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Use and abuse of seismic data in reservoir characterisation

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Abstract

All seismic data contain a mixture of signal and noise. In detailed reservoir characterisation, it is commonly difficult to distinguish between real features and seismic artefacts. This is especially a problem when interpreting seismic attribute maps. Such maps are widely used tools during reservoir description, but serious pitfalls exist, which may lead to erroneous interpretations and fatal development plans for oil fields. A recent interpretation of seismic attribute maps from a seismic survey collected across Gullveig, an oil field located in the northern North Sea, has been used to illustrate how small faults can be recognised and mapped from such maps. We applied available well data (including core data) and two seismic surveys from the same area, and present convincing evidence that the vast majority of linear features seen on the seismic attribute maps are, in fact, seismic artefacts and not faults. The data from Gullveig are furthermore supplemented by observations from the nearby Gullfaks Field and discussions on the topic of seismic noise. We use these observations and discussions to stress the importance of using all available data to guide and quality control the structural interpretation of attribute map features before utilising such interpretations as input to reservoir modelling or well planning. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Seismic data; Gullfaks Field; Gullveig

1. Introduction

Today, most thorough seismic interpretations will be based on an integrated use of seismic inlines, crosslines, random lines, time slices and horizon attributes (e.g. Buchanan, Marke, & Ruijtenberg, 1988; Dalley et al., 1989; Tucker, Franklin, Sampath, & Ozimic, 1985). The challenge today is to fully utilise all information contained in seismic data. To do this, the interpreter needs to combine knowledge within the complex disciplines of geology and geophysics. This is not an easy task, and quite commonly, the lack of a sound geological understanding leads the geophysicist to interpret unrealistic geological geometries. Similarly, the geologist may easily interpret features that the geophysicist would rapidly identify as being noise-related. Obviously, the best approach is a close collaboration between geoscientists from both disciplines. However, this is not the typical scenario in today's oil companies. The increasing demand for more and better data interpretation forces the geoscientist to carry out very detailed interpretation without having time for the important and necessary quality control.

In a series of recent articles, Hesthammer and Fossen focus on the importance of integrating all available data for a sound structural interpretation of seismic data (Fossen & Hesthammer, 1998; Hesthammer & Fossen, 1997a,b). In particular, the problem of seismic noise is dealt with in detail. In these articles more than 20,000 km of seismic data and well log data from 180 wells from the structurally complex Gullfaks Field are used to document the presence of noise and the characteristics of noise interference features. Hesthammer and Fossen (1997b) furthermore stress the importance of using any available data from a given study area to establish the style of deformation around and between faults to evaluate the seismic attribute maps. The main purpose of the previous articles was to help the seismic interpreter to allow a more detailed structural interpretation by demonstrating the characteristics of noise interference features and real structures. In particular, pitfalls associated with interpretation of seismic attribute maps are emphasised, and Hesthammer and Fossen (1997a,b) conclude that, due to the presence of (curvi-)linear noise features on seismic attribute maps, only the more continuous lineaments or groups of lineaments should be interpreted as faults. Hesthammer and Fossen (1997b) state that

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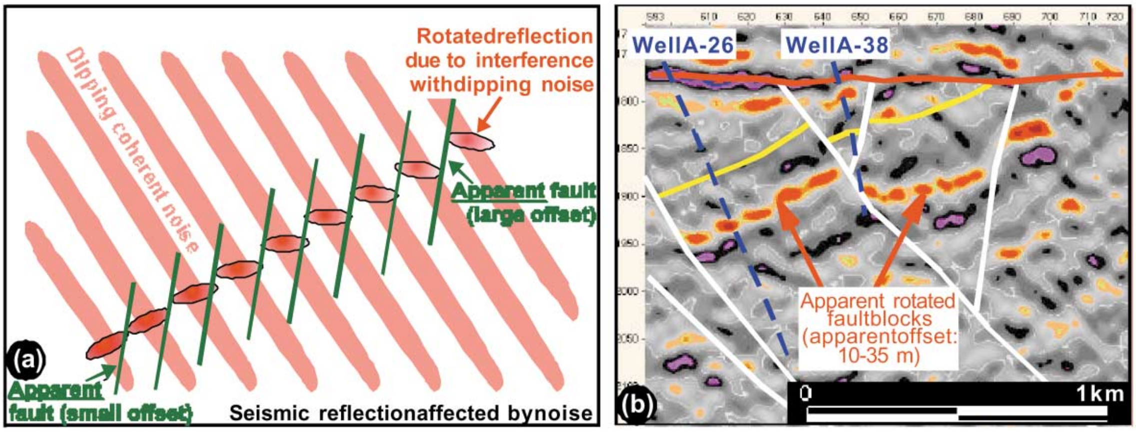

Fig. 1. Many of the (curvi-) linear features observed on seismic attribute maps are caused by the interference of dipping coherent noise with real reflections. This interference causes the real reflection to break up and rotate in the direction of the dipping noise thus causing apparent fault offset in the order of 5–35 m. The amount of offset is strongest where the real reflection is weak (Hesthammer, 1999a).

the (curvi-)linear noise features tend to be parallel to the strike of the dipping reflections (a function of the 3D geometry of the dipping noise and real reflections) and that extreme care must be taken if these bedding-strike parallel features are to be interpreted as faults.

The (curvi-)linear features observed on the seismic attribute maps were found to be caused by the interference of dipping coherent noise with real reflections. This causes the reflections to break up and rotate towards parallelism with the noise features, thus causing apparent fault offset (Fig. 1). The size of the apparent "fault offset" is a function of the strength of the noise feature and the real signal. The weaker the real reflection, the stronger the effect of interference (Hesthammer, 1999a; Hesthammer & Fossen, 1997a,b). Detailed analyses of 23 km of dipmeter data from the Gullfaks Field (Hesthammer & Fossen, 1998) demonstrate that minor faults on the field are generally not associated with fault block rotation. This provides the interpreter with yet another criterion for separating noise interference features from real structures. Furthermore, this important observation allows for removal of much noise by applying relatively strong frequency and dip filters. Quality control against 274 faults penetrated by wells and verified by detailed well log correlation proves that such filtering will not remove the fault characteristics from the seismic data (Hesthammer, 1999a).

As should be evident from the discussion above, the extremely important task of separating geological from artificial information during reservoir characterisation demands the use of supplementary information to seismic data. Still, papers are published where seismic data provides the major basis for interpretation without any possibility for quality controlling the subjective opinions of the authors (e.g. Jones & Knipe, 1996; Townsend et al., 1998). This article uses several seismic data sets and wells from the Gullveig and Gullfaks oil fields, northern North Sea, to demonstrate the uncertainties related to seismic interpretation and how to enhance the interpretation by an integrated approach. Gullveig is used as a case example by Townsend et al. (1998) for discussing the use of seismic attribute maps for small-scale fault identification. However, they did not incorporate any well information or additional 3D seismic data available from the area. It may therefore be of interest to the reader to see how the additional data may add to the understanding of the reservoir characteristics of the area.

2. Gullveig

Gullveig is located south-west of the Gullfaks Field (Fig. 2). The sedimentology of the area is similar to that of the Gullfaks Field (Fig. 3). In general, the oil- and gas-bearing rocks belong to the Jurassic sandstones of the Brent Group and Cook Formation and the Jurassic–Triassic sandstones of the Statfjord Formation. The field is located along the crest of a rotated fault block along the western margin of the Viking Graben. The structural style within Gullveig is similar to that observed within the domino system in the Gullfaks Field to the west, which is described in detail by Fossen and Hesthammer (1998). Recent studies show that the footwalls of the rotated fault blocks are generally remarkably undeformed (Fossen & Hesthammer, 1998; Hesthammer & Fossen, 1998, 1999).

Two 3D seismic surveys have been shot across the Gullveig structure (Fig. 4), one in 1992 and another one in 1996. The 1992 survey is strongly influenced by the dipping coherent noise discussed in detail in several articles (Hesthammer, 1998, 1999a; Hesthammer & Fossen, 1997a,b; Hesthammer & Løkkebø, 1997). In addition, the data are affected by water-layer multiples and multiples of the top Cretaceous reflection. As a result, real reflections in the 1992 seismic survey are highly disrupted and discontinuous (Fig. 4a). One reason for the noisy appearance

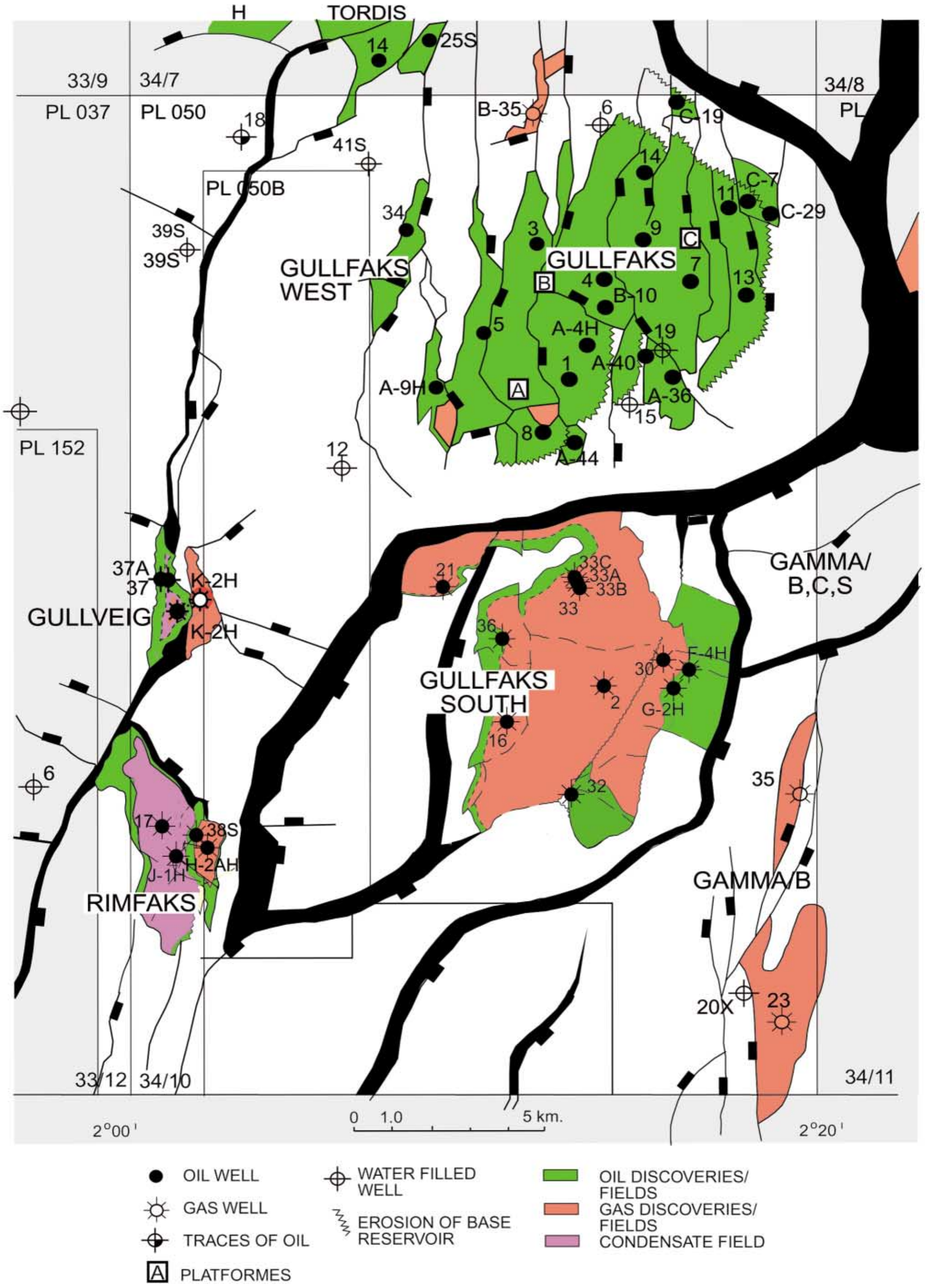

Fig. 2. Location map for the Tampen Spur area. Gullveig is located south-west of the Gullfaks Field.

of the seismic data is that the survey was shot at an oblique angle to the north-trending structure. In addition, the seismic processing may not have been optimal for reducing the effects of noise. The seismic survey shot in 1996 displays much more continuous reflections than the 1992 survey. This last seismic survey was shot perpendicular to the north-trending structure, which may, in part, explain the reduction of seismic artefacts.

Three wells exist in the footwall position to the fault defining the eastern limit of the Gullveig structure (Figs. 5 and 6). Exploration well 34/10-37 (Fig. 5) penetrated the main fault, whereas a sidetrack, 34/10-37A (Fig. 5) and well 34/10-K2H (Fig. 6), is located entirely within the footwall to the main boundary fault.

Core data were collected from all three wells. Within the 46 m cored interval from the footwall portion of well 34/10-37, only eight deformation bands were encountered (clustered at 2630 mMD). The total displacement associated with

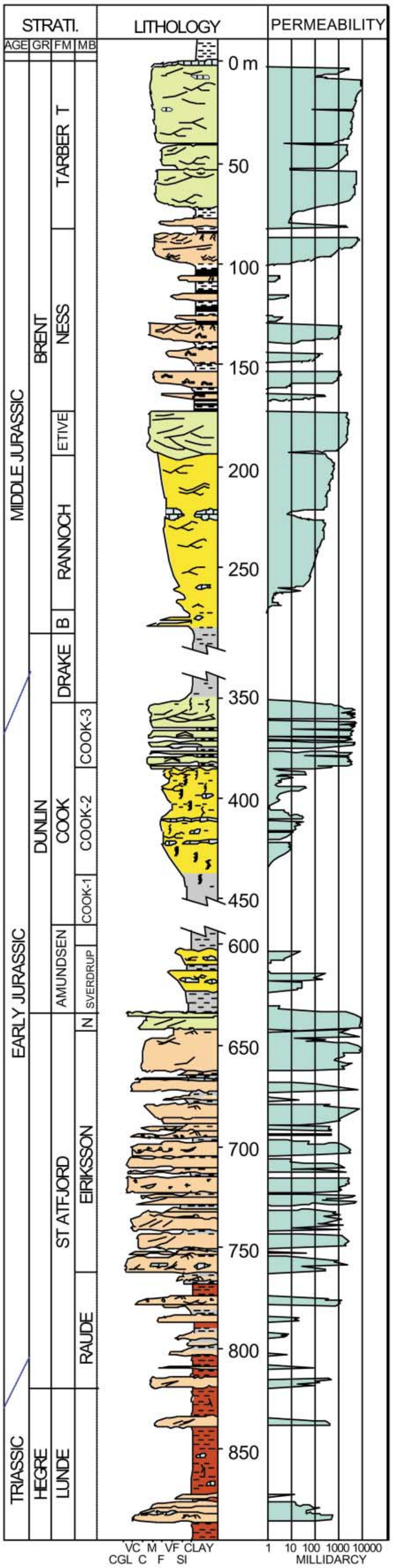

Fig. 3. Stratigraphic column from the Gullfaks Field (modified from Tollefsen et al., 1994).

these deformation bands is very minor (approximately 10 cm). As much as 71 m of core data exist from the 34/10-37A well, but again, only eight deformation bands were detected. Although the displacement along these bands could not be accurately determined, structural core studies from the nearby Gullfaks Field show that the displacement of deformation bands is generally restricted to less than a few centimetres. No clear fault zones (with discrete slip surfaces) exist within the cored intervals from the two wells. Approximately 30 deformation bands were encountered within the 81 m cored interval in well 34/10-K2H. Most of these constitute a narrow damage zone around a minor fault with less than a few metres total displacement located at 3268 mMD.

Well log correlation identified two faults with 140 and 28 m missing section within the Ness Formation in well 34/10-37 (Fig. 5). The same faults were encountered within the Heather Formation in well 34/10-37A (Fig. 5). Based on the 1992 seismic survey, a fault with several tens of metres displacement were expected to be encountered within the Dunlin Group in well 34/10-K2H (Fig. 6b). However, the new seismic survey shot in 1996, which is of far better quality, indicated that no such fault existed (Fig. 6a). This reinterpretation was verified after drilling the well. Although not observable from the seismic data, a fault with 15 m missing section was encountered within the Tarbert Formation. Also, a fault with approximately 6 m missing section may exist within the Ness Formation. These faults are shown by thin, black lines in Fig. 6a.

3. The Gullfaks field

The Gullfaks Field, located north-east of Gullveig (Figs. 2 and 3) has been subjected to many detailed structural investigations (see introduction and references) leading to an enhanced understanding of reservoir characteristics. One of the by-products of the many analyses is a greater understanding of seismic data. In particular, the analyses have demonstrated that there are fewer minor faults on the Gullfaks Field than may be expected from seismic data alone (Fossen & Hesthammer, 2000). In the early stages of field development, the general assumption was that most (curvi-)linear features on seismic attribute maps represented faults. However, as all available well data were subjected to structural analyses, this preconceived belief was proved erroneous (Hesthammer, 1999b). Instead it was discovered that surprisingly few faults existed with displacement smaller than 10 m (Fossen & Hesthammer, 2000) and that only 25% of faults with displacement less than 30 m could be observed in the seismic data (Hesthammer, 1999a). These discoveries demanded a different approach to seismic interpretation, and is today an integrated part of all work related to reservoir characterisation on the Gullfaks Field.

Although many case examples from the Gullfaks Field have been published elsewhere (see Section 1 and references),

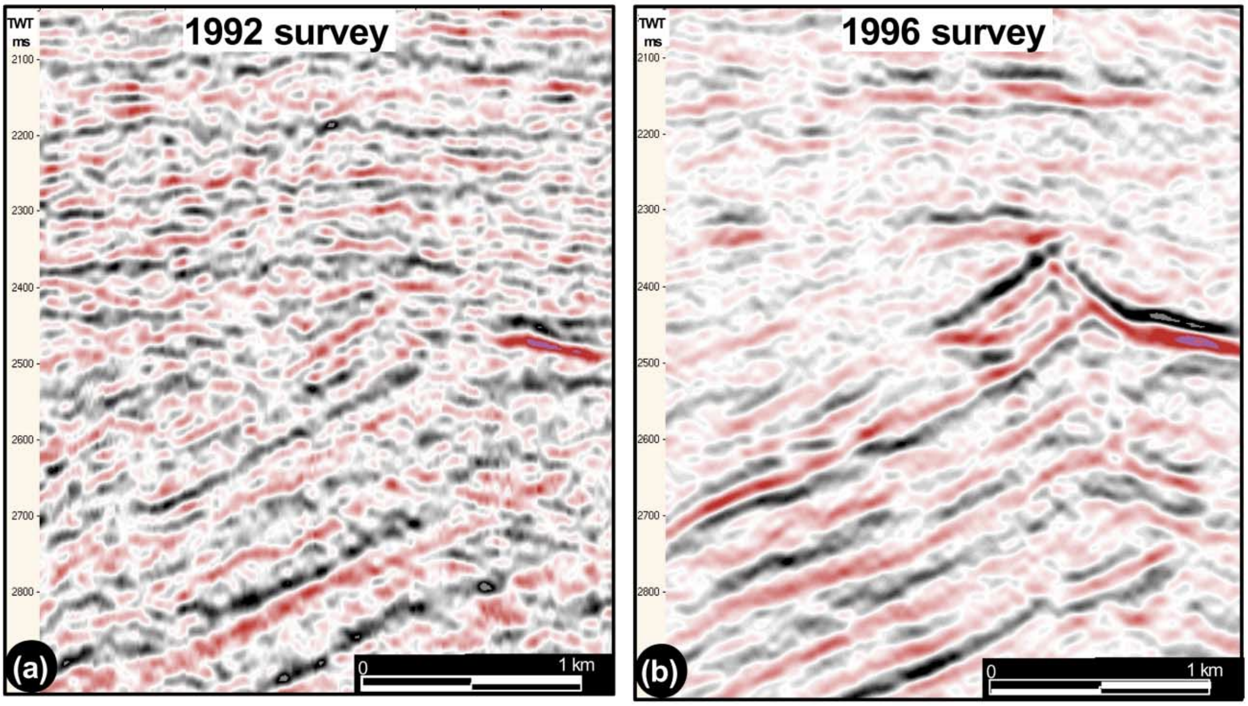

Fig. 4. (a) Seismic E–W section across the Gullveig structure based on the 1992 seismic survey. (b) Seismic E–W section across Gullveig based on the 1996 seismic survey. The 1996 survey is of far better quality than the 1992 survey. In particular, the footwall to the main boundary fault is much better defined in the 1996 data set.

this work will show examples from one area that is particularly well suited to illustrate the problems with seismic noise and thus form a basis for discussion. For a fuller understanding of the structural geology in the area, however, the reader is referred to work by Fossen and Hesthammer (1998) and Hesthammer (1999b). The investigated area is located within the domino system (Fossen & Hesthammer, 1998), which is characterised by shallow (25–30°) east-dipping faults and westerly-dipping bedding (10–20°). In general, the footwalls to the domino-style fault blocks are relatively undeformed whereas the hanging wall is associated with large-scale (seismically observable) drag. Fig. 7a shows a depth-converted structure map of the study area and Fig. 7b shows a timedip map, illustrating the many (curvi-)linear features that may or may not represent faults.

Well 34/10-C-36 is a subhorizontal well drilled subparallel to the dip of bedding, thus providing an excellent opportunity to verify whether or not the (curvi-)linear features are in fact fault-related. Fig. 8 shows a well log correlation panel between wells 34/10-B-12 and 34/10-C-36 (depth is represented by true bed thickness). It is clear from this correlation panel (and correlation with many more wells on the Gullfaks Field) that there is no abnormal bed thickness in the C-36 well. Since the well orientation is subparallel to bedding dip, even a minor fault with only a couple of metres missing section would result in a significant repeat section. There are no indications of any such faults. This is consistent with observations from the many core analyses carried out (Hesthammer, 1999b) showing that the footwall to the rotated fault blocks are relatively undeformed.

Fig. 9a and b shows a seismic cross section and a geological profile along the C-36 well, respectively. Although seismic data allow for the interpretation of many minor faults, well log correlation data is incompatible with such an interpretation. Even the major apparent offset along the base Cretaceous reflection (in the footwall to the main fault) does not represent a fault (but may be an erosional feature). The only fault that exists in the footwall position is located too close to the main fault to be identified in the seismic data. Although it is probably still possible to argue from this specific example that minor faults may exist in spite of the data and interpretations shown in Figs. 8 and 9, the reader should keep in mind the many other analyses published elsewhere. The interpretation is in fact based on a substantial database consisting of comprehensive analyses of 180 wells (including 8 km of core data and 23 km of dipmeter data) that have penetrated more than 270 faults.

Fig. 10 shows a well log correlation panel from wells 34/10-B-12, 34/10-3 and 34/10-B-27. The B-12 well penetrates two faults (associated with 69 and 92 m missing section, respectively) constituting the main fault block boundary to the east. No other faults have been identified in the hanging wall. Rather, the hanging wall is deformed in a more ductile manner as expressed by large-scale drag of bedding. Core

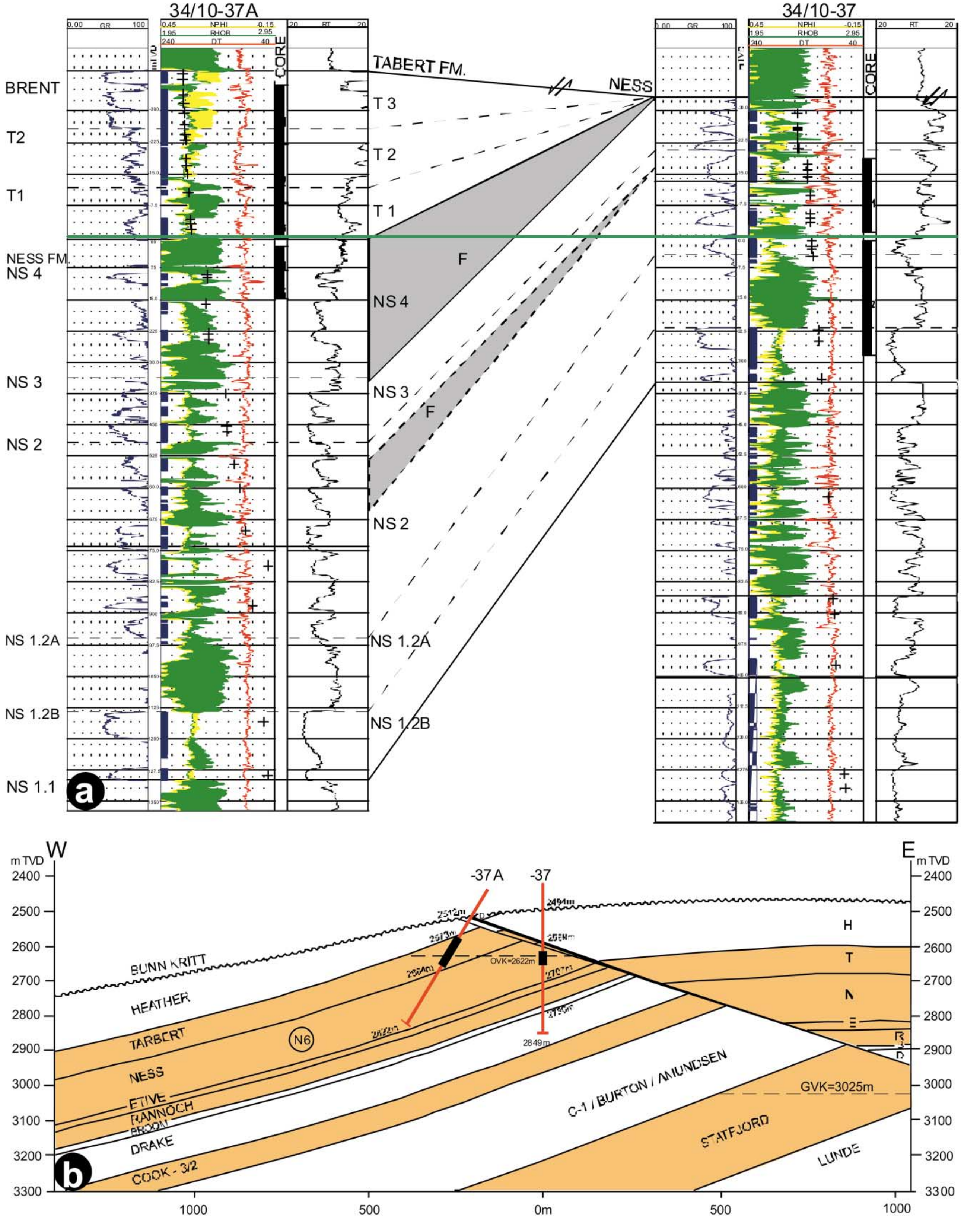

Fig. 5. (a) Well log correlation profile from wells 34/10-37 and 34/10-37A, which are located in a footwall position to the main boundary fault. Two faults have been identified in the wells based on detailed well log correlation. (b) Geological W–E profile through wells 34/10-37 and 34/10-37A.

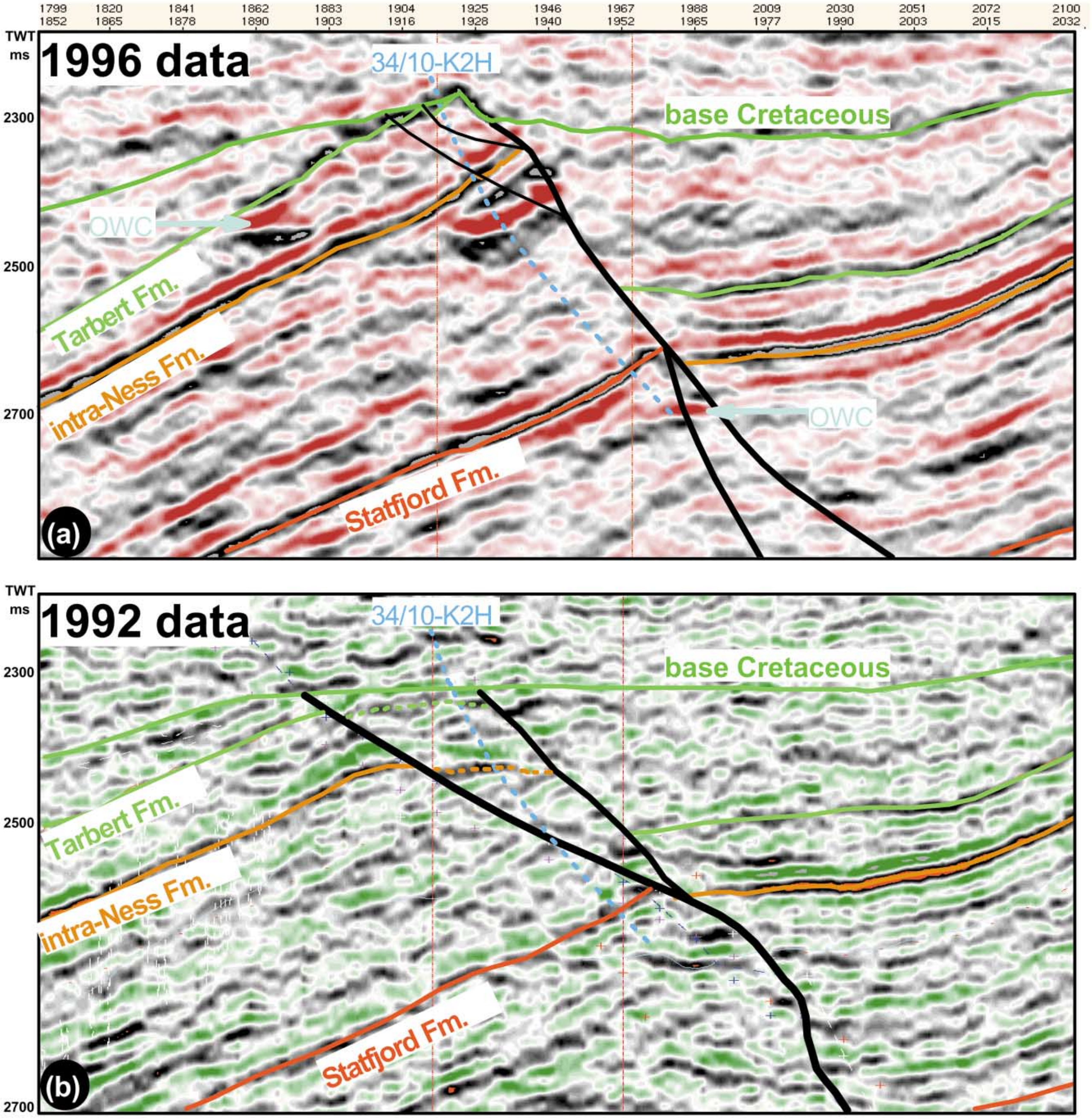

Fig. 6. Seismic profiles along the 34/10-K2H well on Gullveig. (a) Seismic interpretation based on the 1996 survey. (b) Seismic interpretation based on the 1992 seismic survey. Drilling of the well verified the interpretation shown in (a). The oil–water contact is clearly observed within the Brent Group and Statfjord Formation in the 1996 survey, but is absent in the 1992 seismic data set.

analyses from the well suggest that the flexing of the bedding must be by a widely distributed grain reorganisation rather than by discrete faults (Hesthammer, 1999b). Well 34/10-3 is an exploration well that penetrates strata from the Brent Group located in a footwall position to the Statfjord Formation located in a hanging wall position. No faults are identified in the well. Furthermore, of the 120 m cored section, only a single deformation band was encountered (in the Ness Formation) clearly showing that the rocks are more or less undeformed except for the homogeneous grain redistribution. Well 34/10-B-27 penetrated three faults associated with the bounding fault to the east.

The seismic section along the well correlation profile shown in Fig. 10 shows the interpretation based on well log correlation, dipmeter analyses and core analyses (Fig. 11). Without the many supplementary analysed data,

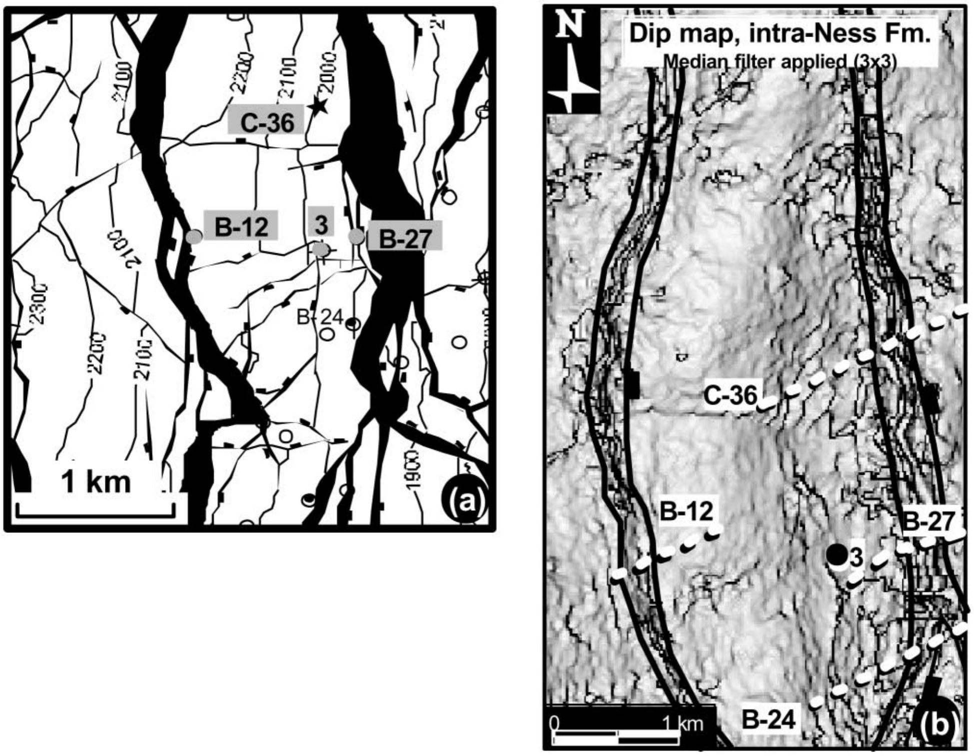

Fig. 7. (a) Structure map from part of the Gullfaks Field. (b) Timedip map based on seismic interpretation of the intra-Ness reflection. The area covers parts of that shown in (a).

seismic interpretation alone would allow the interpretation of numerous small faults (offsets 3–35 m). However, as is documented elsewhere (see introduction and references) most of the offsets along the seismic reflections is caused by the interference of dipping coherent noise causing apparent fault offsets in the order of 5–35 m. If the reader remains unconvinced by the evidence provided in this article, we strongly encourage investigation of the evidence provided in our supplementary articles.

4. Discussion

The results from the three wells drilled on the Gullveig structure indicate that the footwall to the main bounding fault is very little deformed. This may appear surprising, since the wells are located very close to the main fault bounding Gullveig to the east. However, this finding is consistent with observations from analyses of well log correlation data, dipmeter data and core data from more

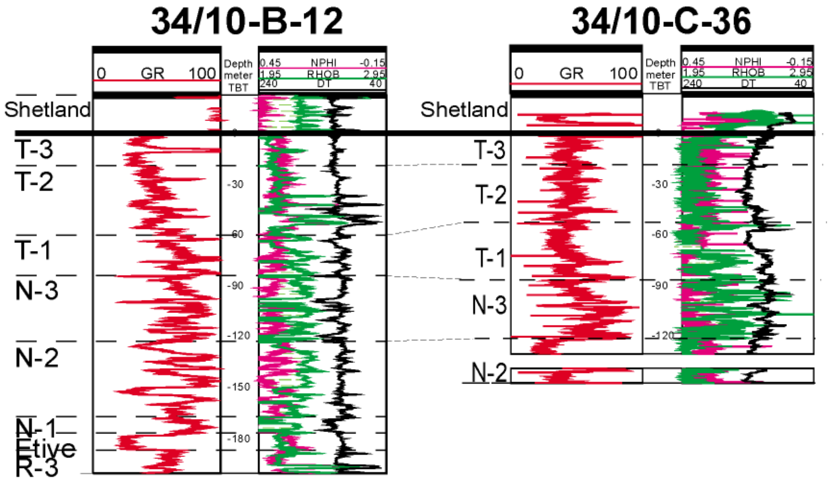

Fig. 8. Well log correlation between wells 34/10-B-12 and 34/10-C-36. See the main text for discussion.

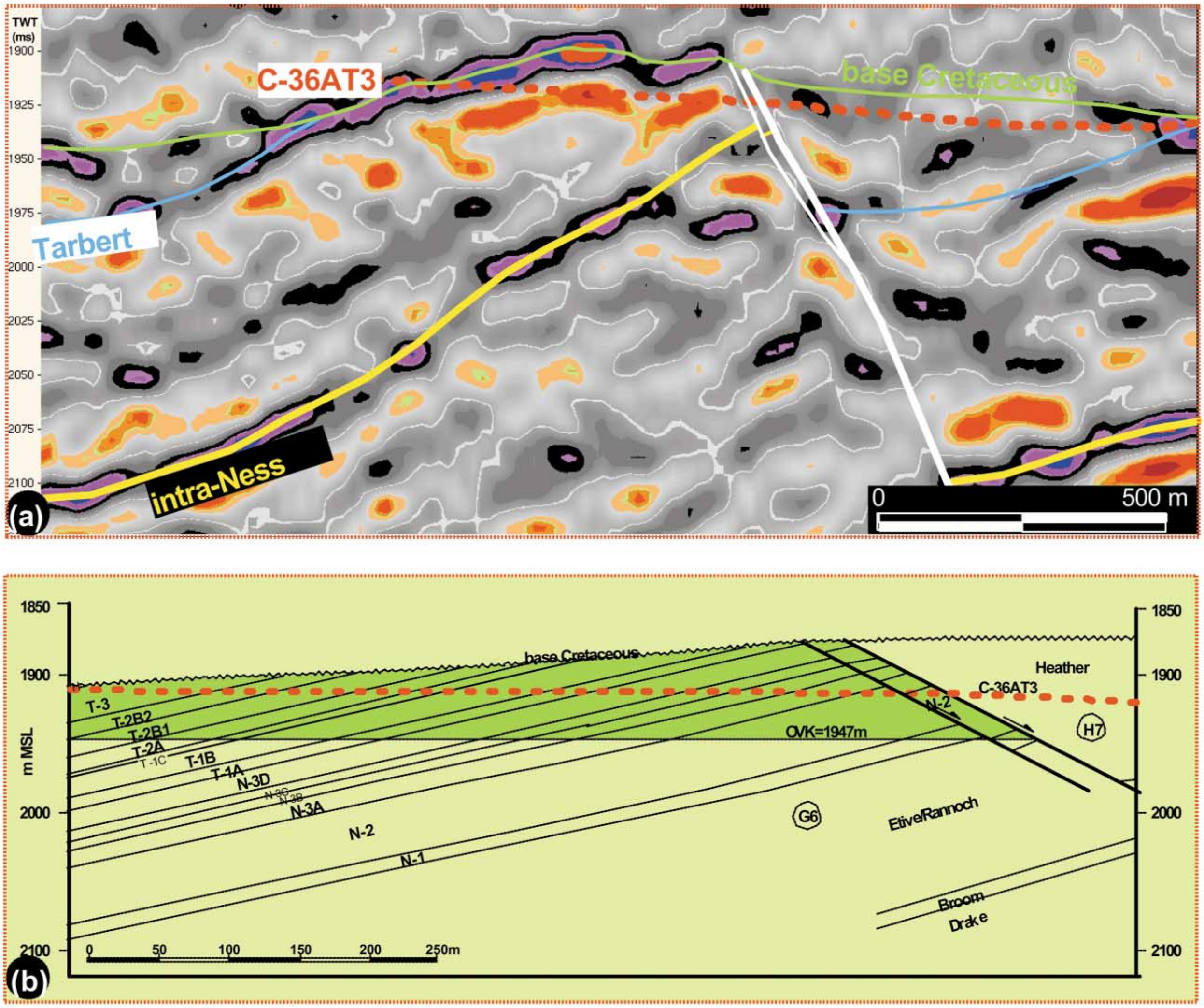

Fig. 9. (a) Seismic profile along well 34/10-C-36. Although seismic data allow for interpretation of numerous minor faults with offsets in the order of 5–35 m, detailed well log correlation from the area and elsewhere on the Gullfaks Field demonstrate that most of the minor offsets of the real reflections are noise-related. (b) Geological profile along well 34/10-C-36.

than 115 km of drilled reservoir (from more than 180 wells) from the Gullfaks Field immediately to the east (Fossen & Hesthammer, 1998; Hesthammer & Fossen, 1998). This important information must be kept in mind when analysing seismic data from the area and similar geological settings.

4.1. Typical noise patterns

All seismic data contain a mixture of signal and noise (Sheriff, 1978). The noise may be random or systematic and have many different sources (Sheriff, 1977; Yilmaz, 1987). The noise present in the seismic data will interfere with real reflections and complicate structural interpretation. Since dipping coherent noise can cause systematic (curvi-)linear features on seismic attribute maps (e.g. Hesthammer & Fossen, 1997a; Hoetz & Watters, 1992), the interpreter is faced with the problem of distinguishing the noise from real features.

The problem with seismic noise is clearly illustrated by comparing seismic sections from several different surveys on the Gullfaks Field. Fig. 12a shows a seismic inline above the reservoir from a survey collected in 1985 (reprocessed in 1992). There are two characteristics in the seismic data that will affect observations within the reservoir. Below the sea bottom, in the interval from 250 to 1000 ms, abundant dipping coherent noise interferes with the horizontal reflections. The interference is so strong that it is difficult to clearly observe the real reflections. This dipping coherent noise is also visible in a data set that was collected in 1995 (Fig. 12b). However, a difference cube (subtracting the 1995 data from the 1985 data) shows that the dipping coherent noise is not located in exactly the same position in the different data sets (Fig. 12c). This mismatch is probably due to the fact that the source and receiver positions between the 1985 and 1995 surveys were not exactly

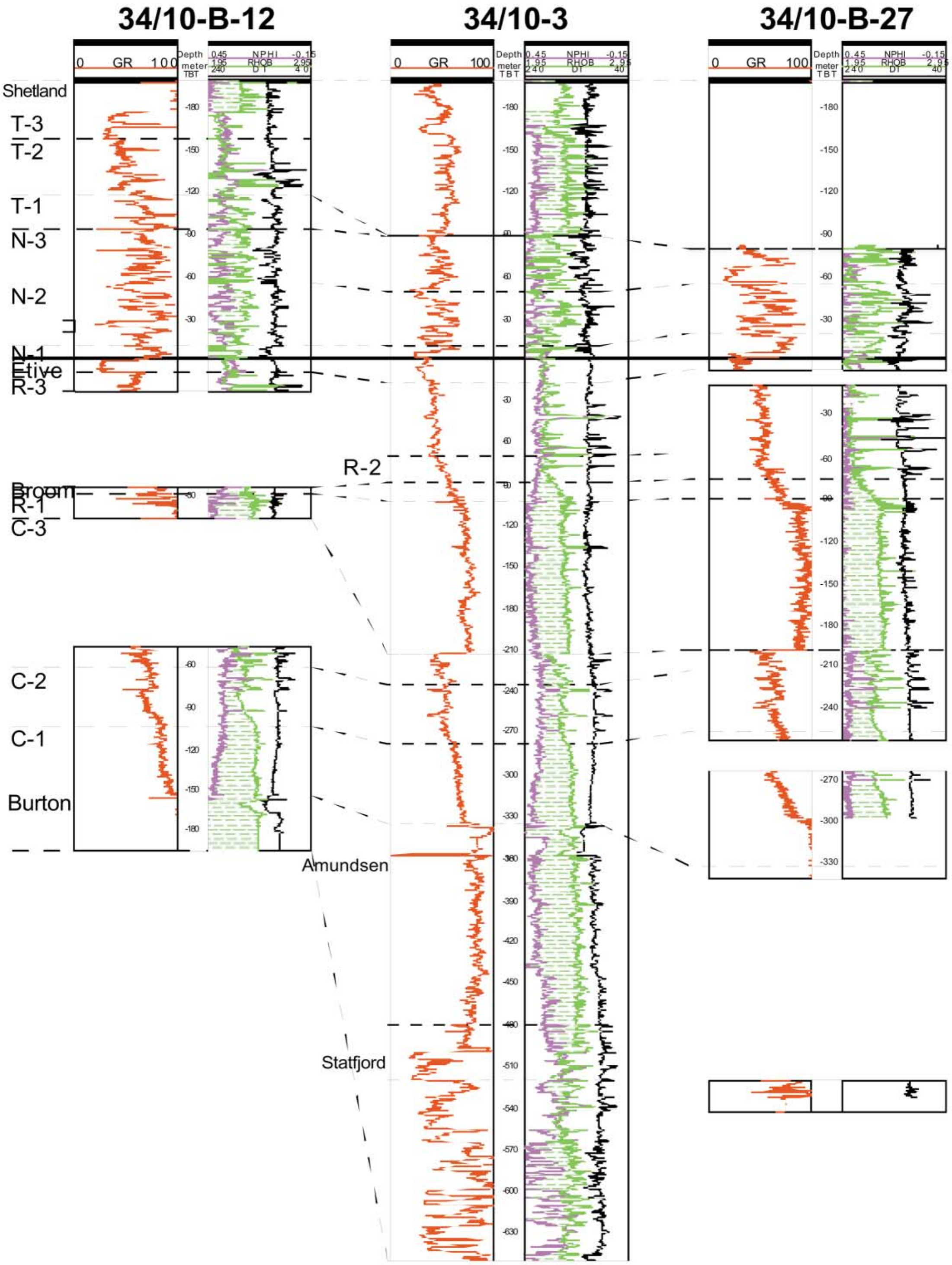

Fig. 10. Well log correlation between wells 34/10-B-12, 34/10-3 and 34/10-B-27. See the main text for discussion.

repeated. The typical variations in individual source and receiver positions are in the order of 50–100 m.

It is important to notice that these variations are prestack effects. After the data have been stacked the uncertainty in the position of each stacked trace is of course much less, but we must expect that such pre-stack mispositioning effects will impact the noise pattern in our seismic data. In addition, different weather conditions will give rise to different noise characteristics in the seismic data. It is therefore likely that the dipping coherent noise appearing in the difference plot is caused by varying acquisition conditions between the two seismic surveys. If the noise displayed the same characteristics

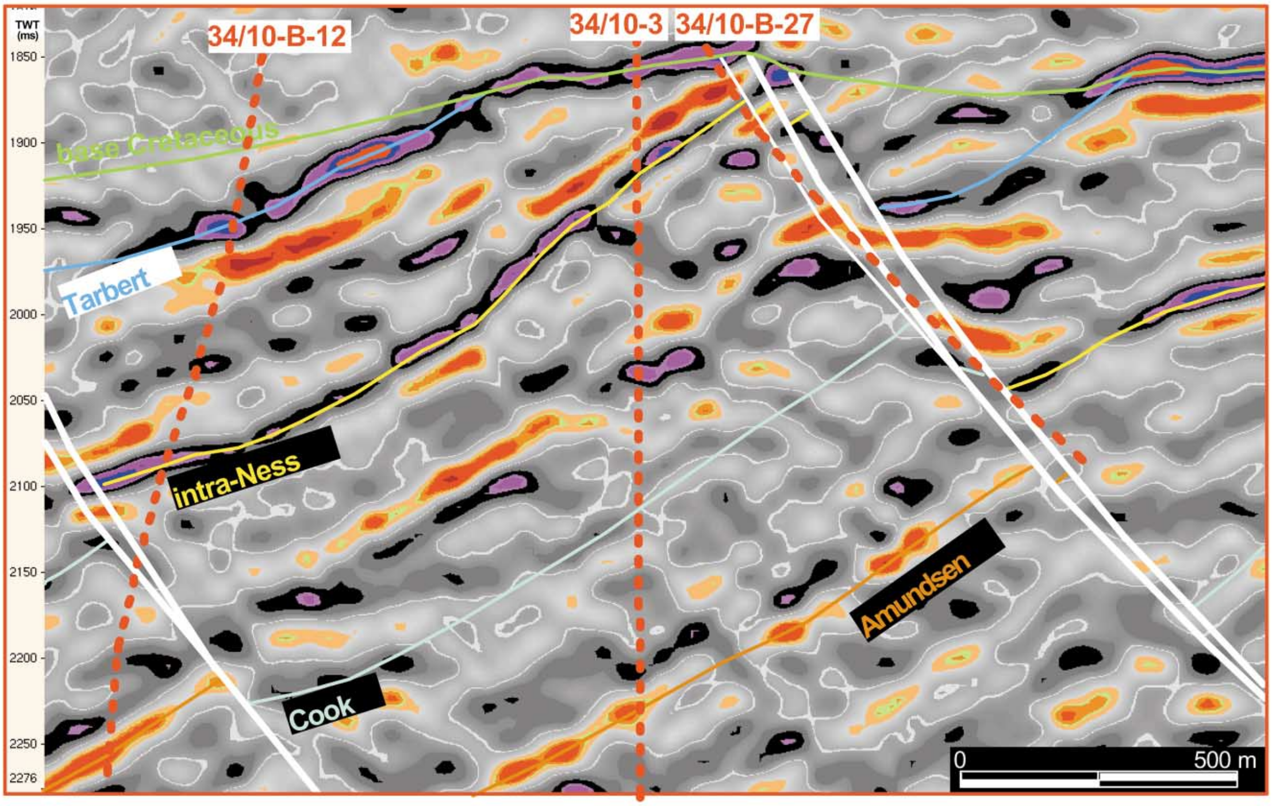

Fig. 11. Seismic profile along the well log correlation panel shown in Fig. 10. Apart from the main faults bounding the rotated fault block, there is very little discrete deformation within the fault block itself. However, the hanging wall is affected by large-scale drag and the deformation mechanism for this flexure is by a widely distributed homogeneous reorganisation of grains.

and were located in identical positions, the signal should cancel out, leaving a smooth picture. This strongly suggests that the dipping coherent noise in the interval is caused by acquisition and processing (non-optimal migration) procedures. Similar noise features are observed by the authors in most marine seismic data and will represent a problem for detailed interpretation (but maybe not for larger-scale exploration studies).

A different type of noise is observed in the interval from 1000 to 1300 ms. Here, strong dipping reflections cause multiples lower in the section. These multiples extend all the way into the reservoir where they interfere with the real reflections, leading to potential misinterpretation. The strong dipping reflections display a circular or "worm-like" appearance on time slices. It is not clear what causes these features. They may be caused by gas that has migrated into and concentrated in sand layers and channels, causing strong diffraction patterns. Alternatively, the structures may represent reworked clay diapirs with strongly mobilised mud/sand beds (H. Løseth, personal communication). The interval from 1000 to 1500 ms on the Gullfaks Field is heavily affected by such structures and therefore represents a problem for optimal seismic imaging of the reservoir.

Fig. 13 shows a seismic section from the Gullfaks reservoir. The data set collected in 1996 (Fig. 13a) is only weakly affected by high-frequency dipping coherent noise. This noise may be effectively reduced by applying a frequency filter that removes high frequencies and preserves the real reflections. However, in the 1985 data set (Fig. 13b), the dipping coherent noise is of much lower frequency. Although it is still possible to remove some of this dipping noise by applying a frequency filter (Hesthammer, 1999a), some of the dipping noise must remain if the real reflections are to be preserved. By applying a dip filter, more of the noise may be reduced but it will be impossible to remove all the dipping noise without seriously sacrificing the imaging of real reflections.

In Fig. 14, it is clear that the processed seismic data from the 1996 survey (Fig. 14a) is much more affected by horizontal multiples than data from the 1985 survey (Fig. 14b), thus complicating interpretation of anything that is not subhorizontal (this is a significant weakness with the new data set). On the other hand, as shown in Fig. 13, the 1985 data are much more affected by low-frequency dipping coherent noise. This noise will interfere with real reflections to a much greater extent than the higher-frequency dipping noise of the 1996 data set. This problem is clearly observed in Fig. 15 where dipping noise interference destroys the continuity of the real reflections in the 1985 survey (Fig. 15b). On the other hand, due to problems with

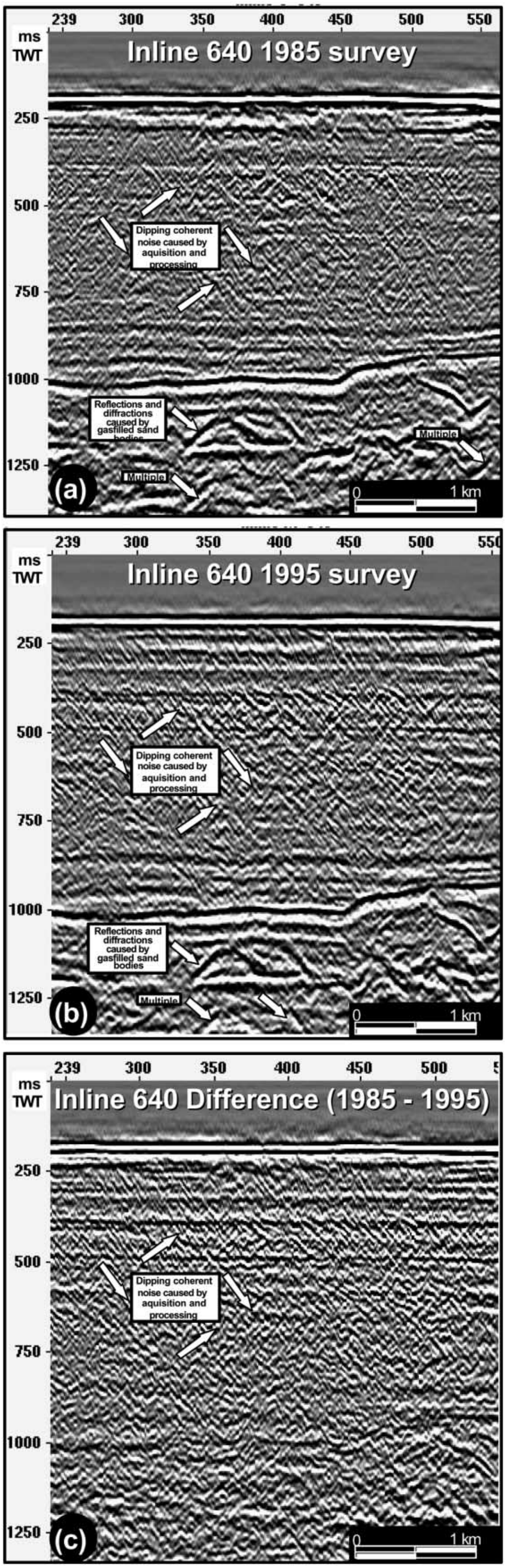

Fig. 12. (a) Seismic section above the Gullfaks reservoir based on a 1985 seismic survey. (b) Same as (a) but based on a 1995 seismic survey. (c) Seismic section based on a difference cube between the 1995 and 1985 seismic data sets.

subhorizontal multiples (water-layer and top Cretaceous), it is difficult in this data set to interpret real reflections in the uppermost part of the reservoir.

4.2. Causes of seismic noise

Seismic noise has several causes, and the most important that we assume are present in seismic data from the Gullfaks and Gullveig area are:

- presence of diffractors near the sea bed;
- complex geology in the overburden (in particular associated with the reworked shale deposits close to the Utsira formation at approximately 1000 m depth);
- the presence of curved shaped bodies in the overburden that act as paraboloid antennas for seismic waves;
- presence of gas pockets above the reservoir;
- complex geology at the reservoir level.

On the Gullfaks and Gullveig fields, several of these effects occur at the same time. The mixture of these effects makes it very hard to attenuate unwanted artefacts in the seismic data. Much of the noise observed is probably related to remaining multiple energy. This is supported by the fact that the near offset data are heavily noise contaminated, while the mid-offset data are much less affected by noise.

In particular, multiple energy associated with diffractions and curved shaped bodies in the overburden is hard to remove. Curved shaped bodies might create unusual amplification effects for some part of the multiple train (paraboloid effect), and such effects will not be handled correctly by conventional multiple attenuation schemes.

Synthetic seismic modelling examples show that even for a perfectly known velocity model, some artefacts occur where two or more seismic events cross each other. This can be seen in Fig. 16b, where we observe discontinuities close to the oil–water contact (at 1950 ms) that can be misinterpreted as small faults. This kind of noise is simply related to the fact that the seismic processing cannot completely resolve the ambiguity when two seismic signals interfere with each other. Furthermore we observe that the noise level is significantly higher in the real data (Fig. 16a) compared to the synthetic data (Fig. 16b). This is probably because only one of the above listed noise causes (complex reservoir structure) was included in the synthetic geological model. Also, Fig. 16b demonstrates the presence of noise in the lower right corner of the section, which we interpret as being caused by remaining multiple energy.

There are several possibilities to reduce the effect of noise. Noise caused by complex overburden geology can often be reduced by pre-stack depth migration. This has been tested on Gullfaks without any major improvements. More severe is, however, noise trains that are created by strong reflectors above the main reservoir and these will be difficult to remove. Gas chimney effects may be reduced by acquiring seabed seismic data. This is currently being

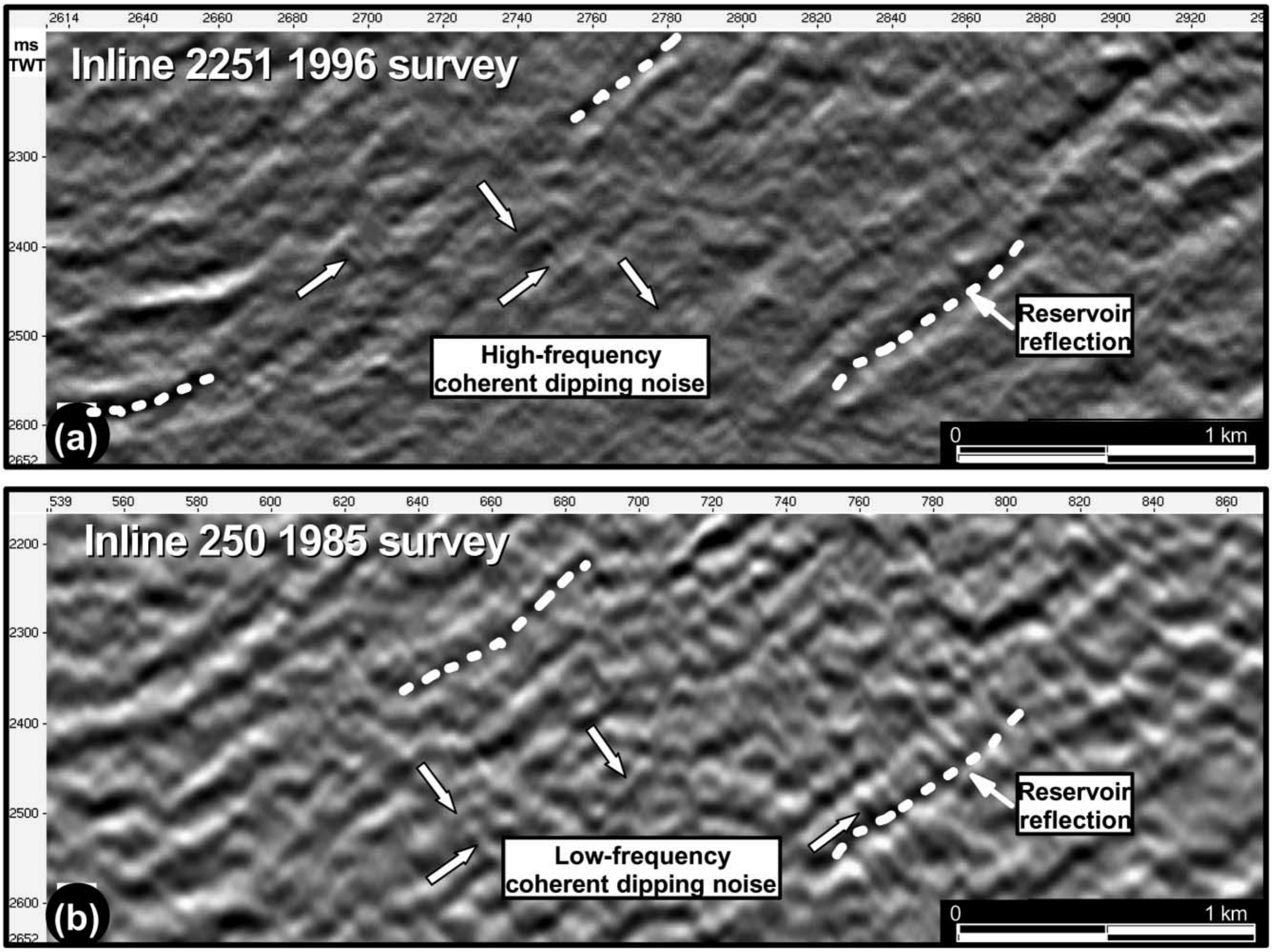

Fig. 13. (a) Seismic section within the Gullfaks reservoir based on a 1996 seismic survey. The section is weakly affected by high-frequency dipping coherent noise. (b) Same as (a) but based on the 1985 seismic survey. This data set is much more affected by low-frequency dipping coherent noise.

considered, and it will be of interest to evaluate if seabed seismic data will improve the illumination through the gas areas and possibly also improve the resolution for the complex reservoir fault blocks. Due to the presence of several (5–6) different noise generating effects on the Gullfaks and Gullveig Fields, it is necessary to rely strongly on complementary measurements, in particular well logging and core analysis.

4.3. Integration of seismic and well data

Townsend et al. (1998) show how a fault with 15 m offset may be modelled in a synthetic seismogram at a fairly shallow (900–1100 m depth) reservoir level (Fig. 17a; Fig. 3 in their paper). An interesting observation from the synthetic seismogram, although not discussed by Townsend et al. (1998) are the diffractions generated by the disruption of the reflections. The geometry of the dipping noise is very similar to that observed on the Gullfaks Field (Figs. 12 and 17b), supporting the findings by Hesthammer and Løkkebø (1997) that much of the dipping noise present in seismic data at reservoir levels is caused by disruptions (due to effects such as shallow gas, channels and faults) of the seismic reflections at shallower levels and incomplete seismic migration during the processing procedures.

An obvious problem is that the noise-interference features may display similar characteristics to real structural features such as faults, which is why Hesthammer and Fossen (1997a,b) encourage the geoscientist to only interpret the more continuous sets of (curvi-)linear features on attribute maps as faults. Fig. 18a shows dehydration crack pattern from a painting (Fig. 18b). The geometry of this pattern is very similar to that discussed by Cartwright and Lonergan (1996) and Lonergan, Cartwright, Laver, and Staffurth (1998). Since the structures interpreted by Cartwright and Lonergan show several tens of metres of offset and occur in areas of very good data quality, there is little doubt that they represent real features.

Townsend et al. (1998) show that seismic attribute maps from the Siri Fault Zone (Fig. 18c) contain similar features, which they suggest may represent a polygonal fault system similar to those described by Cartwright and Lonergan

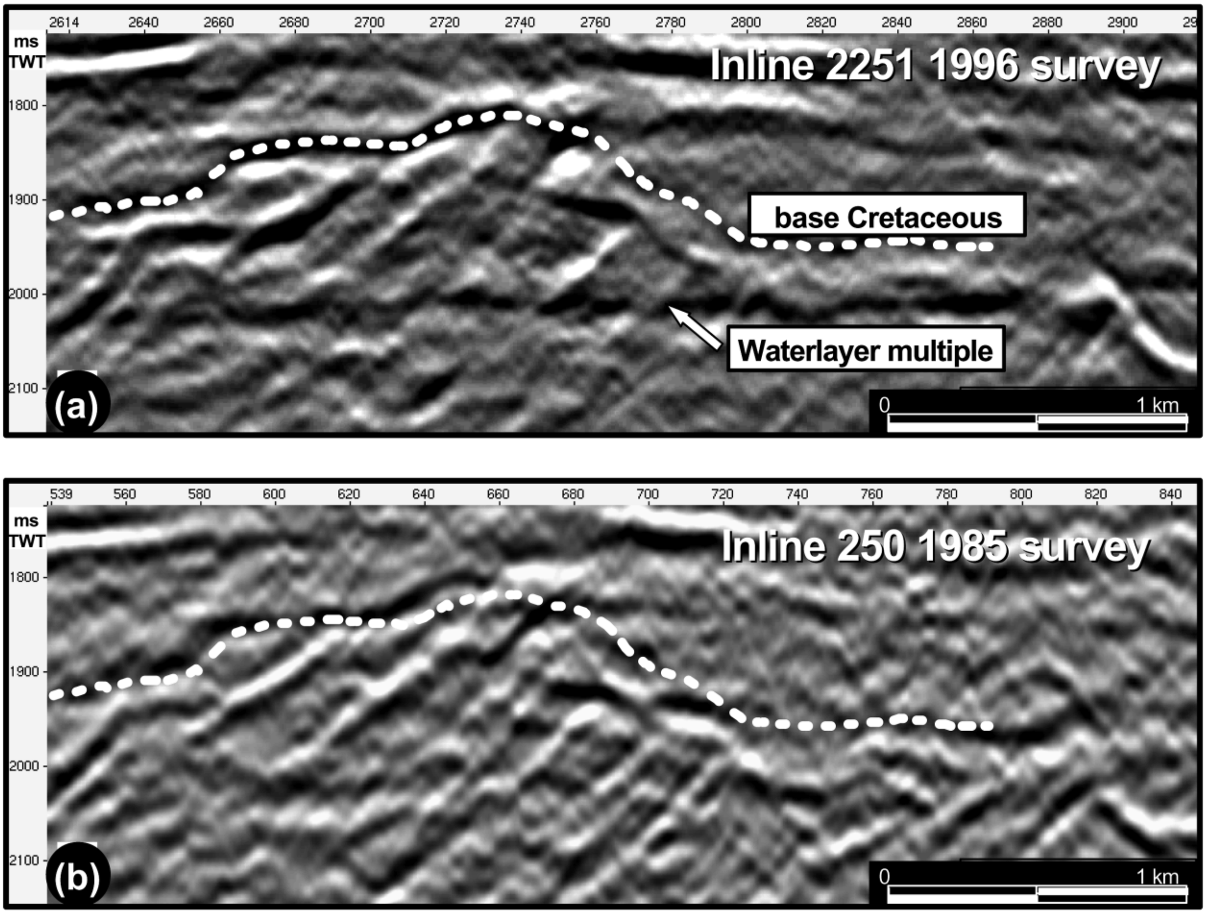

Fig. 14. (a) Seismic section within the Gullfaks reservoir based on a 1996 seismic survey. The section is heavily affected by water-layer and top Cretaceous multiples. (b) Same as (a) but based on the 1985 seismic survey. Horizontal multiples are less pronounced in this data set. However, the data are much more affected by low-frequency dipping coherent noise.

(1996). However, a major difference exists in that the offset of the reflections along the Siri Fault Zone is much smaller (a few milliseconds). Although the seismic data quality is good at this shallow level (approximately 870 m depth), it is not possible to verify that the features represent real faults, and their interpretation will depend on the subjective opinion of the interpreter.

The focus of the example presented by Townsend et al. (1998) is, however, not on the polygonal geometries, but on two more continuous lineaments observed on a seismic timedip map (Fig. 18c, corresponding to Fig. 7b in Townsend et al., 1998). These are associated with a maximum of 11 and 5 ms displacement, respectively. Although no well data are available to evaluate the nature of these lineaments, they appear as a continuation of several (curvi-)linear features. This is the main criteria put forward by Hesthammer and Fossen (1997a,b) to distinguish real faults from noise features. Hence, the two more continuous linear features observed in Fig. 18c are likely to be fault-related. Fig. 18d shows a timedip map of the base Cretaceous unconformity on the Gullfaks Field. The depth to this structure is more than twice that shown in Fig. 18c, and more noise is therefore expected within the seismic data. Also, shallow gas reduces the seismic signal and results in noisy data. Again, several (curvi-)linear features are observed, although with a more chaotic and less continuous signature than those discussed above. Studies of more than 180 wells demonstrate that these features are caused by noise interference. In particular, core data and well log correlation data from the many subhorizontal wells located immediately below the unconformity would rapidly identify a polygonal fault system if this was to exist. Although well log correlation data only identify faults down to 5–10 m displacement in most cases (Fossen & Rørnes, 1996), structural core analyses rules out the possibility for a polygonal fault system on a subseismic scale (Fossen & Hesthammer, 2000; Hesthammer, 1999b). This is based on the knowledge that all faults in the Gullfaks region are associated with a narrow zone of deformation bands. These are readily identified from core data, thus providing an efficient means to observe all faults in the cores.

There are not enough faults observed in the core data to justify the interpretation that the (curvi-)linear features seen on seismic attribute maps represent a polygonal fault system

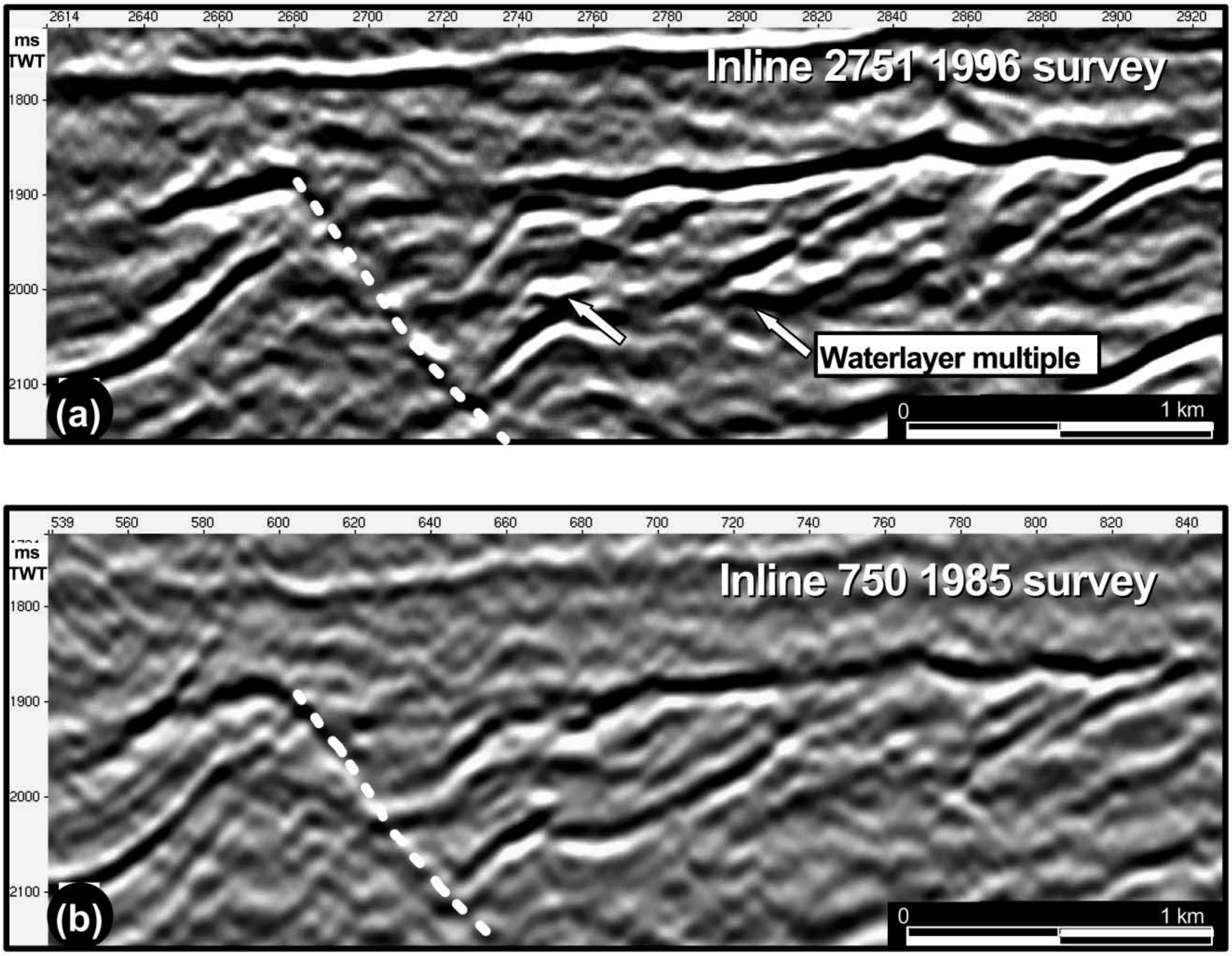

Fig. 15. (a) Seismic section within the Gullfaks reservoir based on a 1996 seismic survey. (b) Same as (a) but based on the 1985 seismic survey.

(see also Hesthammer & Fossen, 1997a,b). In fact, there is evidence that faults with displacement below 5–10 m do not follow a fractal power-law relationship (Fossen & Hesthammer, 2000). Instead, it appears that, due to strain hardening processes during deformation, fewer faults exist with displacement in the range from a few tens of centimetres to a few metres than that extrapolated from a power-law relationship. Such sound evidence cannot be obtained unless the seismic interpreter is willing to undertake detailed analyses of additional available data. Since it is beyond the scope of this article to discuss in detail all findings from these analyses, the reader is referred to the many articles published by the authors on this topic (see references).

The examples shown in Fig. 18 serve to demonstrate that noise interference features are present on seismic attribute maps, and that only detailed well control can verify if the (curvi-)linear features are caused by noise or real structures. This should be kept in mind when examining seismic attribute maps from the two seismic surveys collected across the Gullveig structure. Fig. 19a shows a correlation map (e.g. Hesthammer, 1998) covering much of Gullveig. The map is based on seismic interpretation (snapped to nearest maximum) of the strong intra-Ness Formation reflection from the 1996 seismic survey. In comparison, Fig. 19b is a similar map created from the 1992 seismic survey. This map is similar to that presented by Townsend et al. (1998) (their Fig. 8c). Townsend et al. noted the numerous linear features on the map, which they suggest may be fault-related in many cases. Again, without quality controlling the observations on the seismic attribute maps against well data, this suggestion remains subjective and inconclusive. As such, Townsend et al. (1998) correctly state that “even if an alternative interpretation of these features can be demonstrated, the fault interpretation cannot be discounted”. In other words, unless other data (well data) are presented to verify the seismic observations, any interpretation must be treated with care. In a different article, Jones and Knipe (1996) suggest that the geometries of the linear features on attribute maps may reveal the details of fault zones such as relay structures, fault tip geometries and width of damage zones. Once again, their opinion cannot be quality controlled since no well data are presented. However,

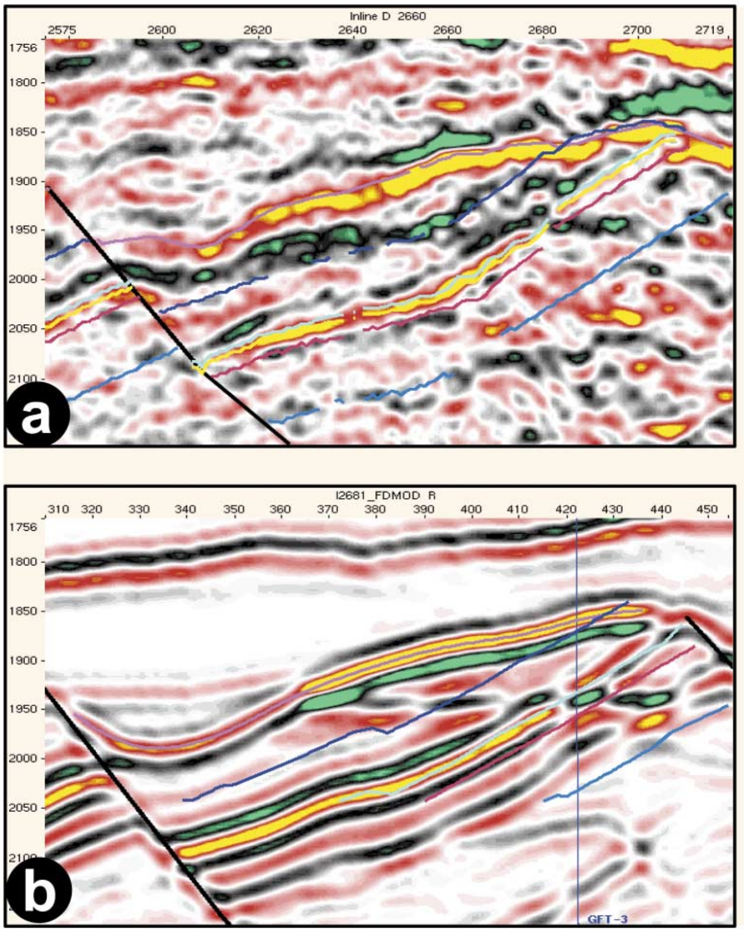

Fig. 16. The figure shows (a) real and (b) synthetic seismic data from a typical reservoir fault block within the Gullfaks Field. In the synthetic model, a very simple and unrealistic overburden was used. We observe discontinuities along the oil water contact even on the synthetic data. Also notice the noise in the lower right corner of the synthetic data that probably is caused by remaining multiple energy.

Hesthammer and Fossen (1997b) use abundant well data to prove that features very similar to those discussed by Jones and Knipe (1996) are noise-related in the Gullfaks area.

An obvious problem for exploration geoscientists is that well data are rarely sufficiently abundant in early stages of development to allow the luxury of complete confidence in seismic attribute calibration. As such, the danger of misinterpretation will always exist in such settings. This becomes a bigger problem as new fields are smaller in size and demands more detailed interpretation to justify field development. If the geoscientist is unfamiliar with results from detailed analyses from fields containing abundant well information (such as the Gullfaks Field), the likelihood of misinterpreting seismic artefacts as real features remains a serious pitfall for the geoscientist.

In the example shown in Fig. 19b, the number of (curvi-)linear features increases towards the main east-bounding fault. As discussed by Jones and Knipe (1996) this appears sound in as much as deformation in general tends to increase close to large faults. However, as demonstrated in detail in numerous articles from the nearby Gullfaks Field by Fossen and Hesthammer (1998) and Hesthammer and Fossen (1997a,b, 1998), the number of (curvi-)linear features observed in footwalls to main faults does not at all correspond to the number of faults observed from well data. In the specific case of Gullveig, these conclusions are supported by the very little deformation observed in wells 34/10-37, 34/10-37A and 34/10-K2H. As observed in Figs. 4 and 6, the seismic data quality in the footwall position to the main boundary fault from the 1992 seismic survey is very poor. Consequently, this area will be more affected by seismic noise interference features as is indicated by Fig. 19b (see Hesthammer & Fossen, 1997a for details on this). In contrast, the seismic data quality from the 1996 seismic survey is of very good quality in the footwall position, and as result, much fewer (curvi-)linear features are observed (Fig. 19a). This is consistent with observations from well data on Gullveig, indicating that the field is much less deformed than what may be anticipated in seismic attribute maps from the 1992 data cube.

The correlation map from the 1992 seismic survey shows a set of NW-trending (curvi-)linear features (location 1 in

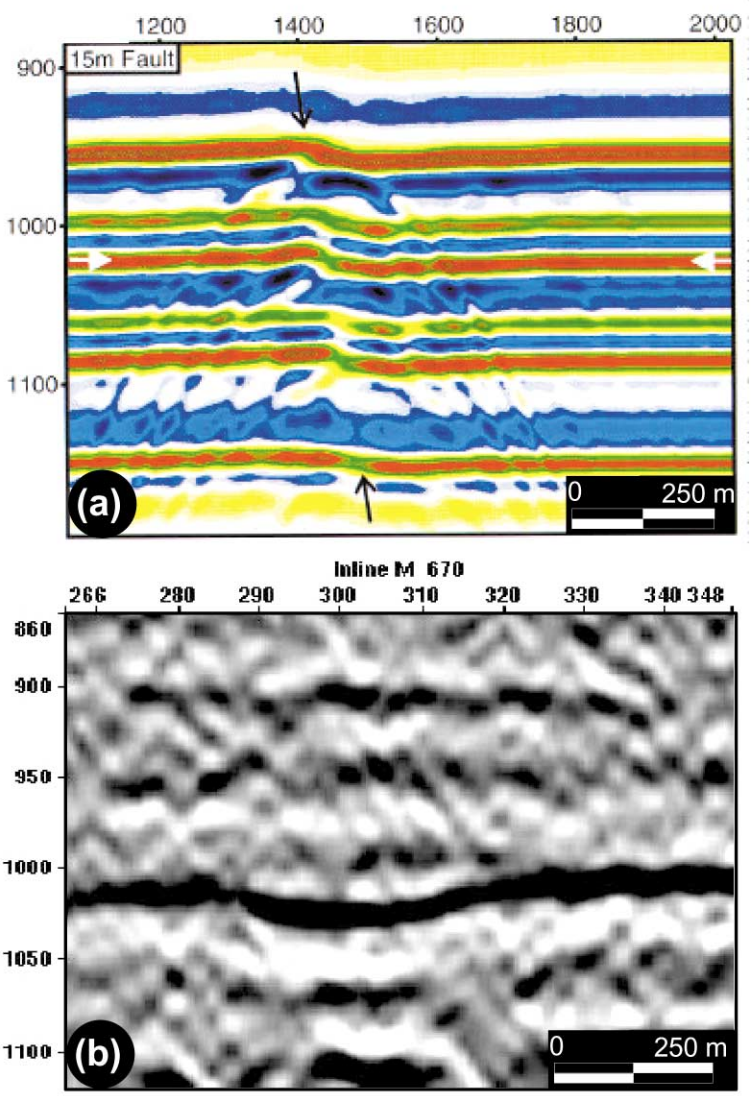

Fig. 17. (a) Synthetic seismogram showing modelling of a fault with 15 m offset at approximately 1 km depth. Modified from Townsend et al. (1998). Several dipping noise lineaments can be identified. (b) Seismic E–W section above the reservoir on the Gullfaks Field. Similar dipping noise features to that observed in (a) interfere with real reflections and cause disruption of the weaker signals. These dipping features may, in part, be a result of non-perfect migration of the seismic data. Although the use of a colour palette with many different colours are useful to identify disruptions of the real reflections, a grey-scale is generally best for the identification of the dipping noise (which may help the interpreter to avoid misinterpreting offsets caused by noise interference as real faults).

Fig. 19b). Although no well data exist to verify that a fault is located in this position, it appears logical to accept the lineament as being fault-related since the offset is quite large (several tens of metres) and the feature follows the criteria for fault recognition put forward by Hesthammer and Fossen (1997a,b), i.e. the lineament appears as a continuation of several minor (curvi-)linear features and the strike is oblique to the strike of bedding.

Townsend et al. (1998) argue that the separation of the fault at location 1 in Fig. 19b represents a relay structure (similar to that presented by Jones and Knipe, 1996) and that, by using automatic fault mapping procedures, the detailed geometries of such structures may improve modelling of the reservoir. If the relay structure interpretation is correct, the methodology presented by Townsend et al. (1998) would increase our understanding of fluid flow in the reservoir. If, however, the separation of the linear features is related to seismic artefacts such as noise interference, the approach suggested by Townsend et al. (1998) would result in erroneous models of the reservoir. Again, without using well information (pressure data, radioactive tracers, well log correlation data, core data, dipmeter data, production data etc.) to increase the understanding of the reservoir properties, any attempts to automatically model reservoir properties may result in a non-optimal development of the field. For instance, if the (curvi-)linear features observed in a footwall position to the main faults on the Gullfaks Field (similar to that observed in Fig. 19b) were

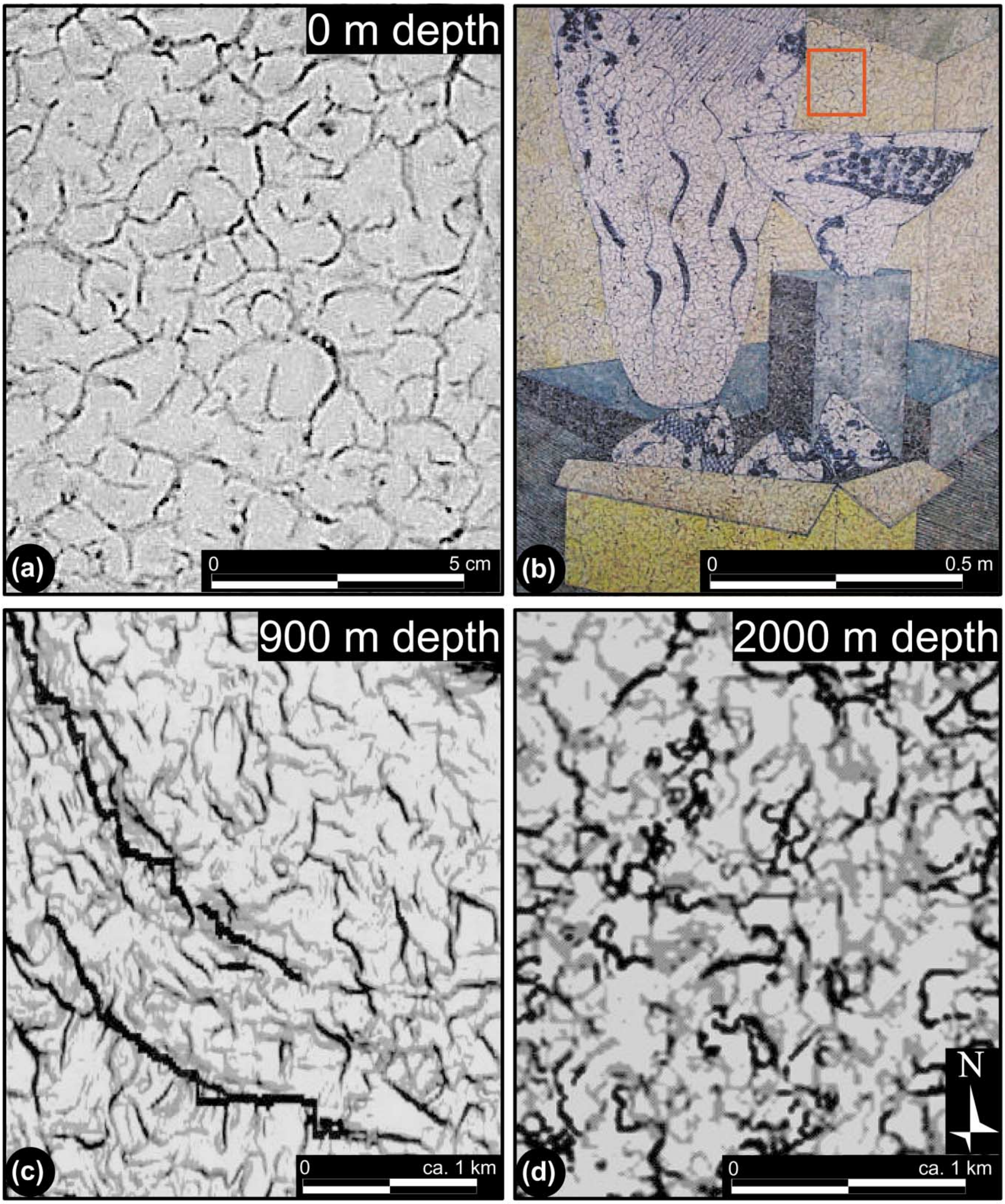

Fig. 18. (a) Water dehydration cracks in a painting cause a polygonal “fault-like” system that display similarities to that observed on many seismic attribute maps (where the reflections are subhorizontal). (b) Painting showing location of (a). (c) Seismic timedip map from the Siri Fault Zone. Modified from Townsend et al. (1998). (d) Seismic timedip map of the base Cretaceous unconformity on the Gullfaks Field. See the main text for details.

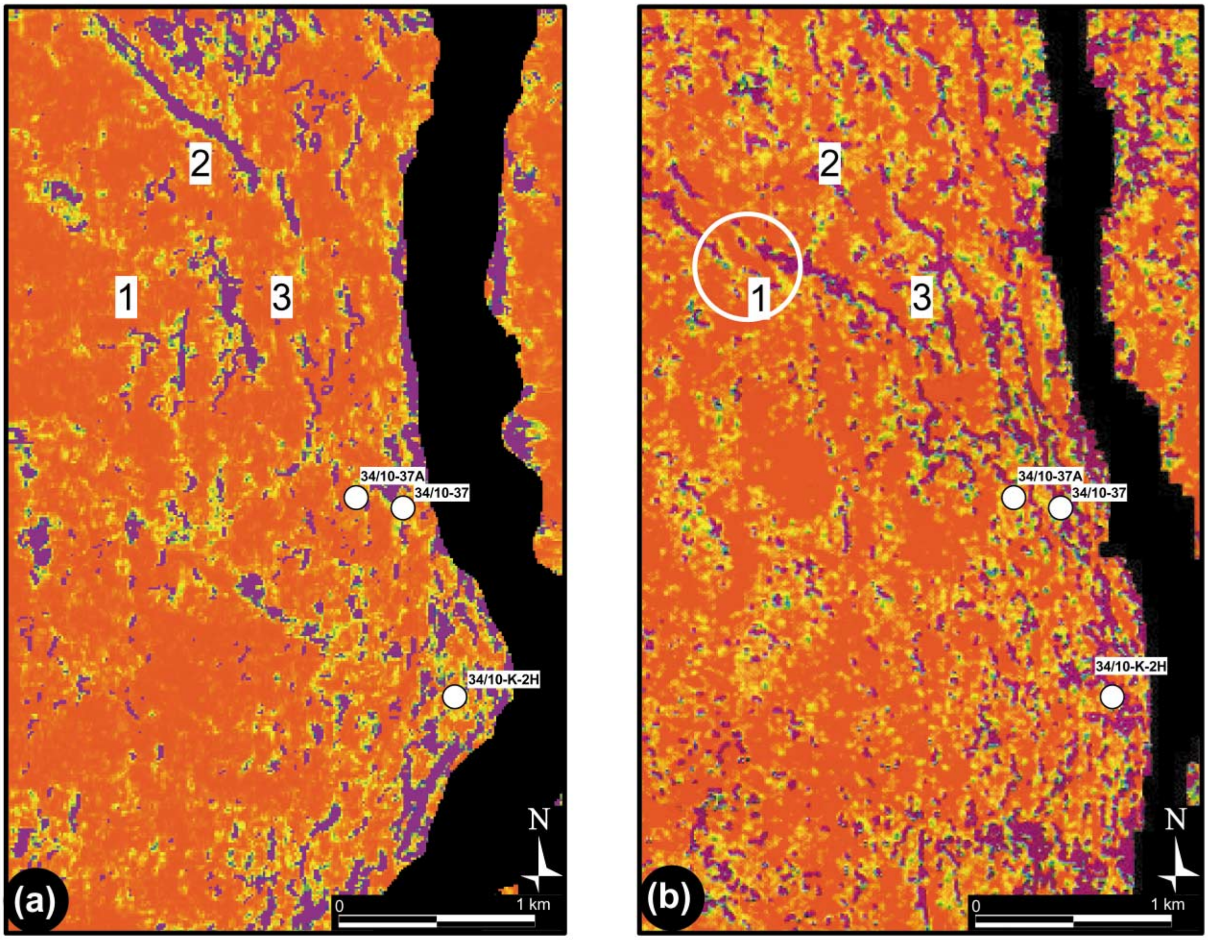

Fig. 19. (a) Correlation map along the intra-Ness Formation reflection on Gullveig based on the 1996 seismic survey. Purple colour indicates zones of poor coherence. (b) Similar map to that shown in (a), but based on the 1992 seismic survey. Modified from Townsend et al. (1998). See the main text for details.

assumed to represent intense faulting, they would have been avoided during future drilling of production wells. Consequently, the recovery factor of the field would have been reduced significantly. As suggested by Hesthammer (1999a) and Hesthammer and Fossen (1997b), it may quickly prove cost-efficient in the long run to improve seismic data quality by better acquisition and processing techniques and even by drilling one or more wells in order to verify or disregard interpretations based on seismic attribute maps.

When comparing the correlation map from the intra-Ness Formation reflection based on the 1996 seismic survey (Fig. 19a) with the map based on the 1992 seismic survey, some clear discrepancies are observed related to the more obvious “fault-features” (location 1 and 2 and possibly location 3). The “relay-structure” observed at location 1 in the 1992 survey is not present at all in the 1996 seismic survey. Furthermore, the “fault” at location 3 in the 1992 data set is not present in the 1996 data set. Also, the correlation map from the latest survey defines a fault-like structure (location 2) that is more or less absent in the 1992 data set. The amount of offset of this feature (several tens of metres) and the continuity observed on the correlation map strongly suggest that this lineament is related to a fault, although the interpretation will have to be subjective as long as no well data exist to verify the fault interpretation. The differences observed in the two seismic surveys highlight the uncertainties associated with detailed seismic attribute analyses. This uncertainty is further emphasised by a recent study carried out by Hesthammer and Fossen (2000) on the Gullfaks Field that demonstrates that only 25% of all faults with displacements in the range of 6–30 m can be identified in the seismic data (after drilling of wells, which prove the existence and exact location of the faults), whereas an average of 67% of faults with displacements larger than 30 m can be identified. This study is based on detailed investigations of 274 seismic section where wells have penetrated faults, and further demonstrates the uncertainties related to detailed seismic interpretation. It is clear that caution must be used if details on fault geometry from faults at or below seismic resolution are to be used for reservoir modelling using automatic mapping routines.

5. Conclusions

Seismic data provides the geoscientist with the most important tool for structural interpretation. However, seismic data alone do not allow for separating noise from real features. The use of seismic attribute maps for detailed structural interpretation has gained increasing popularity in the last decade. The potential for improved reservoir description is great, but erroneous assumptions or interpretation may lead to seriously wrong reservoir models and non-optimal positioning of production wells. We stress the need for using all available well data to quality control observations from seismic data. In addition, the presence of more than one seismic survey will allow the interpreter to increase his/her knowledge on uncertainties related to detailed structural interpretation of seismic data.

Well data from the Gullveig oil field, northern North Sea, show that the reservoir rocks in a footwall position to the main boundary fault is remarkably undeformed. Based on this and observations from the nearby Gullfaks Field, it is clear that most of the (curvi-)linear features observed on seismic timedip and correlation maps from Gullveig must be caused by noise interference artefacts. In addition, the existence of a new seismic survey across the Gullveig structure allows for detailed comparison of seismic attribute maps. The difference between the two surveys helps the interpreter to estimate the uncertainty associated with the seismic interpretation. The conclusions from the Gullveig example contrast with another recent interpretation of the area, where additional, available data were not incorporated. On the other hand, the results are consistent with more extensive studies from the neighbouring Gullfaks Field, where well log correlation data, dipmeter data, core data, pressure data, production data and structural modelling in conjunction with seismic data (one or more surveys) allow for a consistent and accurate structural interpretation. Both the Gullveig and Gullfaks studies have demonstrated the presence of abundant dipping coherent noise in seismic data. This noise interferes with real reflections and causes (curvi-)linear features on seismic attribute maps that display similar characteristics to real structures such as faults. Unless the seismic interpreter is aware of the presence of such noise features and know how to quality control observations in seismic data, erroneous interpretations and non-optimal recovery of oil and gas fields may easily result.

The results from detailed analyses of well data and seismic data from Gullveig demonstrate that extreme care must be taken when trying to model reservoir characteristics by using automated mapping routines to identify disruption of seismic reflections that may or may not represent real structures such as faults. These observations are consistent with those observed on the nearby Gullfaks Field. Any attempts to develop methods for automatic fault mapping should start out by choosing an area with very good well control rather than basing the methodology on subjective beliefs from seismic interpretation of areas with little or no well control. In exploration, the geoscientist is strongly encouraged to investigate nearby areas with good well control in order to enhance the knowledge of the limits and possibilities related to seismic interpretation.

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References

Buchanan, R., Marke, P. A. B. & Ruijtenberg, P. A. (1988). Applications of 3D seismic to detailed reservoir delineation. *Society of Petroleum Engineers International Meeting Proceedings* (pp. 91–97).

Cartwright, J. A., & Lonergan, L. (1996). Volumetric contraction during the compaction of mudrocks; a mechanism for the development of regional-scale polygonal fault systems. *Basin Research*, *8*, 183–193.

Dalley, R. M., Gevers, E. C. A., Stampfli, G. M., Davies, D. J., Gastaldi, C. N., Ruijtenberg, P. A., & Vermeer, G. J. O. (1989). Dip and azimuth displays for 3D seismic interpretation. *First Break*, *7*, 86–95.

Fossen, H., & Rørnes, A. (1996). Properties of fault populations in the Gullfaks Field, northern North Sea. *Journal of Structural Geology*, *18*, 179–190.

Fossen, H., & Hesthammer, J. (1998). Structural geology of the Gullfaks Field. *Structural geology in reservoir characterisation*. M. P. Coward, H. Johnson & T. S. Daltaban. *Geological Society, London, Special Publications*, *127*, 231–261.

Fossen, H., & Hesthammer, J. (2000). Possible absence of small faults in some porous sandstones. *Journal of Structural Geology*, *22*, 851–863.

Hesthammer, J. (1998). Evaluation of the timedip, correlation and coherence maps for structural interpretation of seismic data. *First Break*, *16*, 151–167.

Hesthammer, J., (1999). Improving seismic data for detailed structural interpretation. *The Leading Edge*. *18*, 226–247.

Hesthammer, J., (1999). *Fault geometry and internal fault block deformation in the Gullfaks region, northern North Sea*. Unpublished PhD thesis, University of Bergen, Norway.

Hesthammer, J., & Fossen, H. (1997a). Seismic attribute analysis in structural interpretation of the Gullfaks Field, northern North Sea. *Petroleum Geoscience*, *3*, 13–26.

Hesthammer, J., & Fossen, H. (1997b). The influence of seismic noise in structural interpretation of seismic attribute maps. *First Break*, *15*, 209–219.

Hesthammer, J., & Fossen, H. (1998). The use of dipmeter data to constrain the structural geology of the Gullfaks Field, northern North Sea. *Marine and Petroleum Geology*, *15*, 549–573.

Hesthammer, J., & Fossen, H. (1999). Evolution and geometries of gravitational collapse structures with examples from the Statfjord Field, northern North Sea. *Marine and Petroleum Geology*, *16*, 259–281.

Hesthammer, J., & Fossen, H. (2000). Uncertainties associated with fault sealing analysis. *Petroleum Geoscience*, *6*, 37–45.

Hesthammer, J., & Løkkebø, S. M. (1997). Combining seismic surveys to improve data quality. *First Break*, *15*, 103–115.

Hoetz, H. L. J. G., & Watters, D. G. (1992). Seismic horizon attribute mapping for the Annerveen Gasfield, the Netherlands. *First Break*, *10*, 41–51.

Jones, G., & Knipe, R. J. (1996). Seismic attribute maps; application to structural interpretation and fault seal analysis in the North Sea Basin. *First Break*, *14*, 449–461.

Lonergan, L., Cartwright, J. A., Laver, R., & Staffurth, J. (1998). Polygonal faulting in the Tertiary of the central North Sea: implications for reservoir geology. *Structural geology in reservoir characterisation*. M. P. Coward, H. Johnson & T. S. Daltaban. *Geological Society, London, Special Publications*, *127*, 191–207.

Sheriff, R. E. (1977). Limitations on resolution of seismic reflections and geologic detail derivable from them. *Seismic stratigraphy — applications to hydrocarbon exploration*. C. E. Payton. *American Association of Petroleum Geologists Memoirs*, *26*, 3–14.

Sheriff, R. E. (1978). A first course in geophysical exploration and interpretation. International Human Resources Development Corporation, Boston, 313 pp.

Tollefsen, S., Graue, E., & Svinddal, S. (1994). Gullfaks development provides challenges. *World Oil*, *April*, 45–54.

Townsend, C., Firth, I. R., Westerman, R., Kirkevollen, L., Hårde, M., & Andersen, T. (1998). Small seismic-scale fault identification and mapping. *Faulting, fault sealing and fluid flow in hydrocarbon reservoirs*. G. Jones, Q. J. Fisher & R. J. Knipe. *Geological Society, London, Special Publication*, *147*, 1–25.

Tucker, D. H., Franklin, R., Sampath, N., & Ozimic, S. (1985). Review of airborne magnetic surveys over oil and gas fields in Australia. *Australian Society of Exploration Geophysicists Bulletin*, *16*, 300–302.

Yilmaz, Ö. (1987). In E. B. Neitzel, *Investigations in Geophysics*, Vol. 526. Tulsa: The Society of Exploration Geophysicists (526 pp.).