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Reservoir characteristics of tropical sub-humid fluvial and deltaic deposits inferred from Modern and Holocene sediments of NE Australia and some ancient examples

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This paper aims to highlight the important differences between the lithosomes produced in sub-humid, tropical cyclone-influenced environments and those conventionally regarded as typical of fluvial and deltaic systems in general, by presenting data on Holocene-modern and ancient examples. The modern landscape of sub-humid tropical northeast Australia is drained by several large rivers, some of which have formed sizeable Holocene deltas. One such system is the Burdekin River and Delta, which we have studied intensively over the past 15 years. The sedimentary deposits of the Burdekin River display a number of characteristics that are not consistent with previously extant facies models for fluvial systems. The Burdekin River Delta also has geometrical and lithological properties that make it quite distinct from popular deltaic facies models. This paper summarises the facies, stratigraphy and reservoir properties of the Holocene-modern Burdekin River and its delta, and draws comparisons with well-exposed ancient analogues, specifically Pennsylvanian fluvial deposits in the Sydney coalfield of Cape Breton Island, Atlantic Canada, and the Cretaceous Ferron Sandstone in the Henry Mountains of south-central Utah, USA.

The Burdekin River is the largest river (by discharge) draining northeast Australia and flowing into the Coral Sea (Fig. 1, Fielding & Alexander, 1996; Alexander et al., 1999). Its drainage basin, covering 129,000 km^2, is mainly sub-humid (mean annual precipitation 500-700 mm), although the headwaters in the eastern and northern fringes of the catchment rise in tropical rainforest-covered ranges that receive <1600 mm annual rainfall. Precipitation is strongly seasonal, variable from year to year, and influenced by the passage of tropical cyclones and monsoonal depressions. Intense rainfall events cause short-duration, high-magnitude fluvial discharge events (20,000-40,000 m^3s^{-1} peak discharge events have a return period of 5-10 years). During these events, rapid erosion of the poorly vegetated landsurfaces, leads to transport of clay to large gravel grade sediment through the river system and high suspended sediment concentration. Amos et al. (2004) found that the sediment load was predominantly supply-limited, and suggested that suspended sediment concentrations would be sufficient to promote hyperpycnal underflows at the river mouth during some floods (although with the offshore bathymetric pattern in this case such flows are unlikely).

In mid to lower catchment settings the main river channels (as illustrated by our detailed studies north of Charters Towers; e.g. Fielding et al., 1999) scale with the major flow events. Thus the peak discharge of 5-10 year return interval events are the channel-forming discharges – unlike most perennial systems where channels scale with the 1-2 year return interval events. During these events the channel alluvium is substantially reworked. The channels are straight to moderately sinuous with a variety of barforms, covered by dunes, plane beds, antidunes and gravel patches, with significant, stable arborescent vegetation *(Melaleuca argentea*), mainly in flow-parallel, linear groves (Fielding & Alexander 1996). These trees are often buried within the channel deposits and may accumulate considerable log-jams that may also become buried (Fielding et al., 1997; Fielding & Alexander 2001). The channel lithosome is predominantly well-sorted but compositionally immature sand, with subordinate gravel, and local partings of plant debris-rich and root-penetrated silt. The architectural features of point bars recorded in temperate perennial rivers are largely unrecognizable in the Burdekin River because of the frequent reworking of bars and the big differences in flow structure and sediment flux between successive events, (Fielding et al., 1999). The basal part of the channel body is large-scale (up to 3 m sets) cross-bedded sand, which pass upward into smaller-scale cross-bedded sand. The upper part of the fill shows multiple truncation surfaces, overlain by cross-bedded and plane-bedded sand. Mud layers are formed during the waning stage of large flow events, draping topography and thickening into swales and during smaller discharge events resulting in mud layers in the deeper parts of channels and on bar edges. In some reaches, and particularly on the coastal plain, the channel is flanked by a low-relief levee. Deposition on levees and floodplains occurs during very large discharge events when significant sand is carried in suspension. This has the consequence of generating floodplain sequences with relatively high sand content compared with perennial settings. Such deposits comprise sand beds that show little vertical grain-size variation, interbedded with lesser mud and gravel beds. Except on the very distal coastal plain, individual beds within the levee and floodplain deposits have limited lateral extent and cannot be readily correlated over distances of 10’s of m (Alexander & Fielding, 2006).

Through the Quaternary era, the Burdekin River has constructed a broad delta plain (1260 km^2). The modern Burdekin River discharges onto the Great Barrier Reef shelf, the inner part of which is a gently-shelving surface to about -30 m. The shelf is largely open to the prevailing southeasterly winds and to occasional tropical cyclones and other low-pressure systems. Prevailing winds maintain a turbid, well-mixed water column most of the year and a strong northwestward longshore current on the shoreface and inner shelf. Fairweather wave base is at approximately 15 m, and storm wave base at ~35 m. The tidal regime is mesotidal, semidiurnal and asymmetrical. The main terrigenous sediment input to the coast is from river effluent, supplied largely during short-duration, high-magnitude events associated with tropical cyclones and other rain depressions (Fielding et al., 2005).

The Holocene Burdekin delta platform is composed largely of sharp-based, coarse-grained sand bodies 5-8 m thick some of which show gently seaward-dipping internal bedding surfaces (Fielding et al., 2005; 2006). Some bodies are linear in plan geometry, while others are a more lobate, “teardrop” shape. These bodies are interpreted as channel and mouth bar deposits, respectively, and their dominance in the subsurface demonstrates that the delta was constructed not by wave-working of river effluent (as was the previous published interpretation of the system based on surface observations) but by flood deposition. The moderately-sorted, coarse-grained sand bodies are amalgamated in the upper delta plain, becoming separated by coastal mud beds downdip. The entire Holocene deltaic section is <25 m thick, and typically comprises a basal transgressive lag above a continental omission surface, overlain by a transgressive mud unit, in turn overlain by a sharply-based, composite sand unit of the highstand systems tract (Fielding et al., 2006). Coarsening-upward trends are locally developed. At least 13 discrete deltaic lobes are recognized, representing the interval from c. 10 ka BP to present. The oldest lobes are the largest, with lobe area decreasing through time. These changes are probably due to a combination of decreasing accommodation and changing climate from a pluvial early Holocene regime to the ENSO-dominated climate of the past 4 ka (Fielding et al., 2006).

We suggest that the specific characteristics of the climate, runoff regime and landscape have produced sediment bodies that are distinctively different from the conventional views of fluvial and deltaic reservoirs. But given that many ancient successions were accumulated in similar environmental conditions, such deposits might be better-represented in the rock record than has been acknowledged to date. Examples of fluvial channel bodies from the Pennsylvanian succession of Nova Scotia show characteristics that are remarkably similar to those of the modern Burdekin River, and deltaic deposits of the mid-Cretaceous "Notom Delta" (Ferron Sandstone) likewise show great similarity to the Holocene Burdekin Delta.

Erosionally-based fluvial channel bodies of distinctly different styles are preserved in the Sydney Mines Formation of the Sydney Coalfield, Cape Breton Island. One group comprises often chaotically bedded sandstone, with thin siltstone partings that preserve roots of plants, in which upright, *in situ* tree stumps are preserved. Tree fossils are in many cases preserved in densely-spaced groups (groves), and some are consistently tilted in a downflow direction. Some show centroclinal cross-bedding and other structures indicative of water flow around living trees (Rygel et al., 2004). The internal stratification in these bodies includes upper flow regime structures in significant or dominant amounts, notably flat and low-angle bedding and antidune stratification (Fielding, 2006), with lesser amounts of angle-of-repose cross-bedding. We submit that this distinctive fluvial style is fundamentally different from conventional fluvial facies models, and that it is best explained as the deposits of a seasonal tropical climate regime that was characterized by a flashy, strongly seasonal discharge pattern with prolonged periods of low or no flow that facilitated tree growth on channel floors, as observed in the modern Burdekin River.

Deltaic facies of the Turonian Ferron Sandstone in the Henry Mountains of south-central Utah provide a close ancient analogue for the Holocene Burdekin Delta. A 60-km-long, strike-oriented (north-south) section exposes several discrete deltaic lobes (<5 – 20+ km wide) that pinch out laterally in a manner similar to that observed in the Burdekin Delta, and are of comparable strike dimension. A dip (west-east) section 20 km long shows that individual deltaic sand bodies pinch out downdip (eastward) over similar distances (<10 km) into delta front/prodelta interbedded facies and mud. Individual deltaic lobes internally comprise amalgamated, sharply-based sandstone bodies a few metres thick with clinoform sets proximally, passing downdip and laterally into more interbedded sandstone/mudrock facies. Aside from similarity in external dimensions and geometry of mouth bar/delta front sand bodies, the Ferron Sandstone in the Henry Mountains also shows considerable similarity in component facies and contained physical sedimentary structures. Abundant soft-sediment deformation and structureless mud beds attest to rapid sediment deposition from sediment-laden outflows, possibly under hyperpycnal conditions. The sharply-based mouth bar bodies with internal clinoform sets are closely analogous to those of the Burdekin Delta, suggesting formation in shallow water under a similar discharge regime in a seasonal tropical setting.

Given the case studies outlined above, it is clear that fluvial and deltaic reservoir bodies formed in paleotropical settings deserve to be treated as distinctly different from their counterparts formed under more temperate climate conditions. It is hoped that this paper will stimulate further research into facies architecture of and diagnostic criteria for depositional systems from seasonal tropical environments.

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