Time-Lapse (4D) Seismic Monitoring - Expanding Applications*

Rob Staples[1], Jan Stammeijer[1], Scott Jones[1], Jon Brain[1], Frans Smit[1], and Paul Hatchell[2]

Search and Discovery Article #41601 (2015)
Posted March 20, 2015

*Adapted from extended abstract prepared in conjunction with a presentation given at CSPG/CSEG 2006 GeoConvention, Calgary, AB, Canada, May 15-18, 2006,

[1]Shell EP Europe, Aberdeen, United Kingdom (rob.staples@shell.com)
[2]Shell International EP, Rijswijk, Netherlands

Abstract

This paper highlights the increasingly varied application of 4D and how this is achieved. We are now able to quantitatively monitor pressure injection signals, pressure depletion (compaction) signals, and in many cases, accurately separate the effect of pressure changes and saturation changes. This has been enabled by world-leading marine 4D repeatability (NRMS noise as low as 7%), sparse acquisition systems (enabling high quality 4D from 10 fold data), cheap acquisition (making offshore well decisions from $300,000 swaths), and from intense effort in simulator synthetic and geomechanical modeling.

Introduction – Application to Saturation Change Fields

In the past ten years, time-lapse (4D) seismic has evolved from an academic research topic to a standard way of monitoring reservoir performance, at least within the North Sea and for steamflood monitoring worldwide. In the North Sea this has been achieved largely by the acquisition of repeated marine streamer data and has been applied most widely on fields with aquifer drive (e.g. the Gannet fields; Kloosterman et al, 2002; Staples et al, 2005) or water injection drive (e.g. Draugen; Koster et al, 2000). Other saturation change signals such as gas flood (e.g. Troll West; Eikenberg and Else, 2002), solution gas breakout (e.g. Foinaven; Bouska and O'Donovan, 2000), and steam injection (e.g. Duri; Sigit et al, 1999) have also proved strong signals for monitoring purposes, and the method is now being used to provide evidence for the containment of CO_2 in the Sleipner CO_2 sequestration project (Arts et al, 2002). 4D provides a new piece of data describing the dynamic behaviour of the reservoir fluids in between the wells, often providing a surprise relative to preconceived views of reservoir flow, or even stratigraphy. This provides direct evidence for infill targets (Figure 1) and/or allows Petroleum Engineers to optimize their modeling, field management and well targeting.

A Maturity S-Curve

The economic success of a 4D project is dependent not only on having a sufficiently large signal to be observed over 4D noise, but also on the ability to quickly interpret that signal in terms of sweep patterns, fluid pressure, overburden stress, fault transmissibility, stratigraphic reservoir distributions, etc. In order to communicate these complexities to all disciplines, we use a maturity S-curve, for different signal types. The position on the maturity curve represents a combination of the signal strength and the complexity of interpreting the signal to make conclusions about reservoir conditions. A reservoir may sit in more than one category – e.g. a reservoir may show an easily interpreted waterflood signal and a more complex depletion signal. The curve is only indicative and does not supersede a full technical and business feasibility study for actual projects.

Pressure-Up

More recently, time-lapse seismic has been applied for objectives other than monitoring saturation changes, such as pressure monitoring and compaction detection, sometimes with surprising outcomes. We learnt that pressure-up from poorly communicating water injectors (‘injection overpressure’) can give rise to large signals, as can the ‘relaxation’ from such overpressures, when the injection rate is reduced (Stammeijer and Staples, 2003). However, pressure depletion below initial pore-pressure is much more difficult to detect except when associated with reservoir compaction, or with gas breakout below bubble point. The large signals caused by pressure-up signals (Figure 3) can in some cases totally dominate and mask the effect of saturation changes. Since the pressure-up signals are strong and almost directly linked to reservoir pore-pressure, this category sits high on our maturity S-curve (category 2, Figure 2).

The drive to provide quantitative estimates of saturation and pressure-up changes, even where the two effects interfere, places stringent demands on 4D data quality, and either accurate rock physics measurements or reliable well production data in order to calibrate attribute-driven methods. Methods for the separation of saturation and pressure have traditionally either relied on AVO attributes in a semi-empirical fashion (Tura and Lumley, 1999) or using deterministic rock physics (Landro, 2001). However, because laboratory-based rock physics measurements often differ from the in-situ response, and because AVO methods can fail in a hard rock domain, a new empirical ‘engineering approach’ (Floricich et al, 2005, 2006) provides estimates of pressures and saturations (along with Bayesian error estimation), using a variety of 4D attributes and production data. The new method has also proved robust for three attributes (pressure change, water saturation and gas saturation), and provides further encouragement for complementary production data, including permanent downhole pressure gauges.

Compacting Reservoirs

In the case of compacting reservoirs at depth, stress arching gives rise to overburden/underburden stress/strain changes, which in turn cause overburden/ underburden velocity changes (Hatchell et al, 2003, 2005; Hatchell and Bourne, 2005). The induced overburden/underburden time-shift 4D signals can sometimes be much stronger than the signals in the reservoir, especially for siliciclastic systems. As a result, geomechanical modeling is important in order to predict and invert signals caused by pressure depletion and compaction (Figure 4). Carbonates (category 3) tend to compact most, followed by HPHT fields (category 4), whilst in normally pressured consolidated environments the small compaction signal can be hard to detect (category 6). In the compacting environment, mapping in-reservoir and overburden rock stress is not only vital for finding new potential targets, but also for assuring the hole stability of new wells and robustness of existing well stock.

Although much research is being focused on measuring rock properties in the laboratory and using novel logging techniques downhole, there remain a great number of unknowns in any geomechanical modelling, especially for thick and stacked reservoir systems (category 5). There is therefore increasing demand for other complementary calibration data such as microseismic, downhole compaction and surface deformation data. These data are more economically viable onshore (e.g. Canada, Oman) than offshore, where the costs of monitoring in expensive wells or on the seabed present a challenge. However, recent advances address these cost challenges, such as the waveform migration of microseismic data to allow the location of microseismic events from much lower S/N data (Rentsch et al, 2005; Gajewski et al, 2005). This potentially allows the recording of microseismic events on surface arrays (surface seismometers or Ocean Bottom Cables offshore) even in the presence of facility noise.

Improving Data Quality

The use of 4D monitoring in lower porosity reservoirs (where saturation and compaction signals are smaller), and the accurate separation of saturation, pressure and compaction effects requires improved quality data, and this is being achieved in a number of ways:

NRMS (noise) on the final processed 4D sections in the North Sea was typically greater than 30% just 5 years ago. It was quickly realised that accurate repetition of acquisition was a vital contribution to 4D signal to noise (Figure 5) (Calvert, 2005). Repeated acquisition techniques (repeated sail lines, shot points, source and streamer arrays) alone are insufficient at sea, where currents can significantly deflect streamers. In the North Sea, tidal shooting partly negates this problem, but in the Gulf of Mexico where irregular thermal currents dominate, this is a major headache. The development of real-time systems for monitoring and comparison of baseline monitor source and streamer positioning has allowed great improvements in acquisition (Smit et al, 2005 EAGE), by identifying which lines / areas to repeat - those whose 4D acquisition repeatability during the monitor survey is deemed too poor for the quality required of a specific survey.

Coupled with ever more careful processing of streamer data (e.g. 4D trace selection, sail-line statics), the result is a continuous improvement of 4D data fidelity over the last five years. Even using conventional streamers at 100m spacing, Shell's Shearwater project in 2002 / 2004 achieved 7% NRMS, which we believe to be a record for an actual full field 4D streamer project (Figure 6).

Data fidelity may also be achieved using permanent seismic systems. Onshore systems may be near surface (e.g. Gaz-de-France's gas storage reservoirs) or combined near surface / downhole (e.g. Shell's Peace River), whilst BP's grid of Ocean Bottom Cables (OBC) over the Valhall field represent the most significant fully permanent marine system in place at this time. The $45M upfront Valhall price-tag may appear to limit the use of permanent OBC to big fields with large capital expenditure requirements, but Shell's 'sparse OBC' concept aims to combine the advantages of permanent systems with a low investment cost by exploiting 4D repeatability (Figure 7) (Smit et al, 2005 SEG). In addition to optimum data fidelity, permanent systems can also enable near realtime monitoring of the reservoir, provided a short processing turnaround can be achieved.

Time-lapse technology is also being downscaled for smaller and smarter applications in the form of time-lapse swaths (effectively time-lapse 2D, but with multiple streamers providing a narrow swath of data). This is appropriate in fields with little structural complexity, to provide time-lapse images over specific blocks, or around specific wells.

Conclusions

The extension of 4D seismic from monitoring saturation changes to pressure-up and compaction monitoring has enabled a wide expansion of field applicability, and increased the revenue generated by its use in reservoir management and, most notably, infill targeting. 4D applications that would have been considered experimental just five years ago (e.g. offshore pressure depletion monitoring) are now being used to regular economic advantage.

Its use in lower porosity, more consolidated reservoirs has been made possible by improvements in data-fidelity (due to acquisition and processing improvements). Cheaper, more frequent acquisition and faster turnaround have been enabled both by permanent systems (including sparse systems) and by targeted swath shooting. Finally, improved modelling (e.g. geomechanical modelling and simulator-seismic software) and integration with complementary data sources allow quantified estimates of saturation, pressure and compaction. Further improvements in conventional techniques and the installation of permanent systems will likely see the technique be used in ever greater detail, and more regularly in areas of the world where it is still to become 'the norm'.

Acknowledgements

The authors would like to thank Rodney Calvert, Andy Cook, Peter Schutjens, Raed Kawar, Karel Maron, Nick Beaumont-Smith, Jo Lamens, Charlie Ash, Dave Pritchard, Jakko van Waarde, Maarten Ligtendag, Peter Wills (all from Shell), Richard Tondel (Statoil) and Keith Watt (Concept Systems) for their contributions to the examples shown. We would also like to thank the field partners on Gannet, Tern, Cormorant, M3, Valhall, Shearwater, Sean, Schiehallion, Foinaven, Draugen, Peace River and Maui for permission to publish.

References Cited

Arts, R., O. Eiken, A. Chadwick, P. Zweigel, L. van der Meer, and B. Zinszner, 2002, Monitoring of CO2 injected at Sleipner using time lapse seismic data: in Gale and Kaya, eds., Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies (GHGT6), p. 347-352.

Bouska, J., and A. O'Donovan, 2000, Exposing the 4D seismic time-lapse signal imbedded the Foinaven active reservoir management project: OTC paper 12097, OTC 2000 expanded abstracts.

Calvert, R., 2005, Insights and Methods for 4D Reservoir Monitoring and Characterization: SEG/EAGE DISC (Distinguished Lecture Course) 2005.

Eikenberg, O-A., and R. Else, 2002, 1D modelling - a quantitative tool in 4D analysis on Troll West oil province? EAGE 2002 expanded abstracts.

Floricich, M., C. MacBeth, and R. Staples, 2005, An engineering-driven approach for separating pressure and saturation using 4D seismic: Application to a Jurassic reservoir in the UK North Sea: SEG 2005 expanded abstracts.

Floricich, M., C. MacBeth, J. Stammeijer, R. Staples, A. Evans, and N. Dijksman, 2006, A new technique for pressure-saturation separation from time-lapse seismic: Schiehallion case survey: EAGE 2006 expanded abstracts.

Gajewski, D., and E. Tessmer, 2005, Imaging of passive seismic sources by reverse modelling: EAGE 2005 expanded abstracts.

Hatchell, P., A. vdBeukel, M. Molenaar, K. Maron, and C. Kenter, 2003, Whole earth 4D: monitoring geomechanics: SEG 2003 expanded abstracts.

Hatchell, P., R. Kawar, and A. Savitski, 2005, Integrating 4D seismic, geomechanics and reservoir simulation in the Valhall oil field: EAGE 2005 expanded abstracts.

Hatchell, P., and S. Bourne, 2005, Rocks under strain: Strain induced time-lapse time-shifts are observed for depleting reservoirs: The Leading Edge, v. 24/12, p. 1222-1225.

Kloosterman, H-J., G. Cooke, P. Hague, and J. Stammeijer, 2002, 4D driven asset optimization: EAGE 2002 expanded abstracts.

Koster, K., P. Gabriels, M. Hartung, J. Verbeek, G. Deinum, and R. Staples, 2000, Time-lapse seismic surveys in the North Sea and their business impact: The Leading Edge, v. 19/3, p. 286-293.

Landro, M., 2001, Discrimination between pressure and fluid saturation changes from time-lapse seismic data: Geophysics, v. 66, p. 836-844.

Rentsch, S., S. Buske, S. Luth, and S. Shapiro, 2005, Passive seismic monitoring using a migration technique: EAGE 2005 expanded abstracts.

Sigit, R., P. Morse, and K. Kimber, 1999, 4D seismic that works: a successful large scale application, Duri steamflood, Sumatra, Indonesia: SEG 1999 expanded abstracts.

Smit, S., J. Brain, and K. Watts, 2005, Repeatability monitoring during marine 4D streamer acquisition: EAGE 2005 expanded abstracts.

Smit, S., M. Ligtendag, P. Wills, and R. Calvert, 2005, Permanent seismic reservoir monitoring using the sparse OBC concept: SEG 2005 expanded abstracts.

Stammeijer, J., and R. Staples, 2003, Putting 4D pressures in perspective: SEG 2003 expanded abstracts.

Staples, R., P. Hague, T. Weisenborn, P. Ashton, and B. Michalek, 2005, 4D seismic for oil-rim monitoring: Geophysical Prospecting, v. 53, p. 243-251.

Tura, A., and D. Lumley, 1999, Estimating pressure and saturation changes from time-lapse AVO data: SEG 1999 expanded abstracts.

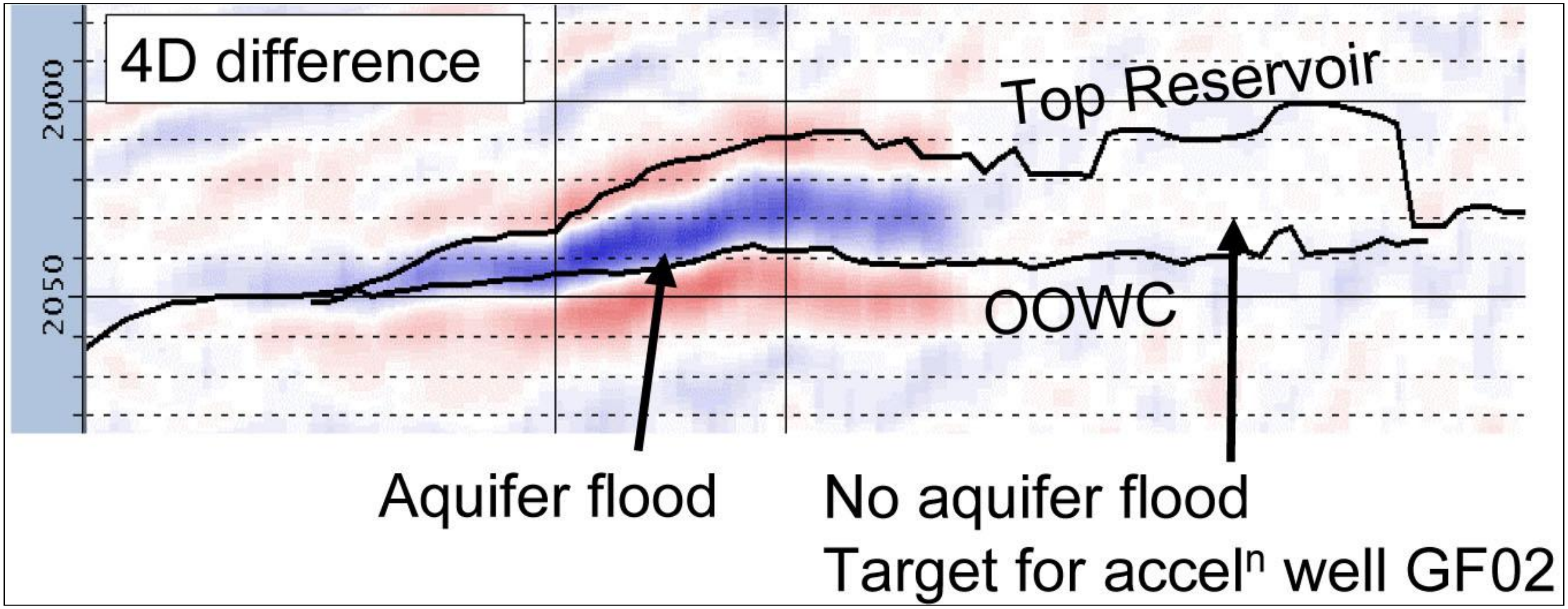

Figure 1. Direct evidence for an acceleration infill target (unswept area) at Gannet F.

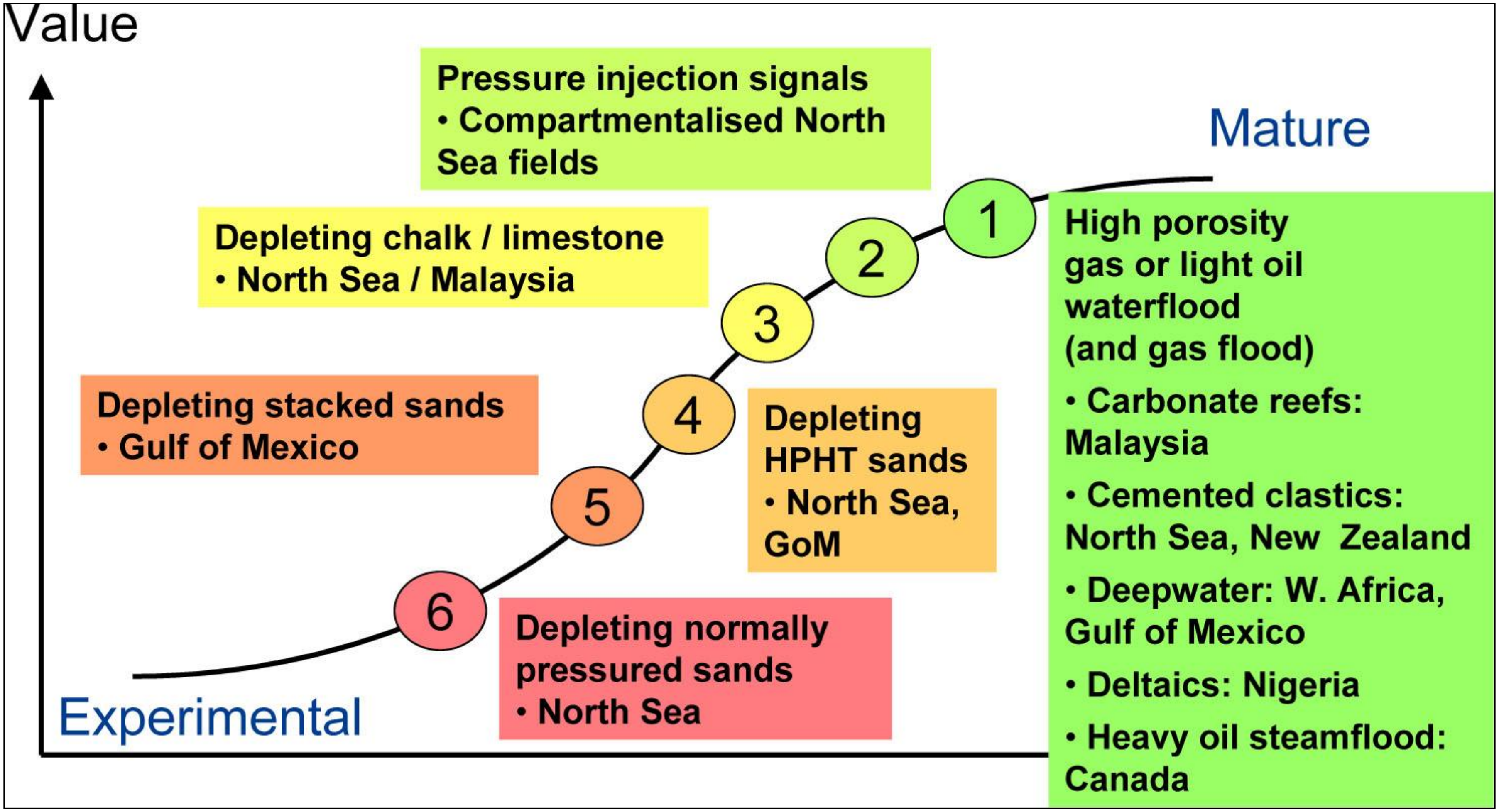

Figure 2. A maturity S-curve for different 4D applications. (For simplicity here, we only show only high porosity waterflood/gasflood. Lower porosity waterflood/gasflood reservoirs (e.g. <22% porosity) would sit further down the curve due to the smaller 4D signal).

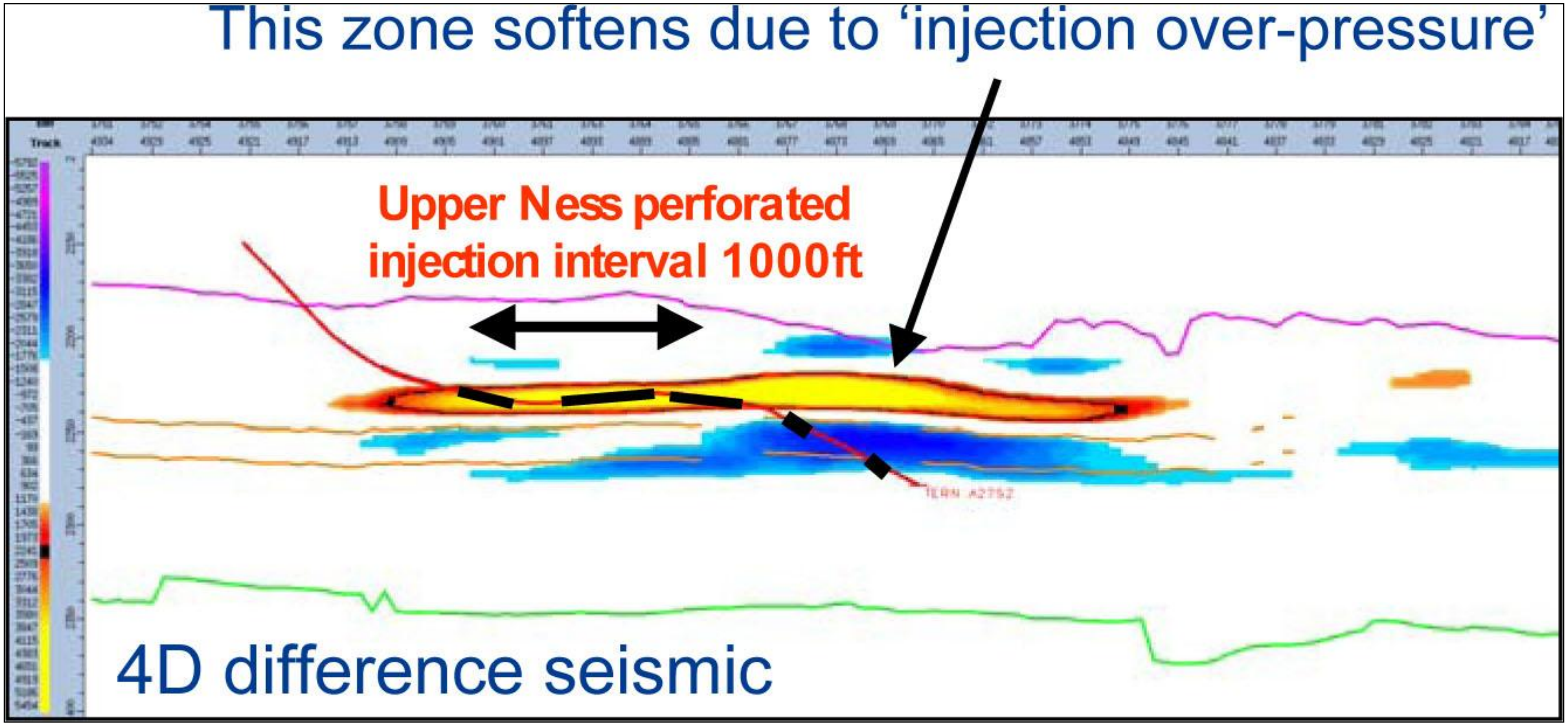

Figure 3. A strong 4D signal caused by injection into an isolated fault block.

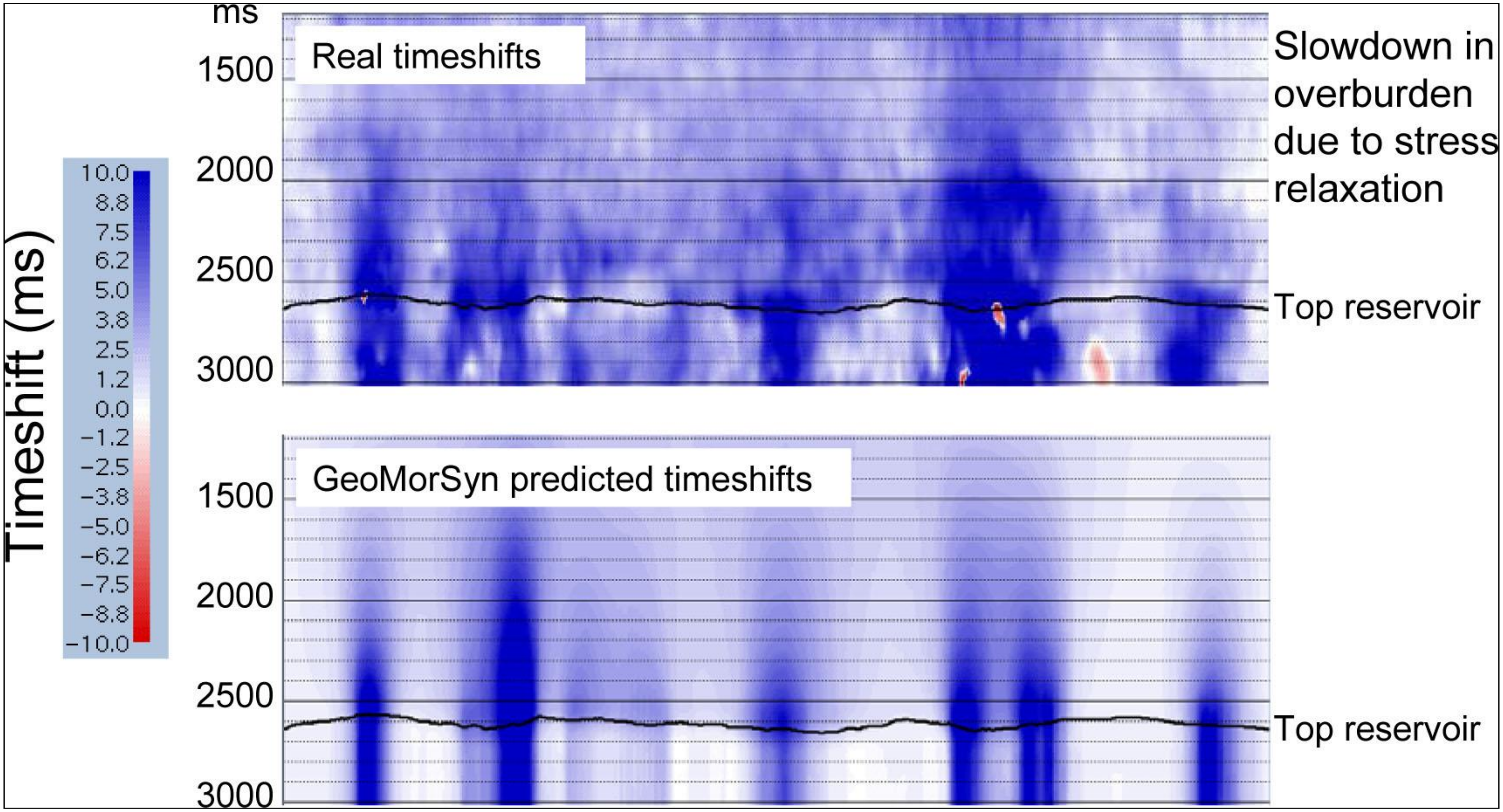

Figure 4. An example of the overburden time-shifts for a compacting reservoir.

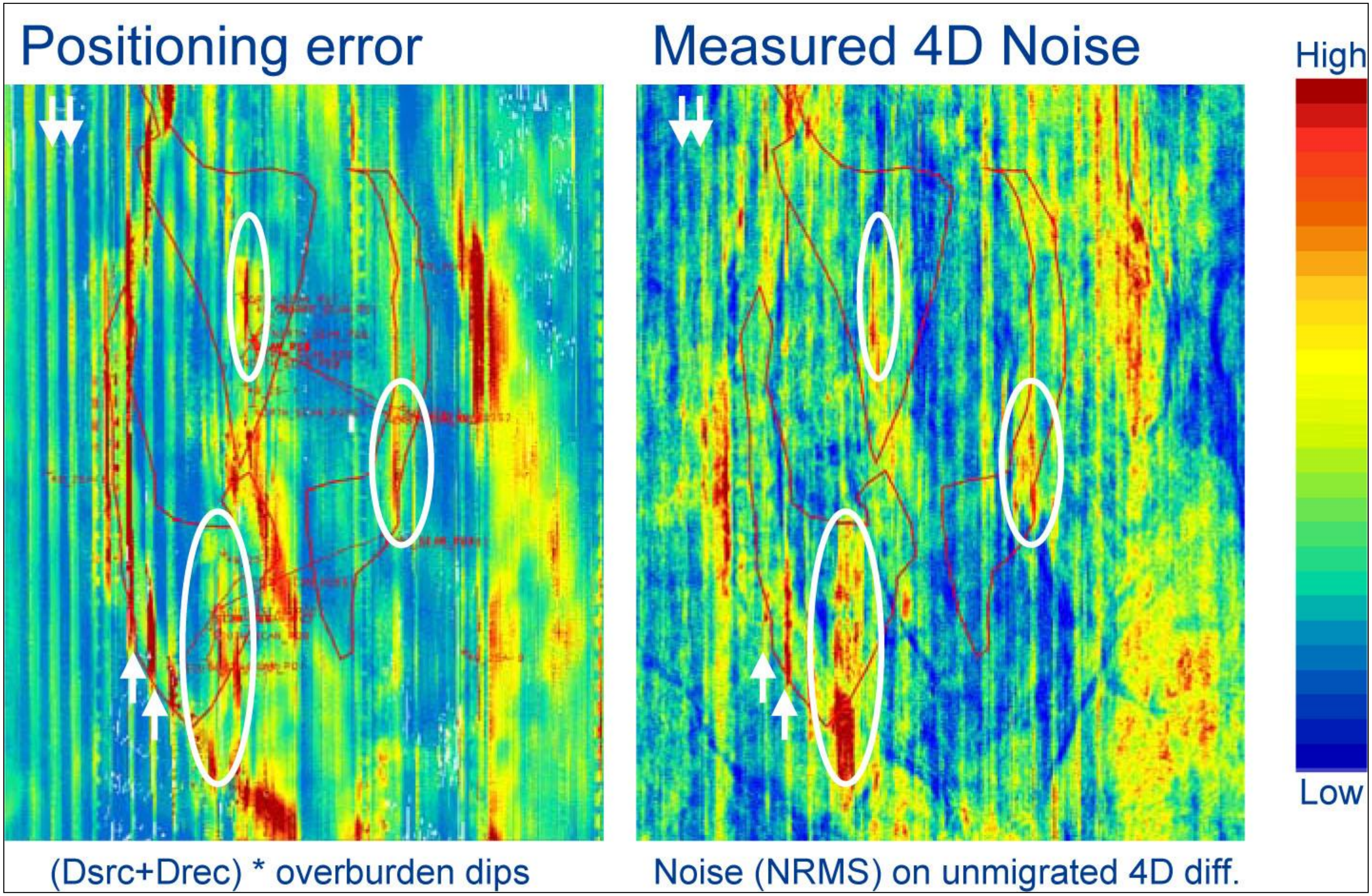

Figure 5. A demonstration of the link between acquisition repeatability (steamer data) and 4D noise.

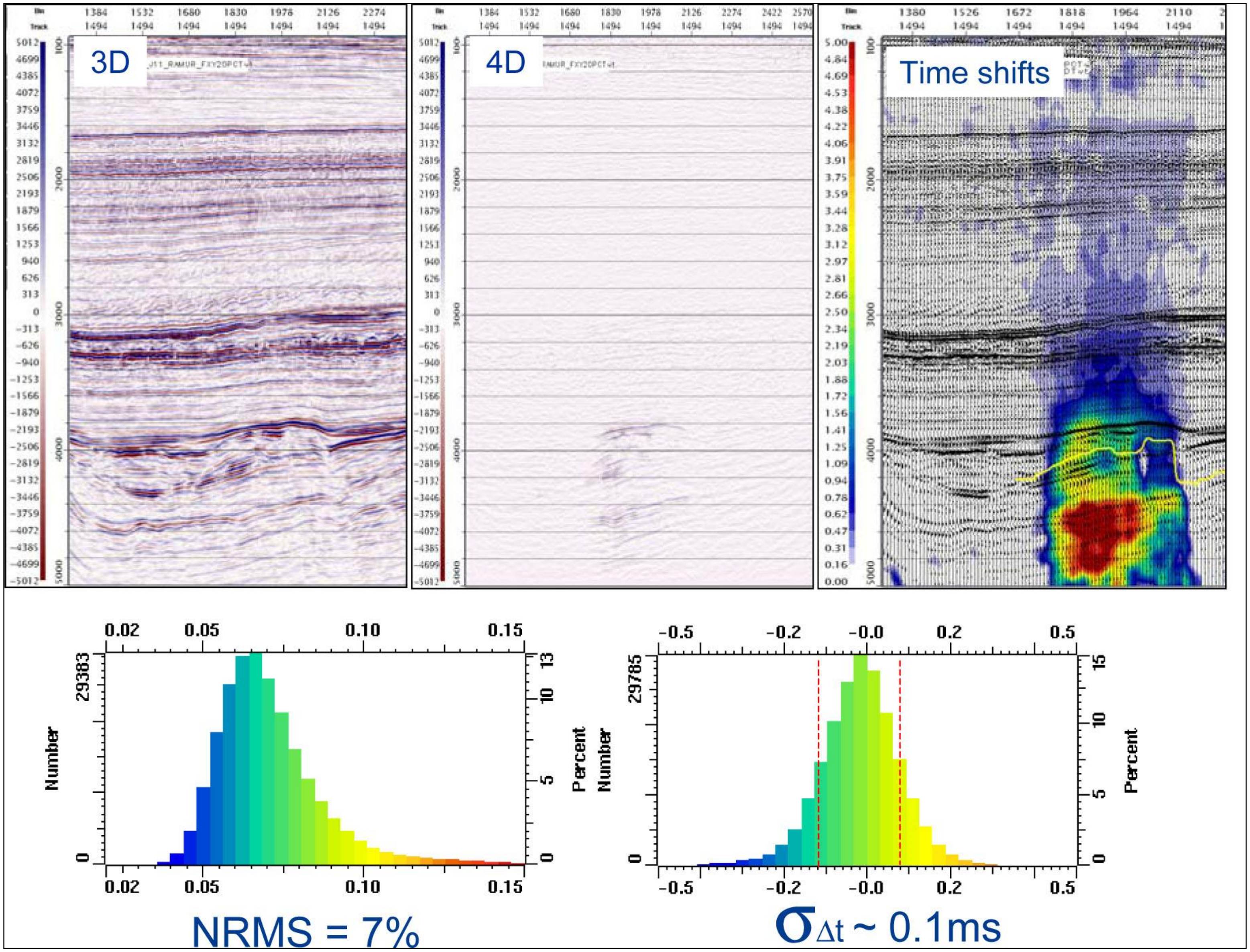

Figure 6. Data from the 2002-2004 Shearwater shoot showing excellent data quality. The histograms shown are diagnostics derived from an area outside the production / subsidence zone.

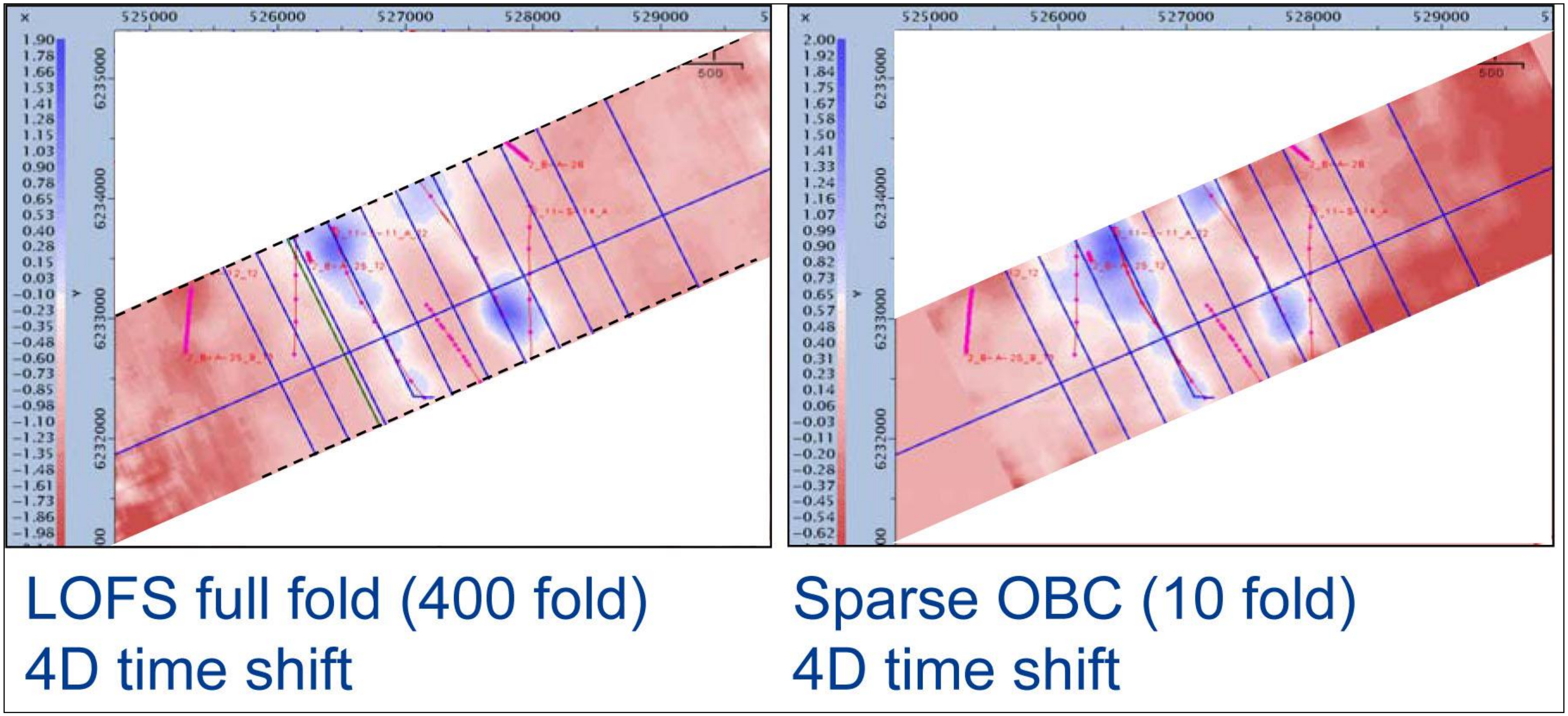

Figure 7. Comparison of conventional full-fold OBC data with sparse OBC data.