Structural styles and their evolution in the North Sea area

Introduction and review

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The understanding of the structural styles and their evolution in the North Sea area has been greatly advanced in recent years. In the past there were many differing ideas varying between the two extremes of listric dip-slip faulting to strike-slip faulting interpretation styles. Now more certain answers can be given from the marked increase in the use of 3D datasets. This is well demonstrated in the 'Structural styles' section.

The section is arranged by region with papers designed to present contrasting viewpoints and to provoke discussion. The section starts with papers covering the whole North Sea area, continuing with more regional papers moving geographically from north to south.

Regional papers

Following an introductory review talk by Williams on the structural models that have been described for the North Sea in the past and the still unanswered questions, Coward sets the regional framework of the area by reviewing the Late Caledonian and Variscan tectonic events that formed the underlying structural fabric to the Mesozoic and Cenozoic North Sea Basin. The key point of the paper is to stress that this underlying structural fabric subsequently controlled the faulting styles of the later evolution of the North Sea Basin. This key point is stressed again by Bartholomew et al., who make clear that, during the Mesozoic evolution of the North Sea area, the underlying structural grain was oblique to the regional extension direction in most areas. Therefore, the corresponding structures, even though formed in an extensional regime, had to have a component of strike-slip movement. It is demonstrated that even though this strike-slip component of movement was very minor compared to the overall extension, it was enough to cause the formation of pop-up and pull-apart structures in many areas of the North Sea. It is also demonstrated that the histories of these structures were very complex, many structures evolving differently through time depending on which underlying shear zone had been active at any one specific time.

On a different regional theme Roberts et al. show that a similar amount of regional extension is obtained using different techniques (flexural backstripping, forward modelling, and fault population statistical analysis). Jurassic extension is estimated to be 15% in the Viking Graben, and 20% in the Central Graben. It is suggested that these relatively low Jurassic extension values indicate that the Triassic extension was equally as important as the Jurassic extension in the stretching history of the North Sea.

East Shetland Basin papers

Three papers are presented from the East Shetland Basin area. Lee and Hwang use the East African Rift as an analogue to the East Shetland Basin, paying particular attention to the compartmentalization of the area into zones of similarly haging faults separated by accommodation zones. Dahl and Solli highlight the compartmentalization of the Snorre area within the East Shetland Basin by NW–SE and NE–SW cross-fault trends. Compressional features formed during the Triassic and Jurassic extensional episodes are highlighted by both papers as being of local importance. They are interpreted as accommodation features formed as a result of a component of strike-slip movement along either NW–SE or NE–SW fault zones within an overall E–W extensional tectonic regime. The paper by Demytenaere et al. gives an illustration of both NW–SE and NE–SW cross-fault zones using a large 3D dataset over the Cormorant Field. Their importance in delineating and compartmentalizing the field is stressed.

Moray Firth papers

The important observation that the Great Glen Fault did not play a major part in the Mesozoic evolution of the Inner Moray Firth area is made by Thomson and Underhill. It was mainly active in the Cenozoic when strike-slip movements along this and other faults has been largely responsible for destroying the hydrocarbon prospectivity in many parts of the basin.

The paper by Hibbert and Mackertich describes the complex area where the Inner Moray Firth structural trends intersect with the Central Graben trends. The importance of the understanding of fault timings and trendology in the compartmentalization of relatively small areas is well illustrated from the 3D data over Block 15/21.

Central Graben papers

Seven papers are included on the Central Graben area. Three of these papers concentrate specifically on the Jaeren High and East Central Graben and the complexities of the supposedly salt-controlled structures.

Holland et al. discuss whether thin-skinned extension or salt dissolution was the major controlling factor on the distribution of Late Jurassic sediment traps on the Jaeren High. They conclude that a combination of both processes had occurred: the extension being dominant in the Triassic, and then salt dissolution taking over in importance in the Late Jurassic. A similar conclusion is reached by Penge et al. for the East Central Graben area as a whole. They also describe the varying geometries of Triassic raft features, all of which initially formed as a result of post-Triassic layer-parallel extension, disconnected from the basement by the underlying Zechstein salt.

Erratt describes various examples of graben margin structures, mainly from the East Central Graben area. He shows that salt withdrawal, commencing in the Triassic, resulted in a complex network of grounded primary withdrawal synclines (Triassic ‘pods’) and intervening areas of salt preservation that were largely in place prior to the Late Jurassic rifting. A wide range of Upper Jurassic graben margin structures was therefore possible, depending on the location and size of the underlying basement fault relative to the location of the overlying Triassic ‘pods’ and salt swells.

In all the above papers, the importance, or otherwise, of any wrench component of movement in the evolution of the area is hardly considered. In contrast to this Sears et al. describe a
series of structural examples from the Central Graben, all of which are described as Upper Jurassic transtensional and transpressional features related to the oblique movement along deep-seated and much older NW–SE-trending basement faults in an E–W extensional regime. All the examples shown come from 3D seismic surveys. The paper by Stewart (in the Jurassic section) describes, again from 3D seismic survey data, similar such transtensional and transpressional features from the Ula and Gyda areas of the Norwegian Central Graben area. Extensive 3D seismic is also used by Sundsbe and Megson to describe similar examples from the Danish Central Graben area. Transtension and transpression is again mooted as the principal mechanism responsible for the generation of the complex structural styles observed.

As well as the oblique nature of the structural styles, a common thread that links these three papers was that the Late Jurassic extensional event reactivated much older fault trends rather than forming completely new faults. The paper by Platt and Philip (presented as a poster display) highlights the importance of good quality seismic in order to identify pre-Mesozoic fault trends which were subsequently reactivated. Such a NE–SW trend is envisaged as the main control on the boundary dividing the Forties–Montrose High into a southern area thought to contain a considerable thickness of Carboniferous coals, and a northern area devoid of the Carboniferous coaly sequence.

The complex structural evolution and variation in structural styles of the Norwegian Central Graben are described by Gowers et al., who stress the importance of making observations rather than fitting data into a preferred model.

**Southern North Sea papers**

The two papers presented on the Southern North Sea gave strongly contrasting views on the structural styles and evolution of the area.

An analysis of Mesozoic fault trends from three Southern North Sea blocks by Arthur suggest that Mesozoic movements on pre-Zechstein faults were oblique because of their oblique orientation in respect to the principal stress axes, but were purely dip-slip (extensional in the Jurassic and early Cretaceous, and compressional in the late Cretaceous) on post-salt sequences due to the decoupling effect of the salt. The orientations of the pre- and post-salt faults are interpreted as being different.

In the Cleaver Bank area, Oudmayer and de Jager clearly demonstrate from 3D seismic survey data that, even though the Zechstein salt does cause decoupling of faults, the general orientations and locations of the faults are coincident in most areas. Tertiary fault patterns observed from attribute displays are interpreted as Riedel shears indicating that there must have been a strike-slip component of fault movement in the post-salt sequences as well as the pre-salt.

**General discussion**

The key points of general agreement and contention from the papers given in the ‘Structural styles’ section are as follows:

**Points of agreement**

1. The North Sea area contains many Paleozoic and older basement fault trends. These are fundamental in controlling the structural styles formed during later tectonic events.
2. Much use is now being made of sandbox-type models in order to demonstrate the feasibility of a certain structural interpretation. Their use is extremely beneficial in gaining a geometrical understanding of possible structures.
3. The use of 3D datasets and attribute-type analyses has enabled more detailed fault mapping to be attained. This greatly enhances the structural understanding, especially in areas of complex structural geometries such as in the Central North Sea area.

**Points of contention**

1. Oblique-slip versus extensional faulting—there is much lively debate as to the existence of normal faults versus oblique-slip faults, especially in the Central Graben area where the presence of underlying salt further complicates matters. The key points stressed by the exponents of oblique-slip are that the strike-slip component of movement was only very small compared to the dip-slip component, and that the same structural styles are observed in areas where salt is not present as in areas where salt is present. It is also worth noting that all papers that use 3D seismic data are exponents of oblique-slip movements.
2. The role of salt—most of the Central Graben papers that believe in purely extensional faulting styles concentrate on the decoupling effect of salt relative to the overlying and underlying formations. The Central Graben oblique-slip papers based on 3D datasets, on the other hand, demonstrate a definite link between faults contained within the underlying and overlying formations.

The high quality of papers given in the Structural Styles Session highlights that there is an increasing awareness and understanding of structural geology within the petroleum industry as a whole. Detailed structural interpretation now forms an integral part of the overall exploration process.