Structure and tectonics of the Gunnedah Basin, N.S.W: implications for stratigraphy, sedimentation and coal resources, with emphasis on the Upper Black Jack group

N. Z Tadros
University of Wollongong


This paper is posted at Research Online.
NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.
CHAPTER 7

GENETIC FACIES ANALYSIS

7.1 Introduction .................................................................................................................. 279

7.2 Lacustrine System ........................................................................................................ 282
   7.2.1 Component facies .................................................................................................. 282
   Lake margin facies ...................................................................................................... 282
   Lake basin facies ........................................................................................................ 289

7.2.2 Facies association .................................................................................................. 292

7.3 Western Fluvial System ............................................................................................... 292
   7.3.1 Component facies ................................................................................................ 295
   Channel fill facies ...................................................................................................... 295
   Channel margin facies .............................................................................................. 299
   Floodbasin facies ....................................................................................................... 307

7.3.2 Depositional architecture - an outcrop study of the Western Fluvial System ......... 311
   Concepts ................................................................................................................... 311
   Field methods .......................................................................................................... 317
   Lithofacies ................................................................................................................. 319
   Sandstone architecture ............................................................................................. 324
   Depositional model .................................................................................................. 326
   Comparison with models based on architectural element analysis ......................... 326
   Comparison with models based on vertical profile analysis .................................... 328
   Conclusion ................................................................................................................. 330

7.4 Eastern Fluvial System ............................................................................................... 330
   7.4.1 Component facies ............................................................................................. 330
   Channel fill facies ...................................................................................................... 330
   Channel margin facies .............................................................................................. 335
   Floodplain facies ...................................................................................................... 335
The study and interpretation of internal bedding, primary sedimentary structures and texture of the main facies form the final step in the systematic stratigraphic analysis of sedimentary basins (Galloway and Hobday 1983a). The photo shows fine cross lamination, microfaulting, plus minor slump and scour-and-fill structures formed by overloading and soft sediment deformation in channel margin deposits of the Western Fluvial System, upper Black Jack Group, in DM Parsons Hill DDH 1.
CHAPTER 7

GENETIC FACIES ANALYSIS

7.1 INTRODUCTION

As the basin is lacking extensive exposures, drill core was almost the only objective tool available for the study. The effective use of drill core in sedimentary basin analysis requires a good understanding of modern basin analysis techniques and of the concepts of depositional systems and sedimentary processes which have already been outlined in the previous chapter. Also important is an understanding of the relationship between sedimentary processes and their produced sedimentary features in drill core, so that the sedimentary facies can be interpreted and mapped, and their three-dimensional geometry and distribution integrated into the depositional systems.

Interpretation of individual genetic facies follows the concept outlined by Fisher and Brown (1984, p.1), viz. "A modern depositional system is an assemblage of related facies, environments and associated processes. An ancient depositional system is, therefore, a three dimensional assemblage of sedimentary facies linked genetically by inferred sedimentary environments and depositional processes.... The fundamental genetic unit is the facies, defined in terms of its composition and lithology, geometry, structural trend, and other characteristics; all in turn, are related to depositional processes". The recognition of individual genetic facies is largely dependent on the identification of comparable units in modern sedimentary environments and other ancient successions.

This chapter focuses on the genetic facies within the Fluvial and Lacustrine Systems of the upper Black Jack sequence. The principal components of the upper Black Jack depositional systems are channel fill, channel margin and floodplain/basin/lacustrine facies.

Recognition of channel fill facies is the key to interpretation and mapping of fluvial depositional systems. Bed-load sand and channel gravel dominate channel deposits and thus form the skeletal framework of the system (Galloway and Hobday 1983a). Recognition and mapping of geometry, composition and internal structures of channels provide the basis for interpretation of channel type, channel networks and ultimately an understanding of the sedimentary environments and associated processes. Mapping and interpretation of the three-dimensional geometry of depositional systems have been discussed in detail in the previous chapter.

Schumm (1960, 1972, 1977) described relationships, in modern channels, between sediment load, channel geometry and sediment type and classified alluvial channels as bed-load, mixed-load and suspended-load types, depending on the ratio of bed-load to suspended load, sediment load transported by the channel and on its cross-sectional dimensions. This scheme is difficult to apply to
ancient sediments as it requires large exposures. Galloway and Hobday (1983a), therefore, applied a modified classification to palaeochannels utilising fundamental attributes of any depositional system, such as composition and geometry of the framework elements, that can be defined from outcrop or subsurface data, or both. Figure 7.1 summarises the composition and geometry of aggrading bed-load, mixed-load and suspended-load palaeochannel fills.

Bed-load and suspended-load channels are two end members of a spectrum of possible fluvial channel types, and the well known depositional models can be placed within such a spectrum (Galloway and Hobday 1983a). Bed-load deposits are dominated by sand and the channel is characterised by a high width to depth ratio and a tendency to erode its banks and produce tabular or sheet sand. Mixed-load channel sequences consist of sand with subordinate silt and clay and are characterised by irregular or "beaded" sand belts, reflecting the sinuous (meandering) nature of channels, and lenticular discontinuous floodbasin sediments between channel fill sequences. Repetitive fining-upward sequences of combined mixed bank- and bed-accretion (point-bar) deposits characterise the meanderbelts. Mixed-load systems are also characterised by extensive floodbasin muds. Suspended-load channels are narrow with stable steep banks; highly sinuous or anastomosed, with sediment range from very fine-grained sand to silt and clay. Channel fill units are encased in fine-grained floodbasin deposits and tend to stack vertically (Galloway and Hobday 1983a).

During the past three decades, facies analysis of fluvial deposits has been based mainly on the integration of one-dimensional attributes, whether they are in a borehole or an outcrop, into a vertical profile and comparison with "formal" facies models (Miall 1977, 1978a, b). The failure to recognise the wide range of channel morphologies, grain size distribution, sedimentary structures and bedforms, which characterise fluvial deposits, resulted in proliferation of "formal" fluvial facies models and their numerous variants (Miall 1985). However, as early as 1965, Allen hypothesised block models of facies associations to deal with the problem of spatial variations of fluvial deposits. Later, Cant (1978) provided a model for the two-dimensional geometry of a braided system of South Saskatchewan type. Further work by other fluvial sedimentologists (Nami and Leeder 1978, Leeder 1978) eventually led to the development of the concept of fluvial architecture and architectural element analysis (see section 7.3.2 below).

In this study the Western Fluvial System has received more attention because of the availability of a reasonably good outcrop at Mount Watermark, west of Breeza, suitable for mapping and analysis, and the good hydrocarbon reservoir potential of the western fluvial sandstone. Study of the outcrop has improved genetic facies interpretation of equivalent drill core. No outcrops of mappable quality were found for the rocks of the Eastern Fluvial System, most probably because of their low resistance to weathering caused by high content of expandable (swelling) clays and tuff in the matrix. Similarly, rocks of lacustrine and floodplain origin have high contents of silts and organic muds interbedded with the sandstone resulting in low resistance to weathering and very poor outcrops. Therefore, facies analysis was undertaken for the Lacustrine and Eastern Fluvial Systems based on drill core only. Coal facies analysis of the Hoskisson's Peat-Swamp System is given in chapter 9.
Figure 7.1. Geomorphic and sedimentary characteristics of bed-load, mixed-load and suspended-load channel segments and their deposits (from Galloway and Hobday 1983a, after Galloway 1977).
7.2 LACUSTRINE SYSTEM

Over much of the eastern half of the Mullaley Sub-basin the top of the Hoskissons Coal is characterised by an upward gradation from coal through sapropelic coal to organic-rich mudstone, indicating the change from the peat swamp to a lacustrine system (Tadros 1986a, b; see appendix 3 for borehole data).

7.2.1 COMPONENT FACIES

The component facies of the Lacustrine System are recognised by their interrelations, geometry, sedimentary and biogenic structures, and by their relation to the overlying and underlying facies (appendix 3). They also have characteristic progradational geophysical log facies (figure 7.2; log facies type "m", figure 6.5) associated with lake infilling, although mixed progradation and aggradational log facies are also important. Finely serrated log patterns of fine-grained lake basin sediments are replaced rhythmically by upward-coarsening log patterns which result from upward-coarsening mudstone/siltstone/sandstone cycles (upper part of log facies type "o", figure 6.5). The lacustrine facies also show resemblance in some aspects to other ancient analogues described by Bradley (1964), Picard and High (1968), Hubert et al. (1976), Hobday (1978) and Picard and High (1981).

The principal components are sandstone/siltstone facies at the margins (lake margin facies) and carbonaceous mudstone facies (lake basin facies) in the central areas of the lake basin (figures 6.20, 7.2 and 7.3). Coal is also associated with the Lacustrine System (e.g. the Howes Hill Coal Member in the south-east).

LAKE MARGIN FACIES

The lake margin facies is present mainly around margins and shores of the lake system (figures 6.20 and 6.17D). Figure 7.3 shows an idealised lake margin sequence underlain by lake basin facies, and photo 7.1 a typical lacustrine sequence in the central sub-basin basin area starting at the base with a gradual change from coal (Hoskissons Coal) to organic-rich mudstone of the lake basin facies followed by upward-coarsening sequence of lake margin facies. Photo 7.2 shows a complete lake sequence in the northern basin area (in DME Narrabri DDH 41) from the top of the Hoskissons Coal at the base to the topmost unit in the Lacustrine System. Figure 7.4 displays the geophysical log pattern of the Lacustrine System in the same borehole. Lithologically the lake-margin facies consists of cross-bedded sandstone, interbedded sandstone and siltstone with common burrows, and abundant plant debris. Thin units of upward coarsening, moderately well-sorted sandstone also occur. Minor sedimentary structures include wavy, lenticular and flaser bedding, ripple lamination with mud drapes, dewatering and scour-and-fill structures, desiccation cracks, and reworked mud clasts (figure 7.3 and photos 7.1 and 7.2).

The bedding and sedimentary structures of the lake margin facies reflect the interaction between fluvial and lake processes. Lake shoreline wave processes resemble those along marine coasts but are
Figure 7.2. Geophysical log pattern of a cyclic lacustrine sequence, upper Black Jack Group in DMF Narrabri DDH 19. Vertical arrows indicate aggradation; oblique arrows indicate progradation (upward-coarsening) log facies (from Tadros 1993i, fig. 14.9)
SEDIMENTARY FACIES

LAKE BASIN FACIES

LAKE MARGIN FACIES

LAKE BASIN FACIES

PEAT SWAMP

DESCRIPTION

Organic-rich mudstone
Graded mudstone/siltstone interbeds
Sparse burrows/bioturbation
Desiccation cracks
Cross bedded sandstone
Climbing ripples
Parallel lamination, sandstone/siltstone
Wavy, lenticular and flaser bedding, ripple lamination with mud drapes
Graded siltstone/sandstone burrowed/bioturbated
Graded mudstone/siltstone laminites, sparse bioturbation towards top
Organic-rich mudstone
Coal/organic-rich mudstone
Coal

Figure 7.3. Idealised vertical section showing sedimentary facies of the lacustrine sequence, upper Black Jack Group (from Tadros 1993i, fig. 14.10, modified after Tadros 1986b, fig. 6)
Photo 7.1. Lacustrine sequence in DM Goran DDH 2, showing gradual change near the top of the Hoskisson Coal from coal to organic-rich mudstone of the lake basin facies followed by rhythmic increase in sandstone of the lake shore/margin facies. Each length of core is approximately 1 m (from Tadros 1993i, photo 14.1)
Photo 7.2 a (above) and b (opposite page). Typical lake sequence in DM Narrabri DDH 41, showing cyclic alternation between marginal and lake basin sediments. The cycles are relatively thin, ranging from 2 m to 5 m, and up to ten cycles are present. Younger cycles shown near the top of the sequence in photo 7.2b are more sand dominant than those in the lower part of the sequence, in photo 7.2a marking the encroachment of the Western Fluvial System. The first two metres of core at the far left of photo 7.2 (a) represent the upper part of the Hoskissons Coal, the topmost part of which shows gradual change from coal to organic-rich mudstone of the lake basin facies. White lines on the Hoskissons Coal are chalk marks drawn during logging of the seam. See text for details of each cycle. Each length of core is approximately 1 m.
Figure 7.4. Geophysical log pattern of the lake sequence in DM Narrabri DDH 41 shown in photo 7.2 (a) and (b). This sequence represents the type section for the Benelabri Formation, discussed in detail in chapter 2. For reference see figure 7.2.
reduced in intensity and scale and produce a variety of features, the most important being wind-tidal flats and delta facies (Galloway and Hobday 1983a).

Wind-tidal flats form an important feature of the lake margin facies. In lake systems, lunar tides are negligible and have insignificant effect on lacustrine sedimentation. Wind-tidal flats in lakes however, develop as a result of wind stress which causes impoundment of the upper layers of lake water against the shore while the bottom layers flow in the opposite direction in order to maintain equilibrium. Impounded water is released in response to changes in wind velocity or direction. The effect of this process on sedimentation is similar to tidal influence, producing similar but smaller scale sedimentary structures such as wavy, lenticular and flaser bedding, ripple lamination and desiccation cracks (figure 7.3). This environment is also favourable for burrowing organisms as sedimentation rates are slow and periodic flooding provides a constant supply of nutrients.

Lacustrine deltas and associated deltaic facies in the Gunnedah Basin are fluvially dominated. Sediments were supplied by eastward and south-eastward flowing streams of the Western Fluvial System (figure 6.20). The streams debouched into the lake and developed small fluvially dominated lacustrine deltas and associated deltaic facies, including channel, mouth bar, crevasse splay and interchannel marsh.

The channel deposits display aggradational log facies (log facies type "d", figure 6.5). They consist of medium-bedded, medium- to coarse-grained sandstone units up to 3 m thick. The sandstone is generally erosively based and may contain reworked mudstone clasts at the base.

In the drill core, mouth bar deposits are typically upward coarsening, moderately well sorted, clean sandstone which ranges from fine- to coarse-grained. Plant debris, including wood fragments and small branches transported during floods, is a common feature of the mouth bar deposits.

Crevasse splays form upward-coarsening sandstone units with sharp bases and fine cross-stratification. Interchannel marsh deposits consist of laminated fine sandstone, siltstone and carbonaceous claystone with thin coal layers.

The palynological assemblages of the burrowed units within the sequence are characterised by absence of spinose acritarchs (McMinn 1993) suggesting that there was no marine influence in these units. The sequence is also characterised by the absence of chemical deposits which suggests that the sediments were laid down in a freshwater environment.

LAKE BASIN FACIES

The lake margin facies passes laterally eastwards into (and interfingers with) the lake basin facies (figure 6.17D). Photos 7.1 and 7.2 and figures 7.3 and 7.4 show examples of typical lake basin deposits overlain by lake margin facies in the Mullailey Sub-basin sequence. The lake basin facies can be recognised in drill core on the basis of several criteria, including lithology, sedimentary structures and association with other facies.
Lithologically, the lake basin facies is sediment starved and consists of organic-rich mudstone grading to finely laminated carbonaceous claystone and siltstone towards the top (figure 7.3 and photos 7.1 and 7.2). In general, the lake basin facies has a homogeneous appearance in core. The organic-rich mudstone is very dark grey to black in colour, of low density (1.6-1.9 g/cm³), breaks with a conchoidal fracture and resembles sapropelic coal. X-radiographs of the organic-rich mudstone show very fine (1-2 mm thick), parallel, varved or graded laminations and an absence of burrows (photo 7.3). The lower part of each lamina consists of very fine siltstone grading upward to black sapropelic material (degraded organic muds). Identified macerals are mainly inertodetrinite and a relatively high percentage of liptinite group macerals particularly sporinite and some alginate.

The geophysical log facies of the lake basin deposits is characterised by a finely jagged/serrated log pattern with moderate gamma and low neutron log responses (figures 7.4 and 7.5; lower part of log facies type "h" and upper part of log facies type "i", figure 6.5).

A significant feature which helps distinguish the lake basin facies is the lack of cross-bedding, desiccation cracks, and biogenic structures including burrows (see X-radiograph photo 7.3), which suggests that deposition took place below wave base in deep, stagnant anaerobic waters. The alternation of finely laminated black sapropelic/organic-rich mudstone with fine siltstone and claystone is attributed to seasonal fluctuation in sedimentation rates. The lower siltstone lamina indicates an
Photo 7.3. X-radiograph of the lake basin in DME Narrabri DDH 39, showing varved or graded laminations of fine siltstone/mudstone (dark) with average thickness of 1 mm to 2 mm, and organic-rich sapropelic mudstone (light grey) of similar thickness. Influx of fine-grained clastics is indicated by increasing frequency and thickness of darker layers towards the top. Core diameter is 65 mm (from Tadros 1993, photo 14.2)
influx of fluvial sediments during the wet season. The black sapropelic lamina suggests seasonal plant
growth (blooming) and settling of degraded organic matter from surface waters onto the lake bed during
seasons with low runoff and negligible sediment influx.

Recognition of the lake basin facies also depends on its association with the overlying (and underlying)
lake margin deposits.

FACIES ASSOCIATION

In the Mullaley Sub-basin, cyclic fluctuations of lake level and variations in sediment influx caused
marginal sediments to interfinger with lake basin sediments (figure 6.17D). A cyclic alternation
between the two facies can thus be recognised in core and geophysical log patterns (photos 7.1 and 7.2
and figures 7.2 and 7.4). The cycles are relatively thin, ranging in thickness from 3 m to 5 m, and up to
ten cycles are present (e.g. in DME Narrabri DDH 41, photo 7.2), but generally averaging six or seven
cycles. Typically, each cycle consists of organic-rich mudstone at the base, grading to
mudstone/siltstone and graded siltstone/sandstone laminite, which in turn passes into mainly sandstone
at the top. Contact with the overlying cycle is either gradational or erosional. The erosion surface may
be overlain by a thin upward-fining sequence of graded fine sandstone, siltstone and mudstone
interbeds with sparse burrows before passing upwards and basinwards into the organic-rich mudstone
(figure 6.20 and photo 7.2). Younger cycles are more sand dominant, marking the encroachment of the
Western Fluvial System over the Lacustrine System (figure 7.3 and photos 7.1 and 7.2). Infilling of the
lake with upward-coarsening sediment sequences was finally accomplished by the continued lakeward
progradation of crevasse splays and lacustrine deltas (photos 7.2 and 7.4 and figure 6.20).

The cyclic pattern of the lake sequence is perfectly represented on the geophysical log facies. Thin
finely jagged or serrated patterns representing the mudstone of the lake basin facies alternate with
progradational upward-coarsening unit representing the gradation from mudstone/siltstone to
siltstone/sandstone laminite and finally to sandstone at the top (figures 7.2, 7.4 and 7.5). The
sequences shown in photos 7.1 and 7.2 and the patterns illustrated in figures 7.2, 7.4 and 7.6 show fine
examples of lacustrine cyclic sedimentation in the northern part of the Mullaley Sub-basin.

7.3 WESTERN FLUVIAL SYSTEM

The importance of the Lachlan Fold Belt as a basin-wide sediment source for the Western Fluvial
System gradually increased as regional subsidence in the east terminated peat accumulation of the
Hoskissons Peat-Swamp System. The percentage sandstone map (figure 6.22) for the Western Fluvial
System indicate that quartz-rich sandstones were deposited by easterly and westerly streams which
were derived from the west in the Lachlan Fold Belt region. The streams were drawn to the east and
south-east by the rapid subsidence, which initially caused the transformation of the Hoskissons peat
swamps into the Lacustrine System, and finally the infilling of the lake (see chapter 6).
7. GENETIC FACIES ANALYSIS

Photo 7.4 A sequence from DM Millie DDH 1 consisting of the Hoskissons Coal at the base and showing gradational change to lacustrine sediments in the middle. Preserved bed-load sediments of the main axial channel complex of the Western Fluvial System dominate the upper part of the sequence between 320.25 m and 306.8 m. Each length of core is approximately 1 m (from Tadros 1993i, *photo 14.3b*)
Figure 7.6. Geophysical log pattern of the channel fills of the Western Fluvial System is sharply defined by low gamma and high neutron log responses (note upward-fining top), upper Black Jack Group in DME Narrabri DDH 17. For reference see figure 7.2 (from Tadros 1993i, fig. 14.13)
7.3.1 COMPONENT FACIES

The principal component facies of the Western Fluvial System are channel fill, channel margin and floodplain/floodbasin deposits. Their geophysical log profile is characterised by predominantly aggradational log facies, locally associated with moderately serrated log facies characteristic of floodplain/floodbasin sequences (refer to appendix 3 for borehole data).

CHANNEL FILL FACIES

The channel fill deposits consist mainly of medium- and coarse-grained quartz-rich sandstone, with quartz conglomerate locally developed. In drill core, the sandstone generally forms medium-bedded units with low-angle medium-scale tabular and trough cross-stratification (photos 7.5 and 7.6; compare with outcrop at Mount Watermark, photo 7.7).

Photo 7.5. Typical sequence of the Western Fluvial System, DM Tinkrameanah DDH 1. Each length of core is approximately 1 m (from Tadros 1993i, photo, 14.3a)
Photo 7.6. Planar tabular cross-bedding in a coarse- to very coarse-grained quartz-rich sandstone of the Western Fluvial System in DM Wallala DDH 3 (left) and DM Gunnadilly DDH 1 (far left). These features are characteristic of channel bar deposits. Scale is in centimetres (from Tadros 1993i, photo 14.4)

Photo 7.7. Close-up of a cliff-forming sandstone outcrop of the Western Fluvial System near top of Mount Watermark some 8 km west of Breeza, showing details of sedimentary structures of a bed-load channel facies. Scale ruler is 40 cm long. The top 10 cm of the scale is placed against a 20-25 cm tabular cross-stratified unit similar to that shown in photo 7.6 (from Tadros 1993i, photo 14.5)
Photo 7.6. Planar tabular cross-bedding in a coarse- to very coarse-grained quartz-rich sandstone of the Western Fluvial System in DM Wallala DDH 3 (left) and DM Gunnadilly DDH 1 (far left). These features are characteristic of channel bar deposits. Scale is in centimetres (from Tadros 1993i, photo 14.4)

Photo 7.7. Close-up of a cliff-forming sandstone outcrop of the Western Fluvial System near top of Mount Watermark some 8 km west of Breeza, showing details of sedimentary structures of a bed-load channel facies. Scale ruler is 40 cm long. The top 10 cm of the scale is placed against a 20-25 cm tabular cross-stratified unit similar to that shown in photo 7.6 (from Tadros 1993i, photo 14.5)
Large-scale trough cross-stratification cannot be positively identified in drill core, particularly in coarse-grained granule and pebble conglomerate. However, small scale trough cross-stratification can be identified in slabb ed large diameter core (65 mm, HQ size core). Only very small scale trough cross-stratification can be recognised in slim core (photo 7.8 and overlay).

Photo 7.8 Small-scale trough cross-stratification, interpreted as bar-top similar to those formed on the tops of sand flats in the South Saskatchewan River (Cant 1978).

a) photograph of a slabb ed core from DM Tinkrameanah DDH 1. Laminae and laminae sets are clearly defined by finely macerated organic material interspersed along contact surfaces.

b) map overlay of the slabb ed core in (a) to show that small scale trough and tabular cross-stratification can be differentiated in slim core (NQ size, 45 mm in diameter). Larger diameter core (HQ size, 65 mm diameter), which is available for many drill holes and is now standard in coal exploration, would undoubtedly improve interpretation. Scale is in centimetres.
Large-scale trough cross-stratification cannot be positively identified in drill core, particularly in coarse-grained granule and pebble conglomerate. However, small scale trough cross-stratification can be identified in slabbed large diameter core (65 mm, HQ size core). Only very small scale trough cross-stratification can be recognised in slim core (photo 7.8 and overlay).

Photo 7.8 Small-scale trough cross-stratification, interpreted as bar-top similar to those formed on the tops of sand flats in the South Saskatchewan River (Cant 1978).

a) photograph of a slabbed core from DM Tinkraneanah DDH 1. Laminae and laminae sets are clearly defined by finely macerated organic material interspersed along contact surfaces.

b) map overlay of the slabbed core in (a) to show that small scale trough and tabular cross-stratification can be differentiated in slim core (NQ size, 45 mm in diameter). Larger diameter core (HQ size, 65 mm diameter), which is available for many drill holes and is now standard in coal exploration, would undoubtedly improve interpretation. Scale is in centimetres.
The channel fill deposits are generally characterised by a blocky geophysical log pattern (figure 7.6; see also log facies type "d", figure 6.5). Individual channel fills are sharply defined by low gamma and high neutron log responses, some having upward-fining tops (figures 7.6 and 7.7; see also basal unit in log facies type "d", figure 6.5).

Figure 7.7. Geophysical log pattern of the channel fill and channel margin facies of the Western Fluvial System, upper Black Jack Group in DME Narrabri DDH 5. For reference see figure 7.2 (from Tadros 1993i, fig. 14.14)
The sequence illustrated in photo 7.5 (and its vertical profile analysis in figure 7.8) shows a typical sequence of the Western Fluvial System preserved along the western margin of the Mullaley Sub-basin in (DM Tinkrameanah DDH 1). The sequence preserved in DM Terrawinda DDH 1, some 12 km west of DM Tinkrameanah DDH 1, is considerably thinner but retains similar character (photo 7.9 and the vertical profile analysis in figure 7.9).

The sequence, between 319.2 m and 306.8 m in DM Millie DDH 1 in the central east, illustrated in photo 7.4, shows a succession through the main axial channel complex. Photo 7.10 and the vertical profile analysis in figure 7.10 illustrate a thick sequence of channel fills of the main axial channel of the Western Fluvial System in DM Gunnadilly DDH 1 in the southeast. The sequence shown in photo 7.11 and the close-up photo 7.12 from DM Wallala DDH 3 is another example from the south-eastern part of the sub-basin, except it demonstrates the gradual change in lithological composition from quartz-rich to dominantly volcanic-lithic detritus sourced from the east (see chapter 6 for detailed discussion).

A cliff-forming sandstone outcrop of the Western Fluvial System near the top of Mount Watermark, some 8 km west of Breeza, provided a unique opportunity for detailed outcrop mapping and the application of the architectural element analysis of Miall (1985). Photo 7.7 is a close-up of part of the outcrop, showing details of the sedimentary structures of the bed-load channel facies. A detailed architectural element analysis has been carried out on the Mount Watermark outcrop and is presented in detail under section 7.3.2.

Integration of vertical profile analysis of drill core and architectural element analysis on the outcrop of the Western Fluvial System at Mount Watermark indicates that this system was dominated by broad, shallow, low-sinuosity streams that carried bed-load material almost exclusively (see detailed study of the outcrop at Mount Watermark in section 7.3.2).

**CHANNEL MARGIN FACIES**

The channel margin facies consist of finely interbedded sandstone, siltstone and carbonaceous siltstone, and, in general, abruptly overlie the channel fill facies. They represent peripheral sedimentation in laterally restricted areas. These sediments are rare in the west, but form a minor component of the fluvial system in the eastern part of the Mullaley Sub-basin. They are characterised by moderately serrated log facies (figure 7.7 and log facies type "e", figure 6.5). Some units grade upwards into thin coal seams and display highly serrated log motifs (figures 7.6 and 7.7; also log facies type "f", figure 6.5).

Levees and crevasse splays form the two principal channel margin facies and are readily recognised in drill core. The levee sequence displays rapid interbedding of sandstone and siltstone, reflecting fluctuating but generally shallow flow depths. Primary sedimentary structures in the levee sequence include small, fine ripples, ripple cross-lamination, climbing ripples, wavy and plane parallel lamination and clay drapes (photos 7.13 and 7.14). Levees support plant growth, and thus their sediments show root disturbance and are rich in plant debris and organic matter (photos 7.13 and 7.14). Soft sediment deformation and scour-and-fill structures are common (photos 7.15 and 7.16).
Figure 7.8. Vertical profile, DM Tinkrameanah DDH 1
Crevasse splay deposits form elongate lobes or fan wedges originating at a crevasse channel cut in the levee. The sediment load of crevasse splays is dominated by silt and fine sand but can also be coarser in dominantly sandy bed-load streams, as is frequently the case with the Western Fluvial System. Internal structures such as climbing ripple cross-lamination reflect rapid sedimentation (photo 7.17). Other common structures include ripple and medium-scale trough cross-lamination, mud drapes, graded bedding and scour-and-fill structures (photo 7.17). Upward-coarsening sequences may develop as the crevasse splay continues to prograde with successive floods over the floodbasin (photo 7.18). Colonisation by plants results in disturbance of underlying depositional structures and the formation of oxidised and leached zones (palaeosols; photo 7.17). Abandonment of a crevasse splay is indicated by upward-fining of grain size and by a decrease in scale of sedimentary structures, with macerated products of organic material commonly preserved on bedding surfaces, laminations and cross-bedding planes (photos 7.19 and 7.20).
Westerly-derived coarse-grained quartz-rich sandstone interpreted as channel fill of the Western Fluvial System in DM Terrawinda DDH 1. The upper part of the sequence is upward-fining to channel margin and floodbasin deposits. Coal seams 7 and 8 at the top and base of the sequence have been sampled. Each length of core is approximately 1 m
Photo 7.10. A thick sequence of westerly-derived, coarse-to-medium-grained quartz-rich sandstone interpreted as channel fills of the main axial channel of the Western Fluvial System in DM Gunnadilly DDH 1 in the south-eastern part of the Mullaley Sub-basin north of the Liverpool Range. Each length of core is approximately 1 m.
Figure 7.10. Vertical profile for the sequence shown in photo 7.10, DM Gunnadilly DDH 1. For reference see figure 7.8.
7. GENETIC FACIES ANALYSIS

Photo 7.11.
(a) (left) Sequence in DM Wallata DDH 3 showing gradual change from westerly sourced quartz-rich sandstone upwards to volcanic-lithic detritus sourced from the east. Each length of core is approximately 0.7m.

(b) (top right) An enlargement of the upper part of the three core lengths in photo 7.11a.

Photo 7.12. (top left).
Close-up of part of photo 7.11 showing intermixed westerly and easterly sourced lithologies. Scale is in centimetres. Core diameter is approximately 65 mm.
Photo 7.13. Channel, channel margin, floodbasin sequence in DME Narrabri DDH 5. Levee facies is between approximately 335.9 m and 334 m. Top 1.2 m is coal. Each length of core is approximately 1 m (from Tadros 1993, photo 14.6).

Photo 7.14. Broadly upward-fining sequence in DME Narrabri DDH 1 interpreted as channel-channel margin deposit of the Western Fluvial System in the northern part of the Mullaley Sub-basin. Planar and trough cross-stratified, medium to coarse-grained sandstone, with sharp planar base above coal seam at 215 m, represent in-channel erosive deposits. Decreasing scale of sedimentary structures and grain size characterise the middle portion; medium trough cross-stratification and truncated laminations indicate dune migration characteristic of midbar. Ripples, tabular planar stratification occur in the finer-grained upper portion. Mud drapes and root disturbance increase progressively upwards. The uppermost metre of the sequence (base at 212.6 m) represents a thin levee deposit characterised by alternating sand, silt and mud layers. Each length of core is approximately 1 m.
Photos 7.15. (above left) and 7.16. (above right). Soft sediment deformation structures in channel margin deposits produced by gravity slumping (figure 7.15) and by overloading (figure 7.16). Sediment overloading causes lateral and vertical movements which can produce faults (microfaults in figures 7.15 and 7.16). Load casts and scour-and-fill structures are also present (figure 7.16).

FLOOD BASIN FACIES

Fluvial channel type determines the extent to which floodbasin sediments develop (Schumm 1960, 1972, 1977). Bed-load channels tend to form amalgamated multilateral channel fills as a result of rapid lateral migration. Here, only remnants of thin overbank deposits are preserved. The Western Fluvial System is dominated by a bed-load axial channel complex and principal tributaries, indicating that a large percentage of the load transported was coarse sediment and that there was a significant lack of fines. Sediments were carried by a south-easterly contributory channel system via an axial drainage complex into a large interchannel lacustrine system developed as a result of a rapid subsidence in the eastern part of the basin. Consequently, development of typical floodbasin deposits was limited to
Photo 7.17. Crevasse splay sequences in DM Parsons Hill DDH 1. Note scour-and-fill structure below 780.4 m depth marker. Each length of core is approximately 1 m (from Tadros 1993i, photo 14.7)
7. GENETIC FACIES ANALYSIS

Photo 7.18. Close-up of a thin crevasse splay in DM Parsons Hill DDH 1 showing subtle upward-coarsening sandstone indicating progradation, followed by upward-fining sequence with laminae of macerated organic material indicating abandonment. Scale is in centimetres. Core diameter is 45 mm. Refer to photo 7.17 for location in the channel margin sequence.

Photo 7.19. (above). Finely macerated organic material preserved on bedding and cross-bedding planes in DM Gunnaddilly DDH 1. Low angle cross-bedding is normally characteristic of crevasse splay deposits. Scale is in centimetres. Core diameter is 45 mm.

Photo 7.20. (right). Finely macerated organic material dispersed near the top of a thick crevasse splay in DM Parsons Hill DDH 1. Note the upward-fining grain size. Scale is in centimetres. Core diameter is 45 mm.
areas above the lake level and in the western region. Elsewhere, floodbasin deposits were modified by the lacustrine processes at the lake margins and deeper into the lake basin (as is discussed in detail under the Lacustrine System).

The sand content of the floodbasin facies may vary considerably depending on the proximity to active channels and crevasse splay centres. Floodbasin deposits in the western part of the Mullaley Sub-basin, and locally in some northern and southern areas, consist of mostly uniform, finely laminated mudstone with sporadic sandstone or siltstone intercalations representing the distal "feather edge" of large crevasse splays. Photo 7.21 displays a good example of variable sand input in a floodbasin sequence in proximity to an active channel. Peat was also part of the floodbasin facies and accumulated in broad areas of sediment by-pass. Primary structures were sporadically destroyed by burrowing, plant growth and pedogenic processes. Desiccation cracks in mudstone horizons are rare, reflecting occasional exposure to wet and dry conditions.
7.3.2 DEPOSITIONAL ARCHITECTURE - AN OUTCROP STUDY OF THE WESTERN FLUVIAL SYSTEM

CONCEPTS

In an attempt to overcome the problem of proliferation of fluvial facies models which are based on analysis of vertical profiles, Miall (1985) proposed a method of facies analysis utilising the fundamental attributes of depositional systems, such as composition and geometry of the framework elements. Miall's proposal is based on work by Friend (1983), Allen (1983) and Ramos and Sopena (1983). The method, which incorporates the most recent concepts in analysis of fluvial systems, has been applied in this chapter and is reviewed together with some relevant aspects of Allen's (1983) work. Miall (1985) subdivided fluvial deposits into local suites consisting of one or more of a set of eight basic three-dimensional architectural elements (macroforms - up to a few hundred metres in width and length) which define a wide range of fluvial depositional styles (table 7.1A and figure 7.11). These are: channels (element CH), gravel bars and bedforms (element GB), sandy bedforms (element SB),

TABLE 7.1A

Please see print copy for image

* Explanations of lithofacies symbols (codes) are given in table 7.1B
TABLE 7.1B

LITHOFACIES CLASSIFICATION AND FACIES CODING SYSTEM OF MIAALL (1978)

Please see print copy for image
The major architectural elements (from Miall 1985); note vertical exaggeration and variable scale foreset macroforms/downstream accreting macroforms (element FM/DM), lateral accretion deposits (element LA), sediment gravity flow deposits (element SG), laminated sand sheets (element LS) and overbank fines (element OF; figure 7.11). Miall also provided examples of twelve fluvial systems to illustrate possible combinations of these elements and suggested that all fluvial deposits are composed of varying proportions of the eight elements.

The architectural elements are defined by nature of bounding surfaces (erosional, or gradational; planar, irregular, curved, etc.), external geometry (sheet, lens wedge, etc.), scale (thickness, lateral extent, etc.) and its internal geometry (lithofacies assemblage, vertical sequence, secondary erosion surfaces, etc.) (figure 7.11). In order to reveal their cross-section geometry, definition of architectural elements requires good outcrops in the order of tens of metres in width preferably with some three-dimensional control. A complete description of architectural elements results from the integration of outcrop information with subsurface data.

The outcrop-scale and complexity of the architectural elements vary considerably. Smaller elements would normally be present as complexes (Allen 1983) within larger elements, thus forming a hierarchy of scales bounded by bedding contacts of variable significance (Miall 1985).
Allen (1983) and Miall (1985) defined a hierarchy of three types of bedding contact (figures 7.12 and 7.13). First-order contacts bound individual cross-bed sets. Second-order contacts bound cosets (complexes of Allen 1983) of the type delineated by first-order contacts, or genetically related lithofacies assemblages. Third-order contacts define the sandstone bodies themselves (sandstone sheets of Friend et al. 1979), comprising groups of elements (or complexes), and usually are well-defined erosion surfaces such as the basal scour surface of a major channel. A third-order contact surface is planar or very gently concave-up overlain by rocks of facies G2 or G3 (see lithofacies description below). Allen (1983) referred to the ordinary non-erosional concordant bedding contacts between strata or laminae in the cross-bed sets as the (zeroth) order of bedding contact (figure 7.13).

Four of the eight architectural elements are the most common in-channel forming deposits in bed-load fluvial systems. Discussion of these elements follows that of Miall (1985).

**Channels (element CH)** vary in size, and major channels are rarely adequately exposed. Therefore, channel geometry can only be reconstructed given adequate lithofacies information. Smaller size channels are more amenable to field analysis. Most of the other architectural elements are contained partly or entirely within the major channels or palaeovalleys (Miall 1985; figure 7.11).

Channels have concave-up, erosional bases and erosional or gradational channel-fill tops. Channel fills are commonly present in a multistory configuration. Each storey is bounded by an erosion surface (figure 7.14).

Definition of the channel margin is necessary for the recognition of the channel-fill element. This requires correlation of closely spaced outcrop or subsurface sections. Defining the channel margin of broad mobile or sheet-type channels, such as in braid plains, may be difficult or impossible. In such cases field analysis is likely to focus on the fill in terms of other architectural elements. Stacked
Figure 7.13. Allen's (1983) summary of the features of the sheet sandstones present in the Brownstones in the forest of Dean, southern Welsh Borders. (A) Hierarchy of bedding contacts, sedimentary facies and position of sedimentation units in depositional sequence; (B and C) hierarchy of lower-order bedding contacts (from Allen 1983, fig. 8)

Figure 7.14. Geometry of individual active channels and their channel fill complex. Numbers above each channel complex are width to depth ratios. A, D represent simple channels; B, E and F display broad channel-fill complexes formed by lateral migration or switching with little contemporaneous subsidence; C shows stacked channel complex formed by vertical aggradation within a relatively stable channel under conditions of rapid subsidence (from Miall 1985, fig. 3)
channel complexes formed by vertical aggradation, either by progressive abandonment, as a result of upstream avulsion or the plugging action of flash floods, commonly show finning-upward successions (e.g. GB--FM--SB--OF or LS--SB--OF; architectural element symbols, table 7.1A).

In high sinuosity systems, channels may be abandoned by chute or neck cut-off and filled by OF deposits which commonly have channelized concave bases.

**Gravelly bars and bedforms (element GB)** in its simple form is represented by "diffuse gravel sheets" a few clasts thick with diffuse, lobate margins and move only during peak flow (lithofacies Gm, massive or crudely bedded gravel). These sheets grow upward and downstream, during episodes of high water and sediment discharge, to form longitudinal bars (Rust 1972) up to 1 metre in height and may show either an increase or decrease in clast size upward depending on their mode of accretion. However, bars tend to fine and migrate downstream and also tend to migrate and fine downstream (Gustavson 1978).

Stratified gravel with planar cross-beds characterise bars built into deep water (lithofacies Gp, gravel, stratified with planar cross-beds, Miall 1978; table 1B). Lithofacies Gp also characterise cross-bedded chute bars where minor channels debouch into pools. Element GB can form multi-storey sheets, tens to hundreds of metres thick, with flat or irregular erosion surfaces between bar sets. This element may also be interbedded with sheets or lenses of element SG: sediment gravity flow. Slack water deposits or bar edge sand wedges represent element GB and comprise up to 10% of element GB.

**Sandy bedforms (element SB)** are fields or trains of individual bedforms such as dunes, transverse bars and sand waves. Dunes occupy the deeper portions of active sandy bed-load channels and form lenses or lobes of trough cross-bedded sand. They may be cut by broad shallow scours or erosion surfaces indicating river stage fluctuation. Transverse bars or sand waves are common in the shallower parts of channels, including the tops and flanks of macroform elements (such as point bars and sand flats). These form sheets of planar-tabular cross-bedding (lithofacies Sr, Miall 1978; table 7.1B).

**Foreset macroforms (element FM)** are large compound bar forms and sand flats (including point bars and bank-attached forms, and represent the most vigorous depositional activity of fluvial flow systems. Macroforms may be up to a kilometre across and contain a complex internal geometry bounded by second-order surfaces that can only be adequately studied in large exposures with three-dimensional control. The macroforms consist of cosets of flow regime bedforms dynamically related to each other by a hierarchy of internal bounding surfaces (Miall 1985).

Macroform geometry and internal structures vary considerably depending on channel depth, grain size, discharge amount and variability. Macroforms accrete sediments by bedform capture on the upstream or flanks and partly by preservation of superimposed bedforms on the advancing downstream face (downstream accreting macroforms element DA). Internal stratification and structures include tabular and trough cross-beds, horizontal laminations, ripple laminations and erosional surfaces (Miall 1985).
FIELD METHODS

Detailed mapping of the lateral and vertical facies relationships and the description of three-dimensional architecture require a good quality (and accessible) outcrop with some three-dimensional control to enable construction of true scale cross-sections showing lateral variability. Information from nearby boreholes can also be useful. Large/long outcrops can be mapped and put together using photomosaics and essential bedding contacts, details of internal cross-bedding, lithological (and palaeocurrent) information can be drafted on overlays (Allen 1983, Miall 1985).

A field mapping method, modified after Allen (1983), Miall (1985) and Glasford (1989), was applied to an outcrop of the Clare Sandstone - the stratigraphic unit comprising the Western Fluvial System - present near the top of Mount Watermark, some 8 km west of Breeza (figure 7.15 and photo 7.22). The outcrop forms a 10-12m high, northeast-facing cliff wall which is roughly divided into two benches, the lower one is masked by dense vegetation and inaccessible for detailed mapping. Detailed systematic examination and mapping of the architectural elements on the cliff wall was carried out on about 26 m of the upper bench. Particular attention was paid to mapping of bedding contacts, for these, as Allen (1983) and Miall (1985) suggest, are the key to the structure and architecture of the sandstone bodies.

Photo 7.22. Mount Watermark is located some 8 km west of Breeza. Outcrop of the Clare Sandstone - the stratigraphic unit comprising sediments of the Western Fluvial System - forms a 10-12 m high, northeast-facing cliff wall just visible as a thin line near the top of the mountain. Photo taken looking south south-westerly
Figure 7.15. Topographic map showing location of the outcrop of the Clare Sandstone on the north-eastern side of Mount Watermark. The arrow points to the cliff wall on which architectural element analysis has been carried out in detail.
Bounding surface hierarchy and numbering systems, similar to those of Allen (1983) and Miall (1985) described above, are used in this study to delineate outcrop-scale fluvial architecture. Miall's third-order surfaces which delineate channel-fill complexes, second-order bounding surfaces delineating downstream accreting macroform, sandy bedforms, small channel fills within the larger complex and first-order bounding surfaces separating individual cross-bed sets are shown on the photomosaic interpretations (figure 7.16), and in detail on three plastic overlays (photos 7.23 - 7.25). Palaeocurrent directions were also measured where possible (see appendix 3).

The cliff wall was photographed using standard (35 mm) and Polaroid cameras. Instant "Polaroid" photographs were extremely useful for sketching various bedding details directly on them, whereas the standard colour photographs were used, later in the laboratory, for the construction of the photomosaic. Visibility of diffused structures on photographs and at the cliff wall was greatly improved when the sun was at high angle, around mid-day. At Mount Watermark, third-order contacts, which are commonly overlain by rocks of facies G2 or G3 (see lithofacies description below), weather back to form shaded linear notches on the cliff wall and extend over several metres, some over nearly half the full length of the outcrop. Bedding contacts, cross-bedding and other structural/architectural elements were later transferred to a drafting plastic overlay and photographically reduced. The pebbly sandstone beds were then marked on the plastic overlay and screened, and a vertical section was drafted on either end of the section. Final reduction of the section to page size was then made (figure 7.16). The section is presented in three parts (photos 7.23 - 7.25) with the architectural elements shown on the plastic overlays. Photo 7.7 is a close-up of the cliff wall showing details of the architectural elements and lithofacies of the middle part of the outcrop.

**LITHOFAECIES**

The following eight lithofacies have been observed at Mount Watermark. They are comparable, and in many respects similar, to facies described by Allen (1983) for the middle to upper Brownstones in the forest of Dean, southern Welsh Borders. Allen also described a rare mudstone facies (M) in the Brownstones but it is absent at Mount Watermark. The facies are partly equivalent to lithofacies described by Miall (1978). Terminology and discussion of the lithofacies used in this study follow that of Allen (1983; figure 7.13).

1) A pebble stringer facies (G1) is a single line of strung-out to crowded quartz pebbles arranged along an erosional bedding contact. The pebbles may be limited to a short distance along the contact, or may extend over several metres. Walker (1976), Rust (1978) and Allen (1983) recognise a similar facies in other fluvial sandstones.

2) A massive conglomerate facies (G2) is the result of an increase in the number of layers of pebbles, which may locally result in an internal stratification. The beds range in thickness from 0.1 to 0.3m and consist of a mixture of sub-rounded quartz pebbles in a matrix of very coarse to granule quartz sandstone. Pebble imbrication is only locally developed. The base is erosional and irregular with occasional scours up to 0.15m deep.
Figure 7.16. Photomosaic interpretations of the cliff-forming outcrop of the Clare Sandstone (the stratigraphic unit forming the Western Fluvial System), near the top of Mount Watermark west of Breeze, showing the areas covered in detail in photos 7.23 - 7.25 and the area of the close-up in photo 7.7. The main sand sheet described in the text spans photos 7.23 and 7.24 and just over half of photo 7.25.
Photo 7.23. (page 321)
The south-eastern part of the cliff-forming outcrop of the Clare Sandstone (the stratigraphic unit forming the Western Fluvial System), near the top of Mount Watermark west of Breeza, and a plastic overlay showing photomosaic interpretations of the main architectural elements (GB, FM, etc.), lithofacies (G1, G2, S1, S2 ... etc.), sand units and bar complexes of the main sand sheets (units 1, 2, 3 ... 12) and hierarchy of bedding contacts [(1), (2), (3)]. For detailed discussion and explanation of codes see text and figures 7.11 - 7.13. For location of this photograph see figure 7.16.

Photo 7.24. (page 322 - opposite)
The middle part of the cliff-forming outcrop of the Clare Sandstone (the stratigraphic unit forming the Western Fluvial System), near the top of Mount Watermark west of Breeza, and a plastic overlay showing photomosaic interpretations of the main architectural elements (GB, FM, etc.), lithofacies (G1, G2, S1, S2 ... etc.), sand units and bar complexes of the main sand sheets (units 1, 2, 3 ... 12) and hierarchy of bedding contacts [(1), (2), (3)]. For detailed discussion and explanation of codes see text and figures 7.11 - 7.13. For location of this photograph see figure 7.16.
Photo 7.25. (page 323 - opposite)
The north-western part of the cliff-forming outcrop of the Clare Sandstone (the stratigraphic unit forming the Western Fluvial System), near the top of Mount Watermark west of Breeza, and a plastic overlay showing photomosaic interpretations of the main architectural elements (GB, FM, etc.), lithofacies (G1, G2, S1, S2 etc.), sand units and bar complexes of the main sand sheets (units 1, 2, 3 ...12) and hierarchy of bedding contacts [(1), (2), (3)]. For detailed discussion and explanation of codes see text and figures 7.11 - 7.13. For location of this photograph see figure 7.16.
3) A cross-bedded sandy conglomerate facies (G3) is more commonly present than facies G2. The beds range in thickness from 0.15 to 0.4 m and consist of quartz pebbles, some up to cobble size, in a matrix of quartz-rich sandstone. Pebble trains show high-angle cross-bedding. The base and top are erosional and irregular.

4) A cross-bedded pebbly sandstone facies (S1) is similar to G3 but with higher proportion of sandstone matrix, and pebble size is markedly smaller. The beds consist of coarse to very coarse quartz-rich sandstone with locally abundant granules. This facies commonly forms medium- to high-angle (tabular) cross-bed sets with granules and small pebbles locally forming trains marking individual cross-bed contacts. The beds range from 0.2 to 0.8 m in thickness and normally have sharp erosional bases and tops.

5) A cross-bedded sandstone facies (S2) is characterised by loss of pebble size quartz grains but still consists of coarse to very coarse quartz-rich sandstone. Thickness range and internal stratification are similar to S1. Bedding contacts are also sharp and erosional.

6) A trough cross-bedded sandstone facies (S3) consists of grouped trough-shaped cross-bed sets measuring, in the vertical profile along the cross-section, from 0.35 to 1 m in width and between 0.1 and 0.25 m in height. The cross-strata are characteristically concave-up and have tangential relationship to the underlying bounding surfaces. The sandstone is medium- to coarse-grained and quartz-rich.

7) A coarse plane-bedded sandstone facies (S4) is represented typically by parallel laminae of coarse to very coarse quartz-rich sandstone with orientation oblique to beds which range in thickness from 0.1 to 0.2 m.

8) A fine plane-bedded sandstone facies (S5) is not common. The facies form thin tabular, wedge or lens-shaped beds consisting of fine- to medium-grained sandstone and characterised by absence of granules and pebbles. Internal stratification is similar to facies S4.

SANDSTONE ARCHITECTURE

The profile, mapped at Mount Watermark, reveals a sandstone sheet, defined by third-order contacts, extending over the full length of the upper bench of the cliff wall. Small sections of two underlying sheets were also mapped at the northern end of the cliff wall. They form the only accessible part of the lower bench, but are too small to allow detailed interpretation, nevertheless, by comparison (figure 7.16), they appear similar to the overlying main sand sheet.

The main sheet is up to 3.0 m thick, revealed in a slightly oblique-dip section on a largely south-easterly-trending profile. It overlies an irregular erosion surface with scour pits and mantled by pebbles of facies type (G1). The upper bounding surface is also erosional and shows a very broad convex-up profile. The sheet is dominated by coarse to very coarse sandstone with no indication of upward-fining, except for the presence of pebbly facies at the base. It comprises six bar complexes (terminology of Allen 1983).
The oldest complex (unit 1) is up to 0.5m thick and appears in an oblique-dip section (paleocurrents are a few degrees off to the west into the cliff face). The unit represents mainly pebble stringer facies (G1), cross-bedded sandy conglomerate facies (G3) and to a lesser extent massive conglomerate facies (G2), and locally contains thin sandstone lenses of plane-bedded sandstone facies (S4). This unit is interpreted as gravely beds and bedforms, element (GB) of Miall (1985). The complex probably represents the base of a channel, axially filled.

The second complex (unit 2) rests on a scour surface descending about 0.5m into the older complex. It consists of pebbly trough cross-bedded coarse-grained sandstone facies (S3), truncated by a pebble-studded second-order erosional surface. The complex is interpreted as sinuous-crested dunes (Cant 1978) deposited in a deep channel during rising flood stage. Similar to the older complex, it probably represents a channel axially filled.

The third complex, exposed mainly in dip section, extends along the full length of the cliff wall and thickens from 0.25m upstream (north-western end of the profile) to just over a metre downstream. At the south-eastern end, it forms a thin draped sandstone sheet riding over the underlying dune bed. The complex comprises mainly cross-bedded simple (S1 and S2) bars. The main bar (unit 3) which entered the section at the right (north-western end) has a tabular to lenticular morphology and split up into two bars towards the middle. It consists of 0.25-0.6m tabular cross-bedding formed by 3-6 cm packets of pebbly- to very coarse-grained sandstone. Unit 4, which also has a tabular to lenticular morphology with similar internal stratification, advances over unit 3 and continues for several metres before it thins out as it rides over the older complex. Units of this complex are interpreted as downstream accreting macroforms element (FM) of Miall (1985), and are recognised by their convex-up second-order bounding surfaces and their internal stratification. These macroforms are probably simple bars deposited in a broad, shallow, low sinuosity channel.

The fourth complex (units 5-8) is sharply defined by second-order lower and upper erosional contacts. It thickens downstream from 0.3m (unit 5 right) to 0.65m (unit 5 left). The units in this complex are represented mainly in a dip-section to slightly oblique (a few degrees off into face). The upstream end of unit 5 and the whole of unit 6 are masked by moss and surface vegetation and complicated further by diffused surface relief of low-order contacts, thus hindering interpretation. The complex consists mainly of cross-bedded simple (S1 and S2) bars represented by unit 5, and pebbly trough cross-bedded sandstone (S3) represented by units 7 and 8. The older unit of this complex (unit 5) is interpreted as a downstream accreting bar macroform element (FM; characterised by their convex-up second-order bounding surfaces and internal stratification) followed by a change in current direction and intensity and the formation of dunes on a locally scoured surface on top of the larger bar macroforms, and thus represent bar-top channels.

Surface moss and vegetation mask large areas of the fifth complex. In addition, much of the remaining areas do not show good relief to enable delineation and mapping of low-order bounding surfaces and internal structures. Therefore, interpretation of this complex is limited. The complex enters the section near the middle, and continues to the south-eastern end (right hand side of profile). Its lower surface
forms a deep scour into the underlying complex and levels off in a downstream direction. A smaller scour about a metre long and 0.1-0.15m deep is also present in the lower surface near the south-eastern end. The upper bounding surface is also erosional, but less irregular, mantled by a layer of quartz pebbles and shows a broad convex-up profile. The complex comprises mainly cross-bedded simple (S1 and S2) bars. The oldest and by far the largest unit in this complex (unit 9) enters the section in an "oblique-dip" direction but seems to swing around to become almost a dip section downstream. It has a tabular to lenticular morphology. It consists of 0.3-0.4m tabular cross-beds. In view of its convex-up second-order bounding surface and its internal stratification, this complex is interpreted as representing downstream accreting macroforms, (element FM) deposited as simple bars in a broad shallow, low sinuosity channel.

Quality of the rock surface deteriorates rapidly upwards towards the top of the cliff wall which makes mapping of low-order boundaries of the sixth complex almost impossible. However, on the little evidence available, it can be concluded that the sixth complex represents a repetition of the underlying (fifth) complex, except it is longer and extends over the full length of the cliff wall.

DEPOSITIONAL MODEL

Although the application of architectural element analysis can provide an excellent means of modelling the fluvial style of an ancient sequence, and has been applied to Mount Watermark, this author agrees with Miall (1985) that uncritical pigeonholing or force-fitting of field examples into any of his models should not be pursued. Therefore, in the following discussion the fluvial style at Mount Watermark is compared with six different models, the first three are based on the concept of architectural element analysis, followed by a comparison with models based on vertical profile analysis, as this helps the transition from outcrop to drill core analysis.

a) Comparison with models based on architectural element analysis

The sequence at Mount Watermark consists of several sand sheets, each containing a number of bar macroform complexes. Each sand sheet is bounded at the base by an erosion surface with scour pits and lined by pebble stringers, which in turn are overlain by cross-bedded sandy conglomerate and plane-bedded sandstone representing base of channel-fill (lithofacies Gm, Miall 1978; table 1b; figure 7.16; photos 7.23 - 7.25). The analysed sheet has a second scour surface marking the base of the overlying unit, which consists of pebbly trough cross-bedded, coarse-grained sandstone (lithofacies St, channel floor dunes, Miall 1978; table 1b) truncated by pebble-studded erosional surfaces. This unit is interpreted as channel bed sinuous crested dunes deposited during rising flood stage. The succeeding group of units are mainly planar cross-stratified (lithofacies Sp, the Platt model, Miall 1977) generally with lenticular morphology, and are interpreted as simple and compound downstream accreting bar macroforms. The units are interspersed by one or two trough cross-bedded sand bodies (figure 7.16; photos 7.23 - 7.25) representing sand dunes developed on locally scoured surface of large bar macroforms as bar top channels.
Fluvial architecture of the sand sheets at Mount Watermark compares favourably with Models 9 and 10 of Miall (1985; figures 7.17 and 7.18) for low sinuosity rivers, and the middle-upper Brownstones of Allen (1983; figure 7.19). Model 9 (figure 7.17) encompasses broad shallow, low sinuosity streams carrying an abundant sand bed-load. The channel is filled with fields of large linguoid bedforms (bars), with deeper channels occupied by trains of dunes. Preservation of a complete macroform deposit may result in a coarsening-upward sequence (Crowley 1983). Partial macroform sequences consist of numerous superimposed sets of Sp (the Platte-type model of Miall 1977, as described below). Other lithofacies, including St (channel floor dunes), Sr (bar-top ripples) and Gm (channel lags) are rare. According to Miall (1985), the typical architecture of this model consists of tabular sheets of element SB, however his block diagram for model 9 (figure 7.17) clearly illustrates grouping of the sheets into a dominant element FM, similar to the analysed sand sheet at Mount Watermark.

Model 10 of Miall (1985; figure 7.18) is characterised by large macroforms (sand flats of Cant and Walker, 1978; sand shoals of Allen 1983; compound bars of Miall 1977, 1981), which in many deposits show fining-upward cycles, recording the superimposition of channel, bar, and bar-top deposits (Cant and Walker 1978; South Saskatchewan model of Miall 1978). Such cycles cannot be thicker than the depth of the channel (Miall 1985), but long term aggradation can lead to thick sequences.
Allen (1983) in his facies model for the middle-upper Brownstones (figure 7.19) leaned most on the evidence of South Saskatchewan River (although he strongly emphasised the importance of lateral accretion in low-sinuosity sand-based rivers). The level erosional base to a sandstone sheet, and the overlying scattered intraformational debris (pebble-lag, lithofacies G1 and G2 described above or Gm of Miall 1978), arise as the river bites laterally into mud-draped valley flats. The complexes (forming a sand sheet) probably represent whole sand flats. The assemblages of "downclimbing bars" (downstream accreting macroforms DA/AM of Miall 1985) emphasise an axial or near axial section in the distal part of a larger sand flat that grew downstream by forward accretion as bars advanced over its top, down its leading face (downstream accreting macroform, DA, shown in the associated dip-section (figure 7.19), and around its flanks (lateral accretion, LA, as shown in strike-section, by half of a bilaterally symmetrical growth structure).

Figure 7.19. Allen's (1983; fig. 19) model for the middle-upper Brownstones of the Ross-on-Wye area, Forest of Dean, South Welsh Borders, showing a wide sand flat exposed in sections parallel with the depositional strike and dip. Vertical scale greatly exaggerated

b) Comparison with models based on vertical profile analysis

The sequence at Mount Watermark combines features characteristic of low sinuosity rivers of the "Platte-type" (figure 7.20a; Smith 1970, Miall 1977) and the "South Saskatchewan type" (figure 7.20b; Miall 1978 based on studies by Cant 1978, Cant and Walker 1978), or its ancient analogue - the "Battery Point Formation" (figure 7.20c; Cant and Walker 1976, 1978, Cant 1978, Walker and Cant 1984). These sequences are dominantly sandy, and there is little vertical trend in grain size in the sand bodies. At Mount Watermark, the sequence is dominated by planar cross-bedded units representing large bars and sand waves characteristic of the "Platte-type", and subordinate amount of trough-cross-bed sets, which in the case of the "end member" in the South Saskatchewan type and Battery
Figure 7.20. Vertical profile models of the (A) Platte-type and (B) South Saskatchewan type (arrows show small-scale cyclic sequences; Miall 1978, fig. 1), and (C) Battery Point summary sequence (Cant 1978, fig. 2; after Cant and Walker 1976)

Point sequence, "represent dune formation in aggrading channels where no cross channel bars formed" (Cant 1978; compare with vertical profiles of the Western Fluvial System in DM Gunnadilly DDH 1, figure 7.10; DM Terrawinda DDH 1, figure 7.9; and DM Tinkrameanah DDH 1, figure 7.8). Cant (1978) and Cant and Walker (1978) interpreted planar cross-bedded units in the Battery Point sequence as "Sand Flat" sequence or sandy foreset bars migrating at high angle to the channel trend.

Channel scour is well represented at Mount Watermark, Units 1 and 2 (figure 7.16; photos 7.23 - 7.25) show multiple scour near their bases, suggesting that channel aggradation may have been intermittent, with a few (but not necessarily short) periods of erosion also occurring, similar to some sequences in the Battery Point Formation (Cant 1978).

Although the outcrop at Mount Watermark does not contain fine siltstone and claystone units at its top, vertical profiles for DM Gunnadilly DDH 1 (figure 7.10), DM Terrawinda DDH 1 (figure 7.9) and DM Tinkrameanah DDH 1 (figure 7.8), clearly show that the sand sheets are capped with thinly laminated and ripple cross-laminated fine-grained units, of variable thickness.
Conclusion

The sandstone sequence of the Western fluvial sequence at Mount Watermark was deposited by discrete, broad, probably shallow, low sinuosity channels. The fluvial architecture of the sand sheets compares favourably with Models 9 and 10 of Miall (1985; figures 7.17 and 7.18) for low sinuosity rivers, and the middle-upper Brownstones of Allen (1983; figure 7.19). The sand bodies were built mainly as bar macroforms by downstream accretion. The deeper parts of the channel were occupied by dune fields. Dunes also formed in bar-top channels. Bedforms and channel erosion as well as bar-top channels occurred at high flow stage as indicated by the coarse-grained sediment fraction. The limited outcrop at Mount Watermark does not allow easy recognition of different types of bar macroforms.

In vertical profile, the sequence at Mount Watermark and other areas in the basin, combines features characteristic of low sinuosity rivers of the "Platte-type" (figure 7.20a; Smith 1970, Miall 1977) and the "South Saskatchewan type" (figure 7.20b; Miall 1978 based on studies by Cant 1978; Cant and Walker 1978), or its ancient analogue - the Battery Point Formation (figure 7.20c; Cant and Walker 1976, 1978, Cant 1978; Walker and Cant 1984).

The sequence formed as part of the south-east-trending axial trunk channel (as indicated by sand body geometry (chapter 6), and palaeocurrent directions (appendix 3), which ensured that the channel-fill complexes amalgamate vertically as well as laterally, but within the confines of the width of the broader axial trunk system.

7.4 EASTERN FLUVIAL SYSTEM

7.4.1. COMPONENT FACIES

The main genetic facies recognised in the Eastern Fluvial System are channel fill, channel margin and floodplain facies. They are characterised by a variable composite of two types of geophysical log facies: blocky aggradational; and highly serrate.

CHANNEL FILL FACIES

Volcanic-lithic conglomerate is the dominant lithology of the channel fill facies. It consists of varying proportions of silicic and mafic volcanics, chert and jasper in a lithic sand and clay matrix (photos 7.26 - 7.28), and generally forms massively bedded units, 1-5 m thick, with minor upward-fining tops (photo 7.29 and vertical profile analysis figure 7.21). The aggregate thickness of these conglomeratic sequences generally ranges from 20 m to 30 m except in the south-east where they exceed 160 m. Clast size ranges from pebble to granule (Photos 7.26 - 7.28) and generally shows a gradual and progressive decrease towards the west. The conglomerate sequences are generally characterised by blocky aggradational log facies represented by a homogeneous geophysical log pattern (log facies type "a", figure 6.5 and 7.22). The high neutron response of the conglomerate units
Photo 7.26. Channel fill, lithic, mainly clast supported, pebble conglomerate of the Eastern Fluvial System in DM Gunnadilly DDH 1. Scale is in centimetres. Core diameter is 45 mm

Photo 7.27. Channel fill, lithic, clast and matrix supported, pebble to granule conglomerate of the Eastern Fluvial System in DM Breeza DDH 1. Scale is in centimetres. Tabular cross-stratification is indicated by the plane of inclination of elongated grains between the 7 and 8 cm mark on the scale. Core diameter is 45 mm

Photo 7.28. Channel fill, lithic, granule conglomerate and sandstone of the Eastern Fluvial System in DM Breeza DDH 1. Scale is in centimetres. Core diameter is 45 mm
Photo 7.29. Part of the Eastern Fluvial System in DM Gunnadilly DDH 1 showing floodplain facies (A) and the New England derived mixed-load to dominantly bed-load tributary channel facies (B and C) which subsequently occupied this location. Each length of core is approximately 1 m.
Figure 7.21 Vertical profile of floodplain, channel margin facies of the New England derived mixed-load and alluvial fan systems in DM Gunnadilly DDH 1 sequence shown in photo 7.29. For reference see figure 7.8 (from Tadros 1993i, fig. 14.32)
Figure 7.22. Geophysical log pattern, Eastern fluvial sequence in DM Narrabri DDH 1, upper Black Jack Group. For reference see figure 7.2 (from Tadros 1993, fig. 14.33)

is in sharp contrast to the signature of the underlying Breeza Coal Member and its equivalents (e.g. figure 7.4) and the overlying highly serrated floodplain tuffaceous coaly sequence (figure 7.22).

Two types of channel fill deposits have been recognised in drill core: axial; and tributary.

The axial channel fills are thick to massively bedded pebble conglomerate and medium- to coarse-grained sandstone with tabular cross-stratification, sometimes marked by imbrication of the grains or by
their parallel planes of inclination (figure 7.23 and photo 7.27). Interbedded siltstone is rare, but where present, is laminated and from 0.1 m to 2 m thick. Locally (in the central, southern and south-eastern parts of the Mullaley Sub-basin), a zone of intermixed lithology is present at the base of the axial channel sequence. The lower part of this zone consists of quartz-enriched lithic sandstone which grades upwards into distinctly lithic sandstone and conglomerate (figure 7.23 and photo 7.11). Enrichment in quartz sands at the base of the channel fill sediments is interpreted as caused partly by initial intermixing of the eastern and western fluvial sediments until the supply of the Lachlan Fold Belt material was completely shut off and partly by reworking of the underlying quartz-rich sediments of the Western Fluvial System.

The tributary channel fills are transitional into the more proximal alluvial fan deposits preserved along the south-easternmost part of the Mullaley Sub-basin close to the present trace of the Hunter - Mooki Fault System. The conglomerate of the tributary channel fills is more dominant, coarser grained and more thickly bedded (4-5 m thick) than that of the axial channel fills (figure 7.23). The conglomerates are predominantly clast supported but some matrix-supported conglomerates 1-2 m thick are recognised. Sandstones are generally coarse-grained and granular with tabular cross-bedding. Cross-bed sets are easily identifiable in core by grain imbrication or by their parallel planes of inclination.

CHANNEL MARGIN FACIES

Levee and crevasse splay deposits represent the channel margin facies and generally consist of laminated claystone/siltstone units 2-3 m thick, interbedded with fine- to medium-grained sandstone, siltstone and carbonaceous siltstone beds up to 1 m thick (figure 7.21). Interbedded tuff, tuffaceous sediments and thick stony coal seams are common in the floodplain facies.

Poorly sorted, irregularly bedded sandstone and siltstone with climbing ripples, wavy and planar laminations, root traces, soft sediment deformation structures and plant debris represent levees. Crevasse splays are represented by fine- to coarse-grained sandstone arranged in either upward-coarsening or upward-fining sequences. Common sedimentary structures are climbing ripple (photo 7.30) and medium-scale trough cross-lamination, fine cross-stratification, mud drapes, graded bedding, scour-and-fill structures and macerated plant debris, generally along stratification planes.

FLOODPLAIN FACIES

Carbonaceous claystone and thick coals are an integral part of the floodplain facies, representing peat swamps established in the broad interchannel areas (figures 6.17F and 7.21; photo 7.29). Subordinate, massively bedded pebble conglomerate and cross-stratified sandstone units with scoured pebbly bases up to 2.5 m thick interspersed with the floodplain facies represent brief incursions of the river channel into the floodplain area (figure 7.21). Also interspersed with the floodplain facies are upward-fining sequences of cross-bedded sandstone with scoured pebbly bases, siltstone and claystone. The siltstone and claystone at the top show fine cross-laminations, climbing ripples and root
Figure 7.23. A vertical profile of axial and tributary channel facies and overlying alluvial fan deposits of the New England derived Eastern Fluvial System. The profile records part of the sequence above the Breeza Coal Member in DM Wallala DDH 3 showing a zone of intermixed lithologies at the base of the Eastern Fluvial System. The interval between 220 m and 212 m is also shown on photo 7.11. For reference see figure 7.8. (From Tadros 1993i, fig. 14.28)
Figure 7.23. (continued)
Photo 7.30. Climbing ripples in fine-grained sandstone/silty sandstone of the channel margin facies in DM Gunnadilly DDH 1 formed as a result of high sedimentation rates during decreased current velocity such as during periods of receding floods. Core diameter is 45 mm.

Traces. These deposits are interpreted as lateral accretion units such as point bars. Tuff and tuffaceous sediments were also preferentially preserved in the floodplain. Photo 7.31 shows an excellent example of the floodplain facies, rich in tuff, tuffaceous sediments and stony coal, in the central western area of the Mullaley Sub-basin.

The channel margin and floodplain sequence is well represented by highly serrate log facies (figure 7.22; log facies type "f", figure 6.5) with sporadic blocky log pattern (log facies type "a", figure 6.5).

Hamilton and Beckett (1984) recognised volcanogenic sheet flood deposits up to 5 m thick which they considered may have been deposited during single catastrophic events. The percentage tuff and tuffaceous sediments and pyroclastic detritus map (figure 7.24) indicates that contemporaneous volcanism contributed up to 19% of the upper Black Jack sequence. Tuffaceous stony coal is commonly preserved within the floodplain facies of the Eastern Fluvial System (photo 7.31).
Photo 7.31. An excellent example of the floodplain facies of the Eastern Fluvial System in DM Brigalow DDH 2 characterised by tuffaceous stony coal interbedded with tuff, tuffaceous sediments and carbonaceous siltstone and claystone.
Figure 7.24. Percentage tuff, tuffaceous sediments and pyroclastic detritus, upper Black Jack Group (from Tadros 1993i, fig. 14.34)