The Jurassic: from regional models to field development; the impact of sequence stratigraphy on hydrocarbon geology

Introduction and review

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As we are reminded in the opening paper (Cordey) of the Jurassic session, over 50% of the proven hydrocarbon reserves of the UKCS Northern and Central North Sea occur within the Jurassic. More importantly with a view to future exploration, the Jurassic probably contains the majority of the undiscovered reserves in the North Sea basin in subtle structural and stratigraphic traps, many of which may only be defined using novel interpretation techniques, such as sequence stratigraphy and detailed 3D seismic. The Jurassic also provides us with an excellent opportunity to study the evolution and fill of an ancient rift system from both sub-surface and outcrop data. The Jurassic session was therefore specifically targeted at developing new insights into Jurassic stratigraphy at both basin and field scales by utilizing seismic stratigraphy (Vail and Mitchum 1977; Galloway 1989), tectono-stratigraphy (Hubbard et al. 1985), sequence stratigraphy (Van Wagoner et al. 1988, 1990) and some novel techniques such as the application of ichnofabrics as an environmental indicator (Taylor and Gawthorpe).

The development of sequence stratigraphy over the past 15 years has contributed greatly to our understanding of basin fill processes but little has been published on its application to the North Sea Jurassic. Sequence stratigraphic models have mainly evolved from the analysis of sedimentary basins with relatively simple subsidence histories, such as post-rift successions of passive continental margins and intra-cratonic basins (Vail and Mitchum 1977; Galloway 1989). These models have proven applicable to the prediction of reservoir, source and seal facies on a field and basin scale in both modern and ancient passive tectonic settings such as the Jurassic of the North Sea. Sequence stratigraphic models have also been applied to the study of fault systems, such as the tectono-stratigraphic evolution of the central North Sea Jurassic graben where lakes developed in areas of low relief and upward migration from the overlying Kimmeridge Clay (Underhill and Partington). The most significant oil reserves in the Jurassic are trapped in Brent sandstone reservoirs in tilted fault blocks charged by downward migration from the overlying Kimmeridge Clay source rocks. Additional source potential occurs in the Central Graben where lakes developed in areas of low relief and reduced sediment supply. The latest part of the pre-rift Middle Jurassic sediments were deposited during a major regressive deltaic pulse in the Brent Province.

The Jurassic in the North Sea is a major hydrocarbon exploration target containing reservoirs in deltaic (Brent), shallow marine shelf (Piper) and deep marine (Brae) settings in the Middle and Upper Jurassic in addition to excellent source rock and seal facies (Kimmeridge Clay) in the Upper Jurassic. Reserves in the above three play systems in the UKCS are assessed at over 20 billion barrels of oil equivalent (Cordey), split roughly 55% Brent, 23% Piper and 22% Brae. As a direct result of this exploration success, Jurassic workers now have access to a large volume of data, comprising over 1500 exploration and appraisal wells and a vast amount of regional and block specific seismic data. In addition, excellent outcrop analogues exist in East Greenland and the UK.

The Middle Jurassic rift

The Early–Middle Jurassic around the British Isles records a major change in basin forming process, with the evolution of two distinct tectonic provinces. Over most of NW Europe, including the western parts of the Hebridean Shelf (Morton), the gentle thermal subsidence prevailing in the Late Triassic was abruptly interrupted by a further phase of rifting in the Central Atlantic and Tethyan provinces to the south. This coincided with a widespread marine transgression over most of NW Europe. In the North Sea, the Early Jurassic was characterized by a period of regional thermal uplift, with associated volcanism in the Central North Sea (Smith and Richie). This uplift is now interpreted as a pre-rift thermal bulge pre-dating the Late Jurassic rifting which was centred on the evolving Witch Ground, Central and Viking Graben triple junction (Underhill and Partington). Middle Jurassic sediments were deposited during a major regressive deltaic pulse in the Brent Province.

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The Late Jurassic rift

The pattern of regional thermal uplift and late stage subsidence which prevailed during the mid-Jurassic was replaced by major tectonic subsidence during the Late Jurassic with the onset of the final and major phase of North Sea rifting (Rattey and Hayward; Price et al.; Partington et al.; Donovan et al.). In general, fault initiation propagated from north to south resulting in a rift duration of around 12 Ma in the Viking Graben (J40–J60) compared to about 7 Ma in the Central Graben (J50–J60) (see Fig. 1 for sequence definition). Large-scale reactivation of Permo-Triassic faults is evident throughout the
province. In the Viking Graben, fault geometries are mostly planar with a basal detachment dipping eastwards under the Fenno-Scandian shield. NE-SW-trending Caledonian (transfer zone) offsets are important as sediment entry points to the graben (Cherry et al.). In the Central North Sea, the presence of underlying Zechstein evaporites allowed shallow detachments to develop with a markedly listric geometry (Hodgson et al. 1992). In the Witch Ground Graben, extension was accommodated by existing NE-SW-trending Caledonian lineaments and possibly pre-Caledonian E-W-trending offsets.

The onset of faulting in the North Sea produced a strongly sediment-starved basin (Milton). Because faults moved at a rate far greater than the rate of sediment supply, sediment infill shows little evidence of syn-depositional growth. A bathymetric relief of up to 2 km was created, which persisted well into the Cretaceous (Rattey and Hayward). The syn-rift basinal areas formed the loci for the deposition of the Kimmeridge Clay.

Two main sand plays were developed during the syn-rift phase:

1. shelf sands (J50) pre-dating the maximum period of fault-driven subsidence (J60) in tilted fault blocks e.g. Piper, Fulmar, ‘Frigate’ and Ula sands (Casey et al.; Wakefield et al.; Clark et al. and Stewart);
2. basinal turbidites developed during the main rift phase (J60) and earliest post-rift (J70) in combination structural/stratigraphic traps, e.g. Brae and Miller sands (Cherry et al. and Garland).

Initial subsidence in the Northern North Sea was very rapid and the area became sediment starved at an early stage with consequently limited development of shelf and coastal plain environments around the basin margins (Milton). As a result, the main Upper Jurassic plays in the Viking Graben involve deep marine sand reservoirs such as Magnus, Brae and Miller. In contrast the less severe subsidence history in the Central North Sea led to the development of a much more extensive coastal plain and shelf. Consequently, Upper Jurassic plays in the Central Graben involve laterally continuous shelfal sand reservoirs such as Fulmar, Clyde and Ula. The underlying control on the distribution of these sands attracts much debate, with Wakefield et al. favouring salt withdrawal and Stewart proposing a fault-controlled mechanism.

**Jurassic sequence stratigraphy**

The stratigraphy of the Jurassic is perhaps the least well constrained of all the major play systems in the North Sea. For instance, in the Tertiary turbidite fan play discussed earlier in this volume, lithostratigraphic and sequence stratigraphic schemes are remarkably similar. This is largely a reflection of the restricted environments of deposition encountered in the Tertiary (i.e. mainly basin floor fan systems separated by widespread hemipelagic shales). Being essentially a post-rift infill of the basin, the Tertiary lends itself to a seismic stratigraphic approach to generate a high resolution sequence stratigraphic framework. This is not the case for either the Middle Jurassic pre-rift section, where sequence boundaries occur at a scale below seismic resolution, or the Upper Jurassic syn-rift interval, which is largely confined to isolated fault-bounded half-grabens. The diverse depositional environments encountered within the Jurassic rift system (e.g. coastal plain, shallow marine shelf, slope and basin floor environments are all preserved in the Oxfordian) has led to the proliferation of separate lithostratigraphic terminology for individual facies in each sub-basin. This has resulted in Jurassic stratigraphy failing to progress in any useful form since Deegan and Scull (1977). As a consequence, this has hindered an overall understanding of Jurassic depositional processes and does little to facilitate the prediction of, and exploration for, the more subtle...
play types. In areas of poor well control, such as the basinal areas of the Central Graben where some 90% of Upper Jurassic well data lies on the shelf, this becomes especially critical. Future exploration of basinal plays demands sequence stratigraphic prediction of reservoir distribution based on the existing dataset.

Sequence stratigraphy in the Jurassic session

Several contrasting stratigraphic schemes or analyses were presented for the Jurassic, e.g. (Rattey and Hayward; Partington et al.; Underhill and Partington; Morton; Surlisky; Donovan et al.; Steel; Clark et al.; Price et al.; Wakefield et al. Stephen et al.). The approach to sequence stratigraphic subdivision varied significantly. Some authors (Donovan et al.; Taylor and Gawthorpe; Engkilde) preferred to divide the stratigraphy into its component systems tracts and parasequences. Partington et al.; Rattey and Hayward; Milton; Stephen et al. and also Price et al. subdivided on the basis of maximum flooding surfaces, while Clark et al. and Morton used conventional lithostratigraphy, occasionally embellished with sequence stratigraphic terminology. Steel subdivided on maximum progradation surfaces, although sequence boundaries and maximum flooding surfaces are also present in his dataset.

Disappointingly, few authors presented predictive uses of sequence stratigraphy. Only Johannessen and Andsbjerg followed the logical process: 'I observe a sequence boundary, therefore I predict fans'. The vast majority used sequence stratigraphy only to a mean of subdividing and describing. Donovan et al. attempted to relate Central Graben Jurassic stratigraphy to the global sea-level curves of Haq et al. (1987, 1988), thus inferring a eustatic, rather than a tectonic control on sequence boundary generation. This is a commonly used line of argument, but relies on the Haq curves being a true record of eustasy and on sequence boundaries being datable to within 0.5 Ma and therefore correlatable unequivocally to the Haq et al. curve. Underhill and Partington pointed out that the Jurassic portion of the Haq et al. curve is derived largely from NW Europe and, in the absence of more regional data (e.g. from North America), the remarkable correlation between this curve and North Sea events proves only a plate-wide causality.

Second-order (5–50 Ma frequency) relative sea-level cycles recognized in the Jurassic (Rattey and Hayward; Morton; Stephen et al.; Underhill and Partington; Partington et al.) are demonstrably tectonic in origin. The cause or driving mechanism for the third-order (0.5–5 Ma frequency) variations is still unresolved and little data were presented at the conference which shed light on this question.

Sequence stratigraphy as applied to the North Sea Jurassic

The Jurassic session at the conference probably represents the first concerted attempt to apply modern high resolution sequence stratigraphic techniques to the Jurassic of the Northern and Central North Sea. Esso and BP appeared to present the most rigorous regional analyses but there were significant differences between the two approaches both in terms of methodology and results (Fig. 1).

The approach adopted by BP (Rattey and Hayward; Partington et al. and Garland) was presented as a fairly rigorous, consistent, stratigraphic scheme applied from regional to development scale. A tectono-stratigraphic framework was derived from regional seismic interpretation (Fig. 1). High resolution biostratigraphy was then used to identify and correlate marine condensed intervals between shelf and basinal successions producing a more detailed stratigraphic breakdown. The resulting subdivision by genetic sequences is not as valuable or as predictive as a full subdivision into systems tracts; however, the BP scheme was presented as a pragmatic first-pass.

By comparison, Donovan et al.'s (Esso) presentation of the Jurassic stratigraphy of the Gannet area applied a more classical sequence stratigraphic approach, based largely on seismic data aided by well correlations, in which sequence boundaries were used to define correlatable unconformity-bound units. This model is inherently more predictive in terms of reservoir distribution, particularly in basin settings. However, the authors made the assumption that all reflection terminations and stratigraphic thickness changes were due to erosion at sequence boundaries. They, therefore, picked several surfaces in the Upper Jurassic as sequence boundaries, which the BP workers (Partington et al.) have interpreted as marine condensed intervals, e.g. the Base Cretaceous 'unconformity' (Fig. 1).

Of the remaining presenters applying sequence stratigraphic analyses, Surlisky's East Greenland study was an excellent outcrop-based analysis of relative sea-level variations. Making an important observation, he pointed out that East Greenland was not just an analogue for offshore Mid-Norway but in reality the other half of the basin.

Stephen et al. and Underhill and Partington have performed several careful analyses of outcrop and well data, and have a methodology of analysis close to that developed in-house by BP. Milton, again using the BP stratigraphic framework, presented the only real attempt to evaluate sediment/sea-level interplay during rifting. These three papers represent fine examples of the applied use that can be made of a rigorous sequence stratigraphic framework.

Conclusions

On the evidence of the Jurassic session, sequence stratigraphy is recognized widely in the UK industry and academic community as a valuable means of stratigraphic analysis. However, the quality of the use of the technique varied considerably. Most presenters used it as a means of stratigraphic subdivision and the schemes presented, particularly by Esso and BP, should form the basis for any future subdivision. Both were able to demonstrate some degree of stratigraphic prediction with their models and have shown the way forward in terms of developing a stratigraphic framework that should assist future exploration and production of Jurassic reservoirs in the Northern and Central North Sea.

A few presenters were able to demonstrate a tectonic cause for second-order relative sea-level variations. The cause of the third-order variations is still unknown. Correlation with the Haq et al. curve does not prove a eustatic cause unless (a) the correlation is precise and (b) it is assumed that the Haq et al. curve is a true measure of eustatic variation.

Hopefully, the various sequence stratigraphic schemes presented at the conference will lead to a more predictive approach to Jurassic stratigraphy and the ideas presented at this conference should stimulate further debate and progress in both sequence stratigraphy as applied to the Jurassic and to tectonically active basins as a whole. I look forward to the outcome of the present European Basins Project to determine a European sequence framework, which should contribute useful data to this debate.

I would firstly like to thank my colleague Nick Milton who contributed much of the critical review of the sequence stratigraphic schemes from a seat in the auditorium rather than from the stage where the view of the presentations was somewhat skewed. Many thanks also to Richard Hubbard and Phil Vingoe who chaired the Regional Overview and Viking Graben sessions and Jerry Matthews and Richard Campbell for their contribution to the initial organization of the Jurassic programme.
References


