Decade of 4D Seismic Monitoring of Carbonate Gas Reservoirs in Offshore Sarawak, Malaysia*

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Search and Discovery Article #41021 (2012)*
Posted September 17, 2012

* Adapted from extended abstract prepared in conjunction with oral presentation at AAPG International Convention and Exhibition, Singapore, 16-19 September 2012,

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Abstract

The use of 4D seismic data to monitor production effects in carbonate reservoirs in the published literature is limited. This is because the acoustic response of carbonates has been shown to be highly variable and the applicability of Gassmann's equation for predicting the impact of changes in saturation on the acoustic properties of carbonates is debatable. Of particular relevance to the carbonate gas fields of offshore Sarawak is the fact that Gassmann's equation predicts that water influx into a gas reservoir would produce a relatively minor acoustic response, which might be expected to be swamped by non-repeatable noise on 4D seismic data.

Therefore, Shell has adopted a cautious approach to implementing time-lapse seismic monitoring of the carbonate gas reservoirs of offshore Sarawak. The first attempt was undertaken in 2001, when six repeat 2D seismic lines were acquired over a medium-sized carbonate gas field. Despite the limitations of repeating 2D seismic data, two of the six lines appeared to show a relatively strong coherent seismic amplitude response at both the original gas-water contact and the point which coincided with the logged producing gas-water contact in the wells.

These encouraging results prompted the first full-field repeat seismic survey, covering two smaller subsea fields in 2005. Both fields showed clear amplitude responses with one related to water influx and the other related to gas expansion into the aquifer. Interestingly, the latter signal is much stronger than the former, which is precisely what Gassmann's equation predicts. In addition to the 4D seismic amplitude response, both fields showed clear time-shifts between the base and monitor surveys, which are attributed to seafloor subsidence and stress relaxation in the overburden, due to pressure depletion and compaction in the reservoir and provide evidence that it is possible to use 4D seismic data to monitor the aerial extent of pressure communication in these reservoirs.

Since then, repeat 3D swaths have been acquired over two larger carbonate gas fields and both have displayed clear amplitude signals related to water influx. These surveys have conclusively demonstrated that, despite the ongoing debate about the impact of saturation changes on seismic velocities in carbonates, 4D seismic monitoring of carbonate gas fields can yield meaningful signals, which can be used to optimize further field development and maximize ultimate gas recovery in future.

Introduction

In recent years 4D seismic monitoring has been widely used to monitor production effects in clastic reservoirs, to the extent that the seismic response of such reservoirs to saturation and pressure changes has become reasonably well understood and is well documented in the published literature. However, given that carbonate reservoirs account for approximately half of the world's oil and gas reserves, it is perhaps surprising that the use of 4D seismic data to monitor production effects in carbonate reservoirs has received considerably less attention. This is largely because the acoustic response of carbonates has been shown to be highly variable and there has been some debate regarding the applicability of Gassmann's equation for predicting the impact of changes in saturation on the acoustic properties of carbonates (e.g. Baechle et al. 2005; Rasolofosaon et al. 2008). Of particular relevance to the carbonate gas fields of offshore Sarawak is the fact that Gassmann's equation predicts that water influx into a gas reservoir would produce a relatively minor acoustic response, which might be expected to be swamped by non-repeatable noise on 4D seismic data.

For these reasons, Shell has adopted a cautious approach to implementing 4D seismic monitoring of the Miocene carbonate gas reservoirs of offshore Sarawak, Malaysia. This approach has involved a gradual shift from 2D repeat seismic acquisition to targeted 3D seismic swaths and more recent plans for platform undershoots to provide repeatable pre-production data for future surveys. At each stage of this journey, important lessons have been learned regarding the applicability of 4D seismic data for monitoring production behavior in carbonate gas reservoirs and these lessons have laid the foundation for further 4D seismic monitoring to maximize ultimate gas recovery in future.

Repeat 2D Seismic Acquisition at the Field A

The first attempt at time-lapse seismic monitoring of a carbonate gas reservoir in offshore Sarawak was undertaken in 2001, when six repeat 2D seismic lines were acquired over the Field A, which had experienced unexpected water breakthrough just three years after first gas. Despite the limitations of repeating 2D seismic data, two of the six lines appeared to show a relatively strong coherent seismic amplitude response at both the original gas-water contact and the point which coincided with the logged producing gas-water contact in the wells. Furthermore, robust time-shifts between the base and monitor surveys were also observed. These can be attributed to seafloor subsidence and stress relaxation in the overburden, due to pressure depletion and compaction in the reservoir and provided evidence that it was possible to use time-lapse seismic data to monitor the aerial extent of pressure communication in these reservoirs.

Repeat Full Field 3D Seismic Acquisition at the Field B & C

These encouraging results prompted the first full-field repeat seismic survey, covering two smaller subsea fields in 2005 (Barker et al. 2008). Both of these fields were developed with two horizontal subsea wells at the crest of the structures. The only real difference was the geometry of the structures with the Field B having a 180 ft gas leg and the Field C having a 560 ft gas leg. By the time of acquisition, Field B had been producing for three years, whilst Field C had been producing for less than a year. However, it was apparent that the two fields were in pressure communication, because Field C already showed signs of pressure depletion when it came on stream, which was attributed to two years of production from Field B

Water breakthrough in one of the Field B wells was observed in 2004, two years after first gas, whilst water breakthrough at the second Field B well was observed within months of completing the repeat 3D seismic acquisition. At this point in time, the field had produced less than 50% of its GIIP and it was believed that the early water breakthrough may have been a localized effect and that the ultimate recovery could potentially be increased by drilling an additional subsea well into an unswept part of the field. However, when the 4D seismic data became available in early 2006, a clear amplitude response was observed at the original gas-water contact and another clear amplitude response was observed very close to the crest of the structure (Figure 1). This implied that the contact rise was broadly uniform, leaving no real pockets of by-passed gas. Based on this observation, the decision was taken not to drill a costly additional subsea well or sidetrack on this field.

The 4D seismic data over the Field C showed a slightly unexpected amplitude response which seemed to imply an expansion of the gas cap into the aquifer, due to pre-production depletion. Interestingly, this signal is much stronger than the signal related to water influx at Field B, which is precisely what Gassmann's equation predicts. In addition to the 4D seismic amplitude response, both fields showed clear time-shifts between the base and monitor surveys, due to seafloor subsidence and stress relaxation in the overburden, once again demonstrating the use of 4D seismic data for understanding pressure communication.

Repeat 3D Seismic Swath Acquisition at the Field E

In 2006, another repeat seismic survey was acquired at the Field E. This field came onstream in 1987 and had already been producing for 15 years when the first 3D seismic survey was acquired over the field in 2002. Pulsed neutron capture logs showed clear evidence for water influx in the central part of the field. However, owing to the size of the field (130) and the fact that it had been developed from a single platform, there was considerable uncertainty surrounding the remaining gas volume on the flanks. Dynamic simulation studies indicated that the degree of water influx was likely to be greater in the central part of the field than on the flanks and that any further gas-water contact rise on the flanks between 2002 and 2006 was likely to be small (<50 ft). This represented a challenge for 4D seismic monitoring. Nevertheless, synthetic seismic modeling using Gassmann's equation for the replacement of gas with water showed that it should be possible to observe a 50 ft contact rise above the expected levels of non-repeatable noise.

Because of the cost of full-field 3D seismic acquisition over such a large field and the relatively low probability of success, it was decided to acquire a targeted 3D seismic swath over the western flank of the field. When processed, this swath showed a weak 4D amplitude response, which is interpreted as evidence for partial sweep of the western flank (Figure 2). However, it also implies that there is a sizeable volume of gas remaining in this area. As a result, plans are in place to drill an 18,000 ft extended reach development well into the western flank of the field in late 2012. Part of this plan involves drilling a pilot hole in this area to confirm the depth of the current contact and validate the predictions of the 4D seismic data

Repeat 3D Seismic Swath Acquisition at the Field D

In 2008, a similar approach of targeted 3D seismic swath acquisition was adopted at the Field D. This field came onstream in 2004 and was covered by a full-field pre-production 3D seismic survey in 1992. However, in this case, the acquisition of two 3D seismic swaths, rather than a full-field repeat seismic survey was partly dictated by the desire to keep costs down and partly by the fact that the Field D platform precluded the acquisition of seismic data over the central part of the field. By the time of repeat seismic acquisition in 2008, pulsed neutron capture logs at three deviated wells showed evidence for no more than 55 ft of water influx in the northern part of the field, which was considered to be just above the lower limit of resolution. However, when the two processed seismic swaths were delivered, they showed strong, but patchy 4D seismic difference responses (Figure 3). These patchy seismic responses are attributed to an irregular water influx, which may be related to the presence of high permeability regions of the reservoir, such as karstified zones. So far, the locations of two subsequent infill wells on this field have been optimized based on the 4D seismic observations.

Conclusions and Future Plans

Although the effects of pressure and saturation changes in carbonates are believed to be highly variable and the applicability of Gassmann's equations is still the subject of some debate, these empirical examples from offshore Sarawak conclusively demonstrate that 4D seismic monitoring of carbonate gas fields can yield meaningful signals, which can be used to optimize further field development.

As a result of the successes to date, a campaign of activities is planned for 2012 and beyond. This involves extended repeat swath surveys over Field D and pre-production seismic undershoots of the platform locations at two currently undeveloped fields, which are designed to lay the foundation for future repeat seismic surveys to maximize ultimate gas recovery from offshore Sarawak

Acknowledgements

The authors would like to thank Tim Barker, Chen Bao Ning, Wong Kah Luk, Cameron Dinning, Lee Bor Seng, Elvis Chung, Khaw Lay Hong and Kok Yip Cheong for their contributions to this work.

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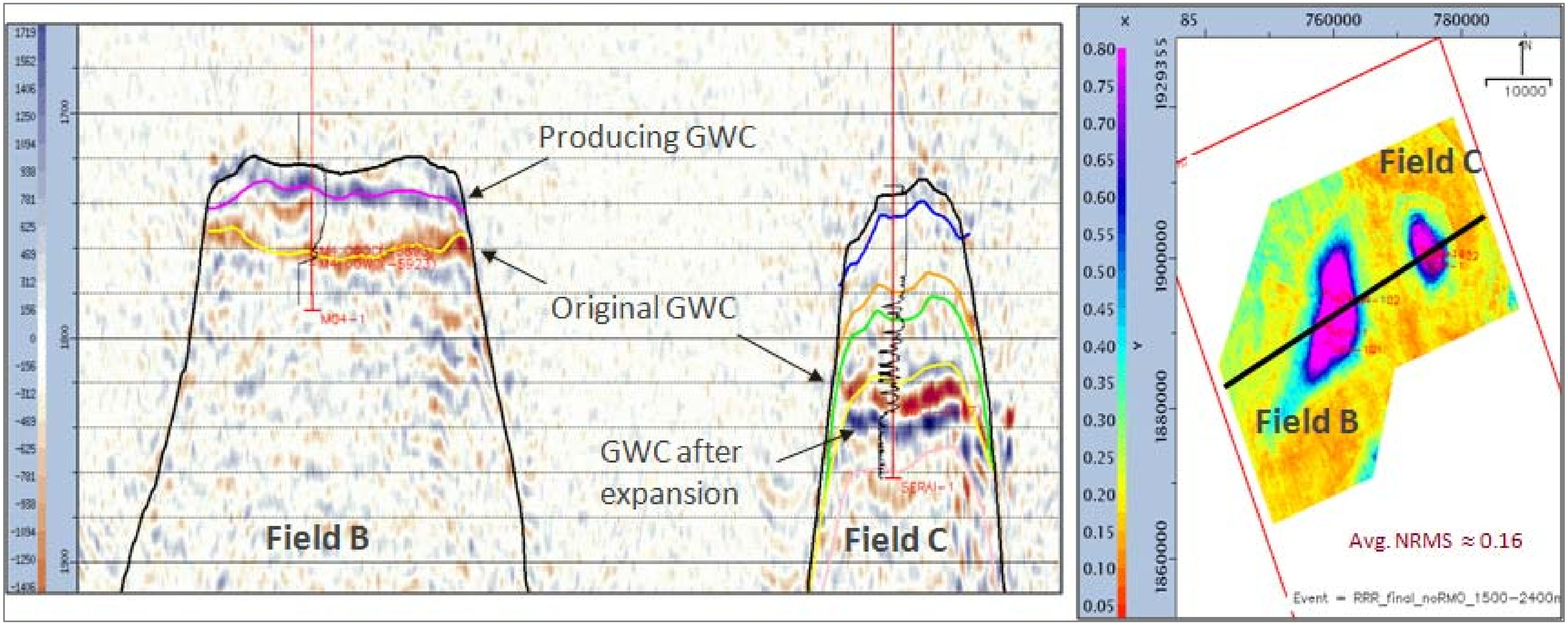

Figure 1. 4D seismic difference data at Field B and Field C.

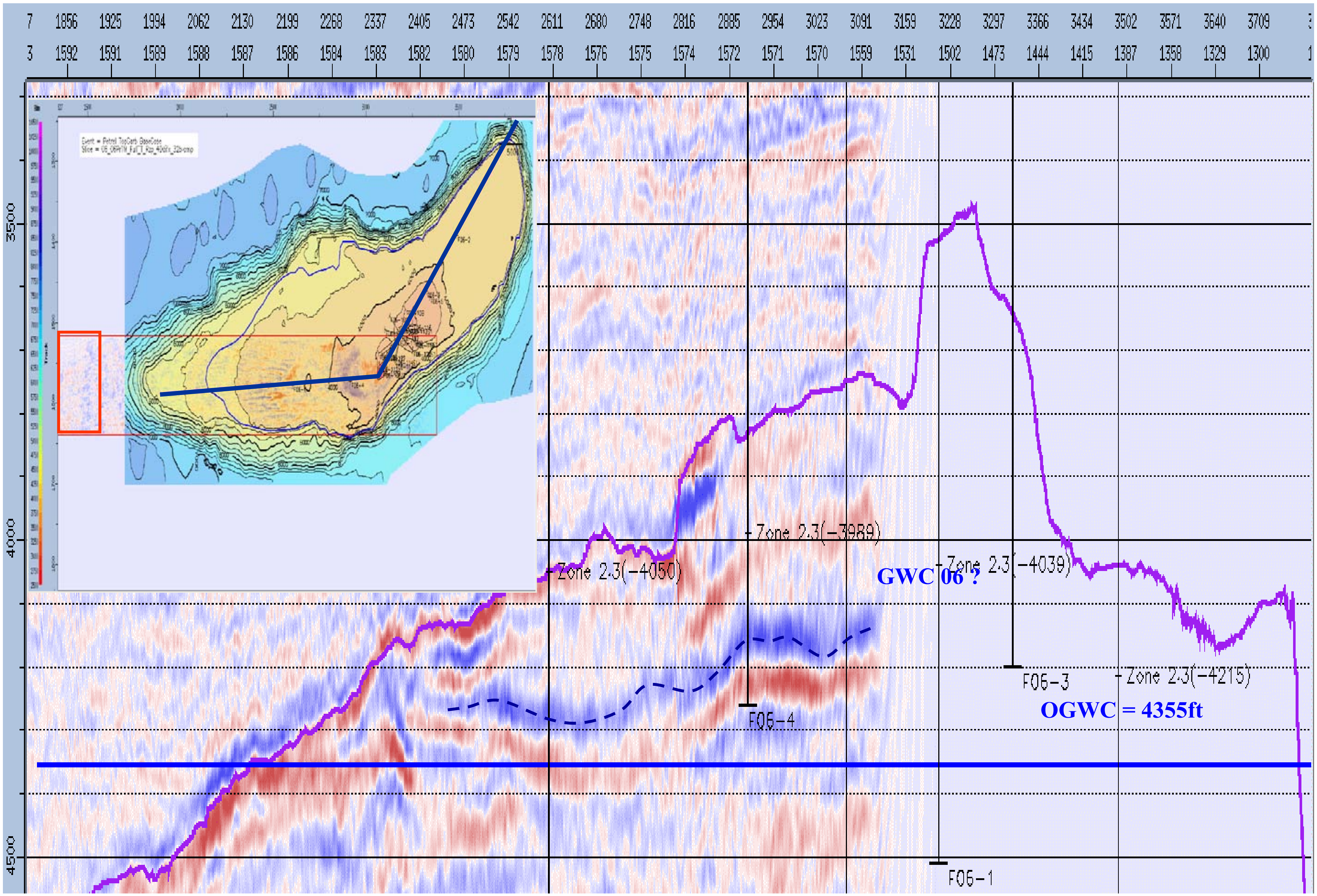

Figure 2. 4D seismic difference data at Field E.

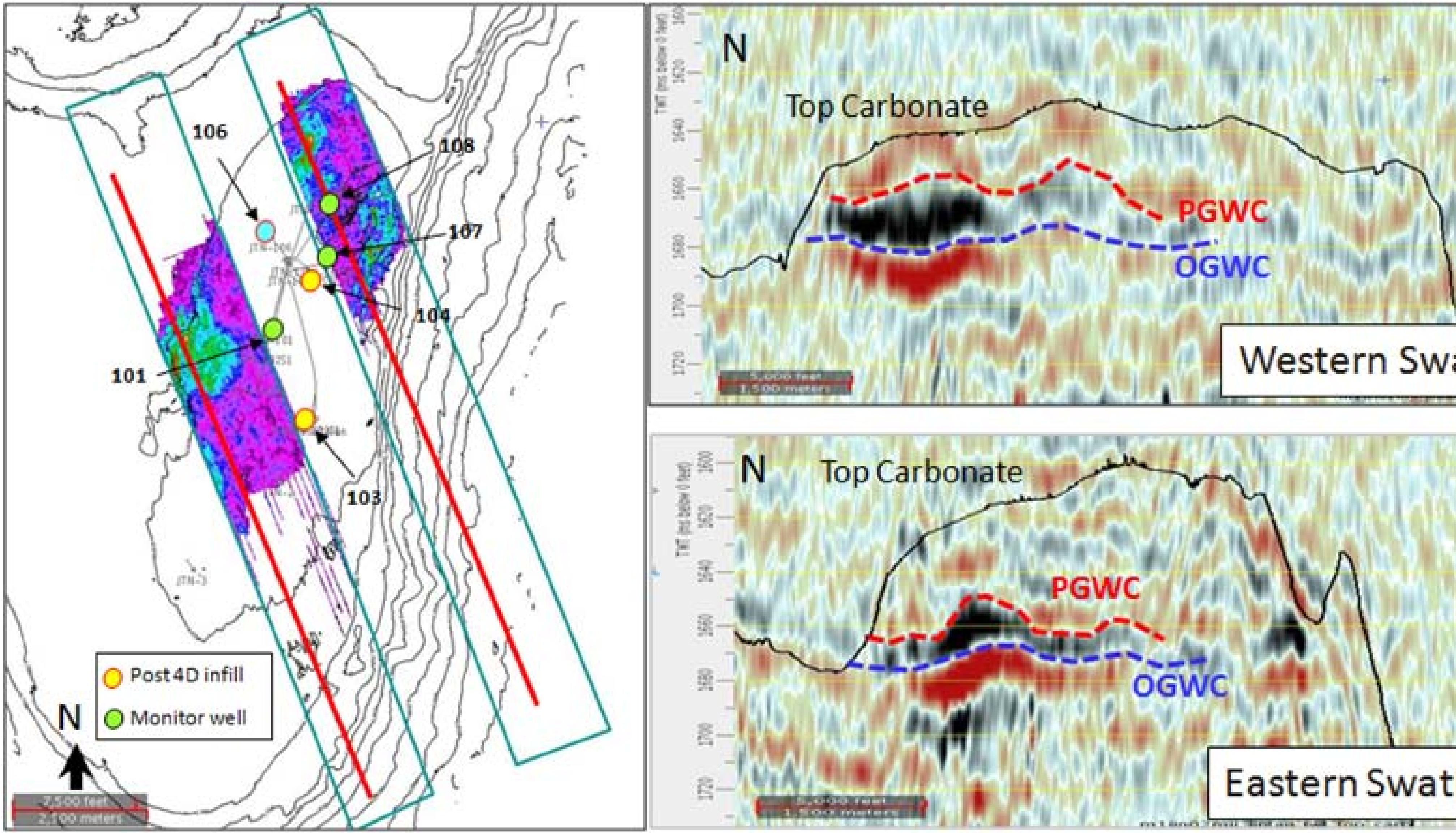

Figure 3. 4D seismic difference data at Field D.