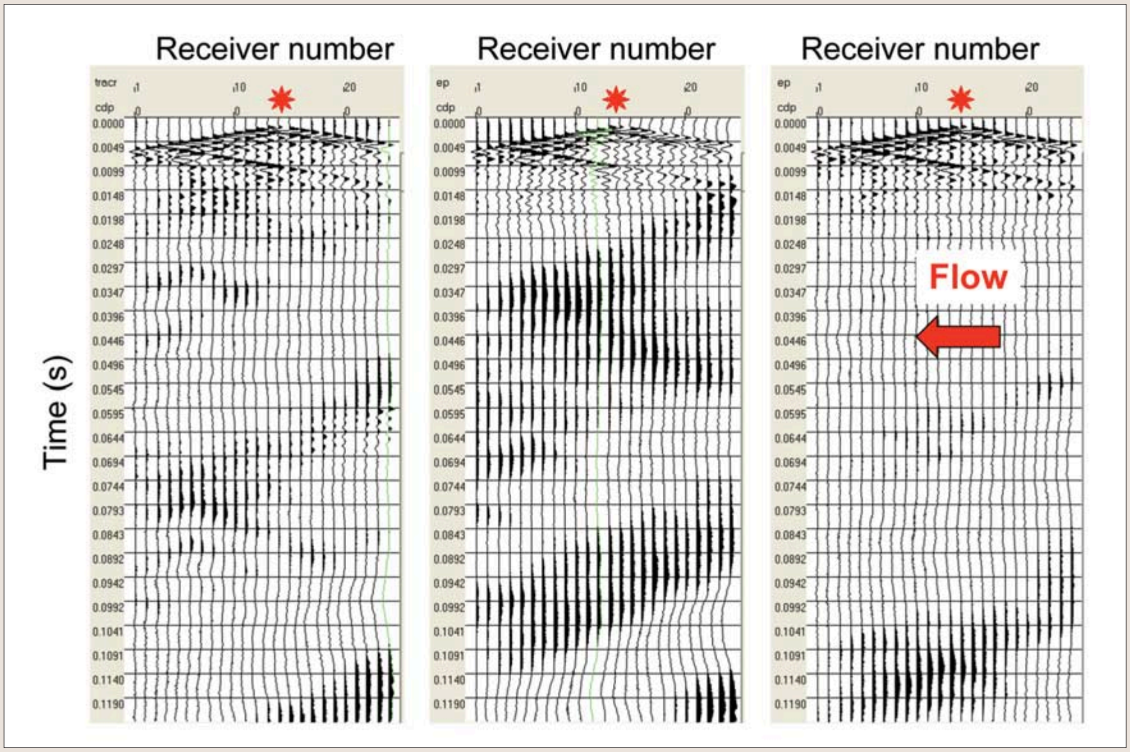


***Figure 14.** Acoustic response of the well with normal gravel pack on the left (containing a sand-free channel at the top) and complete sandout on the right. Note brighter amplitudes of the fast-tube wave in the sanded-out section.*

Figure 15. Recording while flowing at 150 gallons per minute (5100 b/d) in a gravel-packed completion with plugged screen. Each record is a stack of 10 consecutive traces with firings of the source occurring every second. Additionally, the dc-blocking filter is applied, which removes frequencies below 100 Hz.



of the tube-wave arrival upon reaching the perforated section between receivers 5 and 14. The top of each plot contains a schematic of the setup showing the exact location of the perforated section. To reconfirm that the additional attenuation is due to water-filled cavities inside the perforation tunnels, we designed a second set of plugs to completely block the perforation tunnels (Figure 11b). Repeating the same measurement with the new plugs leads to less attenuation as shown on Figure 12b, thus confirming that tube waves can sense small perforation cavities. In the presence of a sand screen, perforation cavities are still sensed as shown on Figure 13. Indeed, the perforated section is manifested by increased attenuation of the fast-tube wave, although velocity remains the same.

Therefore, tube waves can distinguish whether relatively small perforation tunnels are filled with the impermeable plug material or fluid (infinite permeability). This gives a good chance that in practical cases with much longer perforation tunnels we can monitor permeability of the perforation infill.

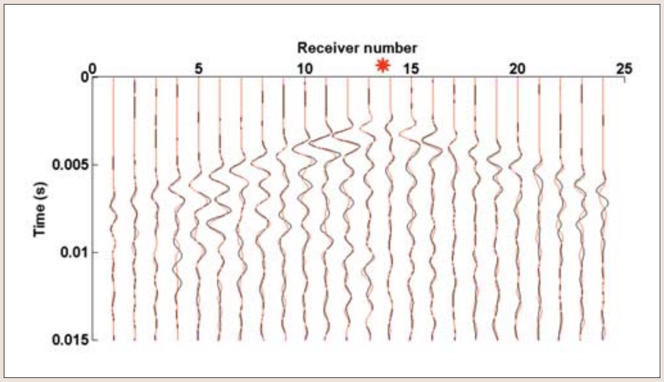


Figure 16. Comparison of records obtained with (red) and without flow (black) in a gravel-packed completion with plugged screen. Flow was 150 gallons per minute (5100 b/d). Both data sets were subject to identical filtering (first, specialized dc-blocking filtering to remove frequencies below 100 Hz, then additional band-pass filtering 50–1000 Hz). Note good agreement between the two sets.

Acoustic signature of sandout. In a horizontal well, the gravel-packing process requires leaving a small sand-free channel at the top of the borehole cross-section, allowing for faster fluid velocities to carry sand across (Figure 4d). In our laboratory experiments, it was particularly important to maintain this sand-free channel in order to clean up the sand at the end of each experiment. In vertical wells, an entire annulus should normally be filled with sand due to gravity forces. In horizontal wells, a sand-free channel usually exists at the start, and it is unclear whether compaction may eliminate it. If, during gravel packing, the complete annulus is prematurely filled with the sand, then it is called a "sandout." After sandout, the fluid velocity drops, and fluid can no longer carry the sand to the rest of the well. One of the unlucky experiments resulted in a partial sandout of the well model (Figure 14). Locating the source roughly at the boundary between normal and sanded-out regions gives the response shown on Figure 14. Clearly, amplitudes in the sanded out section are brighter than in the normally gravel-packed section, whereas the velocities are the same. Therefore, the fast-tube wave amplitude can be used for detection of complete and incomplete gravel packing.

Toward a permanent system—recording while flowing. Results shown so far have been obtained when the well was not flowing. A real-time system would require conducting similar measurement while the well is flowing. To investigate the effects of flow on the signals of interest, we performed the measurement during flow. To increase the signal-to-noise ratio, 10 firings of the source were stacked together. Resulting wavefields for three consecutive 10-s periods are shown in Figure 15. One can see that tube-wave signals of interest are easily recognized in all three records. Notice that low-frequency oscillations (~30 Hz) due to pump noise are also visible despite applying a dc-blocking filter

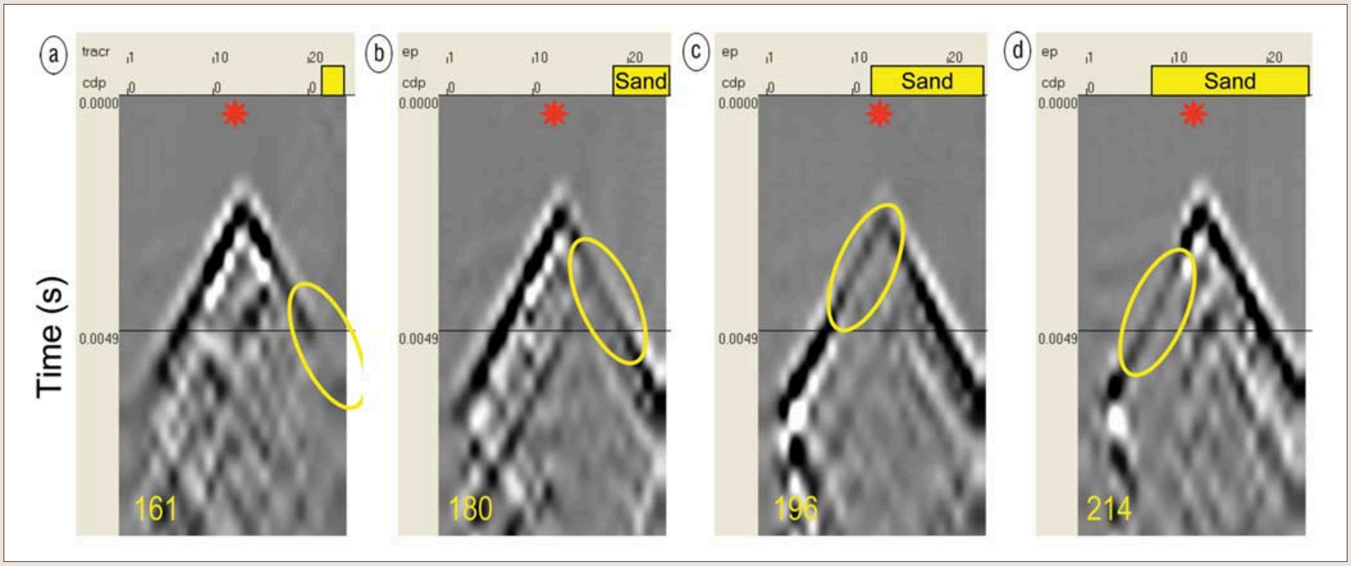


Figure 17. Real-time monitoring of gravel-packing process in a completion with plugged screen and without washpipe. (a–d) denote consecutive time periods. Note that a dim spot anomaly travels ahead of the yellow box, denoting part of the completion where sand packing reached maximum height. To the left of the yellow box, completion is partially packed with a smaller height of gravel sand.

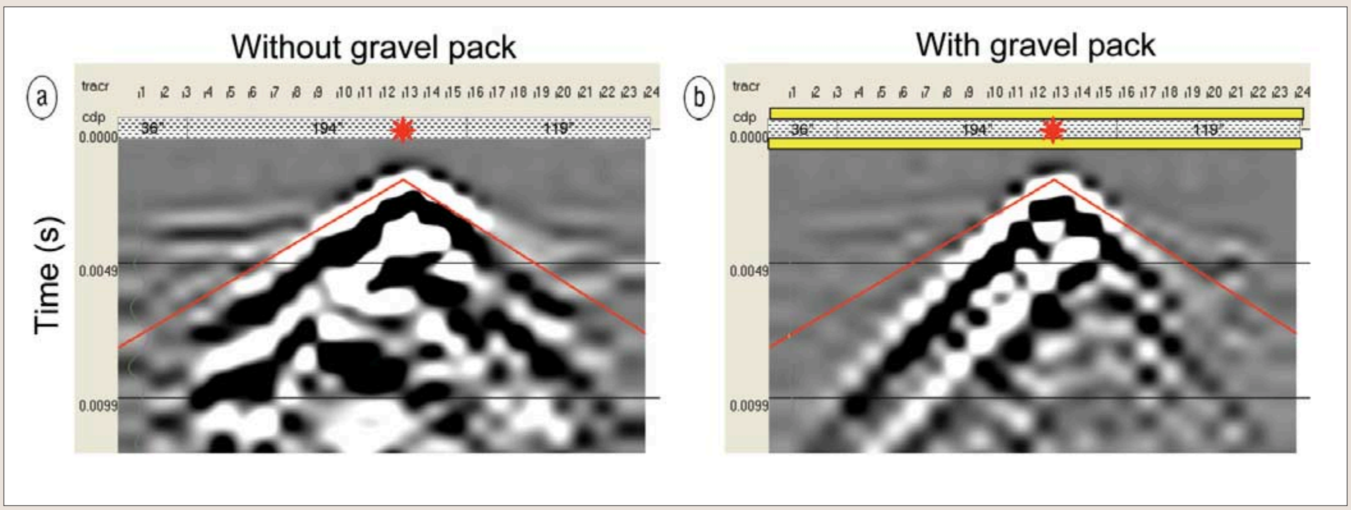


Figure 18. Acoustic responses of sand-screened completion containing washpipe: (a) without gravel pack; (b) with gravel pack. Sand screen is open to flow. Red line shows velocity of 740 m/s and is the same on both plots. Clearly, the presence of gravel pack leads to a slowdown in velocity and an increase in attenuation. Both records are band-pass filtered 100–1000 Hz.

and removing frequencies below 100 Hz. To validate that signals of interest are indeed unaffected by flow, Figure 16 compares records with and without the flow. It can be seen that agreement between the two sets of measurements is excellent. Some low-frequency noise due to flow occurs largely below 100 Hz and is successfully removed by band-pass filtering.

Detecting sand placement with an active permanent system. Once recording during flow is proved possible, real-time acoustic systems can be used to monitor technological processes such as gravel packing. Let us examine three practical scenarios of interest and find out whether parts of the completion with and without sand can be distinguished.

Plugged screen without washpipe. Let us first examine the gravel-packing process of a completion with a plugged screen without washpipe. A washpipe is an additional pipe inserted inside the screen for gravel packing completions with open sand screens. Washpipe prevents the flow going into the screen. Without the washpipe, flow prefers to travel inside the screen. Consequently, the main flow would occur inside the screen, whereas fluid velocity in the annulus becomes small and unable to transport sand along the well. In this experiment with plugged screen, a washpipe was not required. Figure 17 shows four responses obtained during various stages of the gravel-packing process while the well was flowing. Estimated front of the gravel pack is shown with yellow boxes. One can clearly observe that a dim amplitude anomaly is moving across the model closely tracking the back front of the gravel pack. Similar conclusions can be reached by analyzing the acoustic movie of the entire gravel-packing operation. Once the pack is in place, this anomaly is gone. Judging by repeatability and consistency of the response and the anomaly, we believe that this amplitude anomaly is a reliable diagnostic of the pack front.

Sand screen with washpipe. To gravel pack an open screen, a washpipe is a must, and thus it is interesting to be able to detect presence or absence of gravel pack along the com-

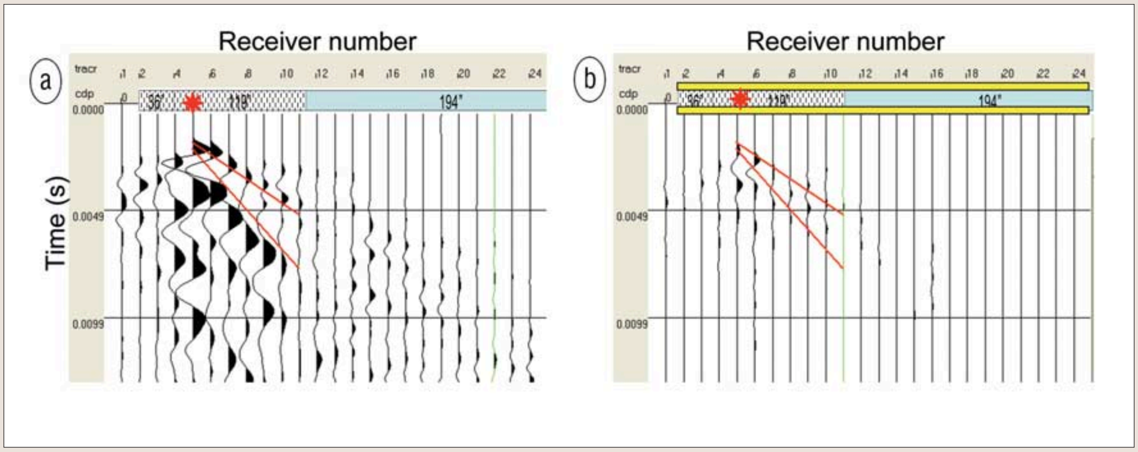


Figure 19. Acoustic responses of sand-screened completion without the washpipe: (a) without gravel pack; (b) with gravel pack. Figures are shown with equal magnification. Note that the presence of sand decreases overall amplitude level and increases attenuation in particular for slow tube-wave arrival.

pletion in such configuration. In the laboratory experiment, a plastic washpipe was used while the acoustic source was placed inside the washpipe. Figure 18 shows that in the presence of gravel pack, we observe tube waves with slower velocity and larger attenuation compared to the same case but without gravel pack. Therefore, tube waves can differentiate presence or absence of gravel-packed annulus even if an additional washpipe is introduced into the system. Numerical modeling confirms that one of the tube waves is slowed by the presence of a higher-density gravel pack.

Sand screen without washpipe. For completeness, we also modeled the case when the washpipe is removed and a sand screen open to flow is maintained. Figure 19 proves that presence of the gravel pack is manifested by strong attenuation of the tube-wave signals. In particular, the slow tube wave becomes greatly attenuated compared to the case of no gravel sand.

We conclude from all three cases that acoustic data can clearly differentiate between presence and absence of gravel pack in the annulus and possibly monitor gravel packing in real time. This can be an additional benefit of the permanent system that was not envisioned prior to the experiments.

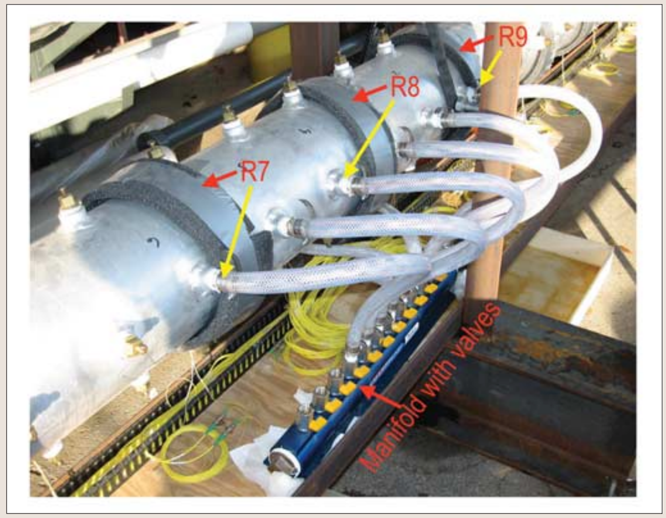


Figure 20. Picture of the setup with connected flowing perforations. Three fiber-optic receivers of interest (R7–R9) are shown with red arrows. Yellow arrows point to the nearby perforation that was used for flow. Water is injected through a single perforation inside the completed well, thus simulating reservoir production.

Detecting flowing perforations with a passive permanent system. While active surveillance represents the main task, a permanent nonintrusive system gives opportunities for passive measurements detecting various flow conditions. We present a first attempt to detect flowing perforations based on passive acoustic data. Figure 20 shows several perforations connected to the water line via a manifold. The water line was chosen to simulate a static flow through the perforations. Water is injected inside the completed well through a single perforation at a time to simulate reservoir production.

Figure 21 reveals that a flowing perforation acts as a constant source of very low-frequency "noise" of about 0–50 Hz. This noise has a structure of ridges with peaks at the perforation location. Gysling et al. (2005) describe similar "convective ridges" that are due to acoustic noise from vortices induced by turbulent fluid flow in pipes. They suggest that those vortices create coherent acoustic disturbances that can be tracked at a distance of about two pipe diameters. Therefore, they use acoustic sensors with a fine spacing (~2/5 of the pipe diameter) to track these signals and thus estimate fluid-flow velocity inside the pipe. Although in our case sensor spacing is too coarse (38 cm or about two pipe diameters), we can still claim that signal can be picked at several neighboring sensors near flowing perforation. Gysling et al. (2005) provide examples of monitoring single and multiphase flow in pipes, suggesting acoustic signals are of similar low frequencies (0–40 Hz). The apparent slope of ridges on Figure 21 is around 20–50 m/s, whereas estimated flow velocity through the perforation is less than 1 m/s (a flow rate of ~4–6 gallons per minute). It is likely that our large sensor spacing leads to severe aliasing and precludes us from estimating such small flow velocity. Nevertheless, we believe the nature of observed ridges is certainly similar to those described by Gysling and coauthors for flow in the pipes. The presence of gravel sand is likely to modify flow conditions and behavior of vortices considerably. These effects should be the subject of future studies where sensor spacing should be substantially smaller.

If only location of the flow is of interest, then the same data can be analyzed in a simpler fashion following ideas of "noise logging" (McKinley and Bowers, 1979). Figure 22 shows strength of the acoustic noise estimated as rms of the entire 16-s trace for each receiver location. Clearly, large noise magnitudes occur at receivers near flowing perforations. When flow is absent, these peaks disappear. Locations of the peaks identify position of the flowing perforations as illustrated in Figure 22a–c where flow is simulated through three different perforations. These pictures are independent of the preprocessing applied and have similar structure, even if raw unfiltered traces are used. Other noise logging

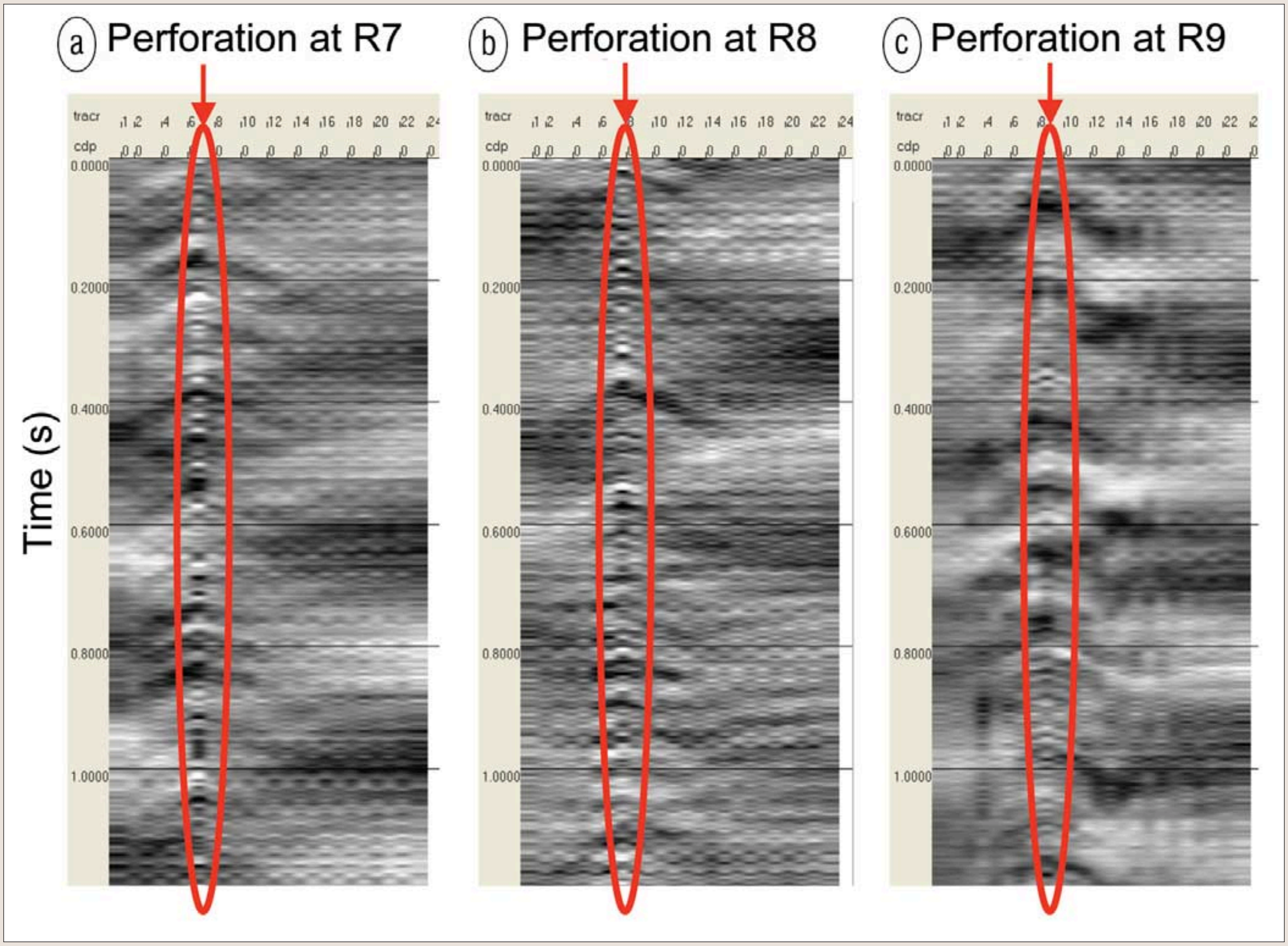


Figure 21. *Acoustic responses of flowing perforations after simple preprocessing (dc-blocking filter removed frequencies below 20 Hz, followed by bandpass filtering 1–100 Hz). Observe low-frequency, ridge-like signals with the peaks located near perforations flowing: (a) next to receiver 7; (b) next to receiver 8; and (c) next to receiver 9.*

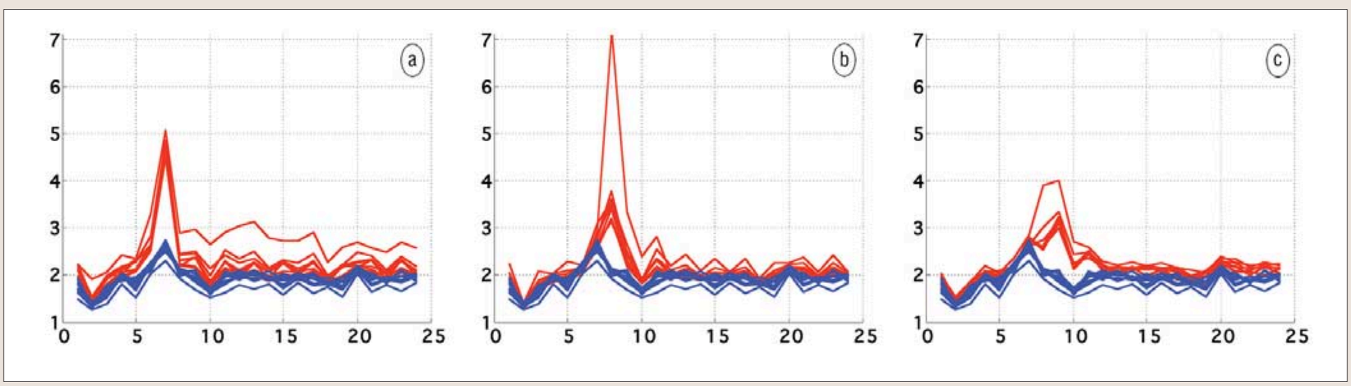


Figure 22. *Same data as on Figure 21 but recast as rms of the longer trace (15 s) versus receiver location. Red curves correspond to perforations flowing: (a) next to receiver 7; (b) next to receiver 8; (c) next to receiver 9. Blue curves show similar measurements of acoustic noise but without flow. Note that in case of flow, the maximum value of acoustic signal occurs next to the perforation and quickly drops away from it.*

ideas can be used to estimate the flow type and rate based on the magnitude and frequency of the signals (McKinley and Bowers, 1979). It is expected that multiphase flow will be much "noisier" as compared to single-phase liquid flow studies here. It may be beneficial to increase the sensitivity of the fiber-optic sensors for passive monitoring. For example, higher sensitivity can be achieved by wrapping longer lengths of fiber on the pipe.

Thus, we conclude that both "noise logging" and "acoustic flow-metering" approaches can likely be applied to identify flowing perforations, fluid velocities, and, ultimately, flow rates. Further work is needed to quantify more precisely what type of information can be extracted from these signals in realistic multiphase flows from reservoir into gravel-packed completions.

Path to deployment. Conducted experiments suggest convincingly that completion impairment, as well as other

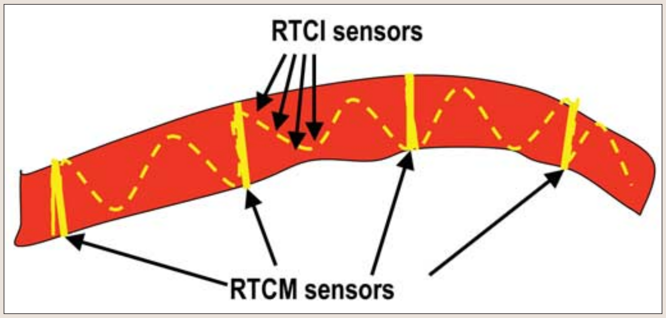


Figure 23. Potential implementation of RTCM (acoustic) and RTCI (static deformation) tools on the same fiber using blue rose interferometric technology.

processes, can be monitored using acoustic data. In the short term, the best chance to apply this technology is to use wireline acoustic logging. Slim acoustic tools with low-frequency monopole sources and receivers that go inside the screen can be easily manufactured. The disadvantage of the production logging approach is that it is not a real-time 4D measurement. It requires downhole access and possible shut-in of the well. The latter two concerns may preclude applications to subsea and other wells with high intervention costs. In addition, repeatability between time-lapse logging runs may be an issue.

The longer-term solution is represented by a permanent downhole system that can be achieved, for example, with fiber-optic sensors and passive noise source as suggested by Bakulin et al. A permanent system is desirable for many reasons. First, downhole access is diminishing, especially to complex deepwater or subsea wells, while intervention costs are increasing. In addition, the permanent system has these important advantages over the wireline option:

- it provides real-time information
- there is no well shut-in required, and, thus, no lost production
- it allows monitoring of gravel packing and other technological processes
- it enables passive measurements characterizing flow, open and closed perforations, cross flow, and sand production

While development of a permanent system may seem insurmountable, it should be stressed that downhole tools with fiber wrapped around downhole tubulars are already under development. For example, real-time casing imager or RTCI (Childers et al., 2007) is expected to monitor deformation of the sand screens in complex deepwater wells as a means to assess compaction. RTCI requires fiber to be helically wrapped around the entire screen and is already addressing various challenges related to downhole placement and connection of the fiber. If RTCI is deployed, then the acoustic system has an even easier ride, especially since it needs only point sensors that can be deployed at a predetermined locations in the most protected place, for instance on the outside of the base pipe.

Finally, as speculated by Bakulin et al. (2008), there are new fiber-optic technologies such as blue rose (Blackmon and Pollock, 2006) that may allow implementing static deformation (RTCI) and acoustic (RTCM) measurements on a single fiber (Figure 23). As for the sources, the most attractive option is to recover signals by cross-correlating recordings from passive noise sources using the virtual source method described by Bakulin et al. Field trials should investigate whether frequency content and distribution of natural noises in realistic completions are sufficient for the task. If not sufficient, then several permanent acoustic sources may need to be deployed along the sandface. Such sources could be mounted on the outside of the tubing or screen. Alternatively, passive flow-driven whistles may be designed to act as "noise" sources with controlled locations.

Summary and outlook. Just as 4D seismic revolutionized our ability to manage reservoir production, real-time completion monitoring has the potential to revolutionize our ability to manage deepwater wells by understanding evolution of flow, drawdown, and impairment in real time. We have presented results of full-scale laboratory tests proving this potential. Further progress could be achieved by performing field trials with available acoustic logging tools run inside sand screens. In 4D seismic, various fluid-flow scenarios are used to predict seismic response and then benchmarked against real measurements. Similarly, RTCM would require the ability to take possible production technology scenarios, predict their acoustic signatures, and benchmark them against actual downhole measurements. While quantitative inversions may or may not be achievable, such closing-the-loop methodology of 4D seismic proved of superior value to reservoir management. We have no doubt that acoustic in-well monitoring following the same methodology would lead to substantial progress in managing deepwater wells.

Suggested reading. "Real-time completion monitoring with acoustic waves" by Bakulin et al. (GEOPHYSICS, 2008). "Balancing act: Gulf of Mexico sand control completions, peak rate versus risk of sand control failure" by Wong et al. (*SPE*, 2003). "Fracture diagnostics with tube-wave reflection logs" by Medlin and Schmitt (*Journal of Petroleum Technology*, 1994). "Specialized applications of noise logging" by McKinley and Bower (*SPE*, 1979). *Quantitative Borehole Acoustic Methods* by Tang and Cheng (Elsevier, 2004). "Downhole fiber-optic real-time casing monitor" by Childers et al. (*SPIE's* 14th Annual International Symposium on Smart Structures and Materials and Nondestructive Evaluation and Health Monitoring, 2007). "Clamp-on, SONAR-based volumetric flow rate and gas volume fraction measurement for industrial applications" by Gysling et al. (*Proceedings of the 13th International Conference on Flow Measurement, FLOMEKO* 2005). "Blue Rose perimeter defense and security system" by Blackmon and Pollock (*Proceedings of the SPIE,* 2006). TLE

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