Seismic monitoring of an old underground blowout – 20 years later

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Abstract
When Saga Petroleum drilled a deep exploration well in the southern part of the North Sea in 1989, it encountered a high pressure zone, and the well developed into an underground blowout that lasted for 326 days. A relief well was spudded 11 days after the blowout, and the underground blowout was successfully killed by pumping drilling mud of high density, 2.25 g/cc, into the blowing well. During this period, Saga Petroleum decided to use shallow seismic data to monitor the underground blowout. Ten monitor surveys were acquired during and after the blowout, and this campaign is probably the first successful time-lapse seismic acquisition done in the Norwegian part of the North Sea. In 2009 some of these 2D lines were repeated, using approximately the same acquisition parameters as in 1989 and 1990. Comparing the seismic data from 2009 with the data from 1990 and 1989, most of the gas appears still to be in the same layers as in 1990. There has been some lateral migration of gas, and only a minor amount of vertical gas migration.

Development of the underground blowout
Figure 1 shows a schematic diagram of Well 2/4-14 with the interpreted underground flow path of gas from the target, which is located at approximately 4700 m depth. The pressure development, measured at the well head, is shown in Figure 2. After the blowout, the blowout preventer was closed, and approximately two hours later the well-head

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pressure had increased from 200 bar to 690 bar. The drilling rig was then removed from the well location.

Three months later, another rig coupled to the well and started various procedures to try to kill the well. At the same time, the relief well (2/4-15) was drilled close to the blowing well. The well-head pressure measured in the annulus reduced from 690 bar to 180–190 bar, and this level remained approximately constant from May to October 1989. During this period, a leakage point into the formation was identified at approximately 900 m depth (Figure 3). In the first months, the leakage flow went all the way to the blowout preventer, through a hole in the overshot, and then escaped through a hole at 1361 m and into the formation at 902 m. When the hole in the overshot was closed in late June, a new hole was created at a depth of 4100 m, and a new flow path was established, as shown to the right in Figure 3.

The blowout lasted for 326 days and Saga Petroleum estimated that 0.33–0.4 million standard cubic metres (MMSCM) of oil and 196–367 MMSCM of gas had escaped from the reservoir level at 4730 m into shallow sand layers (Remen, 1991). This corresponds to approximately 7,800 b/d of oil on average. However, immediately after the blowout, the rate of oil escape was probably over 20,000 b/d. The risk of encountering overpressure in these shallow sands was estimated to be low, since the estimated overpressure was less than 3 bars.

The relief well was located 1184 m south of the blowing well. The location was chosen based upon geological observations that indicated that the shallow sand layers were slightly dipping to the north (Mjelde, 1991). The distance of 1.2 km was based upon estimated sizes of potential craters that could be caused by the blowing well. From approximately 3700 m depth, the relief well was drilled parallel and very close to the blowing well, at a horizontal distance of only 20 m. Figure 4 shows a noise log obtained from this vertical section of the relief well (Slungaard and Smestad, 1991), clearly showing a strong acoustic signal around 4100 m.
At shallow depths, the available well logs in this area are limited. Figure 7 shows a comparison between gamma-ray logs from two neighbouring wells, 2/4-13 and 2/4-16. Well 2/4-16 was confirmed by a video camera lowered into the blowing well. It is also interesting to note that the repeated noise log acquired after the kill operation shows no anomalous signal, confirming that the kill operation was successful.

**2009 seismic acquisition**
The layout of the five 2D lines that were acquired in 2009 is shown in Figure 5. Some key wells in the area are also shown in addition to the blowout well (2/4-14) and the relief well (2/4-15). The baseline survey for all these lines was shot in 1988, prior to the drilling of Well 2/4-14. Seismic repeatability was not considered when the 1988 data were acquired, nor for the first repeated lines acquired in 1989 and 1990. Nevertheless, the same source array, a sleeve-gun cluster of total chamber volume 160 cubic inches was used for all surveys. Figure 6 shows source positions for 12 versions of line 602. Many of these lines are not ideal with respect to repeatability, but three lines are very close to each other and these lines are preferred for conventional time-lapse differencing. For the receiver positions, there was less control and no detailed information about feathering or positions of individual hydrophones is available. In the processing, I assumed that each streamer was straight, with fixed intervals between hydrophones.

![Figure 3](image1.png) The underground flow paths: from May to June there was a leak close to the overshot, and when this leak was fixed, a new hole occurred at 4100 m depth (right panel). In both cases, the flow from the well into the formation occurred at approximately 900 m depth. Courtesy of Saga Petroleum.

![Figure 4](image2.png) Noise log measured in the relief well. The blowing and relief wells are close to parallel in the depth interval 3700–4700 m, with an average horizontal separation of 20 m. The strong signal at 4100 m is interpreted to be caused by a hole at this depth (Figure 3, right). After the kill operation, this signal vanished (dashed line). Courtesy of Saga Petroleum.

**Shallow sands and mapping of gas accumulation**
At shallow depths, the available well logs in this area are limited. Figure 7 shows a comparison between gamma-ray logs from two neighbouring wells, 2/4-13 and 2/4-16. Well
2/4-13 is only 47 m away from Well 2/4-14, and the location of Well 2/4-16 is shown in Figure 5. The horizontal distance between these two wells is 880 m, and there is good correlation between the two logs, indicating that the major interpreted shallow sand layers (low gamma-ray values) are laterally continuous.

According to the analysis done by Saga Petroleum, most of the hydrocarbons that escaped into shallow sand layers went into the sand layer at approximately 840 m depth, which is 87 m thick. Based on several repeated seismic 2D lines, Saga Petroleum mapped the lateral extent of this gas accumulation from the seismic data (Figure 8). Ten months after the blowout, the area of this gas anomaly was estimated to be about 15 km². However, some gas also migrated into another sand layer at 490 m depth (Larsen and Lie, 1990). This shallower sand layer is significantly thinner, but shows up very clearly on the seismic data from 1990. The mapped extent of this shallower anomaly was significantly less (approximately 3 km²). Saga also found a small anomaly at approximately 445 m depth, with a very limited horizontal extent. They also reported that no significant changes were observed between May and October 1990. A vertical profile from line 804 is shown in Figure 9, clearly showing a pronounced pull-down around 520 ms two-way time, corresponding to the sand layer at 490 m. This pull-down is slightly less on the 2009 profile, indicating that some of the gas above this level moved laterally away from the well between 1990 and 2009. This is plausible because the horizontal permeability is significantly higher than the vertical permeability. Figure 9 also shows that the horizontal extent of the 520 ms anomaly increased from 1990 to 2009, roughly from 2.5 km to 3.9 km. A precise estimate of the extent in 2009 is difficult because the amplitude anomaly gradually weakens with distance from the well, which indicates that the gas saturation decreases away from the well.

Time-lapse differences and initial interpretation
Simple raw stacks were produced from data on the original field tapes from 1988, 1989, and 1990 for all 2D lines presented in this paper. No attempts were made to remove multiples and no migration algorithms were applied to the data. Despite these limited efforts on the processing side, it is possible to perform some interesting analysis on the data.

Although the 2D lines were not acquired with time-lapse studies in mind, a conventional difference section obtained after application of a constant scalar shows crisp and clear anomalies (Figure 10). Saga Petroleum identified sand layers at depths of 490 m, 523 m, 562 m, and 605 m, in addition to the sand layer at 840 m depth. The first strong anomaly in
The difference between the 2009 and 1990 data shows a major anomaly at 520 ms, corresponding to the 490 m sand layer (Figure 11). The next major anomaly at 610 ms is interpreted as a multiple of the first anomaly, since the multiple period is 90 ms. There is a very interesting anomaly approximately 1.4 km to the southeast of the well, at approximately 650 ms. This anomaly might correspond to lateral migration of gas within the thin sand layer at 605 m depth. This observation does not fit with the general trend of sand layers dipping southwards, but Figure 8 shows that the difference between gas migration to the south versus north is not significant. For instance, along the 804 line the mapped gas migration is approximately 2.8 km in the southeast direction, and the maximum migration to the northwest is 4.4 km. The 650 ms anomaly to the left of the well in Figure 11 has an extent of approximately 560 m, corresponding to a lateral migration of 560 m within 19 years, indicating slow migration, and low pressures.

An alternative interpretation of the 650 ms event is that it is simply caused by the horizontal gas migration in the sand layer at 490 m depth. A detailed analysis of this event reveals that there is a time shift associated with this anomaly. Another indication that the 650 ms anomaly is caused by the presence of gas at 490 m depth is that its amplitude level in 2009 is weaker than in 1990. This observation supports the assumption that the anomaly is caused by the presence of gas in the sand layer at 490 m.

Figure 12 shows a similar (1990-2009) difference for line 602. There is a clear anomaly at 520 ms, followed by the multiple at 610 ms, and a deeper, strong anomaly around 650 ms, close to Well 2/4-15. The extent of this anomaly is 400 m. It is reasonable to assume that this anomaly also is caused by lateral migration of gas within the sand layer.
Figure 9  Brute stacks of line 804 from 1988, 1990, and 2009. The vertical time range is 400–600 ms and the horizontal extent is 4.5 km. The pull-down close to the well is slightly reduced from 1990 to 2009, indicating less gas close to the well in 2009. Also, the horizontal extent of the 520 anomaly increased from 1990 to 2009.

Figure 10  Difference between 1988 and 1990 for line 840, showing clear anomalies at 520 ms and 650 ms. The vertical time range is 300–900 ms and the horizontal extent is 5625 m.
of gas within the sand layer at 490 m depth, suggesting that the saturation decreases with horizontal distance from the well. Secondly, there is a sharp decrease in the travel time at the well position. This is interpreted as a reduction of gas close to the well, again supporting the assumption that gas is migrating slowly away from the well into shallow sand layers. This does not, however, mean that there is no vertical migration of gas close to the well, it simply means that the lateral migration is stronger than the vertical migration close to the well. There is also another negative time shift anomaly to the northwest of the well, but the cause is unclear. Since the correlation window is relatively wide, these anomalies might include migration of gas in several shallow gas layers. One way to gain some further insight is to use several cross-correlation time windows, and compare the estimated time shifts (Figure 14). For the shallow window (top section in Figure 14), the estimated time shifts oscillate rapidly and are relatively small, indicating no major signals above noise threshold. A potential candidate for an anomaly can be observed close to the southeastern end of the line. If this anomaly is real, it would correspond to gas accumulation in a sand layer above 420 m. The extent of this anomaly is approximately 350 m. However, for the next time window (middle section in Figure 14) this anomaly is not present, so its validity may be questioned. The same anomaly is present in the lower panel (time window from

**Time-shift analysis**

A conventional time-shift analysis for line 804 for the period between 1990 and 2009 is shown in Figure 13. The cross-correlation time window is from 600 to 1100 ms. This time window is relatively long, in order to ensure some stability. There are two major trends in the estimated time shifts. First, there is a clear increase in time shift away from the well, peaking at a distance of 1.2 km away from the well on the southeastern side, and a distance of 1.4 km on the northwestern side. Again, this indicates a close to circular migration pattern of gas around Well 2/4-14. The extent of these two anomalies is around 600–800 m. There is also a small time shift of around 1 ms towards the southeast, close to the end of the line. A possible interpretation of this small time shift is that it is caused by the lateral migration of gas within the sand layer at 490 m depth, suggesting that the saturation decreases with horizontal distance from the well. Secondly, there is a sharp decrease in the travel time at the well position. This is interpreted as a reduction of gas close to the well, again supporting the assumption that gas is migrating slowly away from the well into shallow sand layers. This does not, however, mean that there is no vertical migration of gas close to the well, it simply means that the lateral migration is stronger than the vertical migration close to the well. There is also another negative time shift anomaly to the northwest of the well, but the cause is unclear. Since the correlation window is relatively wide, these anomalies might include migration of gas in several shallow gas layers. One way to gain some further insight is to use several cross-correlation time windows, and compare the estimated time shifts (Figure 14). For the shallow window (top section in Figure 14), the estimated time shifts oscillate rapidly and are relatively small, indicating no major signals above noise threshold. A potential candidate for an anomaly can be observed close to the southeastern end of the line. If this anomaly is real, it would correspond to gas accumulation in a sand layer above 420 m. The extent of this anomaly is approximately 350 m. However, for the next time window (middle section in Figure 14) this anomaly is not present, so its validity may be questioned. The same anomaly is present in the lower panel (time window from

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**Figure 11** Difference between 1990 and 2009. The shallow anomalies close to the well may indicate vertical migration of gas. The vertical time range is 300–900 ms and the horizontal extent is 5625 m.
might be shallow gas accumulations in a layer at approximately 170 m depth. The middle and lower sections in Figure 14 are very similar, with no major changes. Since the sand layer at 840 m depth is situated below 850 ms, we may conclude that most of the gas migration taking place between 1990 and 2009 has

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**Figure 12** Difference between 1990 and 2009 for line 602. The distance from line 602 to Well 2/4-14 is approximately 700 m (Figure 5). The vertical time range is 300–800 ms and the horizontal extent is 5000 m.

**Figure 13** Estimated time shifts (windowed cross-correlation) for line 804 showing positive time shifts away from the well, interpreted as more gas accumulation, and negative timeshifts close to the well, indicating less gas accumulation.
been going on in the depth interval 450–800 m. Furthermore, given that the majority of the escaping gas had accumulated in the 840 m sand layer by 1990, most of it was probably still there in 2009.

The maximum time shift observed is around 3–4 ms, corresponding to a change in pay thickness of 10–15 m. In converting from time shifts to changes in pay thickness, I have assumed an average velocity of 2000 m s⁻¹ and a velocity change of 20% when replacing water with gas, as indicated on the right vertical axis in Figure 14.

**Discussion and conclusions**

Assuming that the time-lapse anomalies observed in 1989 and 1990 are caused by gas, there are several challenges related to long-term monitoring of such anomalies. One of them is that the expected time-lapse seismic difference between gas saturations of 20% and 80% is not huge, and therefore it is challenging to estimate volumetric changes in gas based on time-lapse seismic over 20 years. However, changes in extent as well as travel-time changes might provide rough estimates and at least qualitative indications of horizontal and vertical gas migration.

In addition to relatively poor repeatability due to strong variation in both source and receiver positions between various seismic surveys, there was a lot of non-seismic activity in the area, especially for surveys in 1989 and early 1990. Such noise sources do have an impact on the quality of the time-lapse seismic data.

By studying datasets like the one presented here, we can learn something about how fast gas migrates through shallow sediments close to the seabed, and perhaps also quantify whether any of the gas will reach the water layer within the 20-year timespan. Since carbon dioxide is denser and flows more slowly than gaseous hydrocarbons, I think it is possible to use the 1989 blowout example as a conservative proxy to estimate the lower bound for vertical transit times of carbon dioxide through shallow sediments of the type we are studying.

Furthermore, the LOSEM research project is expected to give information related to well integrity. The 2/4-14 well is cemented all the way to the top. The normal procedure on the Norwegian continental shelf is to use two cement plugs, separated in depth, when a well is permanently closed. The number of wells to be plugged permanently in mature hydrocarbon provinces, such as offshore Norway, is increasing. If such provinces are selected for carbon dioxide storage, the lessons we hope to learn from the problematic 2/4-14 well could be valuable.
Based on the preliminary results from the fast-track processing of the 2009 data set acquired over Well 2/4-14, it seems reasonable to conclude that there has been only minor gas migration into shallower sediments. Both time-shift analysis and amplitude difference analysis show lateral migration of gas, especially within a radius of 1.2–1.4 km from the well. The extent of these anomalies is around 600–800 m. Time-shift analysis indicates that the sand layer that probably stored most of the gas from the blowout still contains around the same amount of gas. However, further analysis and processing of this interesting data set are planned, and some of these initial conclusions might be changed as the project progresses.

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References

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