Introduction to the sedimentology of paralic reservoirs: recent advances

GARY J. HAMPSON[1]*, ANTONY D. REYNOLDS[2], BORIS KOSTIC[3] & MARTIN R. WELLS[2]

[1]*Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK*

[2]*BP Exploration Operating Co. Ltd, Sunbury-Upon-Thames, Middlesex TW16 7LN, UK*

[3]*Badley Ashton & Associates, Winceby House, Winceby, Horncastle, Lincolnshire LN9 6PB, UK*

**Correspondence: g.j.hampson@imperial.ac.uk*

Paralic reservoirs reflect a range of clastic depositional environments developed along or near coastlines, including deltas, shoreline–shelf systems and estuaries. Such reservoirs provide the backbone of production in many mature basins around the world, and contribute significantly to global conventional hydrocarbon production. Strata that host these reservoirs are shaped by a wide variety of depositional processes and controls which reflect the upstream supply of sediment and water, the characteristics of the receiving basin, relative sea level, tectonic setting, and the internal dynamics of depositional systems. Consequently, they exhibit much variability in their stratigraphic architecture and sedimentological heterogeneity, which translates into complex patterns of reservoir distribution and reservoir performances that are challenging to predict, optimize and manage. This Special Publication presents new research and developments in established approaches to exploration and production of paralic reservoirs. It arises from the conference and associated core workshop titled 'Sedimentology of Paralic Reservoirs: Recent Advances and their Applications', which was organized by the Petroleum Group of the Geological Society of London and held in London from 18 to 21 May 2015.

Volume organization

The papers in this Special Publication are arranged into three sections, each with a distinct theme. The aim of this introduction is to provide a broader context for the papers in these three sections.

Subsurface characterization of paralic reservoirs

The first group of papers explores the sedimentological character of paralic reservoirs using subsurface data. The papers consider the subdivision of paralic reservoirs into stratigraphic layers; the dimensions, geometries and distributions of depositional elements (cf. geobodies) within such layers; and facies characteristics within depositional elements. These aspects of reservoir sedimentology all influence fluid flow and hydrocarbon recovery. Stratigraphic layering of paralic reservoirs commonly defines the position of laterally extensive barriers to vertical flow (e.g. mudstone intervals) and the thickness of intervening flow units (*sensu* Ebanks 1987) that are bounded by such barriers. The spatial arrangement of depositional elements controls the lateral extent, continuity and connectivity of fluid-flow pathways within stratigraphic layers (e.g. Weber & Van Guens 1990), and influences the volumetric proportion of hydrocarbon-bearing rock that is contacted by fluids moving through the reservoir layers (i.e. the areal and vertical sweep efficiency). Facies characteristics determine the grain sizes, textures and rock properties (e.g. permeability, porosity) of depositional elements, and they influence in turn the efficiency with which hydrocarbons are displaced from swept volumes of the reservoir at the pore scale (i.e. displacement efficiency) (e.g. Weber 1986).

Reynolds (2016) provides an overview and synthesis of paralic reservoirs, which explains their global significance and identifies their distinctive features across a range of scales. The impact of sedimentology on reservoir characterization and associated field-development strategy is emphasized throughout. This paper explains the overall motivation for previous and current research on paralic reservoirs, including the examples presented in the volume. The sedimentological character and stratigraphic architecture of the Lower Jurassic Cook Formation reservoir in the Knarr Field, offshore Norway, are documented by **Churchill *et al.* (2016)**. In their study, the depositional environments

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and stratigraphic zonation of the reservoir are constrained by integrated sedimentological, micropalaeontological and palynological analyses. The reservoir is interpreted to record a temporal evolution in the depositional-process regime, from net-regressive and tide-dominated in its lower part to net-transgressive and wave-dominated in its upper part. **Heldreich *et al.* (2017)** use a combination of core, wireline-log and 3D seismic data to develop a depositional model for the fluvio-deltaic, Upper Triassic Mungaroo Formation, a major exploration and production target in the North Carnarvon Basin, offshore Australia. Their analysis characterizes the geometries, dimensions and vertical facies successions of depositional elements to aid reservoir characterization and modelling, and discusses uncertainties in interpreting allogenic (external) and autogenic (internal) controls on the architecture of strata that contain these geobodies. Characterization of stratigraphic architectures that may have resulted from autogenic behaviours, such as avulsion of distributary channels in fluvio-deltaic strata, is attempted by **Flood & Hampson (2016)** using a combination of core-based facies and palaeosol analyses, and the application of spatial statistical tools to channelized sandbody distributions in upper coastal plain strata in the Middle Jurassic Brent Group reservoir, Brent Field, offshore UK.

Tidal heterogeneity in paralic systems

Heterogeneity in lithological character is a recurring theme in paralic reservoirs. Arguably, heterogeneity is at its greatest in reservoirs that were deposited under the influence of tidal currents, where intercalation of sandstones and mudstones across a wide range of scales is common (e.g. Nio & Yang 1991). Such intercalations have repeatedly been shown to have a significant impact on fluid flow (e.g. Jackson *et al.* 2005; Ringrose *et al.* 2005) and remain an area of active research (Massart *et al.* 2016). Accordingly, the second group of papers in the Special Publication reviews and extends the literature that describes tide-influenced paralic reservoirs and their outcrop analogues.

Longhitano & Steel (2016) present a generic depositional model for deltas that advanced into seaways or straits in which tidal currents were dominant, based on two well-documented outcrop examples. The model identifies diagnostic aspects of the plan-view geometries, three-dimensional stratal stacking patterns, and vertical successions of facies, palaeocurents and depositional-process indicators in such deltas. The model may allow reinterpretation and improved characterization of hitherto-enigmatic sandstone reservoirs along the margins of elongate marine basins. **Mellere *et al.* (2016)** document the facies characteristics, stratigraphic architecture and palaeogeography of a series of stacked tide-dominated and tidally influenced deltas and estuaries in the Middle Jurassic Bryne and Sandnes formations, Søgne Basin, offshore Norway and Denmark, using core, wireline-log and 3D seismic data. These strata contain complex spatial patterns of reservoir distribution and character, which reflects their deposition in an evolving salt-influenced rift basin. A facies analysis and stratigraphic architectural study of net-transgressive, early Miocene tide-dominated deltaic reservoirs from the Balingian province, offshore Sarawak, Malaysia is presented by **Amir Hassan *et al.* (2016)**. Increased wave influence is characteristic of transgressive intervals in these reservoirs. Vertical and lateral stacking patterns of sequence stratigraphic units reflect tectonic controls on hinterland denudation and subsidence variations, respectively. **Johnson *et al.* (2016)** document the stratigraphic context and internal architecture of an estuarine outcrop analogue (from the Cretaceous Straight Cliffs Formation, Utah, USA) that exhibits variable tide and wave influence. The detailed bed-scale architecture of inclined heterolithic strata from a bayhead delta in the inner estuary is characterized in order to develop diagnostic criteria for bayhead delta depositional elements in subsurface reservoir data. **McLean & Wilson (2016)** use a quantitative approach to outcrop data from the Plio-Pleistocene Erin Formation, Trinidad to document both tidal and river flood signatures in thinly bedded mudstones and sandstones – an approach that is readily, but rarely, transferred to subsurface core data.

Analogue studies

Understanding the distribution and character of paralic reservoirs often relies on insights from a range of analogues, which provide appropriate context or additional detail to aid interpretation of sparse subsurface data. Analogues take many forms: modern sedimentary systems, in which processes can be observed and linked directly to depositional product; sub-modern depositional systems that are imaged at high resolution and in three dimensions using shallow seismic data; analogous reservoirs rich in static and dynamic data; outcrops of ancient strata, which allow preserved stratigraphic architectures and facies characteristics to be observed and integrated across a wide range of spatial scales; and numerical and physical (e.g. flume tank) models that allow the underlying assumptions of our interpretations to be investigated experimentally. The final group of papers in this Special Publication presents a range of paralic reservoir analogues from studies of modern sediments and ancient outcrops.

Lane *et al.* (2016) unravel temporal and spatial patterns of river-channel avulsion in a

Holocene–modern fluvial megafan and associated mixed-influence delta (Mitchell River, Queensland, Australia) using a combination of mapping, vibracoring, trenching and topographical surveying. The resulting patterns of stratigraphic architecture and channelized sediment-body distribution are integrated with vertical facies successions and intra-sediment-body architectural panels in order to develop a generic model of depositional-element distribution within a regressive megafan delta. **Lambiase *et al.* (2016)** characterize sedimentation patterns in the modern Mahakam Delta, Borneo, which is undergoing transgression via retrogradational stacking and switching of delta lobes. Diagnostic core-based sedimentological criteria are presented for three sharp-based sandstone depositional elements (regressive fluvial distributary channels; transgressively back-filled fluvio-estuarine distributary channels; transgressive wave-dominated shorefaces) that appear similar in wireline-log data but have distinctly different geometries, spatial distributions and sequence stratigraphic implications. The stratigraphic architecture of a thick, net-aggradational interval of paralic strata, characterized by high accommodation and high sediment supply, is described from outcrops of the Cretaceous Straight Cliffs Formation, Utah, USA by **Mulhern & Johnson (2016)**. Transgressive–regressive cycles composed of regressive, wave-dominated deltaic and shoreface deposits and transgressive, wave-dominated estuarine deposits can be correlated between successions of different thickness that underwent variable local tectonic subsidence and early compaction. **Gomis-Cartesio *et al.* (2016)** document the architecture of ancient wave-dominated and mixed-influence shelf-edge deltas and underlying gullies and slope channels at outcrop (Permian Waterford Formation, South Africa). The facies character, geometry and dimensions of depositional elements associated with the shelf edge are documented and synthesized into a model for sediment bypass from deltaic distributary channels onto the slope via gullies that become wider and shallower down depositional dip.

Recurring themes and future directions

Heterogeneity in paralic reservoirs is increasingly well understood at all scales. **Reynolds (2016)** highlights that (1) advances in imaging due to improvements in seismic data acquisition and processing, (2) widespread application of sequence stratigraphic concepts, (3) availability of robust facies models, (4) improved use and organization of analogue databases, and (5) increased integration of available data types have all played key roles in allowing heterogeneity from pore scale to reservoir scale to be described in paralic reservoirs. Consequently, reserve volumes and their distributions are estimated earlier in field life, allowing better and more timely development decisions. Despite this undoubted progress, the conference and the papers presented here amply demonstrate that progress continues in the sedimentological description of paralic reservoirs and that several recurring themes represent fruitful directions for future work:

- The tectonostratigraphic context of paralic successions influences their subsidence patterns and preserved thickness, sediment input and routing, and potentially also the process regime (e.g. via suppression or amplification of waves and tides: Stride 1982; Yoshida *et al.* 2007; Ainsworth *et al.* 2008; Wells *et al.* 2010). Spatial and temporal variations in tectonostratigraphic context may result in the development of subtle stratigraphic trapping configurations, and complex spatial patterns of reservoir distribution and character. Integrated analysis of seismic, well-log, core and biostratigraphic data is essential to unravel the stratigraphic architecture of such paralic successions, and thereby to identify and de-risk paralic reservoir targets, even in mature basins (e.g. **Amir Hassan *et al.* 2016**; **Churchill *et al.* 2016**; **Mellere *et al.* 2016**). Analogues have an important role to play in demonstrating the viability of concepts and models that are unproven in a subsurface hydrocarbon-play context (e.g. **Gomis-Cartesio *et al.* 2016**; **Longhitano & Steel 2016**; **Mulhern & Johnson 2016**).
- Theoretical and experimental studies have demonstrated that the internal dynamics of sediment-routing systems may influence stratigraphic architectures across a range of spatial and temporal scales (e.g. Muto & Steel 1992; Kim *et al.* 2006; Muto *et al.* 2007). This key theoretical contribution has yet to be routinely incorporated into the sequence stratigraphic interpretation of subsurface and outcrop data. However, distinguishing allogenic (external) and autogenic (internal) controls on sedimentation is important in predicting the extent, continuity and degree of order in paralic stratigraphic architectures, particularly in subsurface settings where data are sparse (e.g. Wang *et al.* 2011; see also discussions in **Flood & Hampson 2016**; **Lane *et al.* 2016**; **Heldreich *et al.* 2017**). The theory needs to be tested against more ‘real world’ datasets in order to further develop diagnostic tools and predictive models.
- Facies analysis of paralic deposits has traditionally emphasized the use of ‘end-member’ examples, dominated by riverine, wave or tidal processes, at the expense of mixed-influence

depositional systems in which two or more of these processes are significant. In recent years, the stratigraphic architecture of mixed-influence paralic deposits, and the geometry and distribution of the depositional elements that they contain, have been addressed in a new classification scheme (Ainsworth *et al.* 2011), and in case studies of modern and ancient reservoir analogues (e.g. Legler *et al.* 2014; Ainsworth *et al.* 2016; **Johnson *et al.* 2016**; **Lambiase *et al.* 2016**; **Lane *et al.* 2016**). Numerical models may provide a key role in extending this approach by exploring the range of possible stratigraphic architectures and facies distributions that lie between those documented in high-quality outcrop and subsurface case studies (e.g. Edmonds & Slingerland 2010; Geleynse *et al.* 2011).

- Lithological heterogeneity within depositional elements and their constituent facies typically occurs at spatial scales smaller than reservoir-model grid cells. This heterogeneity is arranged in a hierarchical manner (e.g. laminae, laminasets, beds and bedsets: Campbell 1967), and may be architecturally complex due to a combination of cross-stratification, erosional scour, lapout, dewatering and bioturbation. Deriving values of effective permeability, for example, that are applicable at the scale of facies in a reservoir-model grid cell can be far from straightforward, because laboratory core measurements may not sample a sufficiently large volume of the reservoir to represent the heterogeneity present (i.e. Representative Element Volume *sensu* Bear 1972). Similarly, upscaling of core measurements using simple averaging methods may not be appropriate if the measurements do not capture the spatial structure of the heterogeneity. Characterizing the architecture of lamina-scale to bedset-scale heterogeneity is therefore an essential step in deriving values of effective rock properties for a particular facies (e.g. Willis & White 2000; Jackson *et al.* 2005; **Johnson *et al.* 2016**; **McLean & Wilson 2016**; **Reynolds 2016**), although detailed architectural studies at these scales remain relatively rare.
- The recent explosive growth in production from shale gas and shale oil reservoirs, particularly in onshore North America, requires robust sedimentological characterization of paralic mudstone successions. Although not addressed by the papers in this volume, it is clear that paralic facies models must develop to incorporate the geometrical, textural and mineralogical characteristics of mudstones in addition to those of sandstones that are typically the focus of such models (e.g. MacQuaker *et al.* 2007; Schieber *et al.* 2010; Bohacs *et al.* 2014). As well as unconventional shale reservoirs, there is potential to reassess hydrocarbons stranded in the shaly ‘waste zones’ of paralic sandstone reservoirs as reserves in ‘halo plays’ that surround these sandstones.

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